Planning paths for the electrification of small villages using decentralised generation: experience from Senegal

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Abstract

Purpose – The purpose of this paper is to illustrate and discuss the implications of the assessment and choice of electricity supply systems for rural communities of less than 500 inhabitants in Senegal. The paper is based on a study produced by PERACOD (*Programme pour la Promotion de l'Electrification Rurale et l'Approvisionnement en Combustibles Domestiques*), an advising body for the Senegalese Ministry of Energy and Mines.

Design/methodology/approach – The profitability index TEC (*Taux d'Enrichissement en Capital*) is used as the main criterion for the economic evaluation of four technologies: diesel mini-grids, photovoltaic, hybrid (pv-diesel) generators, and solar home systems. Household demand is derived from real data of socio-economic studies which serve as the basis for determining market segments defined by the distribution of the willingness to pay and the levels of service.

Findings – The simulations from nine demand cases show that high investment and/or operation expenditure create an insurmountable barrier given the limited payment capacity of rural populations, demonstrating that projects in this context are not profitable without subsidies. However, decentralised photovoltaic generation technologies are already demonstrated to be the least cost solution when the village lies further than 5.4 kilometers from the transmission grid.

Originality/value – This paper describes a planning path that could enable a faster implementation of rural electrification programs in remote areas considering three main elements, namely; willingness to pay, reduction of levels of supply service and support of communal management. However, the focus of the present work is mainly devoted to an analysis of the first two elements. Finally, the paper addresses the issue of how these technologies can be better implemented by national agencies and investors, with potential application outside of the Senegalese case study.

Keywords – Decentralised energy supply, Energy planning, Rural electrification, Senegal, Willingness-to-pay.

Paper type – Research paper

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1 Introduction

Senegal is a Sub-Saharan country located on the coast of West Africa with about 12 million inhabitants in 2005. The existing power network mainly serves the big cities in the west part of the country as Figure 1 shows. In 2003 about 76% of the urban population and only 12% of rural population had access to electricity (Dahouénon, 2005).

The majority of electricity generated in Senegal comes from thermal power plants. According to the IEA (2007), 75% of the production of electricity in 2004 came from imported oil-based fuels. Generation from hydropower and biomass represented respectively 11% and 12%, with the remainder 2% generated from the combustion of natural gas. By February 2007, the country had a total installed generation capacity of 661 MW, although due to obsolete equipment only about 528 MW is available. The installed capacity of the monopolistic state-owned electricity provider SENELEC is made up of diesel generation (164MW), steam turbines (91MW) and gas turbines (72MW). A combined cycle plant belonging to the independent producer GTI add 50MW of capacity and a further 58 MW of small-scale diesel generators are private owned. In addition, since July 2002 a third of the output of the 200 MW Manantali hydroelectric plant in Mali is exported to Senegal (Owsianowski, 2007).

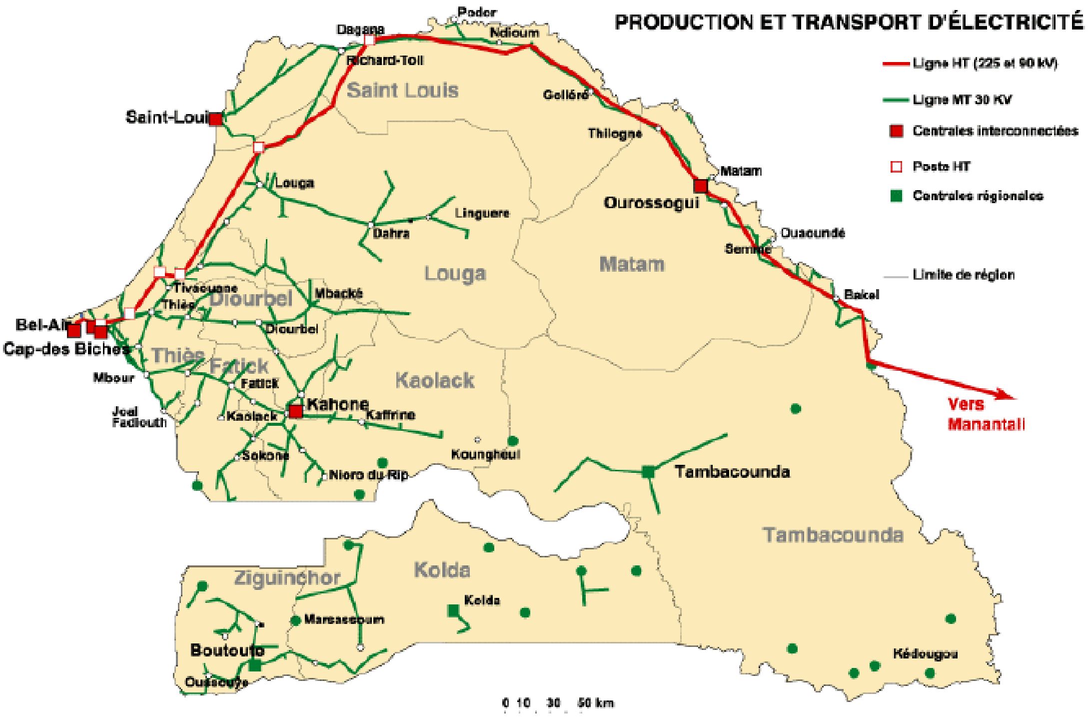

Figure 1. Power generation and distribution networks in Senegal (CRSE, 2007a)

In 1998, Senegal initiated a restructuring process for the electricity sector. As with many other countries, this process involved plans of unbundling generation, transmission and distribution activities, all previously undertaken by the state-owned enterprise SENELEC. The goal was to move towards a liberalised and privatised market. However, at present, only the electricity generation market is open to the private sector and SENELEC remains the only operator in transmission and distribution (CRSE, 2007b). In addition to these market reforms, a National Action

Program was launched to increase country-wide electrification levels – a priority for Senegalese energy and development aspirations (Owsianowski, 2007).

In this context, the Senegalese Agency for Rural Electrification (ASER) and the Regulation Commission of the Energy Sector (CRSE) were created. The ASER has established two main mechanisms in order to achieve the stated goal of 62% rural electrification by 2022:

- PPER (Rural Electrification Priority Programme): the country was initially divided into 18 regions, and later reorganised into 13 regions, that are being concessioned to private investors via a bidding scheme for the installation and management of electricity supply infrastructure for a period of 25 years.

- ERIL (Electrification Projects of Local Initiative): Projects proposed and carried out by local communities or associations under the assistance and financial support of the ASER.

