Comprehensive approach to rural electrification planning and policymaking: A systemic roadmap for sustainable universal access to electricity

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WORKING PAPER INFO

Archive history:
First draft 0.1 2016-03-16: AGG
Present draft 0.18 2016-11-25: AGG, AR, JIPA

Keywords:

Universal Access, rural electrification, planning, regulation, energy policy, Sustainable Energy for All, micro-grids, photovoltaic systems, grid extension, models, energy services, electrification levels, quality of service, governance

Acknowledgements:

This comprehensive approach is built on the foundations, models and research work developed jointly by professors, researchers and students who integrate the MIT–Comillas IIT joint research team on Universal Access. Special thanks are given to Robert Stoner, Douglas Ellman, Claudio Vergara, Reja Amatya, Yael Borofsky, Vivian Li, Patricia Levi, Lily Mwalenga, Cailinn Drouin, Turner Cotterman and Stephen Lee at MIT; and to Fernando de Cuadra, Carlos Mateo, Rafael Palacios and Pedro Ciller at IIT.

ABSTRACT

[Comprehensive approach main features for planning, regulation and policy decision-making]

1 Introduction

Universal Access to electricity and modern domestic heat that satisfies a very essential level of service today, without compromising the satisfaction of future growth in energy needs accompanying the fulfillment of an equitable sustainable development of our communities, is a target within reach of our society.

The achievement of this global goal requires careful consideration of a number of multidisciplinary national, regional, local and individual factors. It will require the massive attraction of private capital and, very likely, the implication of large energy corporations, though small and decentralized approaches, either transitory or not, can not be ruled out and are already taking place. Success will only take place where sustainable and attractive business models can be established, with the active engagement of the beneficiary communities. These models must include:

a) The determination of the more adequate low-cost supply technologies for each customer according to its own location, consumption, needs, traits and circumstances, but approached comprehensively taking into account every user within a whole electrification region.
b) A strong focus in the customer priorities to access energy services; domestic, communitarian and productive; adequate in quality and quantity; sustainable from the social, economical and environmental angles; which guarantees affordability by the least-advantaged population; with efficient and sufficient funding and financing mechanisms that match the needs of the different actors essential for the electrification process; and an adequate risk fencing mechanisms.
c) A decisive political commitment to eradicate extreme energy poverty and to close the energy access gap; the integration and coordination of energy and other economic, social and sustainable development policies; a transparent and sound regulatory framework that clearly defines rights and obligations of the actors involved and, very specially, the remuneration rules for the provision of universal energy services. To this end, it is critical to acknowledge that in most of the environments, non-refundable grants and subsidies will be needed to cover the gap between the cost of electricity service and the capacity of payment of the beneficiaries (as always has been for the extension of the grid to rural areas, both in developing and developed countries).
d) The governance mechanisms that harmonize the performance of those actors, paying close attention to the funding sources of the electrification process and the multiplicative attraction of private capital.

All this requires approaching the problem not only from a broad perspective, but with a daring ambition that matches the magnitude of this challenge, and to do so it is necessary to "*think BIG*", aided by the support computer models and decision-support methodologies that internalize the massive amount of information implied for the detailed design of the different power systems required (grid and off-grid) to provide electricity to each and all customers within a given study area according to their specific needs and socio-economic characteristics.

A comprehensive approach that at the same time apprehends the extent of the adage, which claims that "good government is in the details" or, *a contrario sensu*, that "devil is in the details".

Therefore, models must also consider the inter-dependent entanglement of these energy systems: how new connections impact and require distribution, transport and generation reinforcements upstream: how the particular local, regional or national characteristics of the energy framework are affected by any additional demand of fossil fuels, or by an increased penetration of distributed generation (whether off-grid or connected to the network either now or in a foreseeable future); how social, cultural, economic and organizational perspectives must be factored in by decision makers, providing useful and meaningful information to support their planning and investment decisions.

The different tools and models used for this paper are actual prototypes under development by a joint team of MIT and IIT researchers. They make use of detailed geo-referenced information regarding the location and characteristics of the users, energy resources and existing infrastructure, and of models that produce nearly-optimal designs of the power system for different assumptions and circumstances, therefore firmly informing decision-making for large territories electrification planning. The ambition of these models must also match the challenge ahead, being able to bring together the gap between the needs of all and each individual energy supply and of the whole energy system, and to do so it is necessary, once again, to *think BIG*.

2 Objectives and structure of the working paper

This paper focuses on presenting our key findings about this complex and formidable challenge, after years of joint work and collaboration with organizations and practitioners with broad experience: the main challenges, the limits of present approaches and the necessary strategies and tools to transcend them.

The scope of the paper reaches out to the "big picture" of universal electrification in a certain country, state or large region, but keeping a close-up look on the actual systems (both grid and off-grid) required to supply whether a single household, a small village or a whole area. Building up from that very detailed techno-economic power systems approach, this comprehensive approach aims at achieving an adequate access[1] to electricity supply for everyone, that enables attaining dignifying levels of sustainable development within the next two decades. This is the true great challenge, and falling short is not acceptable.

[1] The Secretary-General's Advisory Group on Energy and Climate Change (SG AGECC, 2010) defines Access to energy as: "*access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses […] needed to improve livelihoods in the poorest countries and drive local economic development.*". A definition of Access to Electricity can be immediately inferred.

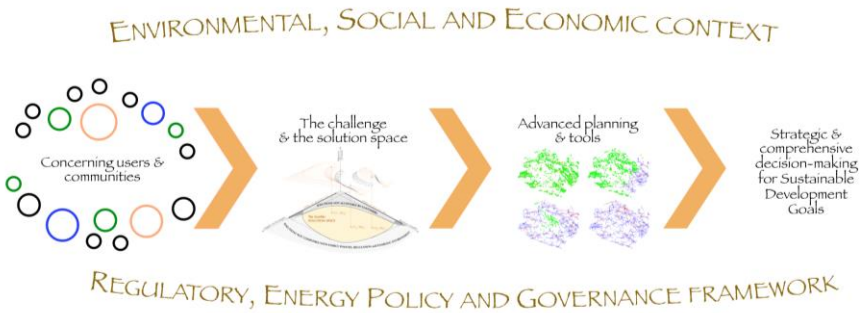


Figure 1 Roadmap milestones, context and enabling environment for universal electrification planning and policy decision-making.

The structure of this roadmap, depicted in Figure 1, starts focusing on context of the universal electrification challenge, following this *Think Big* approach to immediately set the focus on the beneficiaries and their communities, integrating the perspective of the different categories of users focusing on their needs, capacities and opportunities for development (Brazilian & Pielke, 2013; Santos, 2015; Schillebeeckx, Parikh, Bansal, & George, 2012) and providing for future increases in the demand ladder above this "one bulb and a phone charger" minimum level. The following section identifies the main challenges of universal supply of electricity and its implications for the choice over well established and emerging innovative technologies, suitable whether to extend the network or for off-grid electrification (González-García, Amatya, Stoner, & Pérez-Arriaga, 2016); and over the establishment of effective business models, which need to be sustainable over a diversity of social, economic, environmental, geographical and cultural conditions, analyzing their scalability and replicability.

Subsequently the paper briefly describes and characterizes the techno-economic procedure, computer models and decision-making support tools required for advanced planning, including excerpts from case studies developed in India, Africa and Latin America,

This roadmap to Universal Access will ask for an appropriate regulatory, political and financial framework, which enables the attraction of the necessary private capital that will multiply the impact of the unavoidable clear and reliable remuneration and subsidy schemes, together with up-to-the-task public and international funding programs that set this massive electrification effort in motion.

This cannot happen without the active engagement of the beneficiaries and their communities, from the design stages to the final exploitation of the power supply. The scalability, replicability and upgradability of present and future successful approaches will require from the decisive involvement of major companies (e.g. energy utilities, banks, providers along the whole energy supply chain), though good examples of decentralized approaches –either transitory or not– can not be ruled out in many circumstances.

Finally, bringing together the ecosystem of actors that need to be involved in a process of this magnitude will require of governance mechanisms that allow large companies, local entrepreneurs, NGO's, government institutions, international agencies, academia and society to engage in a long term, efficient and sustainable electrification process for everyone.

3 Getting the context right: challenges and boundaries in a roadmap to universal access to electricity

Approaches to Universal Access to electricity, either in theory or in practice, generally present a number of limitations. They come from not considering utterly unacceptable the present inequity in access to modern energy services, with the corresponding legal, budgetary and policy implications, among other considerations; from lack of ambition in the electrification objectives and from the evaluation of the consequences of a more realistic approach; form the shortsightedness of governments, donors and regulatory authorities in establishing the conditions for sustainable business models of a dimension commensurable to the magnitude of the challenge.

3.1 The equity gap

1.2 billion people lack Access in 2013 (ESMAP, World Bank, & IEA, 2013), 85% of them live in rural areas, and 87% in Sub Saharan Africa and Asia (IEA, 2013). Without dedicated policies, in 2030 this amount will still be around 1 billion people. This paper focuses in access to electricity, but it is important to note that 2.6 billion people rely today, and will steel rely in 2030, in traditional biomass for cooking and heating.

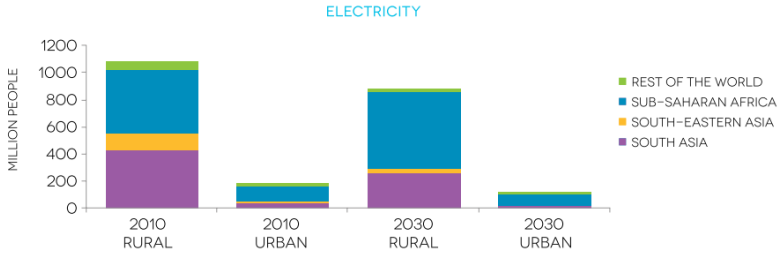


Figure 2 Access to electricity in rural and urban areas in 2010 vs. 2030 (ESMAP et al., 2013)

Fight against energy poverty not only affects developing countries. In 2012 54 million of European citizens (10.4% of the population) were not able to keep their homes warm in winter, or were late in the payment of their electricity bills (Steve Pye et al., 2015).

Universal Access to modern energy services is the first target of the goal number seven (SDG 7) of the Declaration of Sustainable Development Goals 2015-2013, sanctioned by United Nations on September 25th 2015 (Practical Action, 2014; Secretaría General de Cooperación Internacional para el Desarrollo, 2014; UN General Assembly, 2015a, 2015b; UNDP, 2015).

Comentado [AG1]: More than a light bulb perspective

3.2 The ambition gap

Achieving Universal Access to a first acceptable level of modern electricity will require (IEA, 2011b) an approximate investment of 30.6 billion USD a year (60% of which should be capitalized in Africa, and 38% in Asia) up to a total of 640 billion of accumulated investment in 2030, as can be seen in Figure 3.

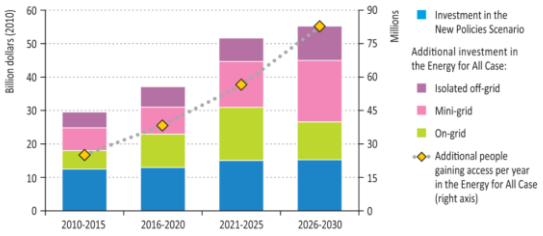


Figure 3 Annual investment in electricity access and amount of new connections per year in the Energy for All scenario (IEA, 2011b)

This amount adds up to no more than a 2% increase in the estimated investment of the New Policies Scenario 2030 (IEA, 2011a) and could be funded with 1.25% of the annual electricity bill of the OECD countries. These calculations are based on the assumption that the initial access threshold is a 250 kWh consumption per year in rural households, and 500 kWh in urban ones, raising up to 800 kWh by 2030, 50 times less that the present per-capita consumption in Spain, or 140 times less than United States or Canada, including productive, community and commercial energy services of our modern society (Brazilian & Pielke, 2013).

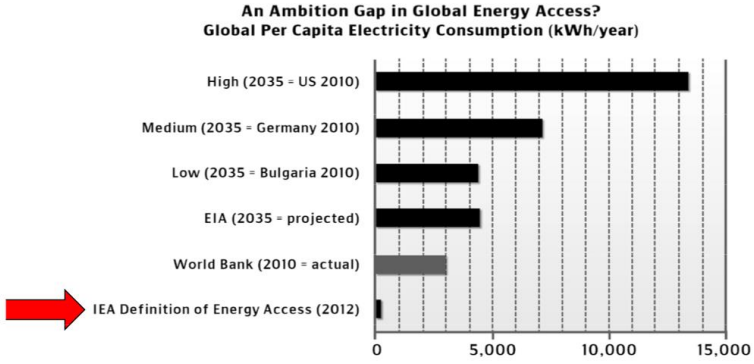


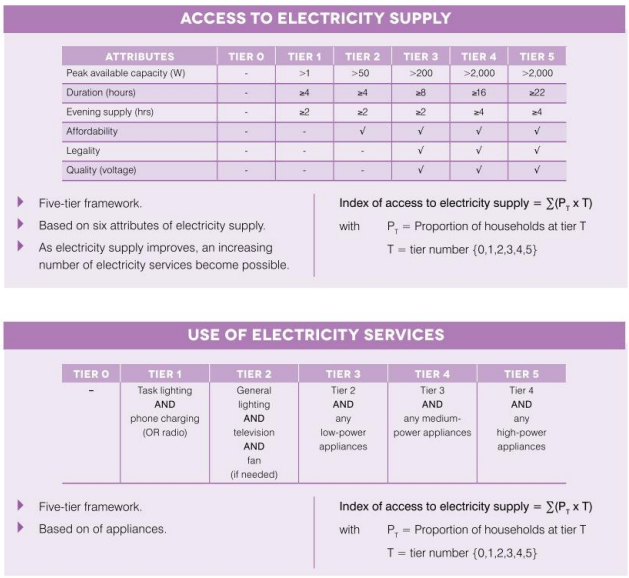
Figure 4 Global per capita electricity consumption in kWh/year (Brazilian & Pielke, 2013)

But this first step up the electrification needs at a global scale cannot be seriously approached without acknowledging that the present inequity in the access to energy services is unacceptable, without daring to lock more ambitious electrification targets and accept their implications, and without creating the conditions to attract the enormous amount of private capital needed to enable the creation of sustainable and viable business models that service the needs of the less-favored populations. "*The world's poor need more than a token supply of electricity. The goal should be to provide the power necessary to boost productivity and raise living standards.*" (Brazilian & Pielke, 2013).

