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Remote Autonomous Energy Systems Project: Towards sustainability in developing countries

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ABSTRACT

Throughout the world, but mostly in developing countries, there are presently regions where electricity supply is insufficient or non-existing. Innumerous authors affirm that this lack of access to electricity is a key factor in perpetuating poverty around the world and compromises the socio-economic progress of those places. Thus, improving energy access is a priority since 1.3 billion people around the world still lack access to electricity, 84% of them living in rural areas.

However, the energy demand in developing countries is completely different from what is observed in the regions like Europe or North America. According to the International Energy Agency, the households in many non-OECD countries still rely heavily on traditional, non-marketed energy sources, including wood and waste, for heating and cooking. Therefore, designing energy systems for developing countries presents a great challenge: designing from scratch a system that is both environmentally and economically viable and that enables social and economic development for the populations.

This work focuses on the development of a system design methodology that optimizes the final solution taking into account a demand growth pathway that reflects the economic development associated with the introduction of electricity.

1. Introduction

Throughout the world, but mostly in developing countries, there are presently regions where electricity supply is insufficient or non-existing. The absence of commercially supplied energy in a society – especially electricity – tends to accentuate the existence of social asymmetry in conditions of living and is a key factor in perpetuating poverty around the world, as suggested by authors like Rifkin [1] or Smith [2]. This can take the form of increased poverty, lack of opportunity for development, migratory flow to large cities and a society's disbelief regarding its own future.

To solve this problem, authors like Pereira et al. [3] or Bekker et al. [4] argue that the key factor for the economic development of the rural environment is the access to regular electric energy. Ruijven et al. [5] present a detailed analysis to the rural electrification benefits, concerning its influence at the community level, at the enterprise level and at the household level. Brew-Hammond in [6] analyzed the sub-Saharan Africa situation and states that the provision of energy services is necessary to pull those countries out of poverty. He suggests further the implementation of an energy for poverty reduction action plan, to foster productive uses and energy for income generation in order to address the key driver for transitioning to cleaner fuels and escaping the poverty trap. And finally, international organizations like the African Development Bank [7] support in their reports that the access to electricity is critical for socioeconomic growth.

The access to modern energy is in fact a key issue to pursuit the United Nation Millennium Goals [8,9], especially the ones related to poverty reduction and environmental sustainability [10]. As a result, some of the most important global financing institutions like the World Bank, the International Monetary Fund or the International Finance Corporation, are nowadays giving priority to improve energy infrastructures in developing countries, where many poor people suffer from a lack of access to modern energy. According to the latest numbers from the International Energy Agency (IEA) [11,12], there are 1.3 billion people around the world that lack access to electricity, 84% of them in rural areas. Without additional dedicated policies, by 2030 this number will drop, but only to 1.2 billion and mostly due to people's migration to urban areas. This means that 20% of the world's population still lack access and the majority of them are living in Sub-Saharan Africa. As a result, the World Bank is planning to expand its support for renewable energy and energy efficiency with special attention to those world areas [13].

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Apart from the lack of infrastructures, there is another crucial issue when analyzing energy systems in developing countries: the kind of energy needs/uses [14], which are completely different from what is observed in the developed regions like Europe or North America. In developing countries, the energy demand should aim at fulfilling not only basic needs like illumination but also socio-economic development drivers like communications infrastructures and access to information and knowledge in order to foster the welfare improvement of these populations [4,6,13]. Further, the use of energy should be very efficient in order to seek the implementation of a sustainable energy system paradigm from the beginning that does not exist yet in the developed regions [15] and can represent in the future an enormous economic advantage of the developing regions compared to the developed ones.

Designing rural electrification systems for developing countries presents therefore a great challenge: designing from scratch a system that is both environmentally and economically viable and that enables social and economic development for the populations. Distributed autonomous electricity systems are one of the alternatives to achieve the objective of providing energy to the population to drive their socio-economic development, while the investment in large centralized infrastructures and distribution infrastructures should only be done in very particular cases (like the energy supply of cities). The indirect positive feedback of such a strategy is the fact that may avoid that the rural population moves to the cities in search of better socio-economic conditions and creating large slum dwellers. Despite rural electrification models essentially focused on the technical mathematical simulations [16] or the purely hybrid versus renewable stand-alone systems using existing software [17] in this paper we consider the design of minigrid systems using a scenario based approach for the demand [5].

This paper reports the ongoing status of the development of a rural electrification design methodology under the Remote Autonomous Energy Systems (RAES) Project, which is expected to be implemented in some of the Portuguese-speaking African countries, starting with some Angolan small isolated villages. The work focuses on the development of a system design methodology that optimizes the final solution taking into account a demand growth pathway that reflects the expected economic development associated with the introduction of electricity. To introduce this system design methodology, we start by reviewing in Section 2 the current trends on rural electrification. In Section 3, we discuss some evidences regarding the rural electrification as a mean to achieve socioeconomic development and propose the hypothesis of the existence of a demand growth pathway that basically considers that the introduction of electricity in a rural community may lead to socioeconomic development, which in turn leads to an increase on electricity demand. Finally, in Section 3.2, we present a methodology to design systems for rural electrification for a specific case study, which takes into consideration the proposed hypothesis and optimizes the design solution. Finally, Section 5 draws the conclusions.

