Rural Electrification in Central America and East Africa, two case studies of sustainable microgrids

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To appear in: Iberoamerican Journal of Development Studies

Please cite this article as: Micangeli, A., Del-Citto, R., Checchi, F., Viganò, D., Nouboundieu, S., Cestari, G., (2018). Rural Electrification in Central America and East Africa, two case studies of sustainable microgrids. Iberoamerican Journal of Development Studies, forthcoming

Rural Electrification in Central America and East Africa, two case studies of sustainable microgrids

Electrificación rural en América Central y África Oriental, dos estudios de casos de microrredes sostenibles

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Recepción/received: 29.11.2016 Aceptación/accepted: 9.1.2018

Abstract

This paper deals with the electrification of rural villages in developing countries using Sustainable Energy Systems. The rural electrification feasibility study is done using Hybrid Optimization Model for Electric Renewable PRO (HOMER PRO). The HOMER PRO energy modelling software is an optimization software improved by U.S. National Renewable Energy Laboratory. It helps in designing, comparing and optimizing the design of power generation technologies.

In this paper, two rural electrification case studies are modelled and analysed using HOMER PRO. Technical and economic evaluation criteria are applied to study the feasibility of a micro-hydro plant in El Díptamo (Honduras), and a hybrid plant composed of photovoltaic module arrays, Diesel generators, and flow batteries, in a small island on Victoria Lake. For both cases, we show the results of the studies of the daily and yearly loads, of the resources available in the area and the economic evaluation of the chosen plants configuration.

Keywords: HOMER PRO, optimization, microgrids, rural electrification, sustainable energy systems, renewable resources.

Resumen

En este documento se trata el tema de la electrificación de aldeas rurales en países en desarrollo donde se utilizan sistemas de energía sostenible. El estudio de factibilidad de electrificación rural se realiza utilizando el Modelo de Optimización Híbrido para Electric Renewable PRO (HOMER PRO). El *software* de modelado de energía HOMER PRO es de optimización, mejorado por el Laboratorio Nacional de Energía Renovable de Estados Unidos. Ayuda en el diseño, la comparación y la optimización de tecnologías de generación de energía.

En este trabajo, se presentan y analizan dos casos de electrificación rural mediante el uso de HOMER PRO. Se aplican criterios de evaluación técnica y económica para estudiar la viabilidad de una microhidroeléctrica en El Díptamo (Honduras), así como de una planta híbrida compuesta de matrices de módulos fotovoltaicos, generadores diésel y baterías de flujo, en una pequeña isla ubicada en el lago Victoria. Para ambos casos, mostramos los resultados de los estudios de las cargas diarias y anuales, de los recursos disponibles en el área y la evaluación económica de la configuración de las plantas elegidas.

Palabras clave: HOMER PRO, optimización, microrredes, electrificación rural, sistemas de energía sostenibles, recursos renovables.

1

Introduction

Electrification of rural areas could represent a problem in developing countries which have difficulties in power generation and transmission (Micangeli *et al.* 2012). According to several studies, political efforts to improve transmission grid and power generation system are to satisfy urban areas and industrial poles loads (Orecchini *et al.* 2002) because of the greater energy demand (Arrambide *et al.* 2012). Recent reports suggest that the use of electrical devices in rural areas in developing countries, for domestic (Micangeli *et al.* 2014b), agricultural, commercial and public purposes, could bring benefits to its inhabitants, especially for basic services related to water (Dell'Era *et al.* 2013, Micangeli *et al.* 2004a, Iannuzzo *et al.* 2013, Michelangeli *et al.* 2013, Noubondieu *et al.* 2017) and communication (Micangeli *et al.* 2014a, Ferrara *et al.* 2015), and to the entire community (IEG 2008).

According to several studies and reports, solutions to bring electricity in rural areas are different: national grid extension, stand-alone systems (Bocci *et al.* 2014), and microgrids. The choice between different solutions depends on various factors, such as: size of community, density of population, economic strength, complexity of terrain and distance from national grid, emergency (Micangeli *et al.* 2004b, Michelangeli *et al.* 2013, Grego *et al.* 2013, Esposto & Micangeli 2010) or development programmes (Alves *et al.* 2009) implementations. Both stand-alone systems and microgrids are very interesting in developing countries to provide electricity (Cataldo & Micangeli 2013, Ten-Palomares 2016) and thermal energy, especially if they are powered by hybrid plants, *i.e.*, powered by different kinds of renewable and non-renewable energy sources, including solar thermal (Kurdgelashvili *et al.* 2012), and biomass-driven devices (Evangelisti *et al.* 2013, Esposto & Micangeli 2010, Bocci *et al.* 2015, Di Carlo *et al.* 2013, Vecchione *et al.* 2013). Climatic conditions and local socioeconomic context have an influence on the choice on which kind of renewable or non-renewable sources are available to be exploited (Arrambide *et al.* 2012, AEREC Programme 2014).

The first community that we analyse in this paper is El Díptamo, Olancho (Honduras), where a long study on attitudes toward sustainability and green economy has previously been performed (Micangeli *et al.* 2014c). According to World Bank data of 2015, Honduras is a developing country with about 45 % of the population living in rural areas, 65 % of which live below the national poverty threshold. Currently, power generation is mainly thermoelectrically powered and closely linked to oil imports (CEPAL 2014). Because of this, Honduras is the second larger GHG emitter of Central America after Mexico (CDIAC Data 2014). In 2017, the 88.7 % of the Honduras population and the

76.3 % of rural population has access to electricity (World Bank Data), being one of the lowest access rate in Central America.

The second evaluation regards the fishermen’s village of *a small Island on Victoria Lake*, in Uganda. According to World Bank Data, Uganda is a developing country as well, with about 83 % of the population living in rural areas, the 27 % of which live below the national poverty threshold (World Bank Data 2016). 85 % of the total energy is consumed in the rural areas where most people live. The main energy source of the country is wood that is extremely important for cooking and heating in rural areas (Di Carlo *et al.* 2013) and constitutes 90 % of rural energy consumption. Regarding power generation, there is an exploitation of the abundant hydric source using hydro-electric plants (695 MW out of the total 873 MW) (Ministry of Energy and Mineral Development 2014). From recent evaluations, the electrical network coverage on the national territory results to be only 15-20 % in 2014 (Ministry of Energy and Mineral Development 2014) (World Bank Data).

2

Materials and methodology

In both case studies, we model and analyse rural electrification using HOMER PRO (Hybrid Optimization of Multiple Energy Resources), an optimization software improved by U.S. National Renewable Energy Laboratory (HOMER Energy 2017). It helps in designing, comparing and optimizing the different combinations of power generation technologies. Technical and economic evaluation criteria are applied to study the feasibility of a micro-hydro plant in El Díptamo and a hybrid plant composed of photovoltaic (PV) modules, a set of electrical Diesel generators, and batteries. A first step is the assessment of the possible electrical load to be served by the microgrid, which is performed thanks to data collected during on-site inspections.

2.1. HOMER PRO: hybrid optimization of multiple energy resources

This simulation tool assists in the planning and design of renewable energy based microgrid. The physical behaviour of each power plant configuration, their life-cycle cost and the energetic and economic comparison were made through the three main operations of the software: simulation, optimization and sensitivity analysis.

In the simulation area, HOMER Pro determines technical behaviour, feasibility and life-cycle cost of a system for every hour of the year. The assessment is made not only for the entire system:

the operation of each component is simulated to examine how the components work in relationship with the entire system.

In the optimization section HOMER displays each feasible system and its configuration in a search space sorted by the minimum cost depending on the total net present cost. In this way, we can find the optimal configuration which satisfies the constraints imposed in the model.

The description of the economic output is set out in the following paragraph.

In the section of sensitivity analysis, the user can analyse the effects of parameter variations in time and the behaviour of the sensitivity variables. The sensitivity variables are those parameters entered by the user and having different values.

Before the construction of the model, the first step needed is the evaluation of the load which could be electric and/or thermal, although in this study we focus on the electric load only. The yearly electric load profile is evaluated by a typical daily shape input. The methods used for the assessment of the daily input load and the simulation of yearly load are set out in the next two paragraphs.

2.2. Evaluation of daily load

In general, evaluating the daily load for communities that are not currently using the electricity is a non-trivial task. The specific context and the lack of public data about the on-going electrification projects and programs provide big uncertainty on the future consumption of the local population. Many factors, like the average income, the demographic increase (due to either newly born or migration), the economic activities and their diversification are factors that likely change in time, in timescales which are shorter than the lifetime of the plant. The correct modelling of these changes in the future years is an almost impossible task, given that the local and national socio-economic context will also affect.

If a greater than expected rise of electricity demand will take place in a timescale of several years, the issue could be faced in this case, for instance, by a revamping of the plant, the inclusion of further power generators (PV modules, Diesel generators, additional turbine, etc.), or by a smart management of the loads by the same community. Given the high uncertainties on this future consumption, and the high investment and logistic costs related to the construction, in the project it was preferred to avoid an oversize and it aims at covering the demand for the estimation provided.

With all these limitations, any rural electrification project needs a rough estimate of the future loads connected to the plant. In this sense, the first necessary step in the evaluation is the assessment of the community buildings. It is necessary to know the number of buildings and classify them into groups according to their intended use. For each group of buildings, we consider the likely, typical electrical devices present in them, through door-to-door surveys. The following step consists in an estimate of the hourly operation for every device in each type of building, and a calculation of the power consumption.