Furthermore, a deficient definition of Access to electricity can misrepresent the challenge. In some countries a village is considered "electrified" when a small percentage of households (in

some cases only 10% of them) receive electricity supply during a few hours a day, even if this supply is not very reliable. This population might prefer decentralized solutions that guarantee a very basic service during the hours when it is most needed.

The Sustainable Energy for All program (SE4all) promoted by United Nations and the International Energy Agency (IEA) defines six electrification levels (*Tiers)* of the so called energy ladder (ESMAP et al., 2013), taking into account on one side the characteristics of the electric supply, and on the other the energy services that the users demand (see Figure 5).



ACCESS TO ELECTRICITY SUPPLY

ATTRIBUTES	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Peak available capacity (W)	-	>1	>50	>200	>2,000	>2,000
Duration (hours)	-	≥4	≥4	≥8	≥16	≥22
Evening supply (hrs)	-	≥2	≥2	≥2	≥4	≥4
Affordability	-	-	√	√	√	√
Legality	-	-	-	√	√	√
Quality (voltage)	-	-	-	√	√	√

- Five-tier framework.
- Based on six attributes of electricity supply.
- As electricity supply improves, an increasing number of electricity services become possible.

Index of access to electricity supply = $\sum(P_T \times T)$

with P_T = Proportion of households at tier T

T = tier number {0,1,2,3,4,5}

USE OF ELECTRICITY SERVICES

TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
–	Task lighting **AND** phone charging (OR radio)	General lighting **AND** television **AND** fan (if needed)	Tier 2 **AND** any low-power appliances	Tier 3 **AND** any medium-power appliances	Tier 4 **AND** any high-power appliances

- Five-tier framework.
- Based on of appliances.

Index of access to electricity supply = $\sum(P_T \times T)$

with P_T = Proportion of households at tier T

T = tier number {0,1,2,3,4,5}

Figure 5 SE4all framework of electricity access level (ESMAP et al., 2013)

In section 4.4 we detail our proposal for setting access to electricity levels that are meaningful from the point of view of electrification planning, which expands the approach of measuring access of households to electricity services, including social and productive needs at community level, therefore providing solid ground to the elaboration of electrification plans and select electrification modes for a whole community of beneficiaries, which will enhance the sustainability of the accompanying business models, taking into account the synergies between the variety of users, the existence anchor loads and a full range of energy services demanded by a specific electrification shire, which is the focus of this comprehensive electrification planning approach.

3.3 The business opportunity gap

Every year, people without access to electricity spends 47 billion USD in low-quality alternative solutions (candles, disposable batteries, phone charging and kerosene for lighting) to satisfy their basic needs for lighting and communication (IFC World Bank, 2012; Lighting

Africa, 2010, 2011, 2013; Prahalad, 2006). Out of a total of 274 million of non electrified households (roughly 1.3 billion people) in 2010, a potential market can be estimated for different electrification modes (or supply technologies) and willingness to pay / capacity of payment, as can be seen in Figure 6.

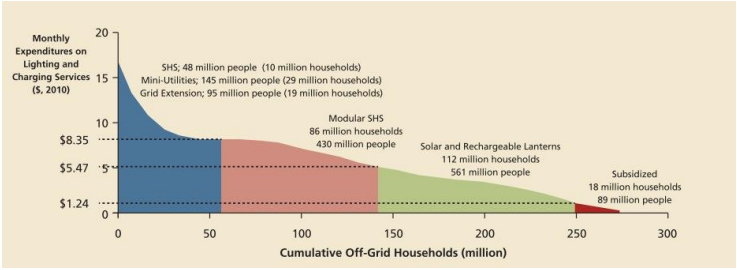


Figure 6: Potential market for access to modern electricity in 2010 (IFC World Bank, 2012)

From this pure market perspective, without taking into account any additional subsidies, up to 290 million people (58 million households) could benefit of a medium quality access to electricity for less than 8.25 USD per month (most of them micro-grids or highly reliable isolated systems, but 95 million people would also get access to the grid extension), representing an actual market of seven billion USD per year. Under this affordability level, 430 million people (86 million homes) could afford very efficient third generation small solar household systems (SHS), which would be able to light two LED lamps and a phone charger, or power small appliances as a radio, with a potential market of another seven billion USD. For the 561 million people (ñ112 million families) with a capacity of payment of less than 5.47 USD, the market of solar kits and portable or rechargeable lanterns will reach 4 billion USD. Finally, under the threshold of 1.25 USD per month, commercial approaches will never be viable, not even to achieve this minimum electrification level for the remaining 90 million people, for whom the need of appropriate subsidies is above discussion.

From the existence and segmentation of this market, two conclusions can be extracted:

1. Sustainable and appropriate business models will be needed for each one of these market niches, at national and regional levels, which will allow the massive attraction of private capital that will be needed to achieve the level of investment needed for Universal Access.
2. The appropriate design of cross subsidies or non-refundable funds would allow closing the financial gap between the appropriate technologies needed for a suitable energy supply, and the capacity of payment of the beneficiary communities, so this suitable level of electrification could be affordable for every household.

3.4 Harmonizing climate change and universal access challenges

Developed and developing countries must confront both the combat on Climate Change and the achievement of universal access to energy. Comparing our outcomes with the New Policies Scenario of IEA, achieving Universal Access in 2030 would increase the global electricity generation in only about 2.5%. The demand on fossil fuels would grow in about 0.8%, and carbon emissions would be increased in 0.7%. These both figures are in fact irrelevant in comparison with the main Climate Change concerns (IEA, 2011b; IPCC WGIII, 2014).

This small increment in emissions is due mainly to the low consumption per capita and high share of renewables that the Energy for All Scenario assumes. But it is difficult to believe that in the long periods of time considered for Climate Change analysis (2050 or for the end of this very century) the consumption of this population will stay under this very low thresholds (Brazilian & Pielke, 2013; Wolfram, Shelef, & Getler, 2012). It is clear that the selection, from the first moment, of an adequate Universal Access roadmap will need to be consequent with a foreseeable growth of energy needs and consumption, and to the energy sources that satisfy them.

Comentado [AG2]: Include collaborative perspective from ICADE paper

3.5 The human, environmental and economic sustainable development challenge

Energy is a pre-requisite for economic development (Brazilian, Nussbaumer, Cabraal, et al., 2010; Legros et al., 2009). On the other side, the prosperity enabled by economic growth fosters the demand of better and higher energy services (IEA, 2004). This virtuous circle can be observed in different countries, but development is a complex phenomenon characterized in many cases by its non-linearity. Achieving a minimum level of lighting and modern cooking improves drastically the health quality of household environment (Legros et al., 2009), but to unchain this virtuous circle a much higher level of energy services will be required, to rise up added-value services in agriculture, commerce, industry or public services.

Though an increase (or reduction) of energy access can not always be interpreted as progress (or decrease) in terms of development (Brazilian, Nussbaumer, Cabraal, et al., 2010), and while energy by itself is not sufficient to eradicate extreme poverty, no country has been able to improve its situation in recent times, without achieving a substantial increase in the use of modern energy forms (Legros et al., 2009). Access to energy improves productivity, generation of local revenues and access to education, as can be noticed in the different graphs shown in Figure 7.

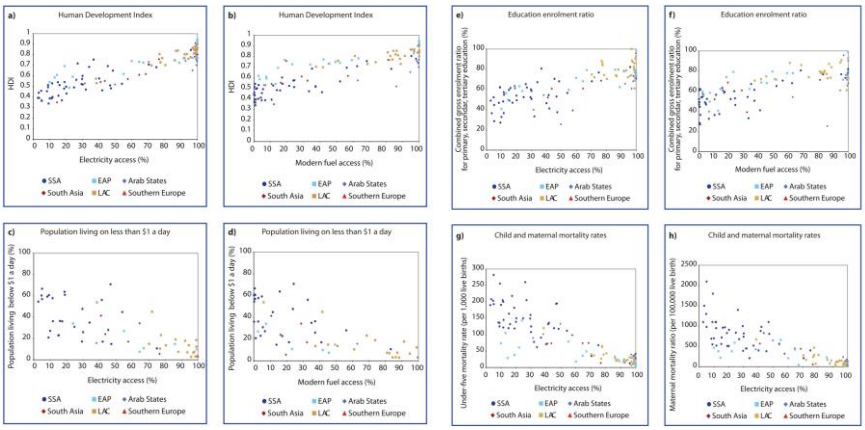


Figure 7 Energy Access and development indicators, PNUD 2007 data (Legros et al., 2009)

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Energy supply, according to the International Energy Agency (IEA) is the most critical factor to achieve the goals of our international development agenda, now established by the Sustainable Development Goals (UN General Assembly, 2015b; United Nations Secretary-General. Ban Ki-moon, 2015). In fact, the need for sustainable, affordable and efficient energy for all exceed the margins established by SDG7, that establishes 2030 as the target year to achieve universal access to electricity and modern heat for all, to become a transversal need to achieve many other of the selected goals. Figure 8 includes a few examples of key energy considerations and services essential for the achievement of the 17 SDG's.

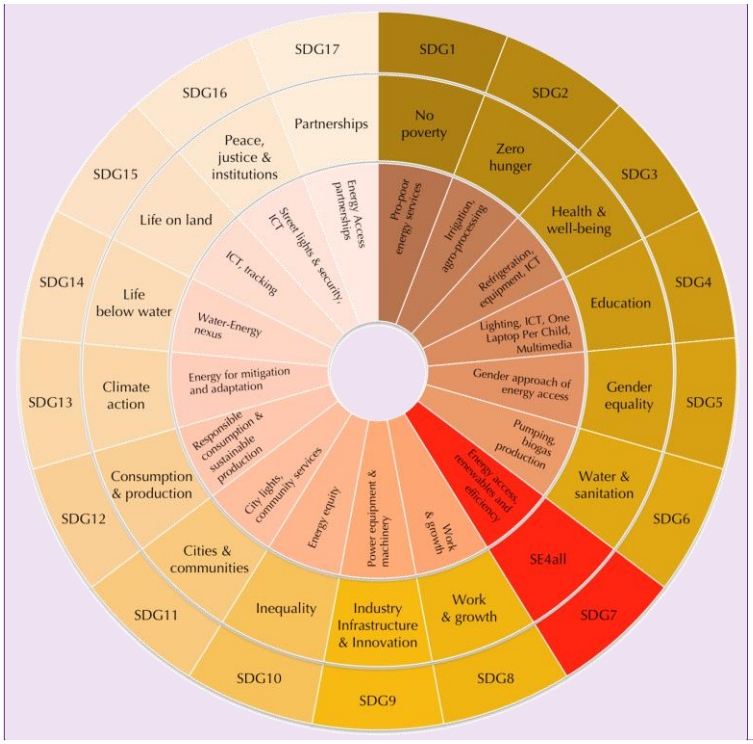


Figure 8: Transversal dimension of energy and key universal access challenges for each Sustainable Development Goal in the Agenda 2030

Energy is a fundamental pillar in fostering agricultural productivity and income generation for impoverished communities (SDG 1 and 2); to the essential energy required for refrigeration, power medical equipment or telemedicine services in health centers (SDG 3), lights and electricity services for learning (SDG4), the impact of electrification in gender equality (SDG5), clear water pumping and biogas generation out of sanitation processes (SDG6), the nexus between the growth in economic activities, job creation and energy requirements (SDG8), the needs to power equipment and machinery for innovation, industry and infrastructure creation (SDG9), the attention to the energy divide impact on inequity (SDG10), the need for light and

Comentado [AG4]: SDG 12 and others, emphasize energy component

community services in sustainable cities (SDG11), responsible consumption of energy by end users and sustainable production energy saving practices (SDG12), the enormous implications of energy in the mitigation and adaptation strategies (SDG13), the water-energy nexus (SDG14), the impact of energy infrastructures in water and land life preservation, or the power required by modern stewardship technologies (SDG14 and 15), the need of street lights or ICT to improve security in cities (SDG16) and the growing need for governance and program partnerships also for sustainable energy (SDG17) are but a few examples of the many threads that entangle sustainable energy and development.

Comentado [AG5]: Add appropriate references

3.6 The favorable international climate opportunity

Universal Access has received an extraordinary impulse in the political and scientific international and national agendas in the past few years. *Sustainable Energy for all (SE4all)* (SG High-Level Group on Sustainable Energy for All, 2012) initiative has been assumed in its integrity by the Sustainable Development Goal number 7 (UN General Assembly, 2015b), establishing global targets for 2030, with the following targets by 2030:

- *«7.1 Ensure universal access to affordable, reliable and modern energy services.*
- *7.2 Increase substantially the share of renewable energy in the global energy mix.*
- *7.3 Double the global rate of improvement in energy efficiency.»*

With two additional aims:

- *«7.a 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.*
- *7.b 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.»*

The International Energy Agency has also developed a Global Tracking Framework to measure and monitor the progress of SE4all/ODS7 targets (ESMAP et al., 2013) promoting the harmonization of surveys, energy data and statistics around the globe.