2. Current trends on rural electrification

Rural electrification is a broad issue that collects efforts from a wide number and type of actors and institutions, from energy agencies -at the regional, national and local levels – to the international community and the private sector. Rural electrification is vital to improve the quality of life of over 20% of the global population who is still lacking access to electricity. Thus, a successful implementation has to take into account not only the technological options, the socio-economic objectives and also the policy context.

2.1. Technology

Rural electrification technology addresses the choice among the available electricity generation technologies and the system layout design. In general three types of energy systems can be considered: systems running fully on diesel, systems running exclusively on renewable energy resources, and finally hybrid systems.

Systems fully relying on conventional diesel generators have the advantage of being theoretically dispatchable on demand. However, in a rural context, the availability of fuel is a critical issue: the isolated and sometimes inaccessible conditions in rural areas make the delivery of fuel to run a system very difficult, and in any case, very costly. Besides, local environmental impacts also have to be taken into consideration: conventional generators are noisy and polluting, and have a direct health impact on users, especially when located next to the houses.

Isolated energy systems running exclusively on renewable energy have the advantage of being fully autonomous, but offer in general a less reliable quality of service. Without a generator backup, substantial deviation from the anticipated daily load profile and/or unusual adverse weather conditions have the potential to bring the system to collapse or necessitate load shedding. To avoid this, these type of systems need to have: a higher generation capacity than pure diesel systems; and must rely heavily on storage systems – usually batteries – so that electricity becomes available even when the renewable sources are not.

A possible and effective compromise solution is the hybrid power system option, which typically relies on renewable energy to generate 75–99% of total supply (in some cases a diesel generator has been installed, but is hardly ever used due to the good performance of the renewable generation technology) [18]. The large penetration of renewables makes these systems almost independent and lowers the energy prices over the long term, and the diesel generator is used only as a backup to assist in periods of high loads or low renewable power availability or to operate the system in maintenance periods. In hybrid systems, the size of the storage system based on batteries can be smaller and suffer less stress (since the state of charge does not vary as much as in the 100% renewable power system), increasing battery lifetime significantly and reducing replacement costs. Hybrid systems often are the least-cost long-term energy solution, capable of delivering the best services of the three alternatives [18].

In terms of costs, a fully renewable energy system design is expected that the levelized cost of energy (LCOE) higher than to a diesel generator or a hybrid solution, and a reduced battery lifetime, as it may be subject to greater stress [18]. System layout socioeconomic impact.

2.1.1. Renewable energy resources

There are plenty of technology assessments throughout the existing rural electrification literature [19–22]; along with the technical characteristics of the renewable power production equipment, its choice relies as well as on the site resource availability [23,24].

Table 1 presents an outline on the renewable technologies usually considered for isolated systems.

2.1.2. Lay-out

In terms of layout, there are two main possible approaches for rural electrification in the literature: autonomous Solar Home Systems (SHS) in each house and public buildings [25] or a centralized minigrid that supplies all buildings [18].

The SHS are typically composed by PV (photovoltaic) module(s) that charge a battery bank and supply DC (direct current) electricity to DC based appliances (such as CFL (compact fluorescent lamps),

Table 1
Technology assessment for isolated systems.

	Strengths	Weaknesses
Diesel generators	Cost-effective (low consumption and low price fuel) Performance and stability (low maintenance) Multipurpose (not exclusive to power production)	Pollution (GHG and particulate emissions) Noisy operation Diesel availability in developing countries
PV systems	Work well for remote locations Require very little maintenance Environmentally friendly (no emissions)	High costs Large implantations areas (approx. 10 m^2/kW) Local weather patterns and sun conditions directly affect the potential of photovoltaic systems
μ-hydro turbines	Automatic operation Efficient energy source (above 50%) Cost effective energy solution Environmentally friendly (no emissions)	Thorough characterization of site local conditions required Energy expansion not possible Large seasonal variability (low-power in the dry months) Environmental impact
μ-wind turbines	Minimal land use – the land below each turbine can be used for animal grazing or farming Automatic operation	The small and micro wind turbines costs are significantly higher than the large wind turbines Variable power output due to the fluctuation in wind speed The small and micro wind turbines are not yet a mature technology and require a lot of maintenance
Biomass systems	Conversion technologies available in a wide range of power levels at different levels of technological complexity Fuel production and conversion technology indigenous in developing countries Production can produce more jobs than other renewable energy systems of a comparable size Conversion can be to gaseous, liquid or solid fuel Environmental impact low (overall no increase in carbon dioxide) compared with conventional energy sources	Production can create land use competition Often large areas of land are required (usually low energy density) Production can have high fertilizer and water requirements May require complex management system to ensure constant supply of resource, which is often bulky adding complexity to handling, transport and storage Resource production may be variable depending on local climatic/weather effects, i.e. drought Likely to be uneven resource production throughout the year

fan, TV, etc) for each individual household. These systems are usually suited for domestic lighting and small power applications, but have limited scope for income generating activities or overall community development, such as the provision of street lighting, safe drinking water and vaccine refrigeration [21].