In the estimate of the hourly power consumption of the electrical devices for a given group, we used this following formula:

$$P_{group} = NnfP_{e,\ d} \quad (1)$$

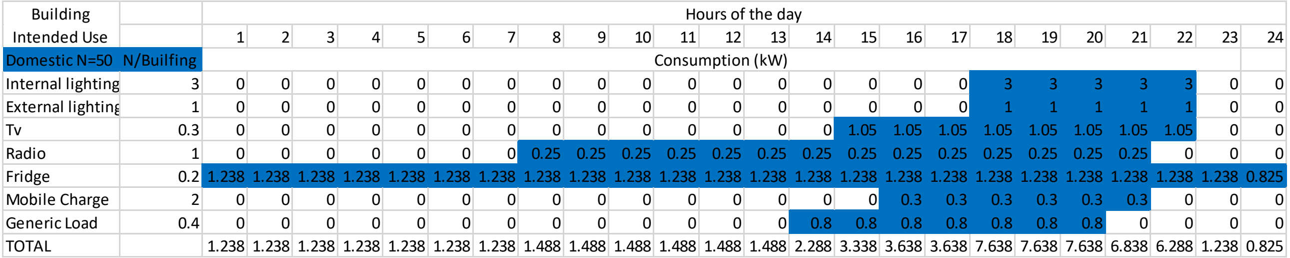
where:

- P_{group}: hourly power consumption of the single electrical device group.
- N: number of buildings with the same intended use.
- n: number of electrical devices in each building.
- f: effective power consumption versus nominal installed power ratio.
- $P_{e,\,d}$: nominal installed power of the electrical devices for every building.

Once the hourly power consumption of each similar group of buildings is obtained, the sum over all groups of buildings gives the hourly and daily loads of the community. Finally, the obtained value has been increased by a security factor which only partly accounts for the uncertainties mentioned above (+10 %).

Figures 1 and 2 represent hourly loads of a typical day for residential buildings for El Díptamo and the small island on Victoria Lake, respectively; the columns represent the hours of the day and the lines represent the devices considered for residential buildings and their power needs, and in the last line it is explained the total requested load for all the residential buildings.

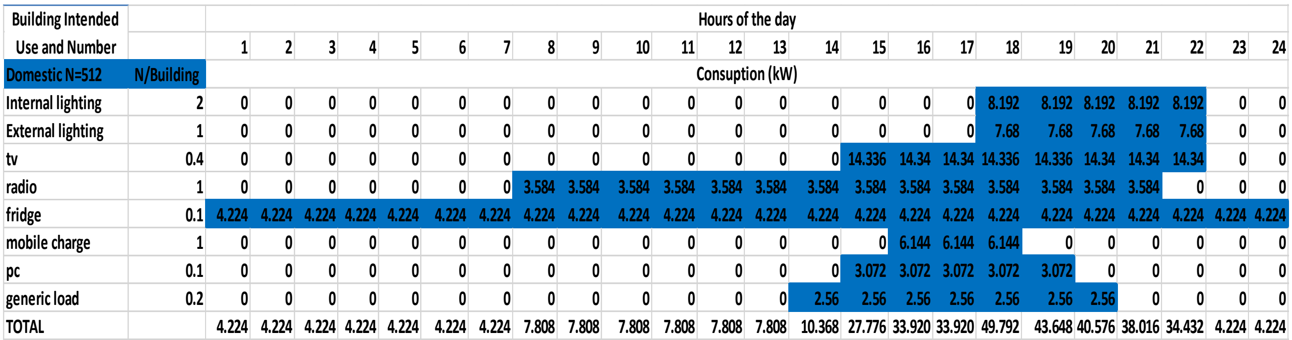
For both cases, users will employ AC power.



Building Intended Use		Hours of the day																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Domestic N=50	N/Builfing	Consumption (kW)																							
Internal lighting	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	0	0
External lighting	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0
Tv	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	0	0
Radio	1	0	0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0	0
Fridge	0.2	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.238	0.825
Mobile Charge	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.3	0.3	0.3	0.3	0	0	0
Generic Load	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0	0	0	0
TOTAL		1.238	1.238	1.238	1.238	1.238	1.238	1.238	1.488	1.488	1.488	1.488	1.488	1.488	2.288	3.338	3.638	3.638	7.638	7.638	7.638	6.838	6.288	1.238	0.825

Figure 1

Hourly loads for residential buildings, El Díptamo



Building Intended Use and Number		Hours of the day																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Domestic N=512	N/Building	Consuption (kW)																							
Internal lighting	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.192	8.192	8.192	8.192	8.192	0	0
External lighting	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.68	7.68	7.68	7.68	7.68	0	0
tv	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14.336	14.34	14.34	14.336	14.336	14.34	14.34	14.34	0	0
radio	1	0	0	0	0	0	0	0	3.584	3.584	3.584	3.584	3.584	3.584	3.584	3.584	3.584	3.584	3.584	3.584	3.584	3.584	0	0	0
fridge	0.1	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224	4.224
mobile charge	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.144	6.144	6.144	0	0	0	0	0	0
pc	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.072	3.072	3.072	3.072	3.072	0	0	0	0	0
generic load	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	2.56	2.56	2.56	2.56	2.56	2.56	2.56	0	0	0	0
TOTAL		4.224	4.224	4.224	4.224	4.224	4.224	4.224	7.808	7.808	7.808	7.808	7.808	7.808	10.368	27.776	33.920	33.920	49.792	43.648	40.576	38.016	34.432	4.224	4.224

Figure 2

Hourly loads for residential buildings, Lake Victoria Island

2.3. Evaluation of yearly load

The yearly load is obtained through adding a daily load stochastic variability over a given baseline. Such variability, quantified by the factor α, is defined by two values: δ_d (daily variability) and δ_{ts} (infra-daily variations), which vary the size and the shape of the baseline load profile, respectively:

$$\alpha = 1 + \delta_d + \delta_{ts} \qquad (2)$$

These values mimic the typical variability of loads observed in grid-connected domestic users. A proper statistical study should be carried out to accurately set these variables, but there is lack of such data for similar contexts. Such statistics can be inferred in the national load data of developed countries, but we think that extrapolating such variability parameters and apply them to our cases is not a realistic choice, due to the very different quality of load profiles (presence/absence of industry, socio-economic situation, etc.). Last, a fine-tuning of such parameters is a second-order uncertainty, compared to the much larger ones mentioned above, regarding the future unknown consumption trends.

To calculate the yearly load of both case studies, an estimation, based on field observation, of typical seasonal daily loads has been done. The calculated profile was then corrected through adding a daily load stochastic variability.

2.3.1. Hydroelectric power

The hydro-electric power output is calculated with the following formula:

$$P = \eta_{hyd}\rho_{water} g h_{net}\acute{Q}_{turbine} \qquad (3)$$

Where h_{net} is the net head measured in meters, considering the friction loss; g = 9.81 m/s^2 is the gravity acceleration; $\acute{Q}_{turbine}$, measured in m^3/s, is the water flow through the turbine; ρ_{water}= 1,000 kg/m^3 is the water density, and η_{hyd} is the turbo-generator efficiency (Harvey *et al.* 1993).

2.3.2. PV output

The PV output depends on the available solar radiation and the plant efficiency, which in turn depends on the orientation of the plant (as much horizontal as possible, given that the location is very close to the equator, but considering practical aspects like deposition of dust, that can be avoided only with a minimum inclination) and on individual efficiencies of the components (modules, inverter, battery pack, cables). Particularly important is the temperature of the modules, which correlate with the solar irradiation. The power output of PV plant can be calculated using the following formula (Lilienthal *et al.* 2006):

$$P = W_{PV} f_{PV} \frac{G_T}{G_{STC}}\left[1 + k_p(T_C - T_{STC})\right] \qquad (4)$$

Where W_{PV} is the peak power output of the PV array at standard test conditions (kW), f_{PV} is the derating factor (%), G_T and G_{STC} are the solar radiation incident respectively at current time step and standard test conditions (kW/m^2), k_p is the temperature coefficient of the power change module (%/°C) and, finally, T_C and T_{STC} are PV cell temperature at current time step and at standard test conditions, respectively (°C).

2.3.3. Economic output

The economic evaluation considers a lifetime of 25 years. Economic outputs are necessary for an evaluation of both plants economic feasibility. The first parameter is the Net Present Cost (NPC, or Lifecycle Cost) that represents all costs during the lifetime of the plant, including capital, and ordinary and extraordinary operation and maintenance (O&M). NPC can be calculated by the following formula (Lilienthal *et al.* 2006):

$$NPC = \frac{TAC}{CRF(i,\ N)} \qquad (5)$$

Where TAC is the Total Annualized Cost (value/year) and $CRF(i,\ N)$ represents the Capital Recovery Factor calculated by:

$$CRF(i, Y) = \frac{i(i+1)^Y}{(i+1)^Y - 1} \qquad (6)$$

Where i is the real interest rate (%) and Y is the number of the year of the useful life of the plant. The second parameter is the Levelized Cost of Energy (LCOE), which compares the TAC with the total energy produced. HOMER calculates this indicator with the following equation:

$$COE = \frac{TAC}{E_{prim} + E_{def} + E_{grid,\ sales}} \qquad (7)$$

Where TAC is the Total Annualized Cost, E_{prim} is the total amount of primary load that the system serves per year, E_{def} is the total amount of deferrable load that the system serves per year and $E_{grid,\ sales}$ is the amount of the energy sold to the grid per year. In our cases, the last two values are zero because there are no deferrable loads and the plants are not connected to the grid.