In addition to these global efforts, many large-scale regional initiatives have been launched, as *Lighting Africa* (and its branch *Lighting Asia*), *Power Africa* by the Government of the United States, and the European Union *UE-Africa Alliance*. The cooperation program *Energysing Development Initiative* by the European Commission assumes the objective of providing access, by 2030, to 500 million people in developing countries, more than one third of the global target. Europa confronts this challenge of Universal Access to Energy in its *Europe 2020 strategy for smart, sustainable and inclusive growth* (European Commission, 2010b) as well as in *Energy 2020. A strategy for competitive, sustainable and secure energy* (European Commission, 2010a), where the Commission states that sustainability needs to be at the core of energy and development policies, balancing the use of limited resources with the fight on Climate Change.

Many individual governments, as Japan, Spain, Germany, United Kingdom, also support in their Post 2015 development agendas, specific actions towards sustainable universal access to modern energy services, enhancing also the level of coordination between their different

programs and mechanisms at national level through the sector-wide approach to international cooperation, and at international level by joining common initiatives sponsored by United Nations, the European Union or by several international consortiums.

Comentado [AG6]: Add ref.

Despite this effervescence of government and public-private initiative, the volume of resources effectively agreed is still far below the amount required even for the most essential level of Universal Access.

4 Concerning users: Good planning is in the details

Given the huge amount of people without electricity access –in many cases even more than what is officially declared–, the planning approach considered here is based on the analysis –using geographical information methods– of large expanses of territory, where millions of people may live and where the first decision to be made is to decide which type of electrification mode –grid connection, independent microgrid or stand alone individual system– is most suitable for each household.

A critical component of this planning effort is the estimation of the demand to be supplied. Several attributes of this demand are of essence to be able to do a good planning job:

i) The expected time profile of this demand, both at the time of connection and its future evolution, which depends on the services or final uses to be provided and the efficiency in their supply.
ii) The value of the utility that these services have for the final user or for the community that this user belongs to, since this has to be commensurate with the effort dedicated to the provision of the services (see Figure 9[2]).
iii) The value for the end consumers of the level of reliability or, in general, the quality of service in the immediate provision of the electricity services.
iv) A minimum level of electricity services (e.g. basic lighting and communication; this will depend on the context) with a minimum quality of service that have to be inexcusably provided to all potential consumers, since this level of access has to be considered a fundamental human right.
v) The location of each and every individual customer to be electrified, the type of consumption, the existing infrastructure and energy resources (for a full list of model inputs, please see Section 5.6)

[2] The figure relates the demand for electricity and its price. The demand for electricity increases when its price drops. The important point here is that the utility for the consumer that is associated to the first watt hour of electricity (the use of the first light and to charge the cell phone) and the price that the consumer is willing to pay for it is very high. Once the most basic needs are covered, the willingness to pay rapidly decreases, especially in those cases where the affordability level is very low.

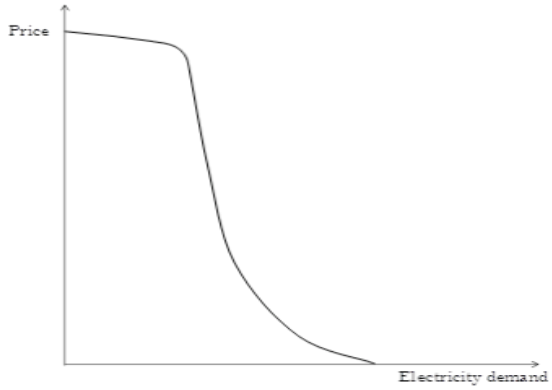


Figure 9: The consumer's utility function or price-demand curve

4.1 What energy for what needs? Individual electrification levels

Planning means to make decisions, choosing among possible options. Another feature in the demand to be characterized is the definition of several meaningful and potentially attainable levels of electricity access for the considered population. These levels would constitute the different targets to choose from in the planning process. And, as it will be discovered when reading this document, demand characterization cannot be isolated in the planner's decision making process from other features in a meaningful planning option, such as the strategy with respect to regulation of off-grid electrification, the priority given to grid connection or the restrictions to the use of fossil fuels in off-grid electrification; they all come together as a package, with demand being just one of the ingredients.

Demand for electricity in rural electrification planning is examined here from several viewpoints, trying to expose the difficulties that exist in its characterization.

4.1.1 A first approach to the difficulties in estimating & characterizing demand goals for electrification planning

This is a list of the difficulties that rural electrification planners typically find when trying to estimate and characterize the demand of the potential consumers to be electrified.

- Difficulty in finding information on the demand of similar population that is electrified already in more or less the same territory and under similar conditions. Official data – like census and available public surveys– typically do not provide the desired level of detail, or they do not do it with sufficient geographical granularity to be useful in this context.
- The utility value of electricity access at different levels and the loss of utility associated to poor quality of service can only be estimated indirectly from other sources of information and with much difficulty and uncertainty.
- Ambiguity in the meaning of "electricity access" makes it difficult to define the target level to be achieved in the rural electrification planning process. For instance, what

does it mean for a household or business in a developing country to "have electricity access"? This apparently simple question has a complex and contested answer.

- Should a household with a solar panel that runs a couple of lights and a cell-phone charger be deemed 'electrified'?
- How about a home connected to an electricity grid that is chronically unreliable and intermittent, like parts of India's grid[3]?

Comentado [AG7]: •Collective satisfaction of individual energy needs: education (cases of communities that prefer electrification in the school or the sports field, instead of individual households in Africa and Andine areas) + joint utility (sharing TVs, refrigeration).
•More than a lightbulb
•Utility vs affordability – Impact of high efficiency appliances – killer 3G technologies

4.1.2 Implications of the lack of a precise definition of access

How electricity access is defined has important implications for what types of interventions the electrification planners will design[4]. For instance:

- Defining access only on the household level might cause planners to forget that household electricity is not the only factor to consider when it comes to creating economic opportunities.
- Setting expectations low will create a situation in which people have access to basic lighting, but will not ever achieve the level of electricity necessary for irrigating fields, powering small manufacturing operations, and other activities that allow people to get out of poverty.
- A grid connection may seem like the ideal electricity access option, but in reality, the grid may not provide very many hours of service per day, and not even on a regular basis. More reliable off-grid systems, like solar home systems and micro-grids, can provide more predictable electricity supply, but typically only a few hours per day.

Among the attempts to define some objective levels of electrification access, the best known is the tiers classification proposed by the World Bank's Sustainable Energy for All Framework. These 5 tiers range from one watt of peak capacity for four hours a day at the bottom, to over 2,000 watts of capacity for over 22 hours per day at the top-most tier. Each tier is also described in terms of the typical electricity services (lighting, phone charging, fan, TV, etc.) that are provided for the corresponding level of consumption. It is important to note that the first classification (based on kW and kWh of consumption) has to be continuously updated with the spectacular advances in energy efficiency that have been recently achieved with LED lights and other appliances[5].

Another much referenced and somewhat questioned definition of electricity access is the one used by the International Energy Agency (IEA) in their popular annual World Energy Outlooks. The IEA defines initial electricity access as 250 kWh per year for rural households and 500 kWh for urban households, projecting that this base level will increase to 800 kWh per person by 2030. Note that this equates to roughly 50-100 kWh/year per person, about 200 times less of that consumed by the average American or Swede, or about 50 times less than the average

[3] In the District of Bihar in India households only receive 1.3 hours of service per day in bad months, and 6.3 hours in good months.

[4] It may have also a substantial impact on future global carbon emissions. But this is a different story, which will be dealt with in a separate document.

[5] Such as color TVs of 6 W or radios of 1 W.

Bulgarian *(lowest in the EU)*.[6] See also Figure 10. This definition runs into the same difficulty – access represented by levels of kW and kWh, instead of services– as the SE4ALL definition that was discussed previously.

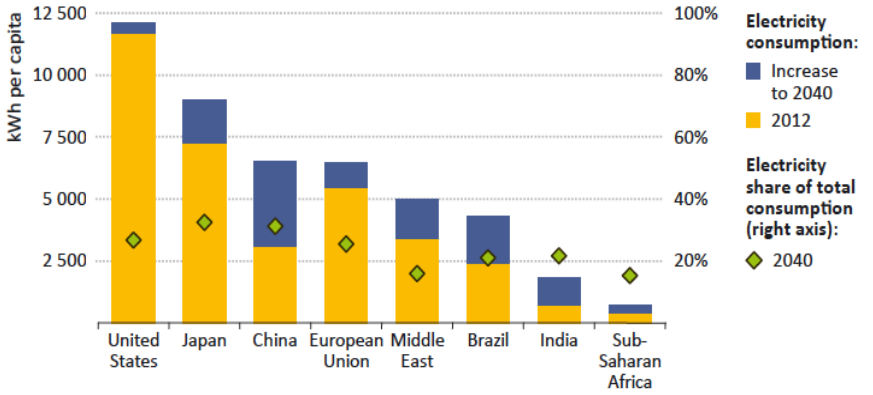


Figure 10: Annual electricity consumption per capita & share of electricity in total final energy consumption by region in the New Policies Scenario (IEA, 2014)

Another limitation in the SE4ALL and IEA definitions is that they do not distinguish between the *supply capability* of the power facilities (i.e. how much power could be supplied at any given time and with how much reliability, or for how long a certain level of supply could be sustained) and the *affordable consumption* that a household, given its level of income, could maintain, paying for the electricity and purchasing appliances.

Comentado [AG8]: Energy vs. Energy Services approach. The issue of efficiency. The need to approach them jointly (3G again)

4.2 An Energy Services approach to the definition of access

This is obviously a critical issue and probably the most relevant input in an electrification planning process. The planner has to decide whether to plan for the expected "natural" demand (the one that other consumers in the region have under estimated similar conditions), or for some estimated demand growth in some future year, or for some demand in addition to the basic residential one (such as productive or community electricity uses), or perhaps just to provide the basic minimum services (the frequently found "two lights and a telephone charger") if the available budget is very tight or the affordability of the consumers to purchase additional appliances is severely limited. Then it might be necessary to define the demand level that can be considered to be compatible with a minimum reasonable standard of living. The preferred electrification mode that the TEP could provide will probably depend much on the demand level that is input to it.

[6] Source: S.T. Coelho, J. Goldemberg, "Energy access: Lessons learned in Brazil and perspectives for replication in other developing countries", Energy Policy 61 (2013).

It is important to note the difference between "supply capability" and "affordable consumption", which has to appear in the specification of what the TEP is supposed to do and the interpretation of the results. Perhaps the ideal target in electrification planning is a level of supply capacity and energy that does not limit the level of electricity demand for services that the household could afford. The number, type and level of service of the appliances in a household –and particularly in households that have recently received electricity access– mostly depend on the affordability level, rather than on the capacity of the electrical supply.

An important consideration is that the demand level should be specified in terms of services – i.e. lighting, communication, entertainment, space conditioning, power for productive activities or cooking– and not in terms of electrical energy consumption or power. An important reason for that is that the efficiency of the appliances is evolving rapidly, and, for instance, it is now possible to provide the same quality of lighting than five or ten years ago with an order of magnitude less of consumption (Phadke et al., 2015).

The demand level to be input to the TEP, and how the input is made in terms of time horizon and what type of services to be included, is very much related to the business model to be adopted and to the utilization of the TEP, since any internal quantitative analysis will have to be adapted in terms of the economic lifetime of the facilities, rate of return, etc.

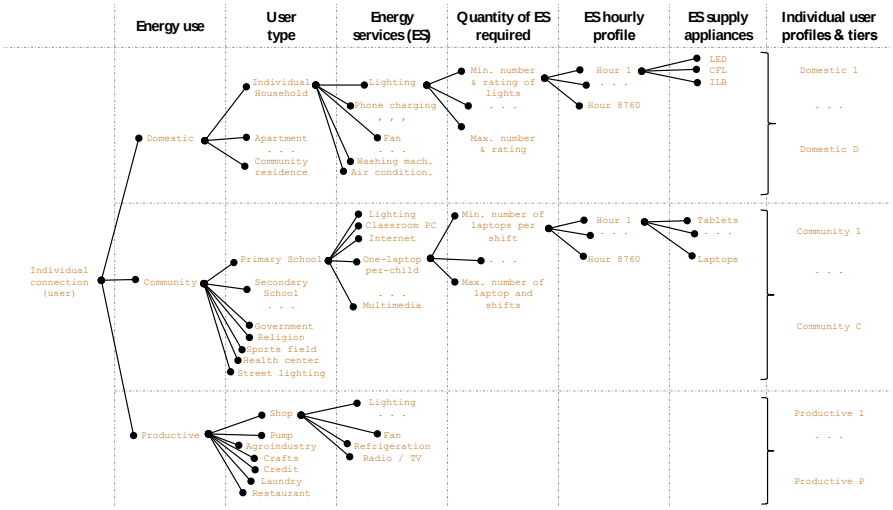


Figure 11: Individual customer Energy Services breakdown

[Explain E.S. approach to individual profiles and levels of electrification, collective satisfaction of individual needs (e.g. soccer fields in Africa or watching TV at community halls or at a neighbour's) and determination of collective profiles and tiers for a whole village or cluster]

It is therefore clear that a new definition of electricity access is needed, one that truly represents the access conditions that matter to the actual consumers involved.

4.2.1 What electricity can provide: Sufficient level of electricity access

Comentado [AG9]: Slow

Electricity can certainly improve the quality of life in a household, by improving lighting, facilitating charging the cell phones and running fans, radios, TVs and other appliances. Electricity can also undoubtedly improve community life, by providing public lighting in streets, schools and community premises, as well as facilitating water access, among other useful services.

The role of electricity in relation to productive activities, either at household or community level is not so clear cut, as most productive uses do not require a substantial amount of electricity (commerce, many forms of craftsmanship, making clothes, etc.) and, in most cases, development requires the joint contribution of several sectors (transportation, banking, education, agriculture, telecommunications, etc.) and therefore electricity access must be considered as a necessary but not sufficient factor for development. The bottom line, in relation with the definition of a minimum level of electricity access, is that the lack of electricity should not be a bottleneck for human development.