Following these initiatives, the rural electrification rate has increased from 6.1% in 1997 to around 9.9% in 2002 (CRSE, 2007c) and an estimated 15% in 2005. This is the result of the emerging conditions which create better incentives for the development of electrification projects. However, most of the existing projects are located in areas with greater population densities, while small villages in remoter parts of the country have been overlooked. This failure is explained by the difficulty of achieving good profitability levels in these areas where relatively high investment is required for new infrastructures, combined with the low demand levels and limited payment capacity of rural consumers. Such “small villages”, defined as having less than 500 inhabitants, represent 84% of the localities in Senegal.

In this context, the German Agency for Technical Cooperation (GTZ) agreed to fund further research into the rural electrification of small villages, initiated and managed by the PERACOD programme (jointly administered by GTZ and the Senegalese Ministry of Energy and Mines). This research led to the study presented in this paper. The research was undertaken by the author as a consultant working with M. Dahouénon, head of the Rural Electrification Division in PERACOD and member of ASER and a highly experienced consultant in diverse cooperation projects in West and Central Africa. This study aims, first, to assess the choice of electrical supply systems for small villages and, second, to explore the measures that could improve their economic feasibility. In this way, comprehensive planning paths for small-scale rural electrification can be identified.

The first section of this paper defines the economic evaluation model, its main parameters and assumptions. Then, the simulation results obtained with real data based on the northeast region of the country are presented. The next section provides a discussion and findings of additional simulations based on the modification of certain parameters in order to optimise the results first obtained. In the final section the conclusions of the study are outlined.

2 Economic evaluation models

2.1 Economic Evaluation Models in Electricity Planning

Previous studies of cost comparisons based on discounted cash flow calculations from the implementation of photovoltaic systems in rural electrification have been well developed in Ericksson et al. (1995) and ASTAE (1996). Other economic analyses have focused particularly in lighting applications like compact lanterns (Rubab et al., 1996) or fluorescent lamps (Gullberg et al., 2005). Dissemination models have been developed for solar home systems, provided by the Grammeen Shakti Bank in the case of Bangladesh, where impacts on women's welfare, children's education and employment and income generation are taken into account as a result of the business cycle (Barua et al., 2001). Van Campen et al. (2000) provides a study about earlier experiences in rural electrification and concludes that a new phase of "photovoltaics beyond the light bulb" should be directed at fully exploiting the potential of these systems for sustainable agriculture and rural development.

Multi-criteria modelling can also be a useful tool in decision making processes where multiple objectives are at stake. For example, Pohekar (2004) presents a comprehensive review of different multi-objective methods applied to sustainable energy planning by illustrating the trade-off between environmental and economic parameters, and by incorporating additional community impacts, in terms of how they affect social and human assets. More recent studies include a wider range of technologies. In Vietnam, Nguyen (2007) analyses the economic viability of household electrification through photovoltaic and wind generators, compared to grid connection taking into account local resource availability. Likewise, Akella et al. (2007) develops the concept of Integrated Renewable Energy System (IRES) for decentralised supply modes, and produces an assessment of the energy share from different renewable supply inputs with the objective of achieving a minimum overall cost of electricity generation, subject to demand fulfilment and resource availability factors. All these models are based on annual estimates of energy consumption without a detailed relationship to demand load curves. In contrast, the study detailed in this paper seeks to integrate the role of production activities within small villages' demand, together with a market segmentation analysis. This is the main contribution of this paper to the literature.

The model proposed in this paper operates on two levels. Firstly, it relates detailed demand behavior to the technical and economic characteristics of decentralised supply systems - in comparison to a standard grid connection – via the use of a least-cost criterion appraisal. Secondly, it offers the possibility of analysing the associated environmental benefits, and to test different segmentation structures and management schemes. Therefore, the model outcomes show the overall effect of different approaches for rural electrification on profitability levels.

However, to which extent can an economic model be sufficient for the elaboration of a planning roadmap? Here, Pohekar (2004) makes clear that in addition to conventional policy measures:

> "…the wide exploitation of sustainable energy should be based on a completely different conception of energy planning procedure. The role of different actors in decision making thus becomes important. Methods of group decision are therefore of primary interest for the implementation of decision sciences in real-life problems" (p.367)

In this way, barriers can be identified and implementation measures can be incorporated into the analysis, which can lead to further action plans necessary for facilitating the electrification process.

2.2 Model structure, main variables and data

To analyse the problem of rural electrification in small villages in Senegal, a microeconomic model was elaborated. This model is structured in four modules as shown in Figure 2. The first module defines and builds the daily demand of the village, which is the basis of the overall analysis. The next two modules consist of a technical dimensioning and an associated economic evaluation that are applied to four configurations of decentralised supply systems. In the last part of these modules the technical solution with the best economic outcome is used to find out the critical distance in which a grid connection has lower costs than an optimal decentralised solution. The fourth module evaluates the environmental benefits of the optimal supply configuration in comparison to a reference case of a pure diesel-engine. It serves to calculate the monetary value of savings in CO_2 emissions that could be achieved through the acquisition of certified emission reductions (CERs) when registering the electrification of a small village as a Clean Development Mechanism (CDM) project.

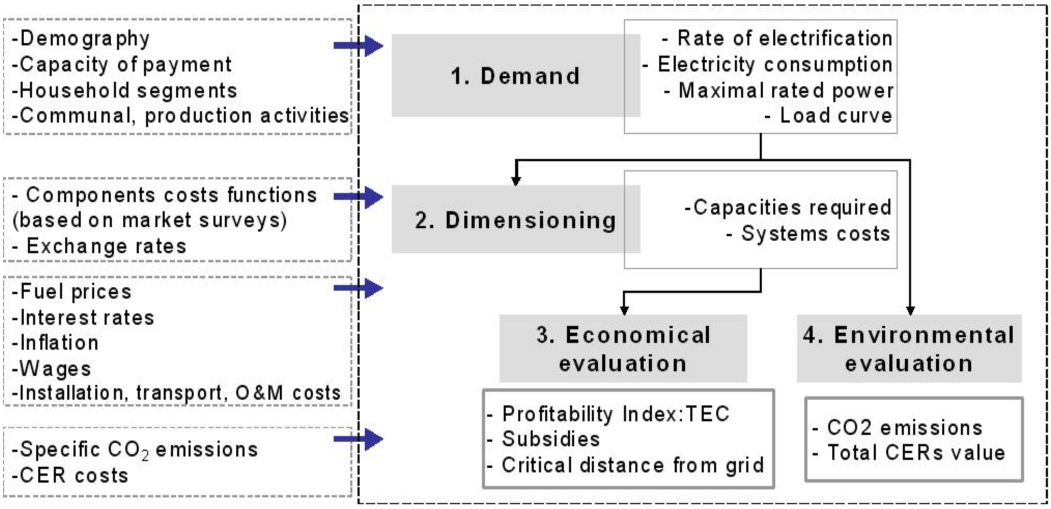

Figure 2. Modules and main variables

The aim of this model is to determine, under the given demand conditions, which is the most economically suitable system (in terms of cost minimisation) and to assess to what extent environmental benefits could offer additional financial incentives for the implementation of “clean” technologies. The economic approach of the model is based on the calculation of a profitability index. This is used as the main evaluation criteria, following Chabot (2004). More details on this profitability index are provided later. Previous investigations conducted by M. Dahouénon at PERACOD and ASER were the main source of local economic data for the study. The demand data of rural populations used in the simulations is obtained from a socio-economic study of the northeast region in Senegal. This information was collected by the GTZ program PSACD (2003) as a requirement for an ERIL pilot project and it is one of the first studies undertaken at a regional scale for rural electrification in Senegal.