In the economic evaluation, Global Nominal and Discounted Cash Flows have been used. Those parameters are the sums, year after year, of the cash flows of each configuration plant, including the initial investment. Other parameters are the Simple and the Discounted Payback Time: those parameters represent the time when the cumulative cash flows, nominal or discounted respectively, cross from negative to positive.

3

Results and discussion

3.1. El Díptamo community

The village is located at 24 kilometres from the closest electrified town (La Unión), thus reaching it by extending the national grid is unfeasible, considering the costs, the small population living there and the same limited reliability of the national service, especially in a region like Olancho, far from the main cities. In the village, there are five groups of buildings with different intended use:

- 1 school.

- 1 health center.
- 50 households.
- 3 *pulperías* (little markets), including owners' houses.
- 4 other business activities, including owners' houses.

3.1.1. Daily and yearly load

In the Figure 3 it shows the hypothetical typical daily load profile of the community. It should be noted that domestic load is estimated to reach its peak (10.3 kW) during the evening, between 7 p.m. and 10 p.m. During the night, the load reaches the lowest values, while during the daytime it shows intermediate values: a typical behaviour, especially for contexts without industrial consumption nor active nightlife.

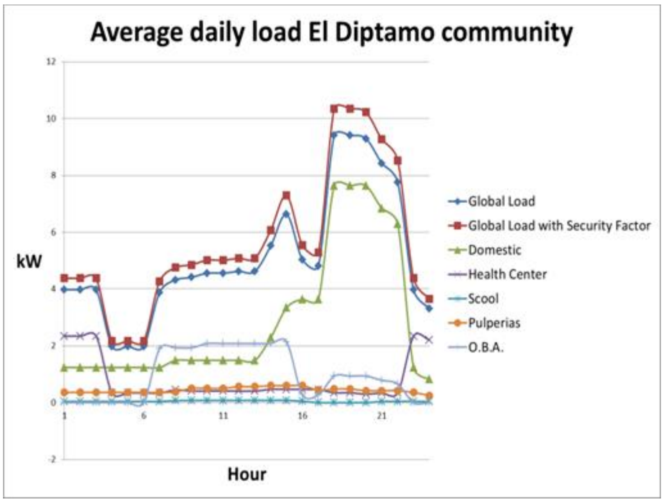


Figure 3

Estimated average daily load, El Díptamo

The yearly load (Figure 4) was estimated accounting for stochasticity, with δ_d and δ_{ts} both set to 10 %. Darker colours indicate low loads while tending to red colours indicate high load. Such variability brings a maximum hourly demand up to 16.6 kW. The annual consumption is about 49 MWh, with an average daily consumption of 143 kWh, as shown in Table 1.

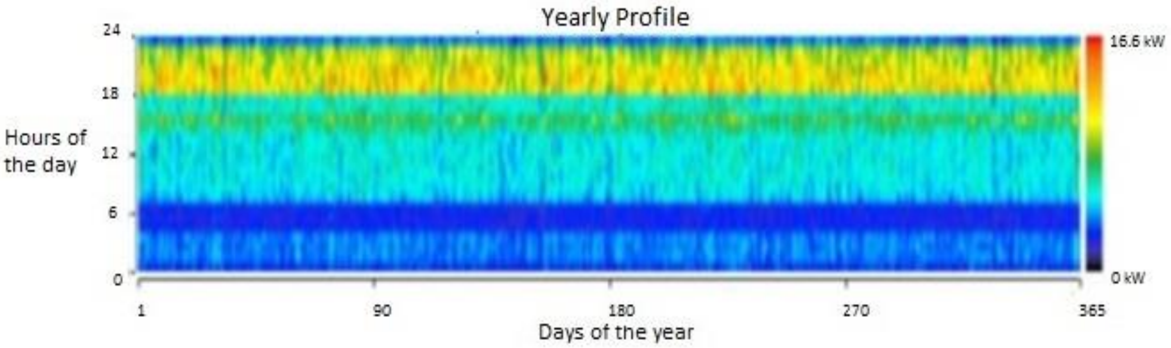


Figure 4

Estimated average daily load, El Díptamo

Average (kWh/d)	Average (kW)	Peak (kW)	Load Factor	Annual consuption (kWh/y)
143.07	5.96	16.56	0.36	49,086

Table 1

Yearly profile load, El Díptamo

3.1.2. Resources and community electrification

During the project development phase, one of the first decisions to be taken was which kind of resource could be exploited. Such decision was motivated more by the specific needs of the project than by technical reasons. As a matter of fact, since the community is in La Muralla National Park, at short distance from a stream (río Díptamo), and the main aim of the donor was not bringing electricity but the environmental protection, the valorisation of the water resources through a micro hydro-power plant seemed the best option. In this sense, a PV system would have provided less added value to the project objectives and, to give a 24-hours supply, it would have needed the installation of batteries, giving much higher capital costs and not-trivial maintenance skills. Instead, the protection of the river as energy source was a win to win solution for the local community and the park safety.

Other renewable energy alternatives would be biomass and wind. However, biomass use in developing countries is conflicting because of the spread deforestation and poor environmental conservation context. This is especially true for Honduras, and especially its central regions, are afflicted by very serious deforestation and wildfire problems, which, together with the diffusion of the weevil plague from Canada, are destroying large extents of the forest. Wind power was excluded since the region is not apparently windy enough. No specific measurements were taken due to lack of resources in the development phase, but the preliminary surveys showed that, according to local knowledge, it was probably not a feasible option. Moreover, other logistic needs were favouring plants composed by components easily transportable through the bumpy road connecting to the village.

Thus, during the project development, it was clear that the best solution for the community, due to the proximity to río Díptamo, is a micro-hydroelectric plant. Moreover, the very good experience of previous similar micro-hydro plants by FHIA (Federacion Hondureña de Investigación Agricola) in Honduras[1] was important for the local expertise already acquired. The project could lean on FHIA personnel expertise in the project management and construction.

As we can see from Figure 5, in Honduras there are two seasons: rainy (from May to November) and dry (from December to April). Specific data for the village location are not available, but the local populations confirmed us the presence of the two seasons stated above, even though recently seasons appear to shift, as in many other countries, very likely due to climate change. An assessment of the precipitation pattern is fundamental because measurements of the río Díptamo flow have been taken for a limited period, due to problems related to the specific project and location. The measurements, taken in March, showed 45 l/s. According to the local knowledge, the observed flow was the typical one for the dry season. Given the limited period of measurements and the intrinsic variability of any hydrological resource, we consider an environmental minimum flow is 25 l/s. This is supposed to preserve the ecological health of the river, with special care about its flow during in the dry season.[2] Note also that the turbine can be manually regulated (by closing inlets) in case of further exceptional reduction required.

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[1] http://www.fhia.org.hn/htdocs/pmicro.html.

[2] See, for instance, Environmental Flow Assessment for the Patuca River (2007). Honduras: Maintaining ecological health below the proposed Patuca III Hydroelectric Project December 15. https://www.conservationgateway.org/Documents/Rio%20Patuca%20Environmental%20Flow%20Assessment%20-%20With%20Appendices.pdf.

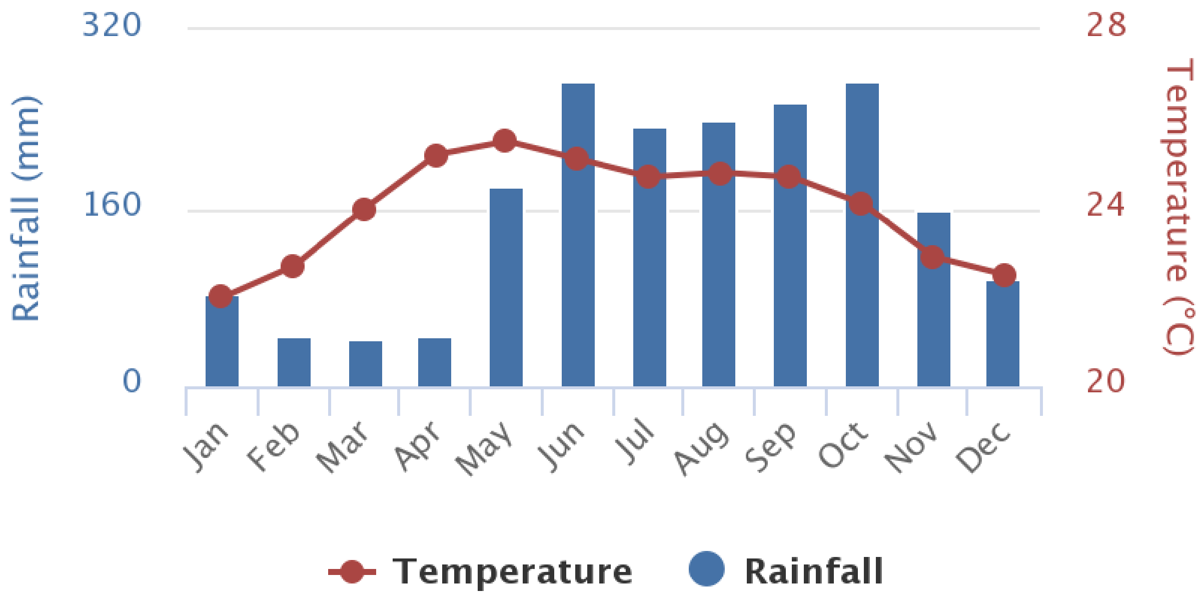

Figure 5

Average monthly temperature and rainfall for Honduras from 1991-2015 (World Bank Data 2017)

The exploitable measured head is 75 metres. Considering the nominal efficiency of the turbo-generator to be 72 % (90 % from the generator, 80 % from the chosen Pelton turbine), we conservatively assume an average plant efficiency of 55 %, also given the usual friction losses (less than 10 %) and distribution losses (less than 5 %). Therefore, the available calculated output power amount to 15.1 kW, which satisfies the community's load, as shown in Figure 6.

