Renewable Energy 35 (2010) 1615–1623

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Review

Renewable decentralized in developing countries: Appraisal from microgrids project in Senegal

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A R T I C L E I N F O

Article history:
Received 23 June 2009
Accepted 17 January 2010
Available online 16 February 2010

JEL classification:
Q42
Q49
Q51

Keywords:
Electricity access
Renewable technology
Environmental externalities
ff-grid

A B S T R A C T

Sahelian developing countries depend heavily on oil-import for the supply of their increasing energy demand. This setup leads to an imbalance in the balance of payment, an increase of debt and budget asphyxia, whereas renewable resources are widely and abundantly available. The objective of this paper is to carry out a feasibility analysis of off-grid stand-alone renewable technology generation system for some remote rural areas in one Sahelian country. A survey conducted in 2006, within the framework of microgrids project, in rural areas located in three different regions in Senegal (Thies, Kaolack and Fatick) permits determination of demand estimations. Two reference technologies are chosen, namely a solar photovoltaic (PV) system of 130 Wc for solar endowment and a wind turbine of 150 W for wind speed. Taking into account the life-cycle-cost and the environmental externalities costs, our results show that the levelized electricity costs of PV technology are lower than the cost of energy from the grid extension for all these three regions. Thus, decentralized PV technologies are cost-competitive in comparison to a grid extension for these remote rural areas. For wind technology viabilities results are attained with a requirement demand lower than 7. 47 KWh/year for Thies and 7.884 KWh/year for the two remaining areas, namely Kaolack and Fatick. The additional advantage of the proposed methodology is that it allows the environmental valuation of energy generated from non-renewable resource.

1. Introduction

In rural zones of developing countries, access to energy is a paramount importance, as it increases the standard of living of rural populations by facilitating, on the one hand, the struggle against poverty [1–5]. On the other hand, it improves the quality of life with the creation of comforts for populations via the acquisition of goods such as radios, televisions and mobile phones [6,7]. Considering particularly Sahelian countries, energy access remains until now relatively low, while the renewable resources – wind speed endowment and sunny radiation potential – stay widely abundant. The endowment of renewable resources assumed that resorts to renewable technologies could increase and improve energy access particularly in remote rural areas [8]. According to that preceding assumption a new and straightforward technique to analyze the cost-effectiveness of renewable technology's adoption in rural areas is required.

The purpose of this paper is to verify this assumption. In fact we compared two different electrical planning expansion policies. The first one focused on the centralized-national network expansion while the second decentralized stand-alone renewable technology scheme. The first option, national network extension, used the conventional diesel technology while the second dealing with stand-alone renewable decentralization mobilized a wind turbine and photovoltaic panel. The life-cycle-cost analysis is retained in this paper. This methodology is performed to quantify and compare the monetary value of energy produced from electricity generation technology. It refers to the total cost of ownership of all selected technology over the lifetime of their operation. Numerous life-cycle-cost analyses have been carried out over renewable technology stand-alone generation [9–12].

This study will be applied to the case of Senegal principally for two reasons. First, we judge that this country remains a suitable representative of the Sahelian countries. Furthermore, a survey carried out in the framework of the microgrids project,[1] allows us to

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[1] The Microgrids project was promoted and financed by European Commission. Its goal is to promote the development of micro-networks and renewable resources for facilitating electricity access in rural areas in Senegal. This project was included in the context of poverty reduction scheme within the context of Millennium Development Goal (MDG) targets. This latter promoted by United Nations (UN) and developed countries targeted to reduce poverty depth in 2015, around the world developing countries.

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doi:10.1016/j.renene.2010.01.015

work with data of potential demand assessed into the selected zones. Three regions have been selected for this project namely (Dakar, Thies and Kaolack). A survey was carried out in thirty villages for the determination of electrical power and energy they need.

Situated on the west coast of the horn of Africa, Senegal is located between 12 and 17 degrees northwest and extends over an area of 196 700 km^2. The population was 12 million in 2007 [13]. It is growing at an annual rate of 2.5%, remaining higher than that of the countries of the OECD,[2] which is an average of 1.6%. Close to half of the population (49%) lives in rural areas [13]. Economic activity remains dominated mainly by the service sector, which contributes to 62.5% of GDP versus 19.2% for the industrial sector and 18.3% for the agricultural sector [13]. Despite the low level of contribution of the agricultural sector in the economic growth, it mobilizes more than 50% of the population activity and is particularly focused in rural regions.