Firstly, a profile of the estimated consumption in the village is required. Demographic data, household segments with their average willingness to pay, communal and working activities and their electrical equipment are basic input data for the model. Exogenous variables are fuel prices, exchange and inflation rates, and technical factors like efficiencies, specific fuel consumption and specific production of CO_2. Endogenous variables are energy production and system costs. The main output data consist of global investments, subsidies required for a defined level of profitability and CO_2 emissions.

2.3 Demand definition

Demand data serves as a basis for the market analysis. The data was obtained from a previous socio-economic study based on surveys in the northeast region comprised of the departments of Matam, part of Podor, and Morphil Island (PSACD, 2003). The study provides real elements about the socio-economic acceptance of rural electrification as a basis for the following viability analysis of this kind of project. It took into account the current energy consumption and the associated costs in households of non-electrified villages, their willingness to pay for the access to electricity and the real diffusion of electrical appliances from already electrified villages.

2.3.1 Regional characteristics identified by the survey

This 2003 survey was distributed to 476 households in 18 non-electrified villages (approximately 17% of the total number of households of the region) and another 60 households of four electrified villages (located within a distance of 30 km of a non-electrified village). The region is characterised by two natural sub regions, Walo and Dieri. While the first one is located along the river Senegal, the second is less accessible and on more arid land. In general, 58% of the population relies on agriculture as its main source of revenue. In addition, commerce (7%) and fishing (7%) are also important activities for the population, but livestock breeding (1%) is only relevant for southern Dieri villages. These communities generally have a medical centre or a primary school. Access to gas and oil products is difficult due to the poor road network quality and to the isolation of places like the Morphil islands.

The survey found that 90% of the population used petrol lamps and about 5% already used photovoltaic panels for their lighting system. Diesel generators were, in a few cases (1%), already in use. All households used electric torches (expenditure on torches continues after the electrification). In most of the non-electrified households there were two petrol lamps per household. Most of the households expressed a desire to own four to nine lamps with the electrification and 17% of the population used batteries, mainly for the operation of television and radios, and in some cases for a fan as well.

2.3.2 The diffusion rate

The diffusion rate of appliances used in electrified villages is important in order to define the grade of penetration of equipment in a medium term (two years). Experience has shown that after electrification the acquisition of electrical appliances is realised between the second and fourth year, which doubles the electric consumption in the period mentioned. The integration of diffusion rates as constant factors into the overall demand load – i.e. in the system dimensioning – is necessary because it reflects the fact that not all rural households will be able to acquire new devices at the same time and otherwise the supply system would be oversized.

The diffusion rates were obtained from the survey (PSACD, 2003) for a range of devices found in already electrified villages. The present paper considers that service for households in small villages will mainly be developed with the basic equipment listed in Table I.

Table I. Diffusion rate of electric appliances after electrification

Equipment	Diffusion rate
Radio cassette	80%
Fan	12%
TV B&W	2%
TV colour	68%
Refrigerator	45%

2.3.3 Household segmentation

The main findings of the socio-economic study are based on the distribution of the willingness to pay and the corresponding expected level of service. The population is divided into four segments which are inputs for the economic evaluation model.

It is important to recognise that the payment capacity among the population in rural regions greatly varies. Only a few households are willing to pay substantially more to have access to electricity and these households expect to get a much higher level of usage from the system. The majority of households will not be able to afford high payments but expect only a basic service for lighting and low power appliances. Hence, the demand is modelled following the approach used by De Gouvello and Maigne (2002) in which four segments with their corresponding levels of service are defined from survey information processed previously in a statistical analysis of multiple components.

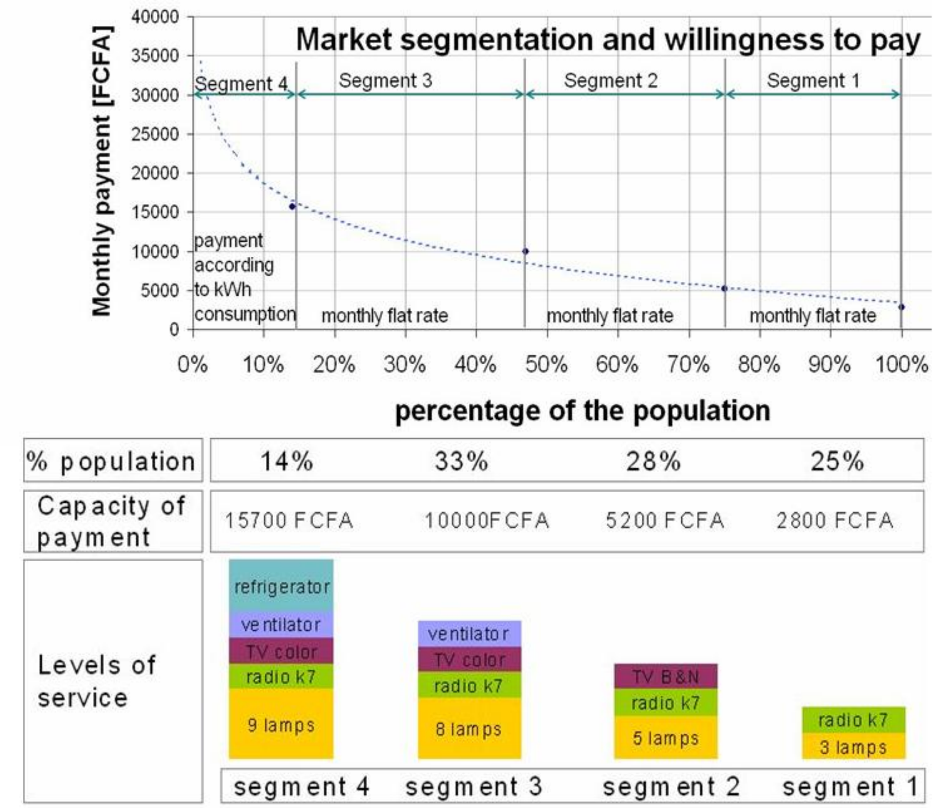

Figure 3. Distribution function of the capacity of payment in Northeast Senegal

The resulting market segmentation from the survey information is summarised in Figure 3. Segment 1 covers 25% of the population that would be able to pay at least 2,800 Francs CFA (about 4 €) per month for the use of three lamps and a radio cassette. In contrast, Segment 4 includes 14% of the population that would be able to pay five times more than Segment 1, but expects to use nine lamps, a radio cassette, a television, a fan and a refrigerator, which demands the highest amount of power. For this reason, users in Segment 4 would rather pay their consumption per kWh. Segments 2 and 3 are intermediate consumers and the main difference lies in the amount of lamps desired, the use of a fan and the type of television.