The minigrid solution is more community-focused, since it is designed to generate electricity on a central location and provide electricity for various applications in different infrastructures spread within a designated geographical area [21].

Chaurey and Kandpal [21] present the comparative features of minigrid and SHS configurations and identify some key issues, like the disadvantage related to using DC appliances in the SHS configuration or the flexibility advantage associated with minigrids like the possibility to connect it to a distribution grid in the future. Operation and maintenance and battery sizing are also more efficient under the minigrid layout. Since O&M on SHS imply dispersed systems requiring services at scattered locations. Regarding storage usage, a minigrid's battery bank capacity is optimized to supply loads within acceptable levels of reliability throughout the year, while in SHS, batteries are designed to have sufficient autonomy to provide all loads at all times throughout the year. Further, the minigrid may be a financially more attractive option if the village has a large number of households, is densely populated and lies in a geographically flat terrain. Still, in rough terrains SHS might be a better option if the community is small and sparsely populated. A technical and economic comparison of both systems can be found in Table 2.

2.2. Policy

In the year 2000, all countries represented at the United Nations General Assembly approved the Millennium Declaration [9], committing themselves to create a new social and economical development paradigm until 2015 that promoted peace, security, human rights, social welfare and environmental protection through the achievement of the eight Millennium Development Goals (MDG) [9]. One of these objectives, side by side with poverty and hunger eradication, universal access to primary education, gender equality, child mortality reduction, improved maternal health, combat to HIV/AIDS, malaria and other diseases and the definition of new economic and financial systems, is to ensure the environmental sustainability of the planet. Although there is no direct reference to energy in the formulation of the goals, the need for access to energy, particularly modern energy, to improve overall welfare is well recognized in the development community. There are several international publications (IEA, UN (United Nations), WB (World Bank)) linking the MDGs with the importance of modern energy access, where it is shown that energy access is a cross-thematic issue [26]. This fact led to a request, by The UN Advisory Group on Energy and Climate Change, for the adoption of the goal of universal access to modern energy services by 2030 [11]. Indeed, this is an enabler to address almost all the MDG.

Access to modern energy facilitates economic development by providing more efficient and healthier means to undertake both basic household tasks and means and social welfare services, often more cheaply than by using the inefficient substitutes, such as candles and batteries. Along with those, modern energy is crucial to income-generating activities such as power water pumping, providing drinking water and increasing agricultural yields through the use of machinery and irrigation (MDG#1 – eradicate extreme

Table 2
Comparative features of minigrid and SHS configurations.

	Technical analysis	Economic analysis
SHS	Individual users; 20–250 W;	Dispersed systems require more expensive O&M services due to scattered locations;
	Mainly DC appliances.	Financially, is the best choice when the community is small and sparsely populated and the village is located in rough terrain.
Minigrid	Community oriented; 5–500 kW;	Cheaper O&M services of the entire system due to its centralized location;
	Mainly AC appliances; Possibility with grid interconnectivity in future.	Financially, is the best choice when the village has a large number of households, is densely populated and lies in a geographically flat terrain.

poverty and hunger). In poverty-stricken communities children usually spend significant time gathering fuelwood, fetching water and cooking. Access to improved cooking fuels or technologies may facilitate school attendance. Besides, electricity availability is important for education because it provides lighting and promotes communication, particularly through information technology (MDG#2 – Achieve universal primary education). Access to electricity and modern fuels reduces the physical burden associated with carrying wood and frees up valuable time, especially for women, widening their employment opportunities. Additionally, street-lighting improves the safety of women and girls at night, allowing them to attend night schools and participate in community activities (MDG#3 – Promote gender equality and empower women). Reducing household air pollution through improved cooking fuels and stoves for cooking decreases the risk of respiratory infections, chronic obstructive lung disease and lung cancer (when coal is used) decreases. Improved access to energy also allows households to boil water, thus reducing the incidence of waterborne diseases. Besides, it improves communication and transport services, which are critical for emergency health care and electricity availability help developing health clinics and hospitals (MDG #4 – Reduce child mortality; MDG #5 – Improve maternal health; MDG #6 – Combat HIV/AIDS, malaria and other diseases). Cleaner energy use reduces greenhouse-gas emissions and global warming. Moreover, modern cooking fuels and more efficient cookstoves can relieve pressures on the environment caused by the unsustainable use of biomass. The promotion of low-carbon renewable energy is congruent with the protection of the environment locally and globally, whereas the unsustainable exploitation of fuelwood causes local deforestation, soil degradation and erosion (MDG#7 – Ensure environmental sustainability). Finally, electricity is necessary to power information and communications technology applications (MDG#8 – Develop a global partnership for development).