Energy consumption per capita (0.19 toe[3]) remains one of the lowest in the sub-region compared to the average of the Economic Community of West African States (ECOWAS) which represents (0.45 toe) and that of the sub-Saharan African region (0.50 toe) [14]. In order to increase the level of electricity access in both rural as well as urban areas a reform of the electric sector had been undertaken. In fact, the traditional electricity supply system via the extension of national network has not delivered satisfactory results. Levels of access, in 2006, remains dichotomized with urban electrification rate (60%) representing four times that relating to rural zones (15%). The lack of infrastructures in rural zones makes electricity access from grid-expansion very costly. Despite the low level of access to electricity, the country has at its disposal a considerable potential in terms of renewable energy resources. Moreover, renewable energy could prove profitable when exploited effectively, particularly for the supply of energy to rural areas located far from the electricity distribution network. The country receives at least 3000 h of sunshine per year [15] and the average solar energy received is estimated in 2.000 KWh/m^2/an [16]. In regard to wind energy, the northern zone possesses fairly significant potential which could be turned to profit generation if exploited [14].

In this context, questioning the effectiveness of stand-alone decentralized-renewable technology against current national network expansion should be interesting to help energy policy-makers, but also microgrids managers, to provide an optimal solution about the capacity planning expansion in remote rural areas.

Furthermore, decentralized electric supply, via the use of renewable technologies, presents some advantages compared to the extension of the electrical grid [3,7,8,17–21]. Renewable technologies do not require fossil fuels for their operation, thus price variations of fuel do not affect the quantity of electricity produced nor the performance of the energy system. From an environmental point of view, they do not emit greenhouse gas emission (GHG) during the electricity-production phase [22,23]. Moreover, being situated close to the point of demand renewable technologies use can save costs relating to electricity transport and distribution. From an economic point of view they improve local employment situation during the installation phase but also during the operation and maintenance process.

In order to investigate these issues this paper is composed in five sections. The description of Senegal's energy sector will be exposed in the second section (Section 2). The third section (Section 3) will expose and explain the methodology retained. The fourth section (Section 4) presents the results and the last section (Section 5) will conclude the paper.

[2] Organisation for Economic Co-operation and Development.

[3] Ton oil equivalent.

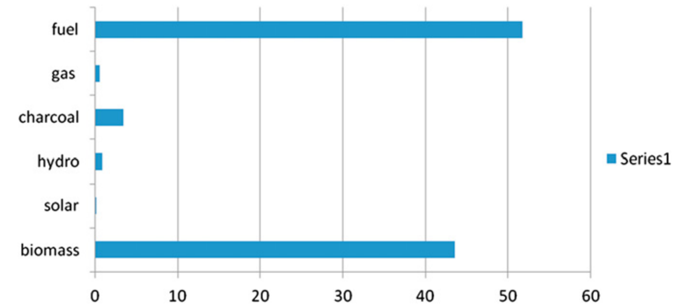

Fig. 1. Structure of energy resources consumption in Senegal (2006) (Kgoe) Kilogramme oil equivalent (kgoe), Source: Ref. [14]

2. Description of the energy structure in Senegal

Like many non-oil producing countries in sub-Saharan Africa, the electricity sector in Senegal is characterized by a dependence on petroleum imports (see Fig. 1). The share of energy produced from fossil fuels is highest as compared to all existing energy sources. Moreover, the increasing effects of fossil fuel imports (78%) over the last six years have produced an imbalance in the balance of payment, since 42% of goods exportation benefits are allocated to the payment of fossil fuel imports [14]. The solar energy, hydro-electricity and energy produced from natural gas remains smallest among all these available resources (Fig. 1).

Furthermore, more than 40% of energy supplied comes from biomass sources. This latter is composed of wood energy and charcoal. The wood energy is the principal source of energy consumption in rural areas while the charcoal is widely consumed in urban and semi-urban areas [14]. The availability of biomass resources as a source of energy supply generates a number of ecological and economic concerns. In the economical point of view, the overexploitation of biomass resource leads to the under-valorization of renewable resource price. Moreover, it leads to the free evaluation of the biomass resources whereas its scarcity will be managed by the next generation. About the environmental concerns it is argued that the overexploitation of biomass conducted to deforestation and loss of biodiversity [18,24,25].

Electricity production is derived mainly from thermo plants which provided close to 83% of production as well, since 2002, as by the hydroelectric dam of Manantali. This latter possesses a capacity of 200 MW within which 35% is intended to be consuming by Senegal. Despite the increase of capacities by the introduction of additional thermo plants, consumption still remains quite low when compared with other sub-Saharan African countries. Table 1 shows the level of Senegal's energy consumption compared to a number of Sub-Saharan African countries.