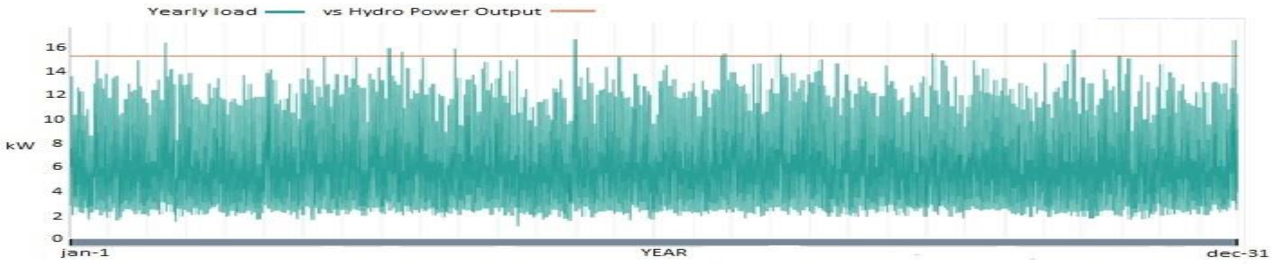

Figure 6

Yearly profile load, El Díptamo

Another alternative, which would be logistically easy but environmentally non-optimal, would be the installation of Diesel generators. As a pure comparison case, we consider a set of 4 generators, each of them with a 4.5 kW power output. Costs of both solutions are shown in the tables 2 and 3, and its O&M costs are estimated according to the past experiences by project developers and local technicians (FIHA 2009, Ten-Palomares 2016).

Micro-hydroelectric component	**Cost [$]**
Turbine + generator	30,500
Pipeline	6,000
Workers	3,500
Staff	12,006
Logistical support	22,365
Civil works	8,000
SUBTOTAL	82,371
Unexpected (5 %)	4,118.55
TOTAL	86,489.55
Operation and Maintenance	500 $/yr

Table 2

Micro-hydroelectric plant cost, El Díptamo

Generators component	**Cost [$]**
Generators (4,5 kW)	950
Installation-transport soundproofing	700
TOTAL	1,650
Fuel	0.74 $/l
Operation and Maintenance	0.56 $/h

Table 3

Generator plant cost, El Díptamo

3.1.3. Economic evaluation

For economic evaluation of both solutions, 25 years plant lifetime, inflation rate and real interest rate respectively equal to 6.1 and 14.3 %, were considered (World Bank Data 2017). The following tables (tables 4 and 5) show both solutions NPC and TAC and the single items that compose them, in $.

NPC [$]		
	Hydroelectric	**Generators**
Capital	86,490	6,600
Replacement	–	14,178
O&M	3,375	31,913
Fuel	–	118,098
Salvage	–	–
TOTAL	89,863	170,763

Table 4
NPC, El Díptamo

TAC [$]		
	Hydroelectric	**Generators**
Capital	12,820	978.29
Replacement	–	2,101.6
O&M	500	4,730.4
Fuel	–	17,505
Salvage	–	–
TOTAL	13,320	25,308

Table 5
TAC, El Díptamo

TAC of generators configuration is higher than hydro configuration because of fuel, O&M and replacement. Thus, the NPC is lower than generators case. In the hydroelectric configuration, the capital cost is much larger than for the generators scenario. The COE of hydro is lower, almost half, than generators: 1.83 $/kWh versus 3.48 $/kwh. The nominal and the discounted cash flows of both configurations are compared in the next figures (figures 7, 8, 9 and 10) and in the Table 6. Outgoing cash flows have been considered in the economic evaluation to show how hydro plant solution allows to save money in time respect to other solutions. In the Figure 7 it is showed the nominal cash flows occurring during the 25 years lifetime: blue represents hydro cash flow, red is the generators cash flow and green is the cumulative difference (hydro minus generators). The cumulative difference starts with a negative value because the higher capital cost of hydro, but it goes to zero in 3.43 years: this value is the Simple Payback. The value of the cumulative difference at 25 years is 515,165 $. Figure 8 has the same meaning than Figure 7, but it regards the discounted cash flows. In this case the payback time, the Discounted Payback, is 5.03 years and the final value amounts to 80,873 $. In the figures 9 and 10 it is showed the trends of nominal and discounted cash flows of both solutions. Also, in those figures, it can be noticed how the hydro cash flows remain approximately equal to the initial value contrary to the generators cash flows that starts with a low value but increases constantly year after year. In those figures the payback time is represented by the value of time where the generators cash flow crosses the hydro cash flow.