Rural electrification is therefore a worldwide recognized work area, vital to an important number of developing countries facing structural transformations such as the consolidation of the peace process, macroeconomic stabilization and gradual economic growth. Now, those countries face the challenge of improving its population's living conditions. At the moment, many of those governments are discussing the development options for the energy sector, an important segment of the basic infrastructure to support economic and social recovery of the country, which intervenes directly in the development of key sectors such as supply and water treatment, sanitation, health, food refrigeration, lighting, domestic heating, transportation, agriculture, industry and modern communications. However, we are only facing the beginning of those policies' implementation: according with the latest available IEA statistics, the Sub-Saharan Africa's rural electrification rate is only 14.3%.

Table 3 presents the figures for modern energy access in the world, by region and by country and Table 4 presents both current and forecasted (according to the IEA New Policies Scenario) numbers for people without electricity access worldwide.

2.3. Investment

A fundamental aspect for the success of rural electrification is how the investment is done. Mainal and Silveira [27] and Balachandra [28] describe respectively the financial and strategic efforts required to implement rural electrification. Fig. 1 presents the regional figures of WB lending for energy access between 2000 and 2008 fiscal years [26]. East Asia and the Pacific and Africa have received 45% of the energy access-related commitments; when accounting Latin America and Caribbean, those three developing regions' energy access investments rise up to 55% of the total WB portfolio budget. Fig. 1 also presents a classification to the main types of investments in energy access and its figures. They comprise policies to support energy access, rural electrification, the household energy transition to modern fuels, and improvements in energy efficiency and productive uses of energy. According with this WB report [26], it was estimated that total WB investments in energy access during fiscal 2000–08 to be about US$4 billion, and it is approximately one-fifth of the total energy related investments.

The IEA estimates that in 2009 $9.1 billion was invested globally in extending access to modern energy services, supplying 20 million more people with electricity access and 7 million people with advanced biomass cookstoves. Regarding the type of financing structure responsible for that, IEA also estimates that bilateral Official Development Assistance accounted for 14% of total investment in extending energy access; multilateral organizations, such as international development banks and funds, accounted for more than $3 billion of such investment in energy access, around 34% of the total. The governments in developing countries were responsible for an estimated 30% of investment in energy access which includes investments made directly by the governments and through state owned utilities. The private sector is estimated to have accounted for 22% of the total investment in energy access. In the case of investment in energy access by domestic governments

Table 3
Energy access in 2009 – regional aggregates [12].

	Without access to electricity		Relying on the traditional use of biomass for cooking	
	Population (million)	Share of population	Population (million)	Share of population
Africa	587	58%	657	65%
Nigeria	76	49%	104	67%
Ethiopia	69	83%	77	93%
DR of Congo	59	89%	62	94%
Tanzania	38	86%	41	94%
Kenya	33	84%	33	83%
Other sub-Saharan Africa	310	68%	335	74%
North Africa	2	1%	4	3%
Developing Asia	675	19%	1921	54%
India	289	25%	836	72%
Bangladesh	96	59%	143	88%
Indonesia	82	36%	124	54%
Pakistan	64	38%	122	72%
Myanmar	44	87%	48	95%
Rest of developing Asia	102	6%	648	36%
Latin America	31	7%	85	19%
Middle East	21	11%	0	0%
Developing countries	1314	25%	2662	51%
World	1317	19%	2662	39%

Table 4
Number of people without access to electricity by region (million) [12].

	2009			2030		
	Rural	Urban	Share of population	Rural	Urban	Share of population
Africa	466	121	58%	539	107	42%
Sub-Saharan Africa	465	121	69%	538	107	49%
Developing Asia	595	81	19%	327	49	9%
China	8	0	1%	0	0	0%
India	268	21	25%	145	9	10%
Rest of developing Asia	319	60	36%	181	40	16%
Latin America	26	4	7%	8	2	2%
Middle East	19	2	11%	5	0	2%
Developing countries	1106	208	25%	879	157	16%
World	1109	208	19%	879	157	12%

Table 5
Sources of financing and the financing instruments they provide [12].

	Grants / credits	Concessionary loans	Market-rate loans	Credit line for on-lending	Partial credit guarantees	Political risk insurance	Equity	Quasi-equity	Carbon financing	Subsidy / cross-subsidy	Feed-in-tariff	Technical assistance
Multilateral development banks	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓
Bilateral development agencies	✓	✓	✓	✓					✓			✓
Export–import banks/ guarantee agencies			✓			✓						✓
Developing country governments	✓	✓					✓	✓		✓	✓	
State-owned utilities							✓			✓	✓	
National development banks		✓	✓	✓	✓							✓
Rural energy agencies/funds	✓									✓		✓
Foundations	✓						✓		✓			
Microfinance			✓									
Local banks			✓									
International banks			✓					✓	✓			
Investment funds							✓		✓			
Private investors							✓		✓			✓

and the private sector, the share of total investment directed to energy access is estimated to be less than 1% of the gross fixed capital formation in these countries in 2009. Finally, IEA forecasts an average future investment of $14 billion per year between 2010 and 2030 [12] (Table 5).