However the major part of electricity produced is consumed by urban populations [14]. While rates of access to electricity in urban

Table 1
Energy consumption per capita of urban and rural populations (Kgoe).

Countries	Urban	Rural
Kenya	220	60
Zimbabwe	300	150
Botswana	390	166
Zambia	200	180
Senegal	170	120

Sources: African Development Bank, 1996.

Table 2
Electrification rates in both urban and rural areas (percentage).

Years	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Rural	1.5	1.9	2.4	3.1	4.1	4.1	4.4	4.7	5	6.4	7.6	7.5
Urban	45.8	46.5	47.3	48.2	49.2	51.3	49.5	50.3	51.4	51.3	52.6	55.4
Total	21.2	22	22.9	23.8	25.1	26.3	25.8	26.6	26.9	28.3	29.8	31.4

Sources: SENELEC (Société national d'électricité du Sénégal).

areas approaches 76% those of rural areas remains around, in 2006, 16%. This low level of access to electricity in rural districts compared to that in urban areas has motivated reforms implementation in spite of consistent budget constraints. In fact in 1998, under the initiative and assistance of the World Bank, the government implemented reforms in the energy sector via the publication of the white paper dealing to the development policy of energy agenda. This latter was composed of three main targets. The first one aimed at the dismantlement of the own-state monopoly electric company (SENELEC[4]). This intended to hang up the involvement of the national and international private sector in order to facilitate and promote the public–private partnership. The second aimed to increase energy supply for a major part of the population particularly in remote rural areas. It leads to the creation of an agency focusing exclusively on rural electrification access topic (ASER).[5] Its function can be summarized in two points. It has, as its principal mission, to develop and provide programs relating to rural electrification. Furthermore, to choose operators and attributes concession rights for any rural electrification program. The final reform orientation aimed to promote the dissemination of renewable energy technologies, particularly in the rural regions. Because the presence of abundant renewable resources seems to provide a good opportunity to promote, encourage and disseminate the diffusion of renewable technologies. However, almost a decade later, the results of the reform remain mitigated in the fact that the electricity sector is still not able to supply electricity to a substantial portion of the population (ref. Table 2)

3. Methodology

The methodology developed is an extension of that used in Nguyen [9]. We introduced, in distinction to the above-mentioned author, the analysis of external effects, so as to take into account the external costs stemming from the use of fossil fuels for the production of electricity. Furthermore, our approach is inspired on life-cycle-cost[6] analysis rather than simple comparison between capital costs. It is composed of four steps. Firstly an analysis of selected technologies is performed. This permits determination of economic and technical factors. Then we determined the quantity of electricity produced by renewable technologies under the meteorological conditions of the three selected areas. An assessment of environmental costs, which is supported by emissions factors, will be presented in a third step. In the final stage, environmental costs integrated into an economic assessment allow the determination of the levelized-electricity-cost. This latter criterion allows us to compare the choice of stand-alone decentralization option via renewable technologies with that of centralization scenario using current national network extension. This criterion remains the most used in terms of comparison of electricity-production technologies. Even if some suspicious remain about their reliability when uncertainty is included into the technology generation investment [28]. It represents the unit cost in KWh of electricity produced by a given type of technology. Its particularity over against criteria can be situated on two levels. Firstly, it compiles and integrates, beyond a simple comparison of capital costs, all operating, replacement, maintenance, transport and connection costs of the technologies considered. Furthermore, it takes into account also fossil fuel and environmental costs of conventional technologies. Total costs are considered in discounted value taking into account the discount rate, interest rate, and the variation of fuel cost. The following Fig. 2 shows the framework of the life-cycle-cost as an approach carried out in this paper.

3.1. Analysis of selected technologies

The photovoltaic (PV) modules produce electricity by directly converting the sun's rays into electricity. The electricity produced is delivered in the form of D.C. current, which is perfect for numerous applications. However, that involves a transformation to alternative course if it is required to be introduced into a distribution network. The energy captured by a module depends on the surface, the nominal power of the panel and the duration of sun exposure. This latter varies according to latitude, season, time of day. However, taking into account the intermittent features of renewable technologies [23,29], the majority of photovoltaic (PV) modules not connected to the distribution network use batteries. The PV-battery power system permits storage of the energy supply during periods of variable meteorological conditions, allowing equilibrium between energy supply and demand. In rural areas of developing countries, this type of technology is highly appropriate for responding to the energy needs of the population [3]