The first basic concept regarding the electricity access is that it has to be defined in terms of services provided, and not of quantity of energy consumed (kWh) or peak demand (kW), since, otherwise, the definition of access would have to change with any progress made in efficiency in the use of electricity and also with the specific customs of the people involved.

This minimum standard will depend on the specific region, among other factors. However, the Spanish Table for Universal Access to Modern Energy[7] has been proposed that an adequate level of energy for universal access purposes that can support a minimum level of dignity should allow:

Comentado [AG10]: Website (about to come)

- Lighting: Average of 300 lux at households, for at least 4 night hours.
- Electronic devices: In particular those for communications (cell phones), education and information (radio, television, computers and laptops).
- Preservation of food: Even if the ideal would be to have access to some electrical refrigerators, other preservation technologies could also provide this energy service, that should at least extend the life of fresh food in 50%, as compared to ambient conditions.
- Moreover, the electricity supply must be:
    - Reliable: With known and enough stable hours of available service, which are also the ones required for their use (e.g. night lighting).
    - Of quality: Adequate voltage rate control that prevents damaging any appliance connected to the system (e.g. +/- 10%) and that guarantees a safe operation and maintenance of the equipment.
    - Suitable: For the essential needs and capacities of each community of users, defined in a participative way and that allows the energy empowerment of that very community.

[7] Mesa de Acceso Universal a la Energía

- Affordable: Users must be able to assume the electricity bill, according to their income levels, so that energy does not collide with the satisfaction of other essential rights and needs. Subsidies, therefore, might be needed in a majority of circumstances, to guarantee this adequate level of service.
- Sustainable, from the social and environmental perspective, in harmony with business models, which are adequate to service this population at the bottom of the pyramid in rural areas.

Comentado [AG11]: Need to extend this to include details about reliability measurement and key findings in electricity access (as different to TIEPI and NIEPI for instance). As well as affordability etc… May be expand here or elsewhere???

4.3 The reference area for the electrification plan: a singular holistic instance for rural electrification (shire)

God is in the detail / the devil is in the details / governing is in the details

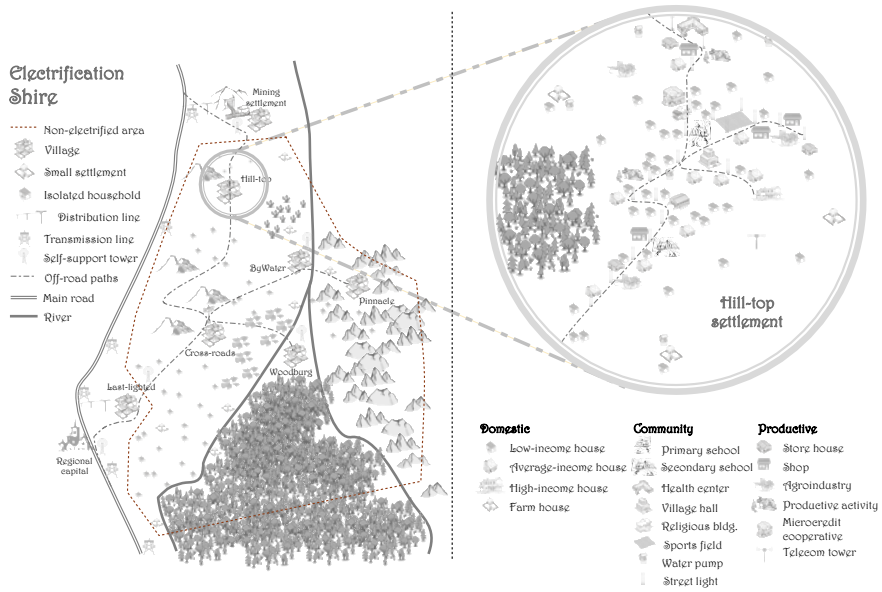


Figure 12: Illustration of geographical contexts in a model *electrification shire* and electricity users and types in a model settlement[8]

[8] Abstraction made from actual user types and consumption profiles studied by the authors in Karambi village, Rwanda. For details on the uses of energy, preferences and multi-criteria analysis of demand, please see (Santos, 2015)

4.4 Setting the target right for the electrification process: the demand targets to be met in the electrification shire

For individual households, from viewpoint of the capability of supply, three access levels would be sufficient:

- Level A or *minimum access level*: The minimum acceptable level of electricity access.
- Level B or *pre-electrification level*: Enough for at least 6 hours of lighting and the use of small appliances for about 2 hours.
- Level C or *adequate electrification level*: 24 hours of supply that can feed medium size appliances.

Comentado [AG12]: Check with work group conclusions

However, in a rural electrification planning exercise, more domestic demand levels might be necessary. Why? The planning activity may want to consider:

- A *natural demand level* for the new electrified consumers that is similar to the demand level of other consumers in the same region and under comparable conditions, including affordability. This is the most likely demand for the new consumers if there is enough capability of supply.
- A capability of supply beyond the demand level that is expected immediately, if the supply facilities have to be compatible with demand growth (this is the usual practice in distribution network planning), or with prescribed productive uses of electricity, or with the possibility of grid connection in the future. <<who pays for the extra costs of including longer term considerations?>>
- A demand level below what corresponds to the current affordability of the potential consumers, because of poor reliability of supply.

Other features, indirectly related to demand characterization, might have to be included in a planning exercise:

- Maximum priority given to the "blanket approach" at minimum access level, i.e. no other activity will be funded until all non-electrified households reach this predefined minimum access, regardless of the cost.
- A different possible approach is to give maximum priority to grid extension, leaving for a later time the supply to isolated rural communities. This option typically coincides with maximizing the number of newly connected consumers. However, this is not necessarily true, since, beyond a distance threshold value, among other factors, grid extension becomes more expensive than some off-grid options, like minigrids or stand alone systems.
- Some entrepreneurs have found that rural electrification is more effective if it starts supplying those consumers who can afford it, with whatever electrification mode is best. Then, it is expected that the electrification process will extend to the rest of the consumers in the area, while trying to minimize the volume of subsidies[9].
- Use a different more relaxed grid code for rural electrification than the standard one, as Fabio Rosa has done. Has this idea been adopted in other places?

[9] This has some points in common with the activities of Mera Gao, asking people in villages to join. Or with the home solar systems installed by SELCO and the solar residential systems in Bangladesh by xxxxxxxx,

- Xxx new technologies may create options, for instance the modular basic kits could compete with expensive grid extensions for the basic consumption niche xxx maybe quick obsolescence and the comparatively low investment costs plays a role here; do not try to cover all possibilities and take risks xxx

5 Universal electrification planning

The objective of universal electrification planning of a whole electrification shire or reference area (country, region, department, province, among other meaningful single geographical units of analysis) is to determine the best way in which electricity will be supplied to each one and every user who has a demand for it, according to his needs, capacity of payment and to the choice of technologies and business models available. Therefore, provision of electricity to each customer is completely specified by the *supply technology* and the *business model*, which will be discussed next.

The *electrification process* is how electrification planning is done. This includes who makes the decisions, based on what criteria or priorities, with the participation of whom and the procedure that is followed to arrive at a decision. On one extreme, the decision maker could be a centralized planner –such as a ministry, a publicly owned distribution company or an electrification agency–, or, on the other extreme, an individual entrepreneur in an unregulated context. In the middle, it is possible to have private entities –companies or NGOs– operating as franchisees or with a license, under specific regulations. A mix of electrification agents is also possible, as it is the case in India and elsewhere.

In general the electrification process will be a complex activity with several phases, interventions of multiple stakeholders, and involving the consideration of many factors in different ways. The outcome of the electrification process will be one of the elements in the solution space, specifying a supply technology for each considered household and a corresponding business model.

In conjunction –depending on the circumstances this could happen before, after or at the same time– with the selection of the supply technology, the planner must look for the most adequate corresponding *business model*, taking into account all the other relevant factors. In principle, this selection cannot be (easily, at least) made automatically, and the search –some sort of trial and error, or iterative procedure– should be based on weighing a diversity of factors, one of which –a major one– is the supply technology that has been tentatively selected.

How to decide among the multiple combinations of supply technologies and business models in the feasible region of the ST-BM plane? One or multiple figures of merit are needed to express the preference for one solution or another. The obvious one, which is always taken into account – and frequently it is the only one – is the cost of supply. But there are many more factors that should be accounted for in the search for the best solution to the electrification planning problem. This will be discussed later and, actually, the discussion of "the other factors" is one of the major objectives of this document. For the time being, it will be assumed here that the objective of the electrification process is to find the minimum cost solution, where the loss of utility for the consumers due to poor reliability is computed as a component of the total supply cost.

5.1.1 What are the real choices in rural electrification planning?

5.1.2 The growing presence of unregulated and unplanned electrification approaches

Comentado [AG13]: Later

According to the estimations of the IEA, a large fraction of the non-electrified population should be provided with off-grid technologies (IEA WEO, 2013 xxx). IEA estimates that 100% of urban consumers should be connected to the grid, while only 30% of rural consumers should be grid connected and the remaining 70% should be supplied off-grid with microgrids or individual stand alone systems.

In multiple places of Sub Saharan Africa it is a fact that a multiplicity of entrepreneurs are offering to cover the very basic electricity demand requirements with *unregulated & non standardized approaches.* In many cases this is done without any exogenous financial support, since the potential electricity consumers are already expending more in alternatives (kerosene lamps, candles and phone charging with third party batteries, which give an inferior service than they would pay for electricity[10]. In other cases these entrepreneurs can benefit from financial support (for instance, to cover the investment costs) from public funds, international aid or NGOs.

The major advantage of the unregulated approaches is their simplicity, since they can avoid all administrative hurdles, including requirements about security, quality of service or compatibility standards. They are meeting an essential need of the non-electrified population, when the governments and the incumbent distribution companies are not responding within a reasonable time range. However, this unregulated or very lightly regulated approach has serious shortcomings that question whether governments and regulators should intervene introducing mandatory changes. The list of shortcomings includes the following ones:

- These off-grid facilities are typically of low quality in terms of wiring, poles and metering, they run on DC voltage and there are meant just to meet the most basic electricity demand. Therefore, in general they cannot be scaled up to provide more services and they cannot be easily connected to the grid[11].
- A direct consequence of the impossibility of electricity connection is that, in case that connection to the grid becomes an option (in principle preferable, because of the lower price and –ideally– better service), the existing decentralized & typically mostly renewable technologies will be replaced by on-grid generation, which in most countries is predominately based on fossil fuels.
- This reduces the options of consumers of improving their standard of living and also of getting out of poverty, as much as this depends on productive uses (either at household or community level) for which insufficient electricity supply could be a limiting factor.
- Unregulated electricity supply leaves consumers exposed to potential abuse of monopolistic power by the supplier.

[10] The actual price per kWh of these basic electricity services is much more expensive than what is paid for on-grid electricity in most systems. Even the poorest people are willing to pay a high price for the first watthours. The utility function for electricity consumption typically starts with a very high value and then quickly declines once the most basic needs are covered.

[11] Recent technology developments in components for off-grid electrification may reduce or even eliminate these limitations.

- An unregulated scheme like this creates risk for investors, since their assets might be stranded if grid connection becomes an option for their consumers. In the end this means higher cost for consumers, since the higher the risk for the investor, the higher will be the cost to be recovered with electricity charges.

5.2 The solution space

The *solution space* is the ensemble of all possible options regarding the diverse formats of provision of electricity access: one choice of supply technology and one choice of business model. For instance, one point in the solution space could consist of an off-grid microgrid, with a solar panel and a battery, supplying electricity to a small isolated rural community, which owns and operates the facilities on a cooperative basis, and where a large fraction of the initial investment has been subsidized with a grant from the local and/or central government.

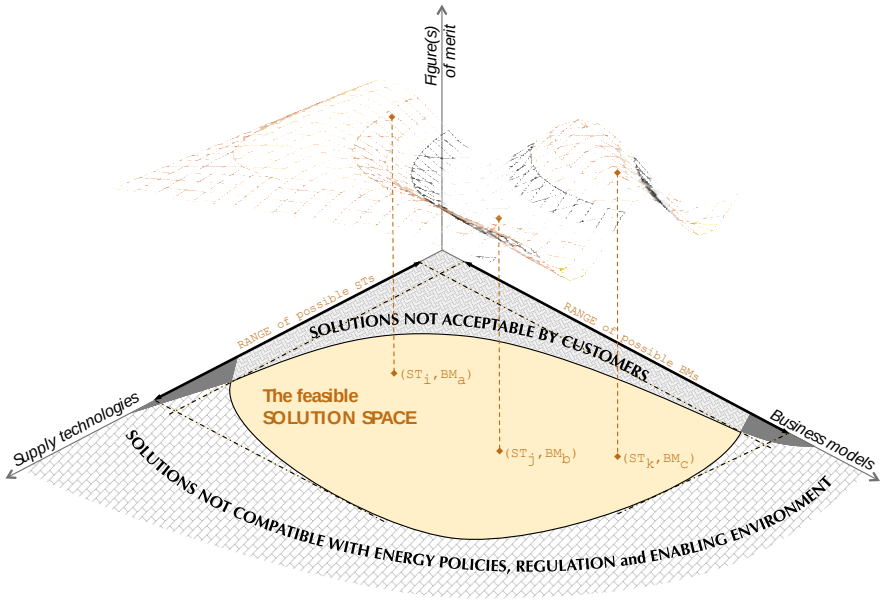


Figure 13 Representation of the *Solution Space*, Supply Technologies (ST) and Business Models (BM) that can provide electricity to community, and of the figures of merit associated with each solution

Figure 13 depicts the *Solution Space*, which is contained in the horizontal plane defined by the axis ST of the different electricity supply technologies and the axis BM of the possible business models. Therefore the points of the solution space are defined by pairs of one supply technology and one business model.