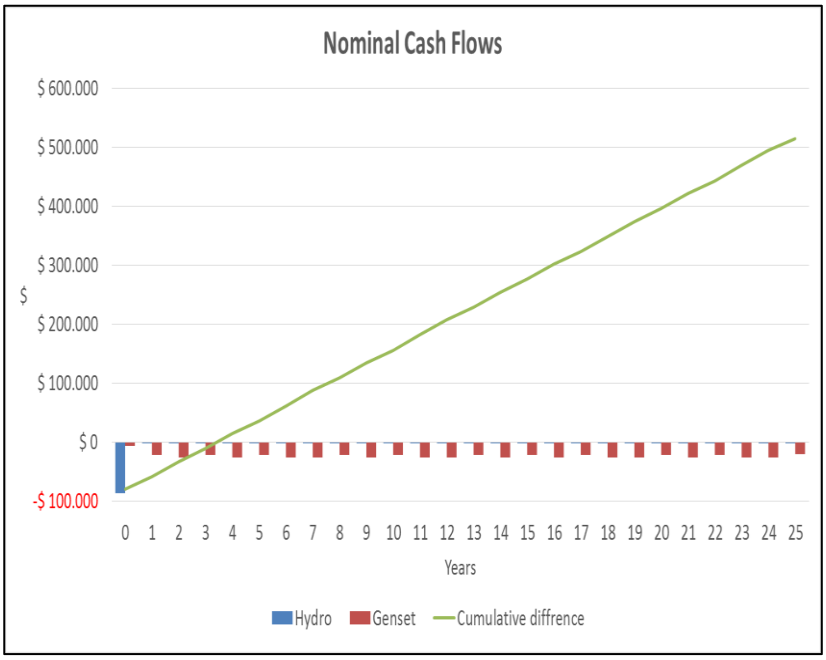

Figure 7

TAC, El Díptamo

Nominal cash flows: hydro, generators, difference

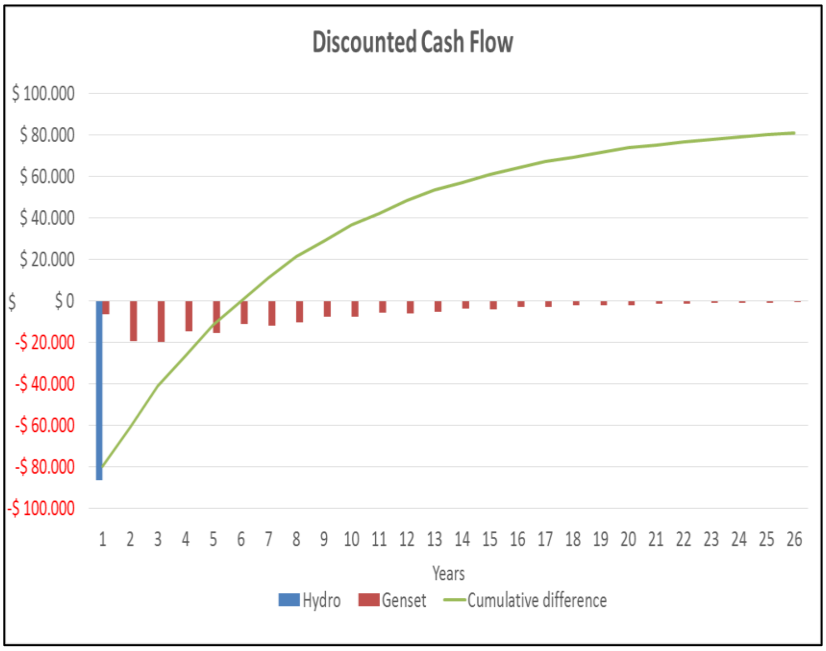

Figure 8

Discounted cash flows: hydro, generators, difference

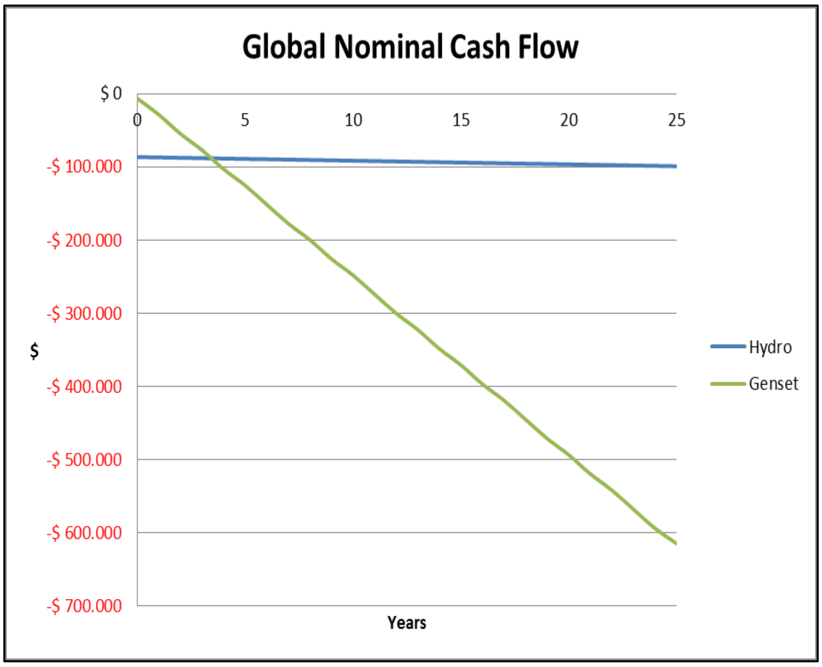

Figure 9

Nominal cash flows: hydro versus generators

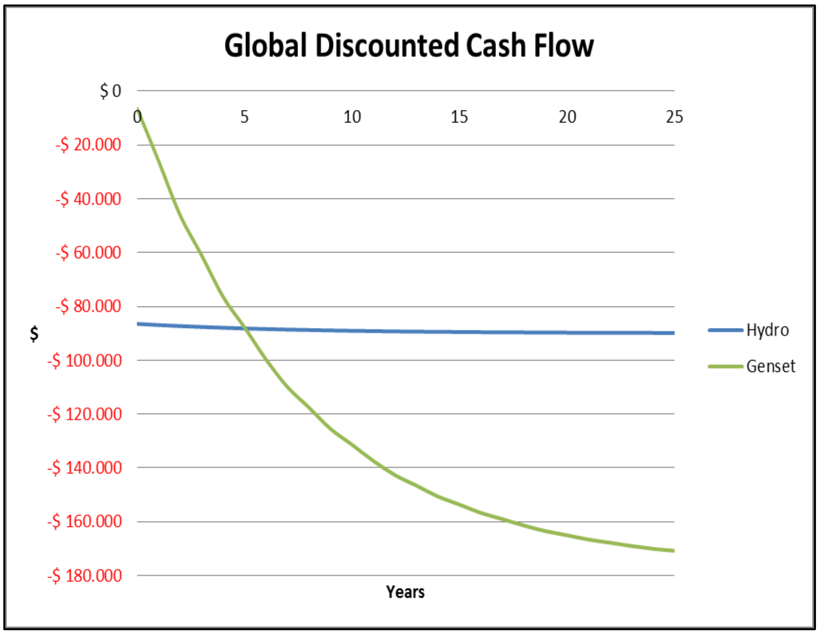

Figure 10

Discounted cash flows: hydro versus generators

Present worth	–80,873	$
Annual worth	17,341	$
Simple payback	3.43	Yr
Discounted payback	5.03	Yr

Table 6

Economic advantages of hydro versus generators, El Díptamo

The result of the economic confrontation between hydro versus generators is shown in the Table 5: the higher capital cost of hydroelectric plant is recovered in a few years thanks to the much smaller operational (fuel, replacement and maintenance) costs.

3.1.4. Environmental and socio-economical evaluation

For environmental evaluation of both solutions yearly GHG emissions associated to the plants operation were considered. Please note that for the environmental evaluation only the yearly GHG emissions associated to the plants operation were considered. A life-cycle calculation of GHG emissions, including the construction and dismantling phase, would be very challenging, and require information which are often impossible to have. A life-cycle assessment, which is a complicated task even for normal products, is notably complicated by the complex nature of the projects in rural areas of developing countries. Particularly, the construction phase implies emissions related to fabrication and transportation of material, which origin is however not always well known (for instance, the cement). Given the small-scale project, and the adaptability required in project management in rural areas, a well-documented and complete inventory of the bill of quantity of the material and its origin is virtually impossible difficult. For this reason, given the intrinsic difficulties of such elaborations, we decided to not include the life-cycle assessment of GHG emissions.

With this approximation, micro-hydro plant presents no emission because it does not require fuel. Generators emissions are evaluated through software emissions factors: GHG emissions versus energy production ratio (kg/kWh) (Table 7).

	Micro-Hydro	**Generators**	**Difference**	
CO_2	0.00	62,293.00	–62,293.00	kg/yr
CO	0.00	153.76	–153.76	kg/yr
Unburned hydrocarbons	0.00	17.03	–17.03	kg/yr
Particulate	0.00	11.59	–11.59	kg/yr
SO_2	0.00	125.10	–125.10	kg/yr
NOx	0.00	1,372.00	–1,372.00	kg/yr

Table 7

Enviromental evaluation – hydro versus generators, El Díptamo

3.1.5. Management

The plant was funded by European Union as the main action of the project Entorno Amigable para el Bosque (Contract DCI-ALA/2014/338-887) managed by Re.Te. NGO.

The project doesn’t fund future technical actions/support after the installation of the turbine; the community has in charge the plant.

A public cooperative, named Directiva de la Micro-Hidro Central, will be responsible of Operation & Maintenance and finance aspects, the cooperative is composed by three women and six men and was born during the action with the aim of manage the plant.

The model of this kind of cooperatives is usually present in rural communities of Honduras with the aim of aqueduct management (Junta de Agua). The Junta de Agua exists in El Díptamo community since 2005.

The members of the cooperative have been chosen by participated process with the community. The process considered community meeting, technical trainings and construction of the plant in collaboration with the community. Technicians involved in operation are members of the community and trained during the project.

The users will pay a fixed fee to have access to the power produced by the plants and the Directiva de la Micro-Hidro Central will be responsible of tariffs. The incomes will be used to pay staff, spare parts and extraordinary operation.

3.2. Lake Victoria Island

This island is in Victoria Lake, at 30 km from the mainland, thus unreachable by the national grid. A fishermen community live on the shore, with scarce access to electricity (only generators and few roof solar panels are present). There are some groups of buildings with different intended use:

- 1 school.
- 30 commercial buildings.
- 15 saloons.
- 43 other business activities.
- 50 households.
- 2 farms (poultry and livestock).
- 1 private fish company.
- 1 fishing processing plant.

3.2.1. Daily and yearly load

In the Figure 11 it is showed the estimated daily load profile of the community, with all the limitations and uncertainties already mentioned in Section 2.2. As in the previous case, it should be noted domestic load is the main load during the evening; the peak happens between 7 p.m. and 10 p.m. and is about 72 kW. Figure 12 represents the load at different hours of the day for different days of the year. As reported in the legend, different colour shows different load: darker colours indicate low load while tending to red colours indicate high load. In this case, peak increases to about 110 kW and the annual consumption is 361,573 kWh, with an average daily consumption of 990.62 kWh.

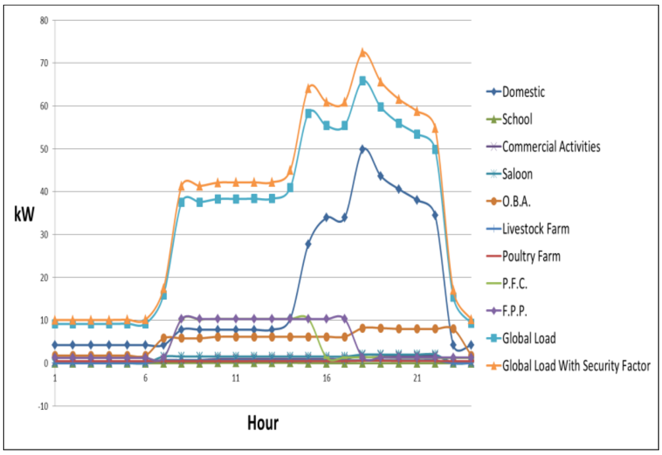

Figure 11

Average daily load, Victoria Lake Island

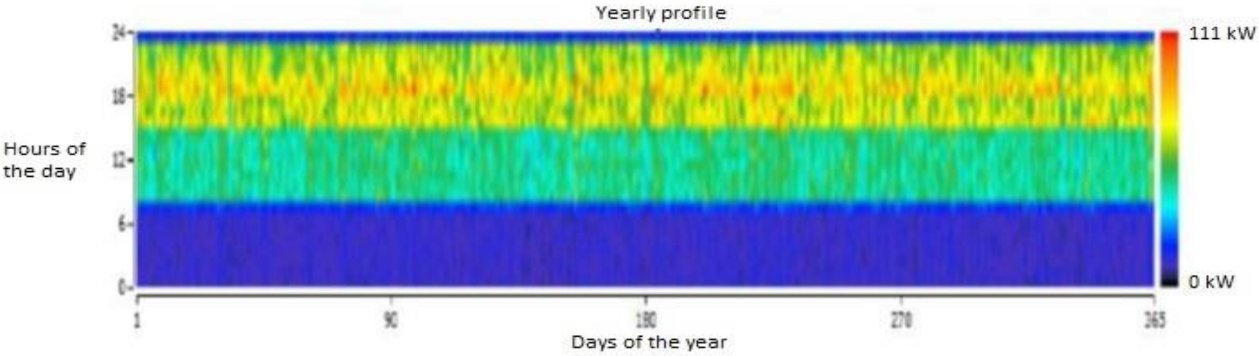

Figure 12

Yearly profile load, Victoria Lake Island

Again, the yearly load (Table 8) was estimated with HOMER PRO, with δ_d and δ_{ts} set to 10 % (see considerations above for these values). In this case, peak increases to about 111 kW and the annual consumption is about 362 MWh, with an average daily consumption of about 991 kWh.