3. Rural electrification as a mean to achieve socioeconomic development

In this section we propose the hypothesis that when implementing energy systems in isolated regions in developing countries, a demand growth pathway will occur, reflecting the socioeconomic development associated with the introduction of electricity. To support this hypothesis, we present a set of indicators that describe the socioeconomic development of countries and regions and then describe in detail the proposed demand growth pathway.

3.1. Development indicators

According to IEA [11], a constructive energy strategy consists of setting targets and indicators in order to monitor rural energy access progress. IEA has come up with the Energy Development Index (EDI), which ranks developing countries in their progress towards modern energy access and it is publishing its evolution in its annual World Energy Outlook reports since 2002.

The EDI is composed of four indicators, each of which captures a specific aspect of potential energy poverty: 1) per capita commercial energy consumption, which serves as an indicator of the overall economic development of a country; 2) per capita electricity consumption in the residential sector, which serves as an indicator of the reliability of, and consumer's ability to pay for, electricity services; 3) share of modern fuels in total residential sector energy use, which serves as an indicator of the level of access to clean cooking facilities; and 4) share of population with access to electricity [11].

Another example of suitable indicators in rural electrification's tracking progress was set by a partnership led by IAEA (International Atomic Energy Agency) and UNDESA (United Nations Department of Economic and Social Affairs) [29], and consists of the thirty Energy Indicators for Sustainable Development (EISD). They are divided into the three sustainability dimensions (social, economic and environmental) and its summarized maturation process can be observed up in [30]. One of the most complete studies where the EISD methodology[1] was firstly applied is the EISD Country Studies Report [29], which demonstrates its use to assess developing countries' energy progress. It allows tracking the current country status, after some measure/strategy being implemented. For instance, for Brazil, it is possible to track the effect of some policy options using selected indicators.

Along with these two energy-related indicators frameworks, the United Nations (UN) uses in its annual Human Development Reports [31] indexes like the Human Development Index (HDI), its Inequality-adjusted form (IHDI) and the Multidimensional Poverty Index (MPI) to characterize the country's human conditions progress. "A decent standard of living", "cooking fuel" or "electricity" are accounted variables in the UN indexes computation. More recently, Nussbaumer et al. [32] proposed a Multidimensional Energy Poverty Index (MEPI), composed of two components: a measure of the incidence of energy poverty, and a quantification of its intensity, and compared it with both EDI and HDI. In any case, the indicators are a positive scale, where the closest to zero means the less developed the country is.

Table 6 presents some of the referred indicators for the particular case of Angola, the proposed case study in Section 4.

The 2010 World Energy Outlook even presents a comparison between EDI and HDI which shows the existence of a direct logarithmic correlation between the contribution of energy services and the advancement of human development (Fig. 8.17 in [11]). However, in the case of Angola, the correlation is not very strong, since the EDI indicator is reasonably good when compared to the HDI. This indicates that energy wise, some energy intensive activities may mask the direct effect on the economic development.

Thus, and since our hypothesis is that the electrification is a key element for economic and social development, Fig. 2 shows, side by side, both the share of population with access to electricity and the residential energy use index (two EDI computation's indicators) [11] compared with the MPI [31]. In this figure, we represent the different countries classified by its geography and we highlight the cases of Angola but also Cameroon and Senegal, which are two of the sub-Saharan countries whose HDI is higher than Angola. Fig. 2 confirms that electrification has a direct linear correlation (0.77) to the poverty index MPI. This correlation is very strong for Latin

[1] The indicators were used according to their previous framework, the Indicators for Sustainable Energy Development (ISED), which were reformulated into the EISD current list.

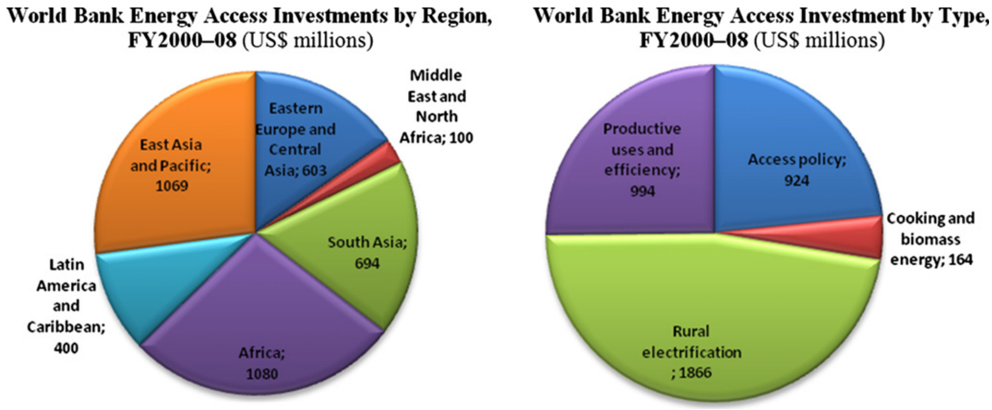


Fig. 1. The World Bank Energy Access Portfolio [26].