Not all possible combinations of supply technologies and business models make sense. Some may not be acceptable by the potential beneficiaries, who will express their preferences implicitly or explicitly. Still others may not be compatible with the existing energy policies and regulation. This is represented in Figure 1 by the forbidden areas in the ST-BM plane. The two major families of constraints[12] for electrification planning have been represented in Figure 1:

- *Consumer traits and preferences*: This includes the consumer preferences and perceptions, and any forms of participation of the consumers in the electrification process, either individually or as member of a community.
- *Energy policy and regulation*: The overall energy policy framework in the considered *shire*[13] and the regulation that develops it for electricity access. One could add here the coordination and mutual impacts with other policies that might be part of a comprehensive development approach, if it exists, where electricity access would be an enabling factor: health and sanitation facilities, schools infrastructure, roads and other transport means, telecommunications, logistics for fuel distribution or financial facilities.

The solutions provided by diverse electrification plans may have different levels of granularity. For instance, some plans may assign the same electrification mode to all the consumers in a sub-district or a village. The maximum level of granularity is achieved when each individual consumer –either household, school, shop or health center– is treated individually.

Comentado [AG14]: Review previous version

5.3 Portfolio of supply technologies (ST)

The *supply technology* is the electrification mode (i.e. grid connection, stand-alone system, off-grid microgrid or some hybrid scheme) that has been chosen to supply enough electricity to power the appliances that provide energy services according to the needs and capacity of payment of each customer, with its technical and economic characteristics, which make an electrification mode to be preferred in a particular situation. It is important to stress again the different between power supply and energy services. The presence of enough supply does not guarantee the access of users to the necessary appliances to provide for the service needed, while the efficiency of these appliances will have a fundamental impact on the quantity of energy needed to provide for these services.

Therefore to compare between different *supply technologies*, not only capacity but also efficiency of the whole energy system (including appliances) must be taken into account. In any case…

Electrification technologies are one of the main factors determining the features of the viable business model for universal access to energy. The interrelations of electrification technologies and supply models are thoroughly described in (Gonzalez-Garcia, Amatya, Stoner, & Perez-Arriaga, 2014), based on the following classification of electrification modes:

[12] Both the "consumer traits and preferences" and the "energy policies and regulation" can be considered also within the category of "figures of merit", therefore weighing in establishing the preference of one solution over another one.

[13] Here we assume that our *electrification shire* resemblres the country, state, province or any other territory with an authority that has full or almost full administrative responsibilities on electricity access.

- Small-and-Pico-Lighting-Systems (SPLS). These light portable devices have emerged as one of the most promising solutions to provide essential supply to un-electrified population (Eisman, Olivares, Moreno, Verástegui, & Mataix, 2013; Kilian Reiche, Grüner, Attigah, Hellpap, & Brüderle, 2010; Lighting Africa, 2013; Lysen, 2013). Recent innovations in higher efficiency (e.g. LED lights or solar panels), lighter weight and more reliable maintenance (e.g. Li-ion batteries) allow these systems to provide chargeable travelling light, stand alone low consumption street lights, or power two or three household lights for up to 4 hours, charge a phone and power a radio or even in some cases a high-efficiency TV, with less than 50Wp. These systems are further classified in solar kits and portable lamps.
- Stand-Alone-Systems (SAS). These independent power systems provide supply for a single house or customer. They can supply household, commercial, domestic and community services ranging from Tier 1 (over 50Wp) to Tier 5 (Alliance for Rural Electrification & USAID, 2011; Bhattacharyya, 2013; S. Khennas & Barnett, 2000; Kishore, Jagu, & Nand Gopal, 2013; NREL, 2001; Palit & Chaurey, 2011; Sigrist, Lobato, & Rouco, 2013). SAS can be powered by a choice of individual or mixed sources from diesel generators to solar, wind, micro-hydro or biomass.
- Isolated Mini-grids (Alzola et al., 2009; Beerbaum & Weinrebe, 2000; Brent & Rogers, 2010; DFID, 2010; Garrett Hardin, 1968; Izquierdo et al., 2011; Kishore et al., 2013; Nouni, Mullick, & Kandpal, 2009; Soto & Modi, 2012; Thomas, Azevedo, & Morgan, 2012). They provide electricity service through distribution networks within a limited area, not connected to the main grid. They can be intended for any mix of domestic, community, commercial and productive uses ranging from Tier 5 down even to Tier 1. Their choice of distributed power sources is greater than the one of SAS, as higher capacity solutions might prove cheaper for a larger amount of customers clustered within the scope of the micro-grid.
- Grid extensión (Brazilian, Nussbaumer, Haites, et al., 2010; Gaunt, 2003; Marquard, Bekker, Eberhard, & Gaunt, 2007; Pachauri et al., 2013; Zomers, 2001).. Being the most common access mode, in some cases the isolation of the users makes commercially impracticable their connection to the grid. Grid extension also faces the challenges of achieving lower connection costs for population with a low capacity of payment and of providing reliable supply while the capacity of the connected system in many countries does not cover the present demand in their system. The emergence of low-cost grid extension technologies (e.g. Single Wire Earth Return) and interruptible connected micro-grids with distributed generation provide resourceful technological perspectives.

Comentado [AG15]: Get rid of Tiers, according to levels proposed in the article

The supply technology has to be identified with all the necessary attributes:

- Grid connection:
  - Layout of the grid extension that connects the households to the existing grid. This grid extension may include low voltage elements, extensions of the medium voltage network, and reinforcements in the medium and high voltage networks.
  - Energy drawn from the grid, requiring upstream centralized generation and its cost.

- Reliability of the existing grid, which in principle should be affected by the new demand that is connected to it.
- Applicable tariffs, in principle equal to other grid connected customers.

- Off-grid supply systems:
  - DC versus AC option, with the associated appliances that could be connected (which are different for AC and DC; this is an area where substantial improvements are taking place, both in terms of availability, cost and performance).
  - Stand alone versus microgrid option. The mix and size of the generation technologies. Siting of the local generation for a microgrid. Single versus multiple generation sources and the coordination among them. A critical factor here is the difference among the O&M costs of the different options, which have to be carefully modeled.
  - In the case of microgrids, the quality of the networks: basic configurations and equipment not capable of being directly connected to the grid, versus grid compatible microgrids that meet the applicable grid code. The possibility of grid connection should condition the adoption of grid-compatible off-grid solutions.
  - Management scheme for the supply and the demand side in the microgrid. This includes frequency (for AC grids) and voltage controls, metering systems and communication, tariff schemes, and the adopted logic to manage limited energy resources.
  - Reliability of supply, which can be considered as a design parameter, with a direct impact on the characteristics of the adopted solution for the supply technology (e.g. size of solar panel, battery and back-up diesel generator) in the classical trade-off between cost of supply and quality of level of service, and also on the management scheme for supply and demand, with the possibility of differentiated levels of quality of supply.

Comentado [AG16]: Review if here or later (planning details)

5.4 Portfolio of business models (BM)

The provision of electricity access is an asset intensive activity, with important operation and maintenance costs and therefore in need of solid financing sources and mechanisms. The fees for the supply of electricity, as well as any subsidies, have to be collected in an efficient and speedy manner. A substantial technical capability is needed to run this activity, which has to be sustained in time, in terms of technical performance and affordability, requiring important innovative efforts and adaptation to the enabling environment and to the socio-cultural characteristics of the beneficiaries. Only a handful of business models can meet all these requirements. The electrification process has to choose one of them.

A large variety of business models have been proposed or implemented in different parts of the world by many different organizations. A detailed description can be found in (González-García et al., 2016), see Table 1. Here only four major categories of business models with a summary of their most salient features will be presented:

1) *Unregulated entrepreneurs*. Off-grid supply facilities are installed and operated by private investors. They can meet the most basic electricity demand needs without resorting to subsidies, but their supply technologies cannot be scaled up to meet larger demands, the quality of service is not good and their networks are not grid compatible. <

2) *Regulated entrepreneurs*. These entrepreneurs also install and operate the facilities, independently or as a franchise of the incumbent distributor in the area. The supply technology must now be subject to some grid code and the facilities must be grid compatible. Their remuneration will consist of regulated tariffs to be charged to the consumers plus an extra amount –a subsidy– to recover the extra costs of supply, including an adequate remuneration of the investment. The subsidy is necessary because the network cost is now higher than in case (1) and the demand per consumer may be higher, with a correspondingly lower willingness to pay per additional unit of supplied energy (Wh). The regulation must specify the conditions of remuneration of the network facilities if they eventually become connected to the main grid, since the ownership and operation of the entire connected distribution network in the region must be assigned to just one distribution company, which by default is the incumbent one. The regulation must also specify the remuneration of the generation connected to any microgrid that becomes connected to the main grid; this generation must be treated as an independent power producer, with a clearly defined remuneration while it is still active.
3) *Licensed non-incumbent (new) utility*. This new utility is given a license to operate (it can be understood as a territorial franchise) in some area, with the obligation of supplying electricity under guaranteed regulated conditions. The electrification mode and the supply technology, as well as some quality of service minimum requirements must be specified a priori. The electrification mode could be grid-connection, microgrid or stand alone individual systems, but, whatever the case, the utility is bound to provide a supply service with some guaranteed performance (under prescribed penalties).
4) *Incumbent utility*. Typically publicly owned in developing countries, but it could be a private company. In principle it can be assumed that the utility is subject to cost-of-service regulation, perhaps with part of the remuneration being dependent of some performance indices.

		Grid Extension	Isolated Mini-grid	Stand-Alone-Systems	Pico Solar Systems
For profit	Small, decentralized	Sunlabob (Laos)	OMC Power (Africa, India), Scatec Solar (India), Sunlabob (Laos), Asantys (Africa, Asia)	Barefoot Power (Africa), Sunlabob (Laos), Soluz (LatAm), Asantys (Africa, Asia)	Barefoot Power (Africa), Sunlabob (Laos), Soluz (LatAm), Teri (India), Asantys (Africa, Asia)
	Large, centralized	NDPL (India), Fenosa-Gas Natural (Guatemala), Condensa (Colombia), Schneider (Global)	NPDCAPL (India), Dresser-Rand (Brazil) Schneider-Electric (Global)	Schneider-Electric (Global)	Schneider (Global), Philips (Africa, India), Tata Power Solar (India)
Non-profit	Cooperatives	Coopesantos et al. (Costa Rica), REB (Bangladesh), NEA (Philippines)	ESD (Sri Lanka), Coopesantos et al. (Costa Rica)	Costa Rica Energía Sin Fronteras (Guatemala)	
	Social enterprises		Mera Gao Power (India)	Grameen Shakti (Bangladesh), AccionaME (México), D.Light (Asia, Africa)	Grameen Shakti (Bangladesh), AccionaME (México), D.Light (Asia, Africa), ToughStuff (Africa)
	NGOs		Teri (India)	Practical Action (LatAm, Africa)	Solar Aid – SunnyMoney (Africa)
Public	Small, decentralized		RVEVESP (India)	Municipalities (Sunlabob) EnDev (Africa, Asia, LatAm)	EnDev (Africa, Asia, LatAm)
	Large, centralized	ONE-PPP (Morocco), Eskom (South Africa), WAPP (West Africa)		Government owned utilities in Peru	

Table 1. Taxonomy of business models and some case examples (González-García et al., 2016).

The adaptation of products and services to the needs of low-income population requires a substantial innovation and development effort (Agbemabiese, Nkomo, & Sokona, 2012; Chow & Brew-Hammond, 2010; IFC World Bank, 2012; Srivastava, Sokona, Mulugetta, & Gujba, 2012; Ulsrud, Winther, Palit, Rohracher, & Sandgren, 2011). In a cost restrictive framework, electrification agents need to design their products according to the different needs and priorities of the users, as described in 4.1, from lighting, phone charging and small readios to productive uses in agriculture, commerce or manufacturing, or community services such as health, education, entertainment or street lights. These customers "at the bottom of the pyramid" also need innovative business solutions that break cultural barriers related to distribution channels, customer engagement or technological change aversion. Supply models must earn the trust of this population, usually affected by margination and exclusion (if only electricity exclusion) and accompany them through the changes brought by the electrification process.

Different electrification modes demand also diverse features of business models, adapted to the socio-cultural background of beneficiaries (Dinkelman, 2011; Eisman et al., 2013; Schillebeeckx et al., 2012; Wilson, Wood, & Garside, 2012; Wimmer, 2012). Solar lamps and kits made possible the success of very innovative energy supply models, that resemble more the retail business of ICT devices, such as cell phones, than the traditional utility-like models of traditional energy companies. The ample variety of sizes and technologies for individual systems results in a constellation of business models associated with single-house-systems, from retail purchase, usually requiring some kind of microcredit mechanisms (Wimmer, 2012) to decentralized utility-like pay per service models (franchises, cooperatives and social

enterprises) where also traditional energy companies can be found. Isolated microgrids require in general a higher degree of sophistication of the supply model, including some demand management mechanisms that prevent the problems associated to the *tragedy of the commons* when a limited amount of energy per day has to be shared among a whole community. Finally, network extension also requires innovation on how to engage with this population, whether cause of their low-income level, seasonality of activities and limited investment or consumption capacity.

5.5 The Techno-Economic Procedure (TEP)

How to find the minimum cost solution? A critical component of the electrification process is typically some kind of *techno-economic procedure (TEP)*, involving some quantitative evaluation or numerical search method that could be implemented in a computer model, and whose purpose is to determine, in a first approximation, which of the *supply technologies*, among the multiple choices in the solution space, appears to be the preferred (e.g. minimum cost) option; alternatively, a set of preferred options could be found. The objective of the search typically is to find the minimum cost solution for the electrification plan. The Reference Electrification Model (REM) model is an example of a TEP. Most actual TEPs are probably performed manually, or with simple computational support, but not subject to a formal mathematical formulation of the problem or an optimization process.

5.6 Input information

A TEP of some kind is an indispensable tool when vast amounts of data have to be handled to come up with an electrification plan for a large region.