Average (kWh/d)	Average (kW)	Peak (kW)	Load Factor	Annual consuption (kWh/y)
990.62	41.28	110.86	0.37	361.573

Table 8

Yearly profile load, Victoria Lake Island

3.2.2. Resources and community electrification

In the island there are no rivers, and the most available renewable energy resource that can be easily exploited is the solar radiation. Wind appears to be scarce, even though scientific data for the specific locations are not available. The same reasons applied for El Díptamo led to discard this hypothesis. Biomass is not feasible because of the higher O&M costs, higher environmental impacts and problems related to the strict legal restrictions on collecting wood resources, especially for the remaining original tropical forest of the islands. A possible hydro-power plant construction of a dam to be fed with solar-pumped water from the lake was discarded for the high infrastructural impact. Thus, the solar PV option is clearly preferred for the high availability of such resource, and for its modularity. In the Figure 13 it is showed daily average solar radiation on the horizontal surface for each month: February and March, with 5,720 and 5,580 kWh/m^2/day, are the months in which solar radiation is maximum while May is the month in which it is minimum (4,710 kWh/m^2/day) (NASA 2017).[3]

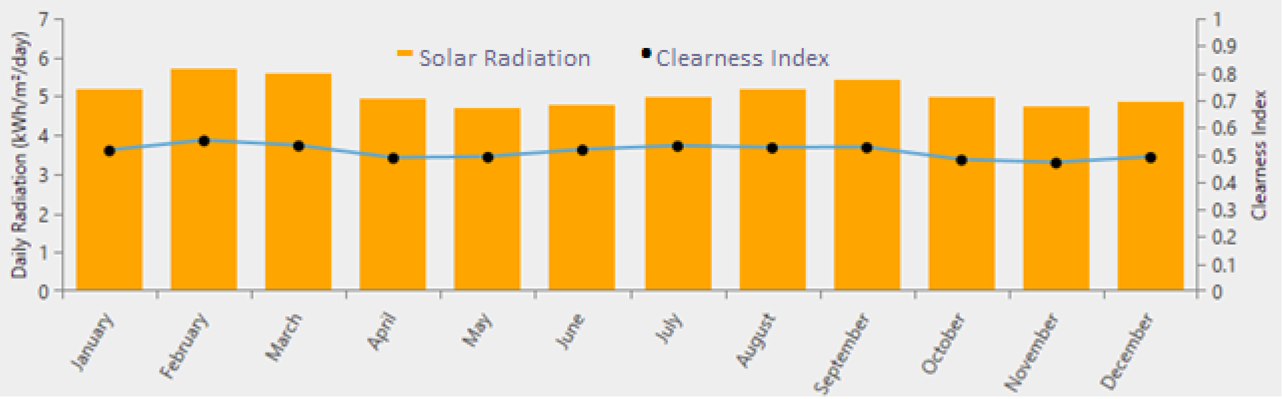

Figure 13

Daily average solar radiation on the horizontal surface for each month, Victoria Lake Island

Because of this, the first solution proposed to community electrification is a hybrid PV + generator configuration. This configuration is formed by a 300 kW$_p$ PV generator, a storage system with 1000 kWh battery bank and a 30 kW Diesel generator to be used as a back-up or to cover unpredicted high peaks of demand. In the Table 9 it is showed the characteristics of the plant.

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[3] https://eosweb.larc.nasa.gov/sse/, accessed 8 August 2017.

Installed Power (kW)	Average Power Output (kW)	Average Energy Output (kWh/day)	Total Energy Production (kWh/yr)	Maximum Power Output (kW)	Hours of Operation
300.00	48.59	1,166.20	425,650.00	265.29	4,381.00

Table 9

PV plant energy production, Victoria Lake Island

In the Figure 13 it is showed that PV generator produces electricity only in central hours of the day, so a battery bank and a generator are necessary to satisfy load in the absence of PV production. The estimated PV energy production available (considering the losses) is 425,650 kWh/yr and almost satisfies the load energy consumption, 361,573 kWh/yr. However, note that the production and consumption occur in different hours of the day.

In the figures 14 and 15 it is showed the estimated battery bank state of charge and the generator power output. The state of charge is maximum when PV generator produces, and it gradually reduces in evening and night time. Generator is in operation to satisfy peak loads: in fact, it produces during evening and night hours, when the load is high and battery bank do not satisfy energetic demand. The bigger the battery capacity, the lower the use of the generator, but the higher the capital costs (Micangeli *et al.* 2017).

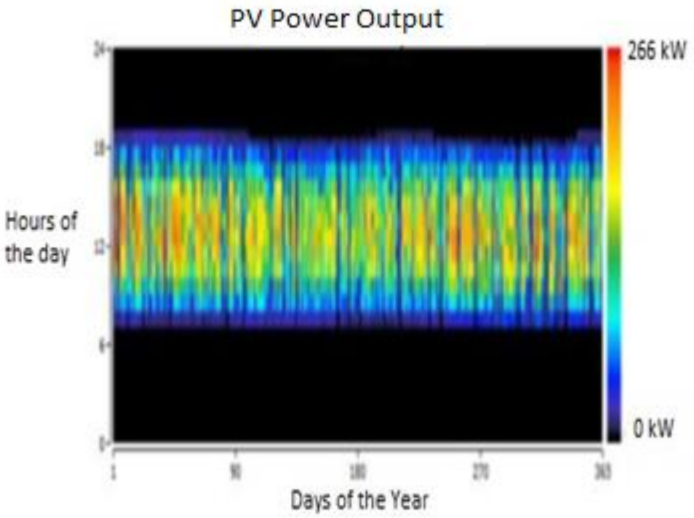

Figure 14

PV power output, Victoria Lake Island

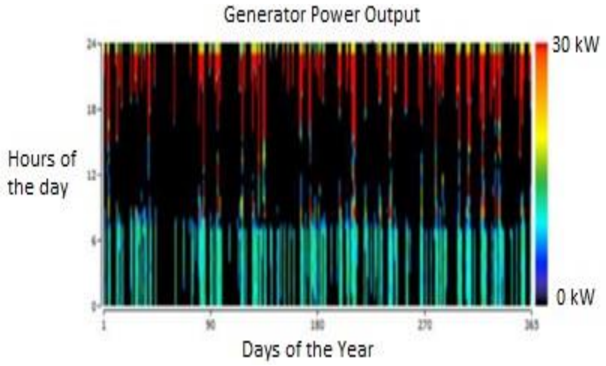

Figure 15

Geneset power output, Victoria Lake Island

Tables 10 and 11 represent battery bank and generators operational parameters during the year. As shown in the Table 12, PV generator contributes to 92.84 % global electrical production while Diesel generators only to 7.16 %. Figure 16 represents monthly production: blue bars represent PV generator production, red bars generators production.

Nominal energy (kWh)	**Autonomy (hr)**	**Energy In (kWh/yr)**	**Energy Out (kWh/yr)**	**Losses (kWh/yr)**	**Expected Lifetime (yr)**
1,000.00	24.23	208,691.00	134,362.00	73,328.00	20*

Table 10

Battery bank operational parameters, Victoria Lake Island

* In the present study there were considered vanadium redox battery with their nominal expected lifetime of 20 years.

Hours of Operation (hr)	**Numbers of Starts (starts/yr)**	**Operational Lifetime (yr)**	**Electrical Production (kWh/yr)**	**Minimum Output (kW)**	**Maximum Output (kW)**	**Mean Output (kW)**	**Specific Fuel Consuption (l/kWh)**
2,000.00	193	10.00	32,836.0	7.50	30.00	16.42	0.33

Table 11

Generators operational parameters, Victoria Lake Island

Production	**kWh/yr**	**%**
PV Generator	425,925	92.84
Diesel Generators	32,836	7.16
TOTAL	458,761	100

Table 12

Yearly plant production, Victoria Lake Island

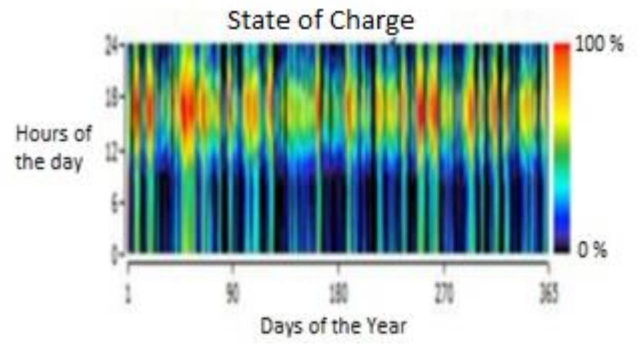

Figure 16

Battery Bank State of Charge, Victoria Lake Island

As for the previous case, we compare the optimal solution with a non-renewable power plant composed of Diesel generators. In this case, it has been assumed to use 3 generators, each of them of 36 kW electrical power output. Costs of both solutions are shown in the Table 13.