In the case of wind turbines, kinetic energy is converted into mechanical energy or electricity via the rotation of the turbine. The power captured by wind turbine is a function of the square of its diameter and the cube of wind speed. When favourable meteorological conditions are met, wind technologies represent a good alternative method for supplying electricity. In the rural areas of the three regions studied (Kaolack, Thies and Fatick) small wind

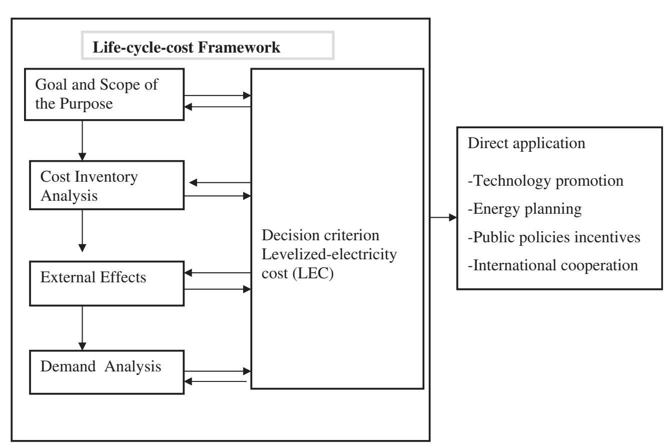

Fig. 2. Life-cycle-cost framework.

[4] Société Nationale D'électricité du Sénégal (SENELEC).
[5] Agence Sénégalaise D'électrification rurale.
[6] This analysis is explained in some papers [19,26,27].

turbines are quite appropriate for the various end-use electrical appliances. Although more costly as compared to those of conventional technologies, the costs connected to renewable technologies have come down significantly during the last few years (Fig. 3) with *Ci* representing the costs of electricity. Advances in research and development and the emergence of the assembly market in developing countries have lowered the cost of renewable energy technology unit. Furthermore, it is argued that [20,30], the learning process of renewable technologies remains susceptible to decrease in the next future years as since more than the last twenty years

Three kinds of technologies are mobilized. The decentralization option is composed of a solar photovoltaic module with a capacity of 130 Wc and a wind system with a capacity of 150 W while the centralized option based on the extension of the distribution network used a diesel group with a capacity of 450 W.

This type of conventional technology has been selected because it corresponds to that being used currently in Senegal for the production of electricity. About renewable technologies, they are in general use, during projects phases in rural parts of Senegal. Their utilization started to be discovered and they are compatible with local conditions and resources endowment. Technologies selected are evaluated through their costs. The latter include capital costs, costs incurred during operating and maintenance, to which must be added environmental, transport, distribution and connection costs when referring to centralized option. Capital costs are composed of the cost of equipment, including engineering costs, and all costs related to installation. On the other hand, operating costs vary according to the option considered. In the framework of a choice in favour of decentralization, incorporating renewable technologies, operating costs are composed of the cost of operating and maintenance. While in the case of centralization, including the diesel group, operating costs are composed of costs of maintenance, costs allocated to the consumption of fossil fuels. These two following (Tables 3a and 3b) present the technical and economical characteristics of the selected technologies during the production and the transport of electricity.

However, deployment of an analysis of the life-cycle-cost requires to taking into account environmental costs linked to the consumption of fossil fuel. Furthermore, external costs vary when one compares conventional and renewable technologies. For example wind and photovoltaic systems can involve higher installation costs than diesel groups or gas turbines but they required relatively low operating and maintenance costs and do not involved use of fossil fuels for their functioning. Following ref. [9] and integrating environmental costs let us consider the expression of life-cycle cost as the following expression.

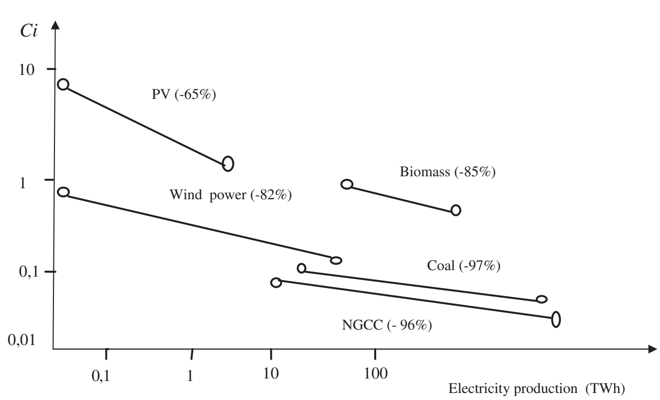

Fig. 3. The learning rate of different renewable technologies (percent), Source: Ref. [30].