However, it would be a mistake to assume that a TEP, because of its capability to produce quantitative results, is able to provide the "optimal electrification plan", even if it is based on an optimization algorithm or on impressive number crunching methods. A TEP should be used as an exploratory tool, one that answers what-if questions, whose answers must be carefully examined by the planners and placed in the broader context that has been presented here.

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.

5.6.1 Regional Inputs

5.6.1.1 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.

Because labeled geo-referenced data for buildings in rural areas is very limited, the first step concerns the accurate labeling of large satellite image data sets. Our team has developed machine learning and computer vision techniques to automatically extract building areas from satellite imagery, which gives us the ability to massively scale the scope of our analyses. We use

a convolutional neural network-powered approach for semantic segmentation to automate image labeling at the pixel-level.

5.6.1.2 Layout of existing transmission and distribution network

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).

5.6.1.3 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).

5.6.1.4 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. Where this information is not actually available, estimates can be done according to the existing network infrastructure and also using night light satellite imagery as a proxy.

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 this mapping tool. But grid extension may require joint consideration of upstream network reinforcements that are needed for the existing electrified and newly electrified customers, and that can be addressed by this methodology and the Reference Network Model.

5.6.1.5 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.

5.6.1.6 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).

In any case, the use of hard reliability constraints is also considered by the REM model, designing systems that guarantee a minimum level of quality for both network and off-grid customers.

5.6.1.7 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.[14]

5.6.1.8 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.[15]

[14] 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.

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

5.6.1.9 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.

5.6.1.10 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.

5.6.1.11 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.

5.6.2 Individual inputs

5.6.2.1 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.

5.6.2.2 Characterization of demand

Comentado [AG17]: Multiusuario (diversos tipos). Crítico / No critic / niveles de suministro para cada usuario

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.

c) Setting a demand target, as for instance in the framework of SE4all a minimum Tier to be provided to each customer.

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).

A rural electrification planner may have different priorities regarding initial or longer term objectives, grid extension versus off-grid supply, maximization of the number of connected consumers, provision of at least a minimum access level, preferences for some geographical region, quotas of subsidies to be allocated to different purposes, etc. All of this is also subject to some budgetary, environmental, political or other constraints. It follows an inventory of planner's choices that appear to make sense. They are divided into two groups: Choices that make sense from a short-term strategic viewpoint and those that include longer-term considerations.

In the *short-term* the planner and regulator may decide to do nothing, which includes no subsidies and no regulation, i.e. allowing entrepreneurs to freely agree with potential consumers on prices and quality of service of off-grid electricity supply, with no requirements of security or quality of service, or holding any kind of license. Another short-term approach is a "blanket" one, i.e. to give priority to the universal provision of a minimum level of access, before any other objective is even considered.

Longer-term strategies include features in the planning exercise that are meant to achieve some future objectives. These are features that might be included in medium to long-term rural electrification planning:

- Require some minimum standards of quality, grid compatibility or scalability.
- Account for estimated demand growth.
- Include productive (both at household and community levels) and other community uses of electricity.
- Account for potential technological improvements, obsolescence of present technology and potential changes in business models or regulation.
- Account for current & expected availability of grid connection & its reliability level.

The challenge now is how to represent these features in explicit meaningful choices in the planning exercise. It seems that there is no clear correspondence between the options that could result from the considerations in this section and the SE4ALL standard tiers classification.

5.7 Additional restrictions regarding technological choices

The more relevant technological factors to take into account at the TEP are:

- *Utilization of local resources*. All potentially useful electricity generation resources –such as wind, mini-hydro or biomass– should be included in whatever TEP is used. This may require detailed knowledge about these resources at local level.
- *New technologies.* The potential discrepancy between economically optimal and socially acceptable solutions may be exacerbated by the presence of what has been

called the "third generation of solar PV technologies", i.e. the portable power packs with compact lithium-ion batteries that have an order of magnitude less weight than the conventional lead batteries, are modular, have built-in controllers and have plug-and-play capabilities. These power packs can be considered as appliances that are simple to install and use, and do not require traditional servicing and maintenance. If they fail, they can be taken to the nearest shop to be repaired or replaced. Note that, from the TEP viewpoint, the marginal cost of grid extension to provide access to some households will probably be much more expensive than the cost of a power pack, so distance and the quality of service provided by either supply technology will be the deciding factors. This has also important implications regarding the business model to be adopted.

- *Technical requirements*. Off-grid technologies may happen to be compatible with an eventual future connection to the grid –"grid-ready"– or not. Also, regardless of the connection, some minimum standards of safety and quality –typically reflected in an official grid code established by the regulatory authority– may be adopted or not. An important issue to be examined is the possibility of official approval of a less strict grid code for electrification in rural areas or just for electricity access. Compliance with technical requirements has a direct impact on the cost of the supply technology options.
- *Consumer participation*: The level of engagement of consumers and their communities in the implementation of the adopted supply technology is an essential part of the choice of business model and the need for local capacity building, to be discussed later, but it has also implications on some cost components of the supply options, such as the costs of maintenance. The possibility of an effective consumer participation, or the lack of it, may render or not possible some technology supply options for the TEP.

5.8 Planning considerations beyond the techno-economic procedure

As it has been shown in this note, a TEP is just part of a broader approach, which has to integrate numerous factors of a very diverse nature, some of which could be incorporated into the TEP, while some others are useful to define the cases to be studied with the TEP or the strategies to be followed, or just to provide context and to understand the implications of an electrification plan.

The "additional factors" can be classified into two groups: those mostly related to the *supply technology* and those closer to the *business model* viewpoint, although they are interrelated. The factors in both groups are influenced by the energy policy and the regulation, as well as by the consumers' preferences and their engagement. They are missing in the TEP, and therefore the solution obtained by TEP might not make sense, or it could be improved substantially.

In the remainder of these notes, the relevant factors for the provision of electrification access will be described. These additional factors will have to be accounted for in different moments of the electrification process: some of them will affect the input data, some others will have to be considered during the execution of the TEP; finally, other factors will be used during the examination and validation of the results of the TEP. The planner may consider to include some

of them as figures of merit –in addition to the supply cost– to be accounted for in the comparison of the different viable alternatives in the solution space.

The "additional factors" have been classified into two groups: those mostly related to the *supply technology* and those closer to the *business model* viewpoint. They are interrelated, and the linkages will be identified. Both groups are influenced by the energy policy and the regulation, as well as by the consumers' preferences and their engagement.

5.8.1 Related to the supply technology.

Why did we say that the TEP produces the supply technology "in a first approximation"? Because important factors are missing in the TEP, and therefore the solution obtained might not make sense, or it could be improved substantially. Some of these factors deserve a detailed discussion, in particular in the specific context of what here has been termed *electrification shire*, and they may vary significantly among shires, although the same types of factors seem to appear consistently.

Institutional inertia.

In most regions, all that the incumbent distribution companies and electrification agencies know how to do is grid extension. Off-grid technologies and business models are foreign to the incumbent firms and institutions and this inertia may be difficult to overcome. Therefore, if decision making for electrification planning is located within these companies and organizations, it is unlikely that they will choose an off-grid solution, even if happen to be the best one in some particular application.

Comentado [AG18]: Review

Energy policy

Regardless of what is economically optimal, the government might want to connect all consumers to the grid, because of multiple reasons (perhaps to please potential voters, if grid connection is perceived by people as the preferred mode of electricity supply; or perhaps to extend the control of the publicly owned distribution companies and centralized generation). Or the opposite, if publicly-owned distribution companies are bankrupt, the government may want to promote private investment in off-grid solutions to relieve the financial pressure of these companies. Or the government may want to encourage the deployment of solar generation, or wind, or biomass, or some local resource, or perhaps an all-renewable mix where diesel is banned or severely limited[16]. Maybe the government wants to reduce dependence from imported fuels or to get rid of some expensive subsidies to some of these fuels, like kerosene used for lighting. These energy policies should appear as targets or constraints in the input data or the model formulation in the TEP.

Energy policy is a political action, with all the implications of politics, good and bad. Politics, and energy policy in general, should look after the interests of consumers, and make use of consumer engagement, at least at local level. But energy policy should take into account broader considerations, such as the allocation of scarce resources to different activities, one of

[16] Different issues have been identified that may advise to reduce or to eliminate the utilization of diesel generators: security hazards, complex maintenance of the generators, theft, corruption of intermediaries and a complex management, as a consequence of all the other issues.

which is electrification, or energy dependency, promotion of cleaner technologies of electricity production or climate change commitments.

Frequently energy policy is driven by spurious interests. There are promises about electrification that are not met, because they were only meant to gain popularity in some elections. There are messages sent to the people that may distort the consumer perceptions regarding the technological choices, such as considering off-grid electricity supply as an inferior category to grid supply, even if the reliability of the latter is poor. There are strong links between energy policy and the next factor: consumer preferences.

Consumer preferences

This encompasses a large number of topics, with direct implications on the choice of the attributes of the supply technology. This can be illustrated with several examples:

i) *Questionable output from the TEP*. The techno-economic procedure or TEP (e.g. the REM model) may produce an output consisting of several small microgrids, relatively close to one another, within what administratively and under a community perspective may be called "a village". Or perhaps a combination of small microgrids and individual stand alone systems. This might be the minimum cost solution from a strict cost minimization viewpoint since network costs increase with longer distances, but cost minimization may not be taken to the extreme and the result of the TEP may not make sense under a social viewpoint. The adoption of a slightly more expensive solution, perhaps consisting of a single microgrid for the entire village, could probably eliminate many social issues. Or maybe in other cases a socially preferable solution could be individual stand-alone systems for everybody. The siting of the generation plant or plants must be decided locally, based on priorities that can only be known at local level. Consumers preference is key in such cases.

ii) *The choice between grid connection and off-grid solutions*. Because of actual facts, or perhaps because of misinformation, potential consumers may prefer grid connection to off-grid solutions, or grid electricity to the one generated with solar technologies. Or the opposite. Multiple considerations have an impact on these preferences, with cost and quality of service probably being the dominant ones, at least from an objective viewpoint. Education efforts to make people understand the trade-offs between the different technology supply options should be an essential part of the overall electrification process. The supply technology has to be the one that is finally accepted and decided by the beneficiaries, after a process where they have been properly informed and engaged. This solution may be at odds with the one initially provided by the TEP, which will have to be somehow adjusted or its output modified to account for the consumer preferences. These consumers preferences will be built from information coming from different angles:

- A specific issue that may play a role in the adoption of the supply technology is the *expectation of being connected to the grid*. If grid connection is perceived as the superior option –even regardless of its reliability– it may be difficult to convince the future consumers to choose an off-grid option, in fear of jeopardizing their chances of being connected to the grid. Grid-compatible supply options may reduce the impact of this concern.

- Another issue is the distortionary impact that *subsidized tariffs* of grid-connected electricity may have on the choice of consumers and on the techno-economic process itself. On the one hand, if grid-connected electricity is subsidized and off-grid electricity is not, the bias in consumer preferences is clear. On the other hand, if the TEP has the objective of maximizing social welfare, subsidies should be ignored, indicating a potential discrepancy between both outcomes.
- *Quality of service* is another issue that may weigh heavily in the consumer preference for on-grid or off-grid solutions. From the consumer point of view, factual information is of essence, regarding the expected reliability of each technology option. In any case, it is difficult choice, because of the different nature of the supply in each case. Individual off-grid solutions that are only based on solar PV and batteries typically provide reliable power for a limited and somewhat variable number of hours per day, every day. Since the limiting factor is the amount of energy that can be consumed daily, energy intensive appliances are mostly out of question. The reliability can be improved by being connected into a microgrid (although it may depend on the adopted demand management scheme, as each consumer now shares a scarce resource with others) and adding a non-intermittent generation source, such as a diesel or biomass generator. In contrast, grid-connection offers a basically unlimited power capacity, allowing the use of all kind of appliances, but it is the experience in many developing countries that grid power is unreliable, with quality of supply being worse in far away rural areas, so that in many cases electricity supply systematically fails at those periods of time when it is most needed.

It is a real challenge to represent quality of supply in a TEP. This could be done by assigning a value to the cost of non-served energy, but it is much more tricky that this. In the first place, there are more and less essential loads, which should be assigned different values of non-served energy. In the second place, one has to distinguish between demand that is not served because the electrification mode is unable to provide that level of demand (this has to do with the capability of the supply mode) and demand that is not served because the facilities fail (grid has no power or the battery is exhausted after a cloudy day). Information about the values of these several costs of non-served energy are difficult to elicit from the consumers, even more if they are potential consumers. Proxies (like the present use of substitutes, like kerosene for lighting) can be used to estimate the cost of non-served energy, but the results are always untrustworthy. An alternative approach, one that can be also implemented in TEPs, is the use of reliability metrics, such as the number of hours per year when demanded electricity is not served, or the number of days per year when electricity is not available during the entire duration of the critical period of the day. It is probably easier to elicit the consumer preferences when these explicit metrics are used. The bad news is that, in our experience, the outcome of a TEP is very dependent on the reliability parameters that are input to it.

The comparison between on-grid and off-grid options can be only complete when the *upstream implications of connection* of new demand to the grid are fully accounted for. This requires evaluating the reinforcements that will be required on the medium and high voltage networks and on the centralized generation.

It may not be obvious to determine which is the supply option that is best for a group of beneficiaries, even with their participation. The minimum cost solution that is provided by the TEP is certainly a first approximation. Specialized techniques[17] can be applied to elicit information from the future consumers and to blend it with the techno-economic information to arrive to the preferred option. Ignoring the idiosyncratic characteristics of the beneficiaries may lead to the adoption of the wrong choices[18].

5.8.2 Related to the business model

Energy policy.

This could predetermine the business model; for instance if the government decides that any further electrification must be done by grid extension of the network of the incumbent distribution company.

Consumer preferences and engagement.

The adopted business model must respond to the consumer preferences. All business models require some level of consumers' engagement; in some of them –e.g. cooperatives– consumer engagement is at the core of the model. Appropriate procedures to elicit consumer information and to channel consumer participation should be carefully adopted.