America and the Caribbean countries, the Arab countries and the East Asia and the Pacific and less strong for sub-Saharan countries and south Asia. The three highlighted countries – Angola, Senegal and Cameroon show a strong correlation though with a bias in terms of MPI, meaning that for the existing electrification rates, the poverty index should be lower.

In what concerns the correlation (0.72) between the availability of energy services in the residential sector and the MPI, by logarithmic variation definition, it is easily deduced that the residential energy use index elasticity is high until reaching 0.2, which means that it has a high impact on the MPI variation. From 0.2 forwards that elasticity decreases – for higher residential electrification rates poverty is always significantly low.

Both Fig. 2 results are supported by Nussbaumer et al. [32] conclusions, i.e., they also reached a negative correlation between MEPI and EDI and MEPI and HDI. The EDI showed a lower level of energy system development for those countries for which the MEPI has identified acute energy poverty and they also confirmed the hypothesis of the strong link between energy and development through the MEPI and HDI comparison.

Thus, we propose in this paper that implementing an energy system is an isolated rural area will induce come socioeconomic development and this development will induce later growth in the rural area demand, due,for example, to the acquisition of more appliances. Evidences of this positive feedback have been described in [33–35].

The demand growth pathway hypothesis is now explained in detail.

3.2. The demand growth pathway hypothesis

The demand growth pathway hypothesis proposed in this paper states that the demand in an isolated system that is electrified will evolve in the following way: 1) at the beginning, the system is designed to fulfill a basic demand. This is described as the Base Scenario; 2) at a later stage, the demand will increase due to the socioeconomic development of the population. This is described as the Welfare Scenario.

The Base Scenario refers to a total demand that only accounts for the use of electricity related to public buildings: the health centre and the school, which is in general also the community centre during the evening period of the day.

The Welfare Scenario takes into account: 1) the use of some electricity uses beyond the basic needs in the health centre and the

Table 6
Important indicators related to a rural electrification assessment.

Indicator(s)	Focus area	Author	Mission	Angola	Rank
EDI – Energy Development Index [0–1]	Energy	IEA	To rank developing countries in their progress towards modern energy access.	0.111	51
HDI – Human Development Index [0–1]	Social	UN	It is a summary measure of human development, measuring the average achievements in a country in three basic dimensions of human development: a long and healthy life, access to knowledge and a decent standard of living.	0.403	146[a]
MPI – Multidimensional Poverty Index [0–1]	Heath Education Standard of Living	UN	It complements money-based measures by considering multiple deprivations and their overlap. It identifies deprivations across the same three dimensions as the HDI and shows the number of people who are poor and the number of deprivations with which poor households typically contend.	0.452	92[b]
EISD – Energy Indicators for Sustainable Development [0–1]	Social Economic Environmental	IAEA UNDESA IEA Eurostat EEA	Improve affordability of and accessibility to modern energy services for the rural and urban poor as well as promoting less wasteful use of energy resources by the rich.	–	–

[a] Angola's HDI is 0.403, which gives the country a rank of 146 out of 169 countries with comparable data. The HDI of Sub-Saharan Africa as a region is 0.389, placing Angola above the regional average. (http://hdrstats.undp.org/en/countries/profiles/AGO.html).
[b] Rank of 92 out of 103 countries with comparable data. This index is only available to 2008.

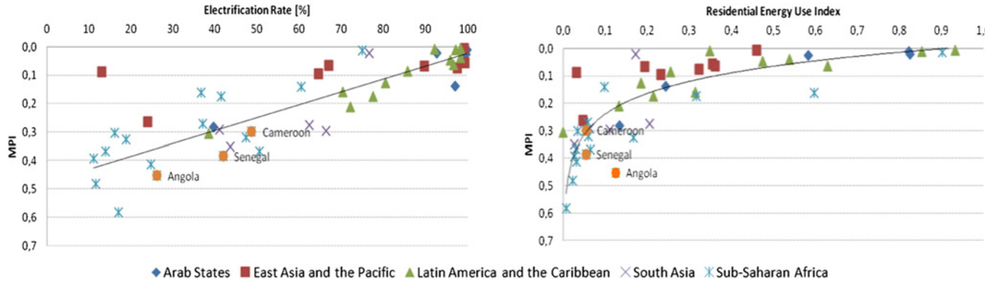


Fig. 2. Comparison of the electrification rate and the residential energy use index to the MPI.

school, e.g. air conditioning; 2) it considers the electrification of the powerful/wealthier families' households in the community with some appliances (e.g. lighting and fridge), based on the demand profile for households from developing countries [36].

In order to estimate the daily energy needs related to each of the previous scenarios and in case there is no detailed information about the community, an approach based on [35] is suggested, as shown in Table 7, where *n* represents the number of households that are considered to be electrified.

4. System design methodology

In this section, we propose a system design methodology to address the demand growth pathway hypothesis proposed in the previous section. The objective is to obtain a system design that can cope with the demand growth, by defining a design solution that is flexible enough to be adjusted from one scenario to the other just by purchasing some equipment and without requiring changes in the system architecture.