Table 3a
Technical and economic features of selected technologies (production).

	PV. Tech	Wind Tech	Diesel Tech
Capacity	130 Wc	150 W	450 W
Capital cost (F CFA)	350 000	160 000	185 000
Op and maintenance (FCFA)	1500	2000	9500
Life expectancy (years)	20	10	3
Capacity. battery (Am)	100	100	
Battery cost (FCFA)	35.000	35.000	
Lifetime battery (years)	3	3	
Charge controller (FCFA)	25 000	25 000	
Lifetime controller (years)	10	10	
Fuel tank investment cost (FCFA)			15 000
Lifetime tank (years)			3
Unit cost of delivered fuel (FCFA/m3)			210/m^3
Heat rate (Kj/KWh)			11 000

[a] International Energy Agency (IEA) ; Service de l'énergie en milieu Sahélien (SEMIS) ; ENDA-TMSources: Compilation by the author based on various sources, including (IEA, SEMIS, ENDA-TM, SENELEC)[a] Values are expressed in Francs CFA ($1 US = 489.207. F. CFA).

$$LCC = C_c + C_m + C_R + Cf + Ce \quad (1)$$

Where *LCC* represents the life-cycle-cost

- Capital cost (*Cc*)
  Capital costs are those linked to the purchase of all system components, such as generators, PV units, batteries and extension costs for tension lines. They are generally defined as the initial acquisition costs for equipment before installation begins. These costs are exogenous for each option, centralized or decentralized, considered.

- Operating and maintenance cost (*Cm*)
  Within a long-term perspective, technologies employed must include maintenance costs. These costs vary according to the options considered. This expense is low for renewable technologies as compared to conventional technologies.

$$Cm = AnnCm\left\{\left(\frac{1+i}{r-i}\right) \times \left[1 - \left(\frac{1+i}{1+r}\right)^N\right]\right\} \quad (2)$$

where *i* represents the interest rate, *r* the discount rate and *AnnCm* correspond to annual operating and maintenance cost and finally *N* represents the number of year considered.

- Replacement cost (*Cr*)

Table 3b
Technical and economical features of selected devices (Transport).

Line medium tension	
Long-term marginal cost of electricity provided (cost of 1 KWh transported via the network) (FCFA)	36 000
Exploitation cost (CFA/km/)	240 000
Length (km)	10
Operating and maintenance costs (FCFA/km/year)	82 500
Lifetime (years)	40
Transformer	
Cost of transformer (CFA/transformer)	2.000.000
Operating and maintenance costs for transformer (CFA/transformer/year)	60 000
Life expectancy (year)	40
Line low tension	
Exploitation cost (CFA/km)	145 000
Operating and maintenance costs (CFA/km/year)	161 000
Connecting costs (CFA/clients)	22 500
Life expectancy (year)	40
Loss (as a percentage)	15%

Source: ENDA-TM

This represents the costs involved during the replacement of certain system components that have a lifetime shorter than that of the project. They can also include replacement costs related to wear and tear of certain devices.

$$C_R = \sum_{i=1}^{V} \left\{ \text{itemcost}^* \left(\frac{1+i}{1+r} \right)^{N_T} \right\} \tag{3}$$

- Fuel cost (Cf)
  These costs measure expenses carried out, during consumption of fossil fuels, for the operation of conventional technologies. These costs are zero for renewable technologies as deployed for a decentralized option

$$Cf = AnnCf \left\{ \left(\frac{1+Pf}{r-Pf} \right) * \left[1 - \left(\frac{1+Pf}{1+r} \right)^N \right] \right\} \tag{4}$$

where Pf represents the increasing share of fossil fuel price

- According to World Bank [31] we assume that the escompte rate represents 4.5%.
- We assume an interest rate of 3%, as recommended by the Central Bank of West African States.
- The inflation rate for fossil fuels, evaluated on the international database, assumes an annual average trajectory of 3% over the last sixty years.
- Environmental cost (Ce)

This cost measures external effects generated by the use of fossil fuels. This cost computed the environmental externalities of the utilization of fossil fuel for electricity generation. This cost is also zero for renewable technologies as we consider these latter technologies do not emitted pollutants during their electricity-production periods. The environmental cost can be represented by the equation below.

$$Ce = HR^*EF \tag{5}$$

where HR represents the heat rate and EF represents emission factor. The heat rate is measured in (Kj/KWh). This latter measured the efficiency of thermal generating station.