Institutional inertia.

This topic has been commented already under the supply technology factors. The finally adopted business model will depend heavily on the allocation of the responsibility for electrification. If this is the incumbent utility, it is likely that the chosen technology will be grid extension and the business model will be the same as for any other grid connected consumer.

Technical requirements.

Any existing technical requirements will condition the supply technology, but also the associated business model. For instance, mandatory grid-readiness adds an extra cost that has to be somehow subsidized.

5.8.3 Related to the funding restrictions

This paper postulates in Section 6.1 the *Iron Law of Rural Electrification*, stating that access to energy requires non-refundable finance consisting on subsidies, incentives or donor money to fund universal access plans. Moreover, along the whole value chain of electricity supply (from the consumers themselves up to incumbent utilities, through retailers and local entrepreneurs) there is a fundamental need to access suitable credit (either commercial credit, micro-credit,

[17] As the ones developed for the doctoral thesis of Javier Santos, IIT, Comillas University (Santos & Linares Llamas, 2004; Santos, 2015).

[18] For instance, in Guatemala, solar homes with batteries and inverters were adopted, so that AC appliances could be used. In the end electricity utilization happens to be only with simple DC appliances and the adopted solution is too expensive and the inverters are failing. As another example, since kerosene or candles are substitutes to electricity for lighting, some people continue using them in parallel with electricity, especially if the reliability of electricity supply is poor.

social, ethical or cooperative credit) that suit the needs and particularities of each business model in particular.

- *Availability of local financial institutions for consumers*. Up-front cash disbursements are typically a serious impediment for people pertaining to the bottom of the pyramid. Successful business models should avoid any significant up-front payments or should facilitate the means for reasonably priced microcredits. The use of microcredits can be facilitated if local lenders are available[19].
- *Financial issues for investors*. Multiple issues converge here. On the one hand the bankability of the project, which depends on cost of supply, the affordability of consumers, and any existing subsidy that is applicable, since we have to remember always the Iron Law. The business model has to make sense, i.e. it has to be financially attractive, to the investor. Budget limitations are essential to determine the scope of any publicly supported electrification plan. Theft issues have to be considered, since they may depend significantly on the electrification mode –think of the difference between a cooperative model and grid connection–.

Comentado [AG19]: Described in section 6

The combined strategic choice of electrification mode and business model may be effective in mitigating any financial difficulties of the company in charge of the electrification, and also of the incumbent distributor, if they do not coincide. For instance, if the government wants to pursue an aggressive electrification program based on grid extension with ambitious access targets, and the distribution companies are in a dire financial situation, it might be possible to reduce the burden of the up-front investment costs of the distribution company by relying on external new firms that undertake investment in grid-compatible off-grid facilities, under adequate regulatory conditions that mitigate the investors' risk. In this approach the incumbent utility only has to provide the annuity of the subsidy to fill the gap that the tariffs cannot cover, without incurring into any additional debt. Maybe a few years later the distribution companies will be financially stronger and they could purchase and connect the microgrids facilities to their grids. The TEP must be able to model these situations and to come up with results that show the pros and cons of the different alternatives from a financial viewpoint.

5.8.4 Sustainability considerations

This is the last and most important factor. Sustainability has several dimensions: financial, technical, social and environmental. And all three are critical. Any electrification plan must have a vocation of indefinite permanence.

[19] To achieve a strong form of inclusive growth, new investments in electricity need to lead to a rise in the relative incomes of the poor, so that growth also reduces inequality. This effect cannot be presumed. Indeed, electrification projects often leave behind poor communities and even when the grid or off-grid systems reach a poor community, evidence shows that connection rates can stay low due to prohibitively expensive up-front costs. When poor families eventually connect, unreliable service, low consumption and lack of productive uses limit positive impacts. In some cases, policies that are intended to benefit the poor, such as tariff subsidies, are poorly thought out and can end up benefiting the better-off and undermining the sustainability of the project. Electrification investments therefore require careful planning to specifically target the poor. (Source: Ana Pueyo's blog at IDS. 2014-08).

- *Financial*. The financial design of the electrification plan must make sense, from the outset and forever. As indicated before, meaningful electricity access requires subsidies, in the up-front investment costs and also possibly in the future tariffs for those that cannot afford them. This has to be fully accounted for in the specification of the electrification plan.
- *Technical.* Distribution networks, and power systems in general, live forever. Transformers, cables, insulators, protections and other gear replaced and upgraded, new circuits are created, but the supply system remains. The same should be the case with off-grid supply technologies, whether they are expected to become connected to the grid or to remain isolated. Here the maintenance procedures are critical and they have to be included in the electrification plan and the selection of the supply technology and business model from the outset. Much has been discussed and written on the topic and much can be learned from successful and failed experiences. Different issues are involved here, from the technical capacitation of local people, to the sense of ownership by the community, to the allocation of responsibility to some stable organization with some utility-like characteristics for off-grid solutions.
- *Social.* This is directly related to the consumer engagement and preferences factors that have been discussed previously. The beneficiaries must accept the business model, individually and as a community, if the electrification plan must survive. As a general principle, the higher the engagement of the community, the higher the chances of a sustainable business model. It can be added that the utility or utility-like models, if well-accepted by the consumers, also provide a sound guarantee of social sustainability.
- *Environmental.* The environmental impacts of universal electricity access have been typically neglected, with the implicit assumption that the level of consumption of these new consumers will be so low that the impact on carbon emissions or other local environmental impacts will be insignificant. However, these assumptions have to be reconsidered, as some authors have pointed out recently. We are talking of a vast number of consumers, which in a few decades are to be expected to reach comfortable levels of electricity demand, as the ones that are now enjoyed in more developed countries. If the wrong supply technologies are adopted now, it will be very difficult to revert that trend later. Sustainability concerns should be present from the outset on the design board of any electrification plan and they should impact the choice of the adopted solution, both from the point of view of the supply technology as for the choice of business model.

5.8.5 Consumer engagement

The level of engagement of consumers and their communities in the implementation of the adopted supply technology is an essential part of the choice of business model and the need for local capacity building, to be discussed later, but it has also implications on some cost components of the supply options, such as the costs of maintenance. The possibility of an effective consumer participation, or the lack of it, may render or not possible some technology supply and business model options.

The participation of the community of beneficiaries in the electrification process must be at the center of the program or project development, from its early design phases to the later maintenance and sustainability of the electricity supply. Success in engaging the community requires also an holistic focus, varied and creative, developing the process according to the cultural and social priorities, economic capacities and environmental concerns. This process

must even be more conscious and sensible with beneficiaries at the bottom of the socio-economic pyramid.

After identifying the reference area, our so called *electrification shire* (single holistic instance for rural electrification*)* subject of the electrification planning effort, a map of any relevant actors and their relationships must be drawn, including individual beneficiaries, local agents and institutions, and national or international authorities. It is very convenient to come into an agreement (either formal or not) with the local authorities, accompanied by aware raising sessions to assess the impact of the electrification on the community. The establishment of an electrification committee might help the coordination with the community. The use of participative methodologies for the analysis of needs, technological and supply mode preferences must focus on community leaders, and specially assure the participation of women (in many ways the beneficiaries more impacted, and involved, in household electrification).

It is also important to take into account those actors and sectors that perceive electrification as a menace (e.g. charging kiosks and other unregulated entrepreneurs; kerosene, candles or disposable battery dealers and shops) exploring the opportunities to somehow involve them in the new business model for energy supply (e.g. as providers of electric appliances, replacements, local technicians for repairs and maintenance, or local collectors of electricity fees).

This process must come along with specific capacitation and empowerment, not only of local technicians and entrepreneurs, but also of final users, trying to involve them, according to their possibilities and capacities, in the implementation of the energy systems themselves, and in the local integration of the business model.

A long-term electricity service requires also built in innovation capacities, upgrading and continuous improvement of systems, which in many developing countries are difficult to guarantee at local or even regional level. The implementation of multi-actor and public-priavet partnerships with companies, authorities, donors and funders, as well as any other relevant actors according to the specific context, favors the sustainability of supply, always involving the representatives of the community.

5.8.6 Setting appropriate scenarios

XXXXXX

5.9 Quantitative tools to plan a road to universal access

A more detailed description of the main components of a successful strategy towards Universal Access can be found in our previous Working Paper[20], 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.

[20] (González-García et al., 2016)

- 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"[21].

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*"[22].

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 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 **¡Error! No se encuentra el origen de la referencia.**.
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).

[21] (Pérez-Arriaga & Stoner, 2015)

[22] (Chattopadhyay, Kitchlu, & Jordan, 2014)

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[23].

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.

5.10 The Reference Electrification Model (REM)

5.10.1 One electro-economic REM model to supply them all

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[24] (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, comparing together the three major electrification modes. This

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

[24] (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.

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[25] 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[26].

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.

5.10.2 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

[25] For example, HOMER and ViPOR, developed by the U.S. National Renewable Energy Laboratory (NREL).

[26] 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.

imperfect reliability. The design of the network is done used a well established distribution network expansion software called Reference Network Model (RNM)[27].

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.

5.10.3 Microgrid Design Software (LREM)

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.
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.

5.10.4 Of friends and foes along the road

6 Regulation as a fundamental enabling factor

Universal access has to be subsidized. In basically any *developed* country it has been necessary to complete the electrification of all consumers, even in the most remote and impoverished areas, with some specific rural electrification plan. Electrification of potential consumers that have low expected levels of demand in areas where the network is not well developed is

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

typically much more expensive than the average cost of supplying electricity to the existing connected consumers. Virtually in every country, electrification of this group of consumers has been subsidized, either with public funds or by a cross-subsidy obtained from an uplift to the tariffs of the existing connected consumers. Also in most cases the fraction of the cost of this plan that could not be charged to its beneficiaries, has been covered by the national budget or by some uplift (extra charge) in the electricity tariff of all the existing consumers. Eventually all consumers in the country have ended up paying the same electricity tariff[28].

The situation is, in general, different in developing countries, where governments do not have the capability to finance a universal electricity access and the uplift to the already connected consumers could be very substantial if the percentage of non electrified population is high. Therefore, regulation has to find different ways to approach the problem. One of the issues to be dealt with is whether off-grid electrification should be regulated or not. Some recent regulatory approaches try to reduce the administrative burden of the standard distribution and generation licenses for small off-grid suppliers while, at the same time, establish some minimum requirements that take care of some of the concerns mentioned above.

Comentado [AG20]: Review with later details

6.1 Equitable rural access to electricity needs subsidies

There is something that must be clear from the outset. We shall call it "the Iron Law of rural electrification planning", and its statement is simple: *Rural electrification needs subsidies*. The explanation of this statement follows.

Rural electrification, whether on-grid but even more if it is off-grid, is substantially more expensive than electrification in urban areas, typically with much higher density of electricity demand. This is a fact in both developed and developing countries, and its corollary is that the uniform tariffs, which almost every country applies to all consumers connected in low voltage, imply a subsidy from consumers in high-density areas, i.e. urban, towards consumers in lower density areas, i.e. rural. Other types of cross-subsidies frequently exist in the tariffs –for instance from industrial to residential consumers, or conversely, depending on the country–.

Achieving 100% electricity access in any country typically means reaching out to consumers with low potential demand for electricity, low affordability and geographically dispersed. Obviously the electrification costs for these consumers will be much higher than the average costs, and even more if the least cost solution is off-grid supply. If the general paradigm of cross-subsidization is applied, it is to be expected that whatever tariffs apply to those less favored consumers should not reflect the actual incurred costs. In many countries there is also a social tariff for those customers with certain characteristics such as low-income and low-consumption that apply to every citizen, disregarding of where the uses lives, whether in rural or urban areas, off-grid or connected.

How to finance these subsidized tariffs? The typical solution in developed countries and many developing ones is cross-subsidization, i.e. apply to all consumers the same average tariff. In many countries there is also a social tariff for those consumers that meet some low income and low electricity consumption conditions, regardless of where they are located. This is workable if the ratio of consumers to be electrified is relatively small with respect to the total number of

[28] In many countries a social tariff exists, which is meant to protect the "energy poor" or "vulnerable customers" , a new category of consumers that is defined differently in each country.

consumers. When, as in many Indian states or in most Sub-Saharan countries, cross-subsidies are not workable because the majority of households are not electrified, governments may be tempted to close the viability gap by providing the needed subsidies from the national budget. While initially popular, this approach may rapidly create an unsustainable fiscal burden and therefore may not underpin a national scale, long-term electrification program.

A shortcut solution to the viability gap dilemma is proliferating in some developing countries. Private entrepreneurs, outside of the regulatory compact, directly negotiate with the inhabitants of a village a weekly or monthly rate per household in exchange for a basic service of a few hours per day of supply for two lights and a telephone charger, or similar combination of small loads. Typically the quality of the necessary infrastructure is low, so it does not meet the minimum requirements for an eventual grid connection[29]. In those places where connection to the grid is a possibility, this means a high risk for the entrepreneurs (who will have to remove the assets if grid-connection happens), higher cost to the consumers (since they will have to bear the cost of the financial risk of the entrepreneurs who may want to recover their investment costs in just a few years) and a waste of material resources. There is also the risk of monopolistic abuse in prices and quality of service by the entrepreneurs, once they become the single supplier in any given village. Finally, another long term consideration – one that should be in the radar of international organizations fighting climate change – is that, unless the solar-based micro-grids built by the entrepreneurs are of grid-compatible quality, they may be eventually replaced by the centralized generation mix, which, in countries like India, is mostly based on fossil fuels. We are now at the right time to guide the adoption of a long-term electrification path in developing countries that is based on renewables, efficient, and economically and environmentally sustainable. In any case, acknowledging that the main priority is to supply electricity to those actually without access, the activities of non-regulated entrepreneurs should be allowed, particularly in those countries where it is not possible to fund grid-compatible off-grid solutions

It seems impossible to explain that the poorest people on the planet will pay for an expensive electricity service (considering the cost of each kWh), supplied by private enterprises that usually operate without any subsidy. The answer lays in the value, or "utility" of the first kWh of supplied electricity, which is usually very high for every consumers all over the world, and anyone would pay a high price for it, while the utility of any additional kWh will decrease very fast. The electricity required to power two lights and a phone charger replaces other also expensive, unhealthy and unsafe alternatives as the use of kerosene lamps, candles and disposable batteries, considering also the cost and time required to purchase replacements and fuel, or going to charge the battery in a kiosk. The value of each additional lamp and other electric appliances such as fans, radios and televisions, decreases very rapidly and stops being accessible for least-favored consumers with lower incomes, unless a subsidy on the tariff can be established.