The design approach consists in designing several solutions for the Base and the Welfare Scenarios independently, and from a small set of the best solutions for each case, choose the one for the Base Scenario that can be best adapted to fulfill a Welfare Scenario. This does not necessarily mean to choose the best technical or most economical solution, but rather the most flexible.

The design approach is described in detailed based on the application to a specific case study.

4.1. The RAES project case study

In this paper we applied the proposed methodology to the RAES project which aims at developing a minigrid solution for rural villages in sub-Saharan African countries like Angola. In particular, we assumed that a typical Angolan rural village has over 5000 inhabitants[2] and, considering 6 persons per household [37], it corresponds to an average of 865 households per village. Regarding existing community infrastructures, we consider the existence of one health center and one school which, during evening time, also operates as a community center. Since this kind of villages usually presents high population density values combined with an unbalanced social structure, we consider in this case we considered that only 1% of households would be electrified in the welfare scenario conditions.

The electricity consumption of each of the buildings in each scenario was based on measurements made by a company that is promoting the investment in such type of villages. In the Base Scenario assumptions, the school is consider to have a refrigerator, some artificial lighting and a TV + DVD equipment to be used by the evening, when the school is functioning as a community centre. The health centre is considered to have also a refrigerator and some artificial lighting, as well as other electric medical equipment.

In the Welfare Scenario assumptions, the school is considered to include in addition to the appliances considered in the Base Scenario a personal computer and a HVAC equipment, while the health centre is considered to include an addition an HVAC equipment.

Table 8 shows a comparison between the daily load energy profiles considered in this study and the ones proposed in order to achieve the MDG [35]. While the community buildings present similar energy intensities, the difference concerning the household load profile is due to the specific estimation in this case of a 24 h a day of electricity demand for several uses (a refrigerator, artificial lighting, a TV, a small radio and a fan) while the reference study cited only considers 4 h a day for lighting purposes.

In both scenarios, and beyond the referred energy uses in those profiles, we considered the use of four PV LED (photovoltic light emitting diode) lamps for public lighting per village, which are accounted only for the economic analysis of the solutions.

Regarding the demand (see Fig. 3), the Base Scenario load peak occurs during the evening, between (17 and 21 h), which corresponds to the use of artificial lighting and entertainment on the community centre, as well as the use of a specific medical equipment in the health centre at the period of maximum solar radiation availability.

The Welfare Scenario (also in Fig. 3) considers the use of indoor thermal comfort conditions in the health centre or IT equipments (computer, projector) in the school and considers household demand for 1% of the households that include a refrigerator, some entertainment appliances such as a TV and a radio, and a small fan to help with the high indoor temperature. It was also considered artificial lighting to promote evening activities as reading and studying.

Supply-wise, in this paper we compare two solutions: a hybrid system and a fully renewable system based on solar photovoltaic

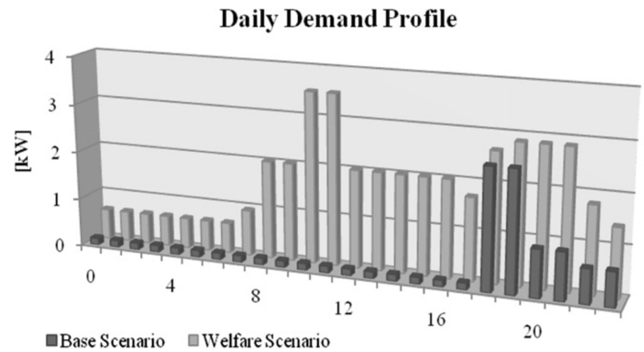
Table 7
Estimated daily energy needs based on Modi et al. 2006 [35] [kWh/day].

	Households	School	Health post	Village
Base scenario	–	5.48	5.48	10.96
Welfare scenario	0.20	5.48	21.92	27.40 + 0.20*n*

Table 8
Comparison between estimated daily load profiles and Modi et al. 2006 [35] [kWh/day].

	Households	School	Health centre	Village
Base scenario	–	5.10	5.76	10.86
Welfare scenario	2.56	11.00	13.76	42.68
Modi et al. 2006 [35]	0.04–0.20	5.48	5.48–21.92	10.96–28.80

[2] Huambo province data.



	Scaled[3] Annual Average Daily Load [kWh/day]	Scaled Peak Load [kW]
Base Scenario	10,9	4,4
Welfare Scenario	42,7	6,4

Fig. 3. Scenario's simulation data.[3]

Table 9
System results.