3.2. Renewable energy supply

Determination of levels of energy production from the utilization of renewable technologies is undertaken under meteorological condition of these three selected areas (Kaolack, Thies and Fatick). In the case of wind technologies, the energy produced varies according to wind speed cubed. However in order to determine the quantity of energy produced a good knowledge of wind speed distribution is required. The Weibull function permits determination of the distribution of the speed. Following ref. [9] the distribution function can be represents as follow.

$$f(\upsilon_r) = \frac{\pi \upsilon_r}{2(\upsilon_{mr})^2} \exp\left(\frac{-\pi}{4} \right) \left(\frac{\upsilon_r}{\upsilon_{mr}} \right)^2 \tag{6}$$

where υ_{mr} represents the average wind speed for each region considered, υr the speed for each year under each given region.

From the above equation, annual energy production can be calculated according to ref. [32], using equation (7).

$$E = \sum_{t=1}^{T} \gamma^* f(\upsilon_r)^* P(\upsilon)^* 8760 \tag{7}$$

With $P(v)$ represents the power of the turbine, the probability density of the Rayleighienne function[7] is represented by $f(\upsilon_r)$, γ represents the efficiency of the system and 8760 the number of hours per year. In the context of photovoltaic technologies, production depends on the surface utilized, nominal power of the module and the daily rate of radiation. According to [32] the production of photovoltaic electricity can be estimated using the following equation.

$$Qp = \gamma^* W_p \frac{br}{b_0 r} {}^*365 \tag{8}$$

where W_p is the maximum capacity of the photovoltaic unit, b_r represents the annual average rate of solar radiation in a given region (w/m2/j) and b_{or} the rate of radiation standard for each region and 365 is the number of days per year.

3.3. Environmental externalities

It is argued that the assessment of environmental effects of energy production plays an important role in the competitiveness of renewable energy technologies [33,34]. Baumol and Oates [35] and Pearce and Turner [36] argue that the externality is hold if the economic activity of an agent has an effect on the well-being of another agent, in the absence of any commercial transaction.

In the framework of energy production these external effects can be assimilated into the emissions generated during the different phases of electricity production, transport and distribution. In particular, these depend on the characteristics of the technology under consideration[8] as well as the quantity of fossil fuel used.

Taking into account environmental externalities remains quite profitable for the diffusion of renewable technologies. Albeit, this latter does not contribute to the greenhouse gas emission (GHG) increasing, it provides environment benefits to remote rural areas in Senegal. Furthermore it is often argued that the utilization of renewable technology can generated a good environment effect in rural areas of developing countries [37,38]. However I gathered main effects within which renewable technology utilization could contribute to the environment well-being saving and a standard of living improvement in rural areas in Senegal Table 4.

3.4. The determination of environmental cost

The evaluation of external costs is performed taking into consideration emission factor (EF). Table 5 shows the different values of various emission factors of Senegal's energy sector. The evaluation of external costs is undertaken on the basis of the following values: 5.666 §/kg of SO_x; 2.293 §/kg of No_x and finally 0.018 §/kg of CO2. The latter, provided by El-Kordy et al. [19] represent estimations of the effects on both health and the degradation of the environment due to polluting emissions. These costs, when discounted, will be introduced into the life-cycle analysis so as to determine the levelized-electricity-cost of these different technologies. The assessment of environmental costs remains a difficult issue to accomplish in the context of developing countries, particularly in sub-Saharan Africa. Moreover, the well-know model inquiring environmental effects of energy production

[7] The Rayleigh function is the value of the weibull function when the charge factor is equal to two [9].

[8] It is important to note that effects, such as the age of technology, types of fossil fuels used, efficiency of technologies and the installation of emission controlling equipment can have a quite impact on the pollution level from other pollutants except a carbon dioxide.

Table 4
Impacts of renewable energy adoption in rural areas in Senegal.

➢ Environment	• Lowering of pollution emissions • Decreasing a biomass consumption • Improvement in vegetation cover
➢ Health	• Reduction of respiratory problems • Reduction of infant mortality
➢ Equity	• Time gain for female population, following a reduction in time collecting wood for energy use
➢ Education	• Increasing of day length via night lighting • Time gain for children
➢ Social	• Creation of social ties (nighttime discussions, etc)

Sources: Inventoried by author.

carried out in Europe (ExternE) required very intensive data collection. This model emphasized on impact pathway methodology required to consider all the step of electricity vector diffusion since the extraction of fossil fuel until the waste disposal. Fig. 4 depicts the process steps of the oil-to-electricity fuel cycle.