2.3.4 The electrification rate

An optimal electrification rate is used to obtain the highest revenue amount from the global capacity of payment in the village (De Gouvello and Maigne, 2002). Additionally, it integrates the fact that, in reality, when electrification is deployed not all households are able to acquire the connection service rights due to personal or economic reasons, even if they have stated their willingness at the previous surveys.

The electrification rate is calculated within the economic model through the integral of the distribution function of the willingness to pay (*DAP*) which indicates the maximum of the revenues function (*CA*), as the following equations show. In these functions, x is the percentage of population.

$$DAP(x) = -a\log(x) + b \tag{1}$$

$$CA(x) = x \cdot DAP(x) \tag{2}$$

2.3.5 Estimation of the electricity consumption

The estimated amount of daily electricity consumption is calculated on the basis of household consumption, communal and production sectors. The amount of existing households is a function of the village population and average family sizes which depend strongly on the region. The model provides a list with average family sizes of all regions in Senegal. The number of households in each segment is obtained after applying the optimal electrification rate to the percentages of the household segmentation. The daily use of standard appliances of a household in each of the four segments is characterised on survey findings and hypotheses about their operating times.

Communal infrastructures consists of public lighting, schools, medical services, administrative offices and religious places. The production sector is comprised of activities like commerce and working machines which are of high importance for the generation of value-adding within the local economy. The consumption of electricity in communal and production activities is calculated similarly to the household sector, with corresponding electrical appliances and operating times. The following facilities are used as input data to model a village of 500 inhabitants.

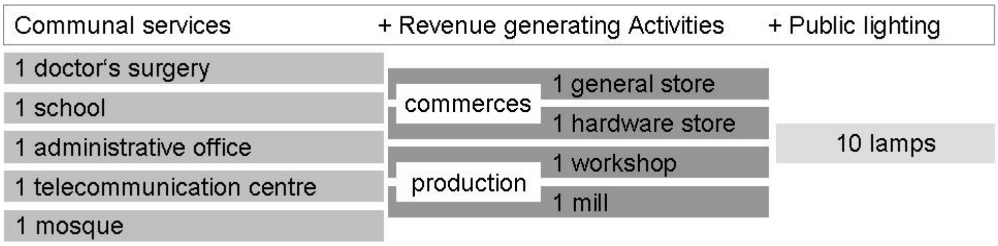

Figure 4. Non-domestic activities in a small village

2.4 Systems dimensioning and components costs

Four configurations of supply technologies where chosen for the comparison: diesel mini-grids, photovoltaic (PV) and hybrid (PV-Diesel) power plants and solar home systems. The dimensioning of the mini-grid supply systems is based on the overall amount of energy consumption per day by hour. In this way, a village load curve is obtained after taking into consideration the electrification and diffusion rates and common schedules of the activities in rural communities. Therefore, the peak consumption and system's capacity can be estimated. In contrast, Solar Home Systems are calculated separately, only according to the daily amount of energy consumption in each facility. At a later stage, the load curve and the required supply system's capacity can be reduced with some adjustments in demand side and service availability parameters.

2.4.1 Dimensioning parameters

After obtaining the demand profile, the components of the systems can be calculated through small programming sequences that are linked to lists of some commercially available products and their main features. The main parameters used for the dimensioning of mini-grid systems are shown in Table II.

Table II. Technical parameters and criteria for the dimensioning

Diesel mini-grid	Photovoltaic mini-grid	PV-Diesel mini-grid
Inverter [48V] : $P_{inv}\,[\mathrm{W}] = \dfrac{P_{peak}}{f_l \cdot \eta_{inv}}$ P_{peak} Load peak power P_{inv} Inverter's power capacity f_l Transport losses factor = 0.9 η_{inv} Inverter's efficiency = 0.91		
Engine $P_{eng}[\mathrm{kVA}] = \dfrac{1.2}{1000 \cdot 0.9} \cdot \dfrac{P_{peak}}{f_l}$ P_{eng} Engine's capacity f_l Transport losses factor = 0.9 The engine operates if the load is at least 1/3 of the nominal power (min. efficiency of 20%) Batteries $I_{bat}[\mathrm{Ah}] = \dfrac{1}{48\mathrm{V}} \cdot \dfrac{C_{bat}}{d}$ d Maximum discharge of batteries = 60% C_{bat} Energy to be supplied by the batteries to avoid the operation of the engine under low efficiency regimes. Fuel storage tank Determined by the operating time of the engine and the specific fuel consumption (0.4 litres / kWh).	Photovoltaic modules $P_{pv}\,[\mathrm{W_p}] = \dfrac{E_{day}}{I_{net}}$ $I_{net} = I_{sun} \cdot \eta_{bat} \cdot \eta_{inv} \cdot \eta_{reg} \cdot f_l \cdot f_T$ E_{day} Village's daily energy consumption [Wh] I_{sun} Average insolation in the country 6.25 kWh/m^{2}day η_{bat} Battery's efficiency = 0.8 η_{inv} Inverter's efficiency = 0.91 η_{cont} Charge controller's efficiency = 0.95 f_l Transport losses factor = 0.9 f_T Efficiency reduction due to high temperatures = 0.9 Batteries $I_{bat}[\mathrm{Ah}] = \dfrac{1}{48\mathrm{V}} \cdot \dfrac{E_{day} \cdot t_{auto}}{d}$ d Maximum discharge of batteries = 60% E_{day} Village's daily energy consumption t_{auto} Autonomy days	Engine $P_{eng}[\mathrm{kVA}] = \dfrac{1.2}{1000 \cdot 0.9} \cdot \dfrac{P_{peak}}{f_l}$ P_{eng} Engine's capacity f_l Transport losses factor = 0.9 The engine runs only to support the peak load and not more than 6 hours a day. Photovoltaic modules $P_{pv}\,[\mathrm{W_p}] = \dfrac{E_{day} - E_{eng}}{I_{net}}$ $I_{net} = I_{sun} \cdot \eta_{bat} \cdot \eta_{inv} \cdot \eta_{reg} \cdot f_l \cdot f_T$ *See abbreviation of the photovoltaic mini-grid* E_{eng} Energy supplied by the diesel engine [Wh] Batteries $I_{bat}[\mathrm{Ah}] = \dfrac{1}{48\mathrm{V}} \cdot \dfrac{(E_{day} - E_{eng}) \cdot t_{auto}}{d}$ *See abbreviation of the photovoltaic mini-grid* Fuel storage tank *See abbreviation of the diesel mini-grid*