Hybrid Solution Components (with installation and auxiliary)	**Cost [$]**	**Generators component**	**Cost [$]**
PV panels	345,271	Generators (36 kW)	19,254
Inverter	212,929	Intallation-transport-soundproofing	7,964
Battery Bank	109,194	TOTAL	27,218
Generators	23,869	Fuel	0.961 $/l
TOTAL	691,263	Operation and Maintenance	3.93 $/h
Fuel	0.961 $/l		
O&M Generators	1 $/hr		
O&M PV plant	3.276 $/yr		

Table 13

Hybrid solution cost and generators solution cost, Victoria Lake Island

3.2.3. Economic evaluation

For the economic evaluation of both solutions 25 years plant lifetime, inflation rate and real interest rate respectively equal to 4.1 % and 18.8 % were considered (World Bank Data 2017). In the tables 14 and 15 it is showed both solutions NPC and TAC and the single items that compose them, in US dollars. NPC and TAC of generators configuration are higher than hybrid configuration, as before: fuel, O&M and replacement are larger for generators. In the hybrid configuration, the main cost is the capital cost, while in generators the main item is fuel. This difference influences the COE of the two configurations, COE of hybrid plant is lower than generators plant: 1.80 $/kWh versus 2.90 $/kWh. The nominal and the discounted cash flows of both configurations are compared in the next graphs, likewise to El Díptamo Community. In the Figure 17 it is compared nominal cash flows: blue represents the outgoing cash flows of hybrid plant, red corresponds to generators plant, and green is the cumulative difference between them (hybrid minus generators). Similarly, to hydro plant in El Díptamo community, the cumulative difference starts negative because the high capital cost of hybrid configuration, but it goes to zero in only about 3 years (Simple Payback Time). In this case, the saving after 25 years is 3,739,833 $. Similar considerations can be made for the Discounted Cash flows reported in the Figure 18: in this case, the payback time (Discounted Payback) is 4.65 years and the saving after 25 years are 400,012 $. In the figures 19 and 20 it is showed the trend of the global nominal and global discounted cash flows of both configurations. In hybrid configuration both nominal and discounted remain approximately constant to the initial value (capital cost) and the little increment is due to the little cost of fuel, to the O&M costs and to the replacement costs. In generators configuration the cash flows increase year after year because the high costs of fuel, O&M and replacement, as shown in Figure 21. In those figures the payback is represented by the time when generators cash flows cross hybrid cash flows while the saving is the difference, at 25 years, between them.

NPC [$]		
	Hybrid	**Generators**
Capital	620,287	81,654.29
Replacement	9,988.1	116,859.57
O&M	27,504.91	150,588.56
Fuel	55,185.6	798,400.31
Salvage	–2,304.8	–38.71

TOTAL	710,671.5	1,147,463.42

Table 14

NPC, Victoria Lake Island

TAC [$]		
	Hybrid	**Generators**
Capital	118,202.66	15,560.17
Replacement	1905.44	22,269.05
O&M	5,241.32	28,696.22
Fuel	10,515.39	152,143.48
Salvage	–439.22	–7.38
TOTAL	135,425.86	218,661.28