At the moment it will be difficult to assimilate this model in the context of developing countries. The lack of quantitative data, the low level of environmental sensitivity, and the presence of a significant informal economy, made difficult this kind of analysis. This present paper intended to lay out the environmental damages of electricity production in Senegal using emission factor.

3.5. The assessment of energy demand

Like exposed earlier, the analysis of energy demand is based on a survey carried out within the context of microgrids program. Instead a survey had been undertaken between September 18 and October 5, 2006 in three different regions of Senegal (Fatick, Kaolack and Thies). Three kinds of surveys have been conducted. Namely the village surveys, the household surveys and finally the technical surveys [15].

The village surveys were carried out by interviewing people chosen by the chief of the village. The household surveys were mainly processed in two steps. A contingent evaluation was carried out, in the first step, with the aim to determine the willingness-to pay for electricity access. Some "strategic bias" was probably present so that the true willingness-to pay was probably higher than that defined during the survey. Moreover, the second step emphasized to collecting data concerning domestic behaviours related to energy consumption. Finally the technical surveys allow listing the driving forces and productions units [15]. Thirty non-electrified villages were selected; thirteen in the region of Kaolack, seven in Fatick and finally ten villages in Thies. Thirty-four households survey sampling were performed in these villages. Two

Table 5
Data on emissions factors.

	Oil	Diesel	Natural Gas
CO_2 (kg/GJ)	36.7	37.05	28.05
No_x (mg/GJ)	0.15	0.0824	0.34
SO_x (mg/GJ)	0.998		0.34

* Data on CO_2 emissions were collected at the IPCC Guideline 2006 for National Greenhouse Gas Inventories. These data correspond to emissions factors focused on level I.
* Emissions factors for other pollutants (No_x and SO_x) come from the report of the Senegalese Association of Standardization (SAS). These correspond to emissions standards that the energy producer must respect under normal operating conditions.Sources: IPCC + SAS.

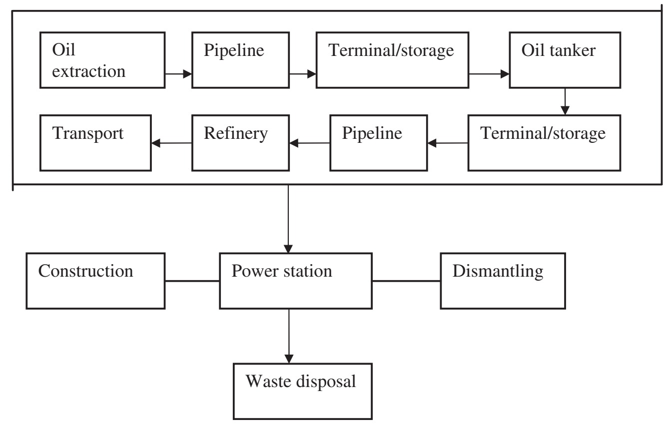

Fig. 4. Pathway analysis of Environmental effect in Energy Industry. Sources: ExternE (1995).

criteria guided the choice of the selected villages. One criterion was the distance issue, all the villages are situated within a radius of 10 km from the SENELEC distribution network. To simplify we assumed that the distance to grid-connection is lengthened to 10 km. A second selection criterion was that related to the population of each village under study. The villages have been divided according to number of inhabitants, into three types of villages: the small villages, medium-scale villages and large villages. The small villages are these with a population varying between 250 and 350 inhabitants, medium-scale villages are these varying between 500 and 750 inhabitants, and finally large villages are composed of 1000–1500 inhabitants. However, according to the nature and capacity of technologies considered in this article, only the demands of small villages will be experimented in this paper. The technical capacities of the selected renewable technologies coupled with the meteorological conditions in the three different regions do not allow the satisfaction of medium-scale and large village requirements. Moreover, the microgrids project aimed to build micro-network, allowing the supply of electricity to remote rural areas, with capacities higher than those selected in this paper. Obviously with higher technical capacities we could satisfy energy demand from all type of villages with various sizes. But in a decentralized–stand-alone option, technologies selected can be quite different to those selected in a micro-network option [39]. Like this paper is dealing with stand-alone option, technologies came up should be socially acceptable and technically feasible. Furthermore, these selected technologies are not unrealistic, because they have been implemented during the PROVEN[9] project, which aimed to reduce poverty level in rural areas of Casamance. Their use has been mastered and they are compatible with local conditions and resources. They have acquired a level of social acceptability, which confers them a fairly wide advantage in terms of dissemination.