The components of stand-alone systems are calculated similarly to the photovoltaic mini-grid, with the difference that the variable E_{day} corresponds to the daily consumption of each household, communal or production activity. The batteries used as references are 12V monoblock, instead of 2V banks as in the mini-grid systems. In general, different charge controllers are required depending on the photovoltaic current output. Low power consumption facilities are calculated as 12V systems, all others are designed as 24V systems. The dimensioning is based on $50W_p$ and $100W_p$ photovoltaic modules. Only high power consumption activities such as those in Segment 4 households, the general shop and the workshop require an inverter. If the current required by electrical appliances like a mill of 1500 Watts, is higher than 45 Amperes, then a relay is integrated to the system.

2.4.2 Capital costs

The investment costs of the main components were modelled with linear equations that are a function of the installed capacity (C_{inv}, C_{bat}, C_{eng}, C_{pv}). In these equations, α and β were determined according to previous works of Dahouénon (2005) or to a group of existing products in Senegalese or European markets. The cost functions for the components in each system (k_{inv}, k_{bat}, k_{eng}, k_{pv}) were used as the basis for the economic evaluation of mini-grid systems.

$$k_{inv} = \alpha_1 \cdot C_{inv}[\mathrm{kW}] + \beta_1 \tag{3}$$

$$k_{bat} = \alpha_2 \cdot C_{bat}[\mathrm{kWh}] + \beta_2$$

$$k_{eng} = \alpha_3 \cdot C_{eng}[\mathrm{kVA}] + \beta_3$$

$$k_{pv} = \alpha_4 \cdot C_{pv}[\mathrm{kWp}] + \beta_4$$

In the equations shown above α_1 = 1138EUR/kW and $\beta_1 = 0$ after considering inverters from 2.5 to 20kW. In a similar way, α_2 = 77 EUR/kWh and $\beta_2 = 0$ with batteries analyzed in the range from 0.5 to 3kWh of capacity. Diesel engines from 10 to 50kVA have shown a cost curve with the constants α_3 = 174EUR/kVA and β_3 = 3050EUR. Photovoltaic module costs (determined by α_4 and β_4) depend on the system type: after information from ASER (Dahouénon, 2005) the average cost of photovoltaic in mini-grids is 2500 FCFA/Wp (3800EUR/kWp) and in Solar Home Systems it increases to 4600 FCFA/Wp (7000 EUR/kWp) which includes the mounting rack.

In Solar Home Systems, 24V inverters are required and therefore different costs should be considered. Additionally, the costs of charge controllers and, if necessary, a relay are associated directly to a list of available products which are chosen for every single system.

Other hardware costs like a low voltage connection network (PA 4 x 16 mm² cable lines in the case of mini-grids), interior installations and systems' accessories are also taken into account. Indirect investment costs due to engineering, infrastructure, transport and installation are calculated applying certain factors given by Dahouénon in previous projects at PERACOD. The latter indirect installation costs are not applied in Solar Home Systems, because they are included within the cost of photovoltaic panels.

Engineering and planning is assumed to be 3-4% of the investment costs in each system. The infrastructure required for a diesel engine is fixed by 900,000 FCFA, about 1370EUR, and for a photovoltaic mini-grid system is 7% of the costs of capacity installed in W_p. Installation works in the diesel generator system are estimated to be approximately as 8% of the generator cost and for the photovoltaic system as 5% of the investment costs. Transport of materials is a function of the distance from the village to the main port in the country using the specific cost of 500FCFA/km.

2.4.3 Operations and maintenance (O&M) costs

O&M costs include costs of fuel, maintenance and personnel. They are based on different assumptions depending of the supply system. Fuel prices in Senegal have been fixed by the local government and by 2005 the price of diesel was 540 FCFA/litre. The maintenance costs for the engine, photovoltaic and hybrid systems are assumed to be 4%, 1% and 2% of the investment costs, respectively. The annual expenditure in personnel is 1,200,000 FCFA for the engine and the hybrid systems, half of this amount for the photovoltaic system and one third for the solar home systems.

2.4.4 Replacement costs

The system components are to be replaced regularly according to the assumptions on the life of standard products. A small diesel engine is expected to be replaced after 15,000 operating hours. The output of photovoltaic modules is normally guaranteed from producers for 30 years. Batteries are assumed to function for 8 years and, similarly, inverters and charge controllers for 10 years. All provided interior and public lamps have a nominal life of 8,000 operating hours.

2.4.5 Payment scheme

In order to simplify payments and the billing process, households in Segments 1, 2 and 3 are required to pay a constant rate according to the willingness to pay expressed. Their respective consumption is limited on a monthly basis. Only consumers in Segment 4 require a meter and pay their real consumption in kWh. It is important to mention that transaction costs incurred from billing and payment collection activities are not integrated in the model.

Communal and production activities are classified within the given household segments according to their monthly energy consumption. In this way, a payment scheme related to the amount of energy consumed is assigned: the group with the highest energy consumption equivalent to the fourth segment will pay their monthly consumption in kWh. The other three segments will pay a fixed monthly tariff determined by their capacity to pay.

The ASER has used a retail price of 120 Francs CFA per kWh in rural electrification projects. In reality non-electrified villages are willing to pay a much higher specific tariff for the expected consumption shown. In our analysis the ASER tariff is applied as recommended in the fourth segment of households and equivalent production activities.

2.5 Economic analysis

A profitability index (outlined by Chabot as TEC, *Taux d'Enrichissement en Capital*) is used as the main criterion for the economic evaluation of the supply systems and is defined as follows (Chabot, 2004):

$$TEC = \frac{NetPresentValue}{Capital\_Investment} \tag{4}$$

In comparison to the Net Present Value (NPV), the profitability index (TEC) allows for an evaluation of the performance of the capital invested. Although different projects could generate the same amount of net profit, it would be more attractive to choose those projects in which less capital is required for the initial investment, i.e. the higher the TEC, the more efficient the capital has been allocated.

Following Chabot (2004), an overall profit of at least 20% of initial investment costs is considered to be satisfactory for service providers in this context.

The calculation of the net present value is based upon the following assumptions: a time frame of 30 years, 2% inflation, 10% nominal interest rate, annual increase of fuel prices of 4%. The profitability index expected by investors ($TEC_{expected}$) is defined to be 0.2 and there is an annual increase of payment tariffs and component costs which is proportional to inflation.