Table 15

TAC, Victoria Lake Island

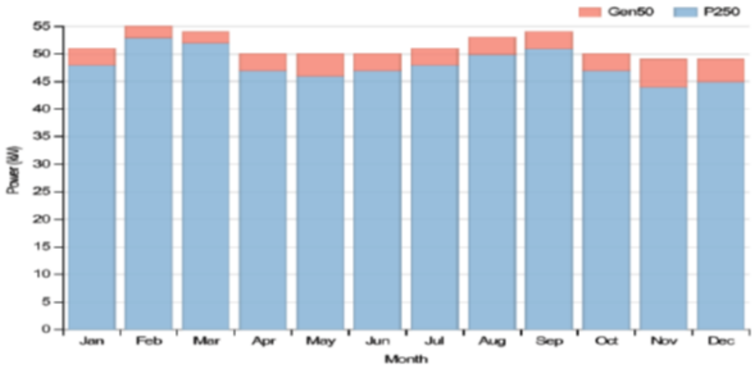

Figure 17

Monthly plant production, Victoria Lake Island

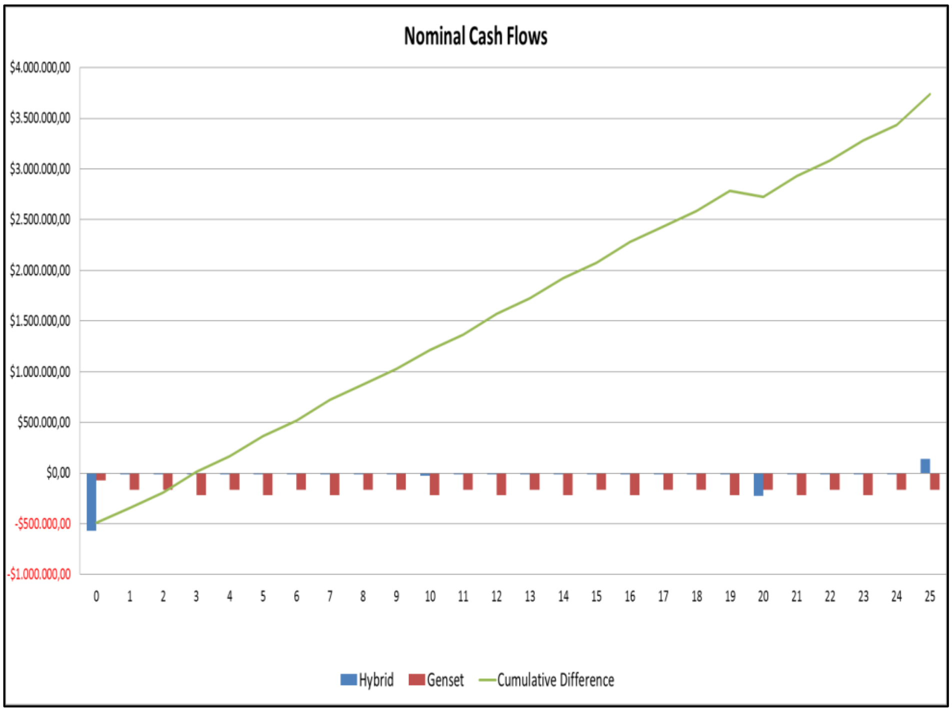

Figure 18

Nominal cash flows: hybrid, generators, difference

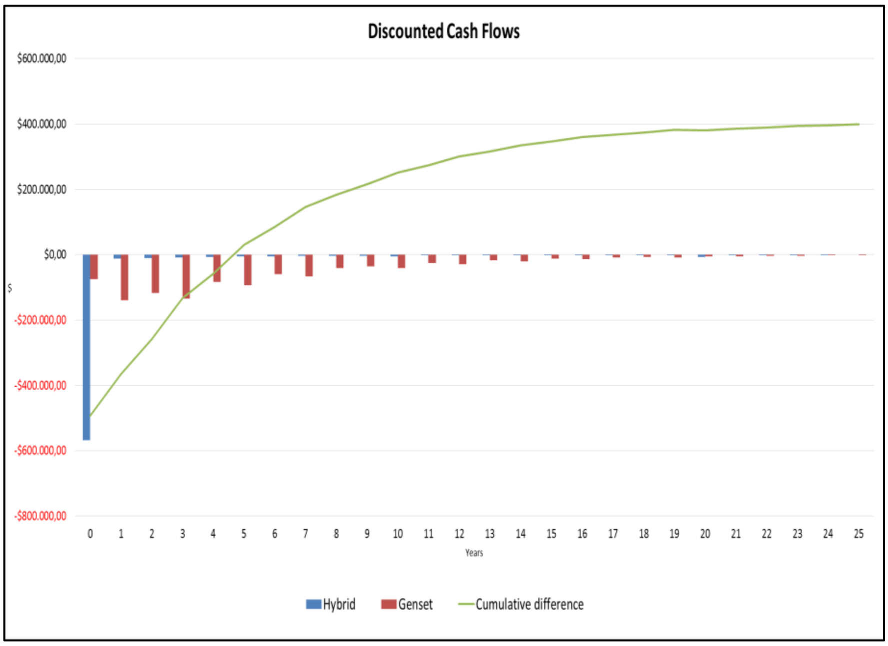

Figure 19

Discounted cash flows: hybrid, generators, difference

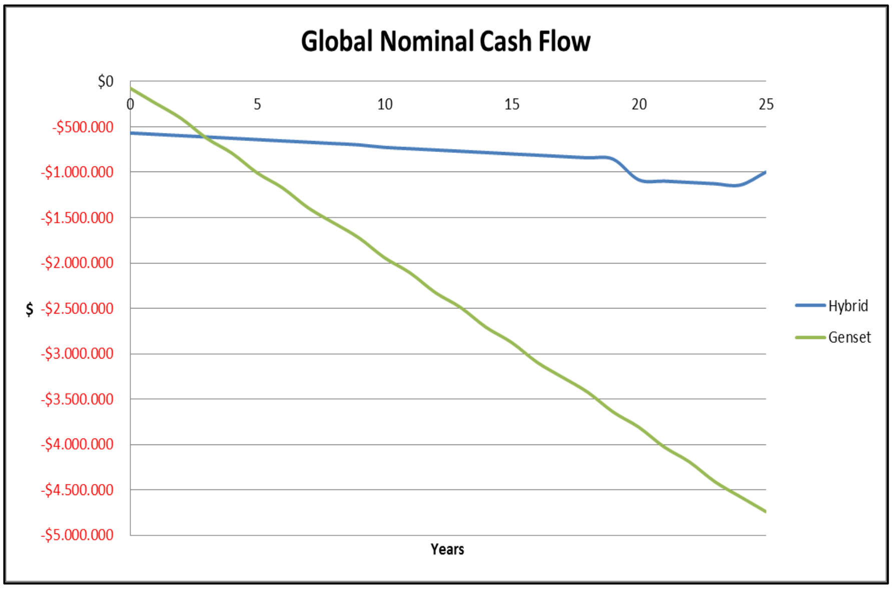

Figure 20

Nominal cash flows: hybrid versus generators

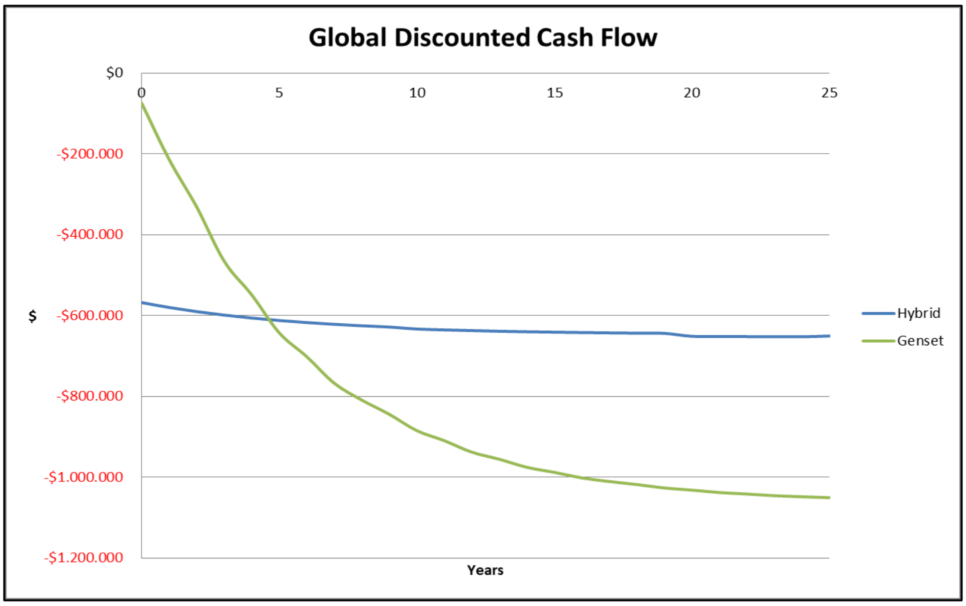

Figure 21

Discounted cash flows: hybrid versus generators, difference

The result of the economic confrontation between hybrid versus generators is shown in Table 16: the higher capital cost of the hybrid plant is recovered in a few years thanks to the much smaller operational (fuel, replacement and maintenance) costs.

Present worth	436,791.88	$
Annual worth	103,901.51	$
Simple payback	2.94	yr

Discounted payback	4.65	yr

Table 16

Economic confrontation, hybrid versus generators, Victoria Lake Island

3.2.4. Environmental evaluation

For environmental evaluation of both solutions yearly GHG emissions associate to the plants operation were considered (Table 17). As before, in these estimates it is not considered the entire life-cycle of the plant, for the reasons explained above. The hybrid plant presents lower emissions because fuel consumption is lower than purely generator plant. Both generators emissions are evaluated through software emissions factors: GHG emissions versus energy production ratio (kg/kWh).

	Hybrid (FV + generators)	**Generators**	**Difference**	
CO_2	28,819.00	416,944.00	–388,125.00	kg/yr
CO	71.14	1,029.20	–958.06	kg/yr
Unburned hydrocarbons	7.88	114.00	–106.12	kg/yr
Particulate	5.36	77.58	–72.22	kg/yr
SO_2	57.88	837.30	–779.42	kg/yr
NOx	634.76	9,183.30	–8548.54	kg/yr
Total	29,596.02	428,185.38	–398,589.36	kg/yr

Table 17

Enviromental evaluation – hybrid versus generators, Victoria Lake Island

3.2.5. Management

This project has a better business opportunity due to the relatively higher incomes of the community, compared with the Honduras community. We considered the possibility of the participation of private funds and, in this case, the private fund is the owner and responsible of the plant. The business opportunity is selling energy; there will be necessary the training of local staff composed by technical and customer service.

Everything is managed and supervised by the investors, who take important decisions such as routine maintenance or personnel management. The regulated fee (decided by the dedicated national regulatory agency) paid by users to the investment company depends only on the energy consumption. There are no components of the tariff which are fixed or related to the maximum usable power cost (like in developed country national grid fees). The situation is also different compared to many cases in developing countries where users pay a fixed rate according to the number and type of connected devices, due also to the lack of a dedicated meter. The pre-payment energy is via mobile, also avoiding the flow of cash, which can cause social and management problems.

4

Conclusions

In this paper it is studied some technical, environmental and economic aspects of solutions that can be taken in rural areas without access to electricity in developing countries. We have considered communities from two different countries, Uganda and Honduras, which share some problems, like poverty and electricity shortage, but differ in many other features. Projects have already been developed and implemented and they are currently in the first operational stages.

The HOMER PRO software was used to carry out this study, through which various adoptable solutions have been studied, renewable or hybrid configurations. Technical and operational values have been evaluated for each solution, and subsequently, the most cost-effective one has been chosen and compared with a non-renewable based case.

First, we underline the similarity between the two simulated load profiles, which share the same main common three-bands load features:

1. A demand peak in the evening, driven by the domestic consumption, which represents in both cases the main load.
2. A night load, which represents the minimum.
3. An off-peak daily load, which is intermediate.

Different shapes of the load would result in the case of large consumers in specific hours, like heavy machinery for medium or large businesses.

Local availability of natural resources has been evaluated before adoptable configuration selection and, in both cases, they influence this choice. Environmental impacts are important to consider discard non-renewable solution, use of biomass, and other possible invasive solutions. Considering this, it appears that the best adoptable solution depends on geographical location and on the natural local context: the best solution for El Díptamo is a micro-hydroelectric plant, while the best solution for the small island on Victoria Lake is a hybrid PV-generators configuration.

Economic and environmental analyses have been done for each solution in both case studies, with three main results:

1. Renewable or hybrid configurations are less expensive, considering 25 years plant lifetime, in comparison with non-renewable configurations. Comparing economic indicators, we can see an economic convenience in micro-hydroelectric and in hybrid solution in respect to base cases. In fact, the micro-hydro solution and the hybrid solution have lower NPC and TAC than the base case. This influences the COE of every configuration: hydro and hybrid COE is about 1.80 $/kWh, among half of base case COE. This convenience can be also seen through the comparison of annual O&M costs: for hydro and hybrid plants, they are lower than the generators case; an investment in renewable or hybrid-renewable configuration can be repaid in 5 years or less, compared to an investment in non-renewable configuration.
2. What we have just said leads us to affirm that renewable or hybrid solutions are more competitive at the economic level, compared to non-renewable solutions, also in developing countries, with weak economies and where factors like inflation and real interest rate are unpredictable. This kind of solutions serves to save money, that could be used differently by population.
3. This kind of solutions brings to save fuel and so to reduce GHG emissions, with savings of tens to hundreds of tonnes of CO_2 every year, compared with alternative solutions based on fossil fuels. The use and diffusion of renewable energy in developing country, instead of traditional energy systems, is a strong contribution to reach the recent objectives of greenhouse emission reduction, set by the international community in the COP21 of Paris.

A deep analysis of the social impacts, here not faced, is a complicated issue, and it relies on very practical issues related to the project management, the confidentiality of data and the lack of appropriate resources and management of an ex-post proper evaluation and monitoring. We think this is a problem in common to many projects. In this paper we presented the information in our hands. A review of the potential and really observed impacts of the rural electrification is given by Barron and Torero (2014), and references within (particularly, Bernard & Torero 2009, Barron & Torero 2014). The author of the review collects different papers present in literature, regarding monitoring and evaluation of projects in North Africa, Sub-Saharan Africa, Asia and Central America. He concludes that there is a systematic lack of monitoring of the impacts and the conclusions about the impact are not providing a unique and definitive answer. Such impacts are also difficult to be evaluated because a simple comparison, for instance, of individuals before and after the project, is biased by a series of factors which can concur to change their personal socio-economic situation. Moreover, in his paper and the references within, it appears that, while the electrification allows a reduction of solid fossil fuels for lighting, the cooking behavior, relying on contaminating and toxic fuels, is apparently not affected. Electricity is seen mostly as an additional source of energy, rather than a clean alternative. Moreover, we note that in the literature much focused is posed on incomes and expenditures for separate, but very little is explored regarding quality of life and effective annual saving power. The theoretical reasons for positive impacts are several: reduction of health problems due to less kerosene consumption, increase of income, women empowerment, enhancement of education. However, in the few cases where such impacts were addressed, there is little evidence for them. This issue needs to be addressed in future works if data coming from a proper evaluation and monitoring phase are available. We also note, however, that data are often not disclosed, thus it is difficult to have an independent, objective and complete study of the impact for a given project. This is especially true when the private sector is involved, and data about consumption and prices are strictly confidential. In our case, we are not in possess of the data and the resources to carry a long-term monitoring but that should be implemented and should be a crucial part of the project management.

Another important issue is related to the tariff, which, besides guaranteeing the covering of O&M costs and (in case of private capital investment) the pay-back to investors, should be affordable, agreed with a well-informed community before the project, and regulated by the dedicated national agencies. Moreover, training and hiring local personnel for the O&M has a direct impact, and, in case of a private management, should also guarantee wages decent enough to improve often difficult living conditions of the local population. During the implementation phase, there should be training activities directed to a responsible consumption (*e.g.,* which electrical devices can be afforded and bought, how much they consume) and to the new ideas for a diversification of new small-scale (bars or hairdressers) and medium-scale businesses (mills or ice machines). In this sense, given the very high unemployment rate and the low purchase power, the wages should not merely adapt to the market labor price (often very low and biased by lack of jobs, spread poverty and illegal activities), but should meet the sustainable development objective, contributing to it on a small-scale level.

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