		PV [kW]	Diesel [kW]	Battery units	Inverter [kW]	Initial capital [€]	Operating cost [€/yr]	Total NPC [€]	LCOE [€/kWh]	Renewable fraction [%]	PV production [kWh/yr]	DG production [kWh/yr]	Excess electricity [%]
Hybrid system	Base scenario	1.1	4.5	4	1.0	8953	1350	24,435	0.535	27	1830	2921	6.74
	Welfare scenario	1.1	2.8	8	3.0	10,175	4389	60,515	0.339	4	1830	14,857	0
PV system	Base scenario	4.4	–	32	4.5	27,874	2495	56,486	1.238	100	7321	–	27.3
	Welfare scenario	35.2	–	36	6.5	138,086	9697	249,308	1.399	100	58,569	–	67.2

(PV) panels due to the climate and geographical conditions. The reason to exclude technologies micro-wind turbines is that the average known wind speed (there are no accurate wind data for Africa and additionally there is no wind atlas including Angola) in those villages is around 3.5 m/s – the usual cut-in speed for wind turbines – which turns unviable the wind power production [18]. As for the micro-hydro power production, it would only make sense to consider this kind of electricity production if there were small rivers in the villages' area, which is not the most common situation.

4.2. Results

For each scenario, we compare the two system configurations obtained through HOMER® simulations. HOMER – Hybrid Optimization Model for Electric Renewables – is an optimization model for distributed power developed by National Renewable Energy laboratory, USA. It simulates the operation and associated costs of a system by making energy balance calculations for each of 8760 h in a year. In this work, the assumed diesel price was 0.6 €/l, which is the estimated price in Angola. The results are summarized in Table 9 considering different parameters: initial capital, yearly operating costs, total net present cost, and LCOE, renewable fraction and excess electricity.

The Hybrid configuration is considered to be the most cost effective on both Base and Welfare scenarios compared to the PV system. In the case of the Base Scenario, the initial cost increases over 200% from the Hybrid to the PV and the LCOE doubles. For the welfare scenario, the LCOE increases 4 times more, while the investment is 13 times higher. The PV system was also shown to be less efficient than the hybrid system as the unused electricity in the fully renewable solution achieved 27.3% in the Base Scenario and 67.2% in the Welfare Scenario.

The hybrid system solution to cover the Base scenario (combined PV, Diesel generator and batteries) is however significantly different that on obtained to cope with the Welfare Scenario, which included more batteries and inverters and a lower installed capacity of Diesel Generator. This is due to the demand profile characteristics of the Base and Welfare scenarios as the daily load is 292% higher in the Welfare Scenario, while the peak load is only 45% higher. Therefore, to evolve the hybrid system solution of the Base Scenario to the solution of the Welfare Scenario would be very complex.

The results from Table 9 indicate the solution to the Welfare Scenario would represent only a small increase in terms of the required initial capital (14%) and even a lower LCOE (−37%), when compared to starting in the Base Scenario. This means that in this specific case, the best option to cope with the demand growth pathway hypothesis would be to install the hybrid system prepared to the welfare scenario, even if in the initial condition – the base scenario – the solution is not optimal.

When applied a fuel price sensitivity analysis, it was verified for the Hybrid system that the obtained base scenario results were quite vulnerable to its variation: an increase in the diesel price means an increase in both installed PV and storage capacity. This analysis is particularly relevant in isolated rural areas, where access to diesel may be difficult and expensive. On the other hand, the welfare scenario configuration has a critical point, i.e., in spite of a crescent PV capacity due to a higher diesel price, once this price is over 1.2 €/l, the optimal configuration remains unchangeable.

In the situations in which there is no access to diesel and the system needs to rely on PV and storage, the difference between the Base Scenario and the Welfare Scenario is very significant as shown by the 400% higher initial capital requirements and the 13% higher LCOE. As such, it would be more beneficial to start the electrification of the village by considering the Base Scenario, which requires a lower installed capacity and more easily allows the transition to a minigrid solution in the case access to diesel becomes available in the future.

5. Conclusions

This paper showed how rural electrification may contribute to socioeconomic development of rural isolated areas in developing

[3] Scaled data resulting from accounting uncertainty effects during HOMER simulations.

countries and proposes the hypothesis that when implementing an energy system in a rural area, as it will induce socioeconomic development, it will also imply an increase of the energy demand. This hypothesis, called the demand growth pathway hypothesis, has been already observed in some cases of rural electrification, and is described as the evolution of a Base scenario demand to a Welfare scenario demand.

The paper proposes further a system design approach that takes into consideration this hypothesis. The approach consists in designing a set of optimized solutions for both scenarios and choose the solution that is more easy to evolve from one scenario to the other. The methodology is applied to the case study of rural electrification of Angola. The results show that a hybrid configuration is the most technical and cost effective solution when considering the scalability of the system from a base scenario to one where a certain welfare has been achieved through social and economic development. The results are analyzed using a sensitivity analysis that considers the highly volatile availability of fuel, since developing countries, especially in rural areas, are known to deal with unstable fuel prices and security of supply issues. Therefore, the two best options for the initial stage of electrification in this case study are the welfare scenario hybrid system (in this system configuration is the one with the lowest LCOE and its initial cost is only 12% higher) or the base scenario PV system, if the scarcity of Diesel is a major decision issue.

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Nomenclature

EEA	European Environment Agency
Eurostat	Statistical Office of the European Communities
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LCOE	Levelized Cost of Energy
LPG	Liquefied Petroleum Gas
UNDESA	United Nations Department of Economic and Social Affairs
WB	World Bank

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