If the TEC is negative or lower than the acceptable level of profitability, then the subsidies required are calculated as a percentage of the investment of the supply system (Chabot, 2004):

$$Subsidies = \frac{TEC_{expected} - TEC_{present}}{1 + TEC_{expected}} \tag{5}$$

The supply system with the highest profitability index has also the lowest production costs per output unit. Comparing the levelised costs (*pc*) of the most profitable decentralised solution with those of connecting the village to the grid allows us to determine the critical distance in which decentralised supply systems become attractive (see the equation below). Grid transmission losses of 15% were assumed.

$$pc_{grid}(km) = \frac{f_{Investment\_fix} + f_{Investment\_MT}(km) + f_{replacement} + f_{el\_purchase}(kWh)}{el\_production_{discounted}} \text{ where } pc_{ref\_grid}\left[\frac{FCFA}{kWh}\right]$$

$$pc_{crit\_grid} = \min(pc_{decentralised\_prod}) \tag{6}$$

2.6 Environmental analysis

Besides achieving reliable and profitable supply systems the model evaluates the potential benefits of clean technologies, which is a fundamental element of sustainable development plans in rural communities.

Daily carbon emissions are calculated in each of the engine based systems. The amount of emissions depends on the amount of fuel consumed by the engine, which varies during the day according to its load level as the following equation defines.

$$E_{CO_2}\left[\frac{kg}{year}\right] = 365 \cdot \sum_{t=0}^{23}\left[P_{consumption}(t) \cdot \varepsilon_{nom}\left[\frac{kgCO2}{kWh}\right] \cdot f_{efficiency}\left(\frac{P_{cons}(t)}{P_{nom}}\right)\right] \tag{7}$$

Where the factor $f_{efficiency}$ is a function of the load level of the engine, which is the ratio between the actual power consumed (P_{cons}(t)) and the engine's nominal power (P_{nom}). ε_{nom} is the emissions factor and $P_{consumption}$ is the power required in each hour of the day.

In order to estimate the real achievable savings of CO_2 in electrification projects, a reference case should be defined. Under CDM guidelines, there are two simplified methods to define the baseline for small scale electrification projects (defined as projects with a maximal capacity of 15 MW) (UNFCCC, 2006):

– *Mini-grid supply systems*: the baseline is a diesel generator system with less than 15kW and a load factor of 25-50% that corresponds to emission factors between 1.4 and 2.4 kg CO_{2e} per kWh. Load factors of 25% are applied in cases of systems with 24 hour service and load factors of 50% are used for a temporary service of four to six hours a day, with productive applications.

– *Individual distributed systems or SHS*: the baseline case considers transport losses of a mini-grid in the total energy consumption of all individual applications and diesel engine's constant emissions factor of 0.9 kg CO_{2e}/kWh.

The baseline analysis follows the equation shown above, which reflects the cumulative emissions of a pure diesel-engine running the entire day under different load levels.

3 Simulation scenarios

The data used refers to population segments, willingness to pay and levels of service according to the expected utilisation of certain electrical equipment in the northeast region of Senegal. The basic scenario corresponds to a service with 24 hour availability and estimated energy consumption without service restrictions for such a region.

Modifications in demand were systematically introduced at the village level in order to determine whether an adjustment to the consumption behaviour, payment and segmentation could suggest better conditions for the financial feasibility of rural electrification projects.

Nine scenarios intending to rationalise the energy use (in schedules or equipment) were called demand cases. To obtain the optimal case, the willingness to pay of the population and the village segmentation were modified systematically to observe which profiles of villages and which levels of service facilitate obtaining the highest profitability rate.

Finally, in a later stage, the model has integrated the calculation of required subsidies when an association or cooperative manages the project. This option assumes that these groups have a higher interest in getting access to electricity; and therefore, expect a lower level of profit. The last results explore an alternative concept for the management of electrification projects.

4 Results

4.1 Demand characteristics

In the Matam region, a small village of 500 inhabitants would typically have 50 households. Based on the distribution curve of willingness to pay shown in Figure 3 and electrification costs defined previously in section 2, an optimal electrification rate of 61% within the village has been found (see Figure 5).

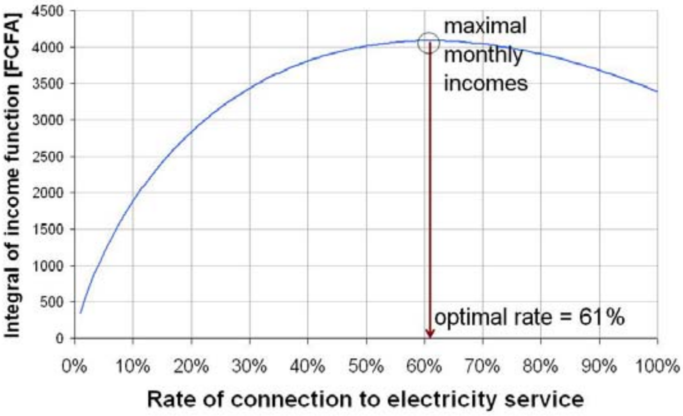

Figure 5. Calculation of the optimal electrification rate

The calculation of domestic consumption shown in Table III is based on information obtained from the socio-economic study (PSACD, 2003). The poorest segment represents 25% of households, where each household expects a daily electricity consumption of 189 Wh. Households in Segment 2 have a daily consumption of 305 Wh. In Segment 3 the household's consumption rises significatively to 944 Wh due to fans and colour television. The use of a refrigerator in Segment 4 doubles its consumption to 1,977 Wh per day.

Table III. Energy consumption in each household's segment

		Segment 1			Segment 2			Segment 3			Segment 4		
Amount of households	50			25 %			28 %			33 %			14 %
Consumption of electrical appliances	[W]	Units	Operating time per day [h]	Electricity per day [Wh]	Units	Operating time per day [h]	Electricity per day [Wh]	Units	Operating time per day [h]	Electricity per day [Wh]	Units	Operating time per day [h]	Electricity per day [Wh]
lamps	11	3	3	99	5	3	165	8	3	264	9	3	297
radio	5												
radio cassette	15	1	6	90	1	4	60	1	4	60	1	4	60
TV B&N	20				1	4	80						
TV color	80							1	4	320	1	4	320
fridge	100										1	10	1000
fan	60							1	5	300	1	5	300
freezer	112												
daily electricity consumption [Wh]				**189**			**305**			**944**			**1977**

The first demand case, designated with the label "original" in Figure 6, is built based on expected behaviour of Senegalese rural communities following the socio-economic study described in section 2 and refers to a supply service available 24 hours a day. A softer, "optimised", load curve was obtained after rationalising the use of some electrical applications in demand cases, which reduced the amount of energy load by 32%. Moreover, production and communal activities were encouraged to shift their operation to particular times of the day in order to allow a more efficient supply. Demand management is a relevant issue in this context, as the electricity consumed by relatively few places should be generated under higher costs per output unit. In this way, a simple and soft curve can lead to a more energy efficient and economically efficient supply of energy.