An important long term consideration for international organizations engaged against climate change is that, unless the isolated microgrids and other isolated systems implemented have enough quality, grid compatible, when the grid comes their equipment will be replaced by the generation mix that, for instance in cases like India, is mainly powered by fossil fuels. Now it is

[29] There are exceptions to the general rule of unsubsidized but low quality infrastructure off-grid supply systems, as the Grameen Shakti electrification project with stand-alone solar systems in Bangladesh.

the time to set the course of our roadmap to universal electrification in developing countries towards renewable and clean energies, efficient and sustainable, from the economic, social and environmental perspectives, procuring the economic support that will be required for the universalization of access to electricity.

6.2 The electric power industry context

The structure and ownership of the electricity companies of generation, transmission, distribution, retail and system operation must be understood, as well as the current decision making processes for investment and operation in distribution, but also upstream in generation and transmission. In particular, it is important to know how the distribution companies are remunerated, and how the consumer tariffs are set, including existing subsidies, for instance to irrigation. The financial situation of the distribution companies is of essence here, since they cannot be expected to connect new customers who cannot pay the full cost of service[30] when there are no or insufficient subsidies. Obviously this situation is still direr if the distribution company is bankrupt, as is the case in some developing countries.

In many regions the incumbent distribution company and the electrification agencies know well how to extend the grid. On the other hand, off-grid technologies and their business models are alien to them, and this institutional inertia might be difficult to overcome. If decision making depends on traditional actors, it is difficult that they will select off-grid solutions, even if they were better for a particular situation or framework.

6.3 Grid compatible microgrids

Grid compatible, predominantly renewably powered micro-grids have many advantages and should be supported by regulation for many reasons:

a) They are less likely to be discarded when the grid ultimately arrives, thereby reducing the risk of loss of capital for the micro-grid investor and therefore increasing the likelihood that they will be built in the first place.
b) Since they can provide a level of service similar to that of the grid, and in many situations a *better* level of service, they reduce the consumer concern that establishing a micro-grid will only tend to delay the arrival of the grid.
c) In those places that can be eventually reached by the grid, privately financed micro-grids reduce the pressure on the incumbent distribution company to extend the grid and delay the financial burden on the incumbent until the time when the connection takes place.
d) Generation from the microgrid could eventually become connected to the network as it arrives, providing distributed energy resources, most of them renewables, and reducing the transport costs and losses

Even for those isolated communities for which grid connection is not economically efficient, the first best off-grid supply option should allow demand growth beyond the basic two-lights and telephone charger, because the medium and long-term electrification targets for such

[30] For instance, if the distribution companies are broke and the tariffs for final consumers are subsidized, there will not be incentives for the incumbent distributors to connect new consumers to the grid.

communities should be commensurate with the electricity services that are enjoyed by grid consumers.

However, in view of the fact that the first priority is to provide electricity access to those who do not have it, the activity of unregulated independent entrepreneurs can be allowed, in particular in those countries where presently it is not possible to finance grid compatible supply options or (for isolated communities) scalable off-grid solutions.

The key message is that substantial regulatory effort should be devoted to incentivize private investors to adopt grid-compatible off-grid supply options for communities where grid-connection is a possibility, and scalable off-grid supply options for isolated rural communities. The corresponding regulation should include the following features:

i) The supply technology – network and generation infrastructure, operation standards, metering and protection schemes – must be subject to some officially approved grid code so that the micro-grids and any stand-alone systems are grid compatible, or can be made so via a series of approved upgrades (for potentially grid-connectable supplies) or scalable (for isolated communities).

ii) The remuneration for the off-grid suppliers will consist of regulated tariffs to be charged to the consumers, plus an extra amount –a subsidy– to recover the extra costs of supply, so that the "total efficient costs of supply", including a reasonable return on invested capital, are paid for.

iii) The "efficient off-grid costs of supply" for every community will be determined by the regulatory authority, for some minimum quality of supply to be guaranteed. Incentives (and penalties) will be defined to reward (penalize) performance above (below) the minimum standard. Note that a remuneration that is based on some standard prescribed "efficient costs of supply" incentivizes innovation by the supplier to apply technologies and procedures that reduce total operation plus operation costs of supply, since this increases the margin of revenues minus costs. Innovative approaches are thus rewarded.

iv) The regulation must specify the conditions of remuneration of the network facilities if they eventually become connected to the main grid, since the ownership and operation of the entire connected distribution network in a given area must be assigned to just one distribution company, which by default is the incumbent one. The regulation must also specify the remuneration of the generation connected to any micro-grid that becomes connected to the main grid; this generation must be treated as an independent power producer, with a clearly defined remuneration while it is still active.

v) The subsidy may be provided in the form of a tariff "top up" to the service provider by the government, or in the form of a one-time cash payment, or capital subsidy. In either case, the amount of the subsidy should be calculated in the manner described above based on a technical plan that meets all regulatory requirements. An efficient "reference plan" may be used by the regulator for each project as the basis for determining the subsidy, or a more cost-efficient plan provided by a developer.

7 Comprehensive universal access and energy policy roadmaps

7.1 Selecting the best possible policy choices

Building a successful strategy for universal access to modern energy services requires the assessment of the diverse present and future needs of energy services for development with a user centered approach[31]. It also needs to consider the technological alternatives together with the funding restrictions and regulatory environment according to the country strengths, to make use of limited resources in an efficient manner[32].

To do so, countries need to establish an appropriate framework for the energy transition, involving the final users and establishing the right incentives and regulatory measures to guarantee the long-term sustainability of the supply models. The diversity of user profiles, energy sources, geographic and socio-economic constraints requires the consideration of multiple technological solutions for electrification and modern heat, as well as a variety of scenarios and pathways to address universal access, taking into consideration their interactions with other energy, economic, environmental or social policies competing for usually scarce government resources. Utilities in charge of electrification of large regions may also find this model useful for the assessment of their investment strategies[33].

7.2 The Model for Analysis of Strategic Energy Roadmaps for All (MASTER4all)

The research group is developing a *Model for the Analysis of Sustainable Energy Roadmaps for all (MASTER4all)*[34] based on the MASTER_SO model[35] developed at IIT, for the provision of useful insights about the trade-offs between different technological, financial, environmental and energy policy alternatives specifically focused on energy poverty reduction and energy transition to modern supply.

[31] (Brazilian & Pielke, 2013; Schillebeeckx et al., 2012)

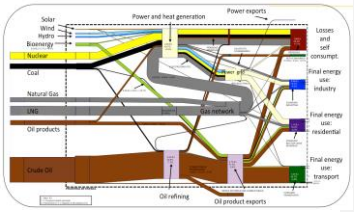
[32] (Brazilian, Nussbaumer, Haites, et al., 2010; IFC World Bank, 2012; Smail Khennas, 2012; World Bank, 2010)

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

[34] The MASTER4all, although not part of the expected deliverables, will be fully developed by the end of the second year of the *Low-cost Energy Technologies for Universal Access Project*.

[35] (López-Peña, Linares, & Pérez-Arriaga, 2013)

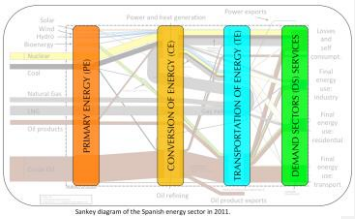
1- The process starts with the description of the initial stage of the energy system, considering:
    a. The energy services provided to the final users, considering the whole energy system, with a detailed focus on energy services required by people depending on traditional energy supply (Tier 0 for electrification and heat) or with a poor modern service.
    b. The energy flows from each energy source to the final energy services supplied and the transformations and transport processes, which can be described in a Sankey diagram.



Sankey representation of energy flows in the Spanish System (ref)

2- The model requires an abstraction process to describe the energy system and flows in terms that the model can optimize following these flows upstream from the demand sectors (DS) through the transport (TE), conversion of energy (CE) to the primary energy (PE) either imported or from the national supply.

    For the description of the Demand Sectors, MASTER4all can consider the national energy system as a whole (single node) or specifically take into account geographical diversity in terms of number of user profiles with equivalent energy needs, electrification mode and supply technologies, generation potential, costs and capacity of payment. This classification of users can be established according to national surveys and expert estimation of supply in a few similar regions, but it can also receive a thorough classification of users if used in combination with GISE4all model.



MASTER4all abstraction categories

3- MASTER4all now calculates the optimal supply within a year, according to two main policy perspectives but integrating several optimization choices.
    a. Blanket electrification: This social approach is associated to a political logic frame for equitable energy access, where targets are universal use of electricity for every customer, usually under a rights based approach, with adequate quality, environmental and social performance. Blanket optimization focuses on minimizing lack of energy access with minimum subsidies considering budget restrictions.
    b. Selective electrification: This business approach is usually divided in three stages: initial connection, densification of supply and reinforcement or upgrading of service. The focus is on commercial strategies that allow small positive financial

returns with lower costs and higher sustainability, but poor households receive access last (or not at all if they cannot afford it). Priority of selective approach is on business model development and market minimization of costs, with or without any subsidy scheme.

MASTER4all starts the optimization procedure from the detailed characterization of energy services required by each access profile[36] and considering the supply technologies available for each class of users, capacity of payment, incentives and subsidies and other energy policy restrictions, and providing also an estimation of the social cost of CO2 emissions, pollution and energy deprivation. Other political objectives can also be considered as minimizing emissions, energy losses, reliability, fossil fuels, energy dependency, renewable supply or efficiency targets.

Establishing the cost for energy deprivation poses and important challenge. Though a growing number of academic references and policy documents emphasize the impact of access to modern energy services on income generation, health, education, environmental and social development, there are no reference values or standard methodologies for the quantification of the cost of energy poverty. Establishing and appropriate cost for different electrification and heat supply levels will allow the model to address the energy access choices according to a rational energy access ladder.

The estimation of the social cost of emissions faces similar problems. Where CO2 markets exist, the cost of emissions can be established using the CO2 price. Additionally, the model can consider a maximum cap for the total emissions of the energy systems, as well as limits per sector or technologies, also providing the opportunity of setting appropriate targets for renewables and energy efficiency, covering the different SE4all goals.

MASTER4all can be set to optimize the investment decisions considering the existence of present capacity (brownfield operation) or without considering any previous capacity (greenfield operation), or to optimize the actual operation of the existing capacity (without investing in any new capacity).

7.3 Enabling environment for the roadmaps

[36] Type of energy services for basic access: ES:

- Residential: lighting, charging phone, radio, TV, fan, heating, cooking, fridge, washing machine or others.
- Productive: specific agricultural, industrial and commercial appliances as pumping, electric saws, sewing machines, or others; depending on the traditional and modern productive sectors.
- Community: street lighting, health, education, sanitation, telecommunications.

7.4 Community engagement

The participation of the community of beneficiaries of an electrification process must be at the center of the project development, from its very early stages to the long-life care and assessment of the electricity service.

Comentado [AG21]: Review with previous version

A successful engagement of the community requires a holistic, eclectic but also creative approach, developing the process according to its cultural, economical, environmental and social particularities. This process needs to be even more mindful with beneficiaries at the bottom of the socio-economic pyramid.

The following indicative list of tasks derives from international development practices and specifically from the expertise of social organizations experienced in projects of electricity access in different countries of Africa, Asia and Latin America:

1. Identification of the pilot site(s).
2. Mapping of relevant actors: Identification of counterparts and interlocutors of the community and their relationships, involving three levels:
    a. Individual beneficiaries.
    b. Local institutions and organizations (school, government, economic and social actors).
    c. Systemic actors and governance links (promoter, authorities, regulators, micro-financing, donors, incumbent utility and others).
3. Agreement with the local authorities
4. Informative and awareness-raising sessions on the electrification process and its expected impacts (opportunities or menaces) in the community.
5. Early community assessment of actual energy needs, preferences on technology and business model particularities, socio-economic and environmental impact. Use of a participative methodology, involving their formal and informal leaders and people of note, putting special care in the participation of women representatives.
6. Establishment of a community electrification committee for coordination and for the integration of local human, social and environmental potential in the electrification process.
7. Take special care of those actors damaged by the electrification process (former providers of electricity, charging kiosks, shops that sell kerosene, candles and batteries). Explore opportunities to involve them in the business model.
8. Detailed individual assessment of needs particularized for each type of beneficiaries of electricity: domestic, communitarian (school, health center, government buildings, street lighting, sports fields and other places for community gatherings) and productive (agricultural users, shops, tailors, hairdressers, etc.).
9. Capacitation and empowerment of users and demonstrative sessions.
10. Capacitation of local technicians and/or local entrepreneurs.
11. Establishment of service contracts.
12. Participation of the beneficiaries, according to their capacities and possibilities, in the actual installation of the power system and local incardination of the business model.
13. Participation of the community in the management and maintenance of the electricity service (e.g. fee collection, basic maintenance, community links, local entrepreneur, whether on his own or supported by a bigger service provider).

14. Customer care, incidence management, assessment of quality of service and satisfaction of users.
15. Multi-actor agreements or alliances with enterprises, authorities, donors and financers or other relevant actors should always involve representatives of the communities.

7.5 Council for electrification: governance of a complex ecosystem

8 Conclusions

9 Acknowledgements

10 References

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