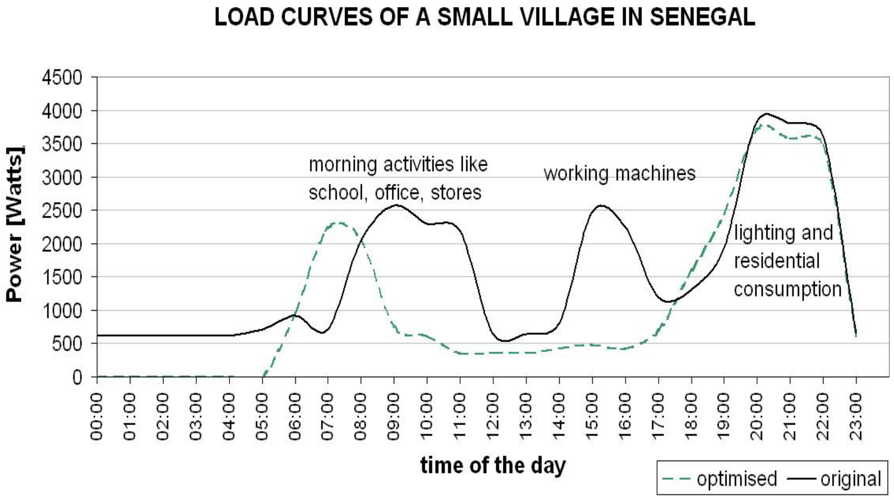

Figure 6. Optimisation of demand cases in a small village

The model shows that an optimum service in small localities with 500 inhabitants has an overall daily demand of 22 kWh with a peak of 3.7 kW and the following characteristics:

- Electricity availability from 6 a.m. until midnight.
- Management of production appliances: non-simultaneous use, low-power equipment.
- Reduction of the amount and use of communal, non-productive equipment like fans and televisions.

4.2 Supply system's characteristics and costs

Schedules for the operation of diesel engines are necessary. Under optimised demand conditions, the supply systems show the following costs (Table IV).

Table IV. Technical characteristics of supply systems in a small village

Component	Diesel engine	PV system	Hybrid system	SHS
Inverter	4.4 kW			600W
Engine	5.5 KVA	-	5.5 KVA	-
Photovoltaic modules	-	6 kWp	3.1 kWp	6.7 kWp
Batteries	10 kWh	37 kWh	20 kWh	60 kWh
Investment costs	**14.5 m FCFA**	**28.9 m FCFA**	**24.5 m FCFA**	**45 m FCFA**

In all demand cases, photovoltaic systems generally require the highest amount of initial investment: 29-42 million francs CFA (44-64 thousand EUR) for PV-mini-grids and 45-64 million francs CFA (68-97 thousand EUR) for a constellation of Solar Home Systems.

Diesel generators in pure or hybrid systems must be replaced often, every four to ten years depending on the daily operating hours and require large annual operation expenditures due to the consumption of fossil fuels (about 2 to 3 million Francs CFA, 3,000-4,500 EUR at current level prices).

4.3 Economic evaluation

Among the supply systems evaluated, only photovoltaic mini-grids achieve a reduced profit given by a positive TEC of 0.01. The minimal amount of subsidies required for an electrification project in Senegal with a profitability index of 0.2 over 30 years is 4.7 million FCFA or 7,165 EUR (see Figure 7). This is achieved through the photovoltaic mini-grid with the demand conditions mentioned above.

Only 25 tons of CO_2 emissions could be saved per year through the electrification of a small village based on a photovoltaic system. This amount represents about 2% of the investment costs when the project is accredited in the CDM scheme for a 21 year-period under forward fixed-price contracts of 5USD per tonne CO_{2eq} (assuming current CER prices typically used in CDM projects and ignoring the registration and transaction costs). However, with a broad establishment of carbon markets, higher prices of CERs and an important reduction of transaction costs are expected in the long-run.

The choice of a decentralised supply system is financially sound if small villages lie further than 5.4 km from the MV grid lines. This critical distance was calculated on a levelised cost of 535 FCFA/kWh (0.81 EUR/kWh) for a photovoltaic mini-grid.

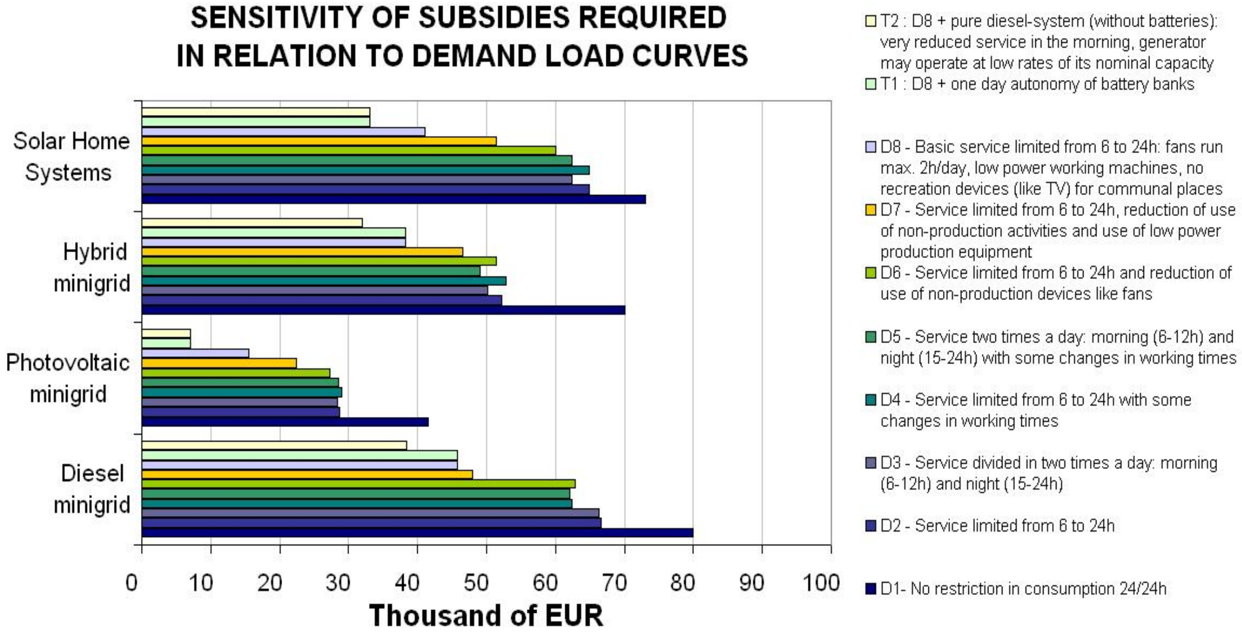

Figure 7. Profitability results in terms of subsidies required

5 Discussion

Overall, high initial investments for photovoltaic based systems and/or growing annual expenditures for the consumption of fossil fuels have resulted in insurmountable barriers to the capacity of rural populations to pay for electrification. Therefore, rural electrification projects in this context are not reasonably profitable for investors without subsidies. The photovoltaic mini-grid has been shown to require the lowest amount of subsidies.

The tariff used by the ASER for high consumption in rural electrification regions of 120 FCFA/kWh underestimates the willingness to pay from the richest segment of rural communities, which is equivalent to at least 308 FCFA/kWh. Although this willingness to pay accounts for only 14% of the population, it could significatively improve the profitability of the project.

The so called “clean” technologies applied to these small scale projects do not produce substantial financial gains resulting from the environmental benefits. Considering registration and transaction costs of each CDM small-scale project, or even many of them bundled into a large one, the CDM scheme does not provide significant incentives in the choice of clean technologies for rural electrification of small villages.

5.1 Alternative approaches for rural electrification

When proposing schemes for rural electrification in small villages, it is important to differentiate between the perspectives of users and investors. The classical approach proposed by De Gouvello and Maigne (2002) adapts supply to the four levels of service based on the middle/average necessities of all the population segments and relates this to their capacity of payment. Meanwhile, in the investor approach the richest groups are set as the priority in order to secure a high level of income, which keeps the electrification project profitable. However, this approach usually reaches a low rate of electrification within the village.

After understanding these two different interests and using the model presented here, we have attempted to answer the following question: how could rural electrification become viable for both consumers and investors, in the localities with less than 500 inhabitants? We have found three primary points, which together form a planning path:

- *Pre-selection of villages*: electrification can be immediately feasible, without subsidies, in villages where the willingness to pay of the poorest segment is at least 3320 FCFA (5EUR) per month. Solar Home Systems and hybrid mini-grids become profitable without subsidies when the poorest segment can pay at least 4,700 to 5,000 FCFA (7-7.6 EUR) respectively.
- *Reduction of service levels at the supply side:* if the capacity of payment is lower than those of the preselected villages, then the supply should be limited to two or three service levels (instead of four) which correspond mostly to the middle income groups. Fulfilling the energy needs of the richest household segment is highly expensive, and contrary to expectations, it produces a considerable reduction of the profitability index.
- *Management leadership by communal associations:* if, after these previous steps no investors are motivated to participate in the electrification project, then incentives to have communal associations taking the management leadership should be considered. Groups working for community interests will generally expect less profit than investors, which translates into a lower amount of required subsidies. A lower subsidy requirement is likely to ensure faster realisation of projects.

This path should then facilitate the implementation of electrification in small villages. These findings result from additional simulations after adjusting separately the willingness to pay, the population segmentation and the reduction of expected profitability index by 50%.

The present model is principally based on monetised flows of payments and costs under different supply schemes that have been available from real data of socio-economic studies and recent technical information on power systems. However, in remote areas where higher illiteracy and difficult regional access are present, some key issues like the training of villagers in the use and maintenance of the systems, and the increase of organisational support capacity in human resources or regional branches, involve further costs that should be also taken into account. Furthermore, a risk analysis has been only carried out by means of a sensitivity analysis of the assumptions on interest rates and fuel prices. However, existing risks in the deployment of the project like thefts, human-induced breaks, natural hazards or system failures have not been quantified nor integrated in the analysis so far. In general, these additional costs would not greatly change the ranking of the technologies evaluated, but it would rather show that the real cost of rural electrification has been undervalued.

5.2 Considerations for the broad implementation of new strategies

Before new approaches for a faster deployment of decentralised technologies in rural electrification can be implemented, it is necessary to identify actual barriers and new tasks which need to be undertaken by the different private and public sector actors. The results of this study were therefore presented to a pool of experts from the ASER, development organisations and banks, independent consultants and private businesses. In this framework, the following facts have been identified as relevant issues to be reinforced:

- *Demand management.* National programs to promote the distribution of efficient appliances should be created. Devices to control energy consumption (as part of the supply system) are to be identified. Public awareness for good practices which avoids high consumption of energy and agreements about public and production usages are to be enhanced in remote localities.
- *Willingness to pay*. Statistical information about rural populations should be standardised and collected regularly. Methods for surveys should be defined by a central institution like the ASER. Regions are to be classified by priority based upon socio-economic studies.
- *Levels of service*. Community and investor awareness about the cost effectiveness of simplifying the market segmentation should be raised, i.e. the needs of the richest segment should be adapted to a lower level of service which excludes own refrigeration. Instead, refrigeration systems in small communities can be planned as a shared activity.
- *Communal management schemes.* Incentives and technical support for communities or associations to lead their electrification process should be created by national agencies and facilitated through simplified administrative processing. Formation of local technicians as well as administrative personnel should be offered continuously. Information networks of existing communities under this management scheme should be updated as a medium of mutual assistance at a regional level. A specific unit of the ASER could define and clarify legal responsibilities within the associations to ensure the good functioning of projects.

Although a detailed discussion of social mobilization and an associated cost-benefit analysis of this approach in relation to rural electrification are beyond the scope of this study, it is necessary to recognize that this is a critical issue in helping rural communities to use energy as a means for income generation and, in consequence, should be fully investigated as part of rural energy planning.

Incentives for the support and promotion of photovoltaic technologies created by ASER are an appropriate instrument for facilitating the choice of the most profitable supply system. In a further stage, other implementation studies should be carried out, specifically concerning the practical aspects of communal management, logistics and technical training. Additionally, a nationwide information network should be developed to ensure that different regions will have easy access to different services for the installation, maintenance and upgrading of their supply system.

6 Conclusions

In the long term, both photovoltaic-based systems (PV-mini-grid and Solar Home Systems) are likely to offer the technical solutions with the best economic performance for various demand simulation cases for villages with less than 500 inhabitants. When proposing alternative criteria for a planning path for rural electrification to different Senegalese stakeholders, it was pointed out that the information contained in socio-economical studies is very useful, in order to understand consumer needs. However, we recognise that this is a time consuming activity. In particular, it seems likely that small enterprises that want to present an ERIL project will require further assistance. Experience has shown that it is difficult to manage this kind of project through communal associations, mainly because responsibilities and property issues are not clearly defined. From this perspective, the supply of only two or three levels of service are, initially, likely to be the most feasible criteria private investors can follow. Whichever path is chosen, the capacity of national agencies and private businesses has to be reinforced in order to react faster and in a cooperative way through a sustainable deployment of electrification planning schemes.

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