Analysis of demand levels is based on the two principal steps. Substitute energy expenses are determined, in the first instance, so as to permit calculation of the level of electricity service that ought to be appropriate for one household. Moreover, like expressed earlier, a contingent assessment was conducted allowing the determination of monthly willingness – to pay by households for electricity services. The combining of these two steps permits a characterization of energy needs of households. Table 6 presents

[9] PROVEN was a project funded by the « Fondation Energie pour le Monde ». Like lot of small-scale projects in Africa, they targeted to promote best practice approaches of off-grid rural electrification using renewable energies in rural Africa.

Table 6
Estimation of electrical energy demand.

Regions	Kaolack	Fatick	Thies	Total
KW/d	7.77	13.05	12.82	33.64

Sources: Microgrids Project Final Report.

the various estimates of demand for these three regions. We note that maximum consumption held in the region of Fatick despite the fact that only seven villages were investigated. The region of Kaolack, where one finds the largest number of villages investigated, presents the lowest levels of consumption.

4. Results

As argued earlier the levelized-electricity-cost (LEC) was chosen as a decision criterion for the choice of a competitive technology among the three technologies pertained. In order to evaluate the levelized-electricity-cost we first determined the quantity of electricity provided. This variable is come up in discounted value.

$$QE_f = \frac{(\text{kwh.produite})_j}{(1+r)^N} \tag{9}$$

QE_f represents the quantity of electricity provided by each type of technology; j the number of technologies employed ($j = 1, 2, 3$); r the discount rate and N the number of years under study.

According to Weisser [26] the levelized-electricity-cost can be obtained while dividing the total cost from equation (1) by the quantity of electricity provided from the preceding equation (9).

$$\text{LEC} = \frac{\text{LCC}}{QE_f} = \frac{\text{LCC}}{\frac{(\text{KWh.produite})_j}{(1+r)^N}} \tag{10}$$

In this article, thirty rural areas situated in three different regions of Senegal (Thies, Kaolack and Fatick) were analyzed. Three types of technologies were considered. A diesel generator with a capacity of 450 W for centralized scenario, a decentralized-renewable option which included both a wind turbine with a capacity of 150 W and a photovoltaic panel with a capacity of 130 Wc. Our methodology inspired of life-cycle analysis provided the levelized-electricity-cost for the different technological options.

However, according to metrological conditions in these selected areas, the levelized-electricity-cost (LEC) of renewable technologies (PV and wind) are identical for two regions included in the paper (Kaolack and Fatick).[10] Instead these regions present the same meteorological conditions. This uniformity at the level of meteorological issue justifies also the energy produced for renewable technologies, using the Weibull function, for the two above-mentioned regions. As a result, in terms of the cost associated with the life-cycle-process, these areas present the same value.

About wind technologies, the competitive LEC corresponds to the unit cost of one KWh produced, not exceeding 7.47 KWh/year for Thies and 7.884 KWh/year for the regions of Kaolack and Fatick. In fact, taking into consideration meteorological conditions, wind production is 7.47 KWh/year for Thies and 7.884 KWh/year for the regions of Kaolack and Fatick. However, as demand (cf. Table 6) is higher than potential wind energy supply, the wind technology doesn't presents viability results in our example, as the LEC is tied to a production level lower than the demand requirement for all three areas. Finally it can be noted, from Table 7, that the diesel technology presents the higher levelized-electricity-cost. As a result, it is not competitive as compared to PV technology. Beyond the operating and maintenance costs, which are quite high, transport and distribution costs of the diesel generator remains very high for a competitiveness of centralized-national network expansion scenario.

Table 7
Levelized-electricity-cost of technologies employed in all three Regions. (F CFA).

	Kaolack	Thies	Fatick
Diesel Group	757.88	570.45	410.98
PV Techno.	102.865	73.4638	102.865
Wind technology	115.813	122.23	115.813

We assume a rate of loss of 15% at the level of electricity distribution.
We also assume that the transport network is made up by an average line of 9 km and a low line of 1 km.

Although few works are available on life-cycle analysis for adoption of renewable technologies in Sahelian countries, our conclusions are similar to those obtained by certain authors in regard to other developing countries. In conducting feasibility analysis for the adoption of renewable technologies in the case of Vietnam, Nguyen [9] has shown the competitiveness of PV technology compared to conventional centralized-national network extension scenario. According to the same author, the competitiveness of the decentralized wind option depends on installation location. In analyzing the economic viability of the autonomous PV system in India, Kolhe et al. [12] conclude that: the PV system is comparable in economic terms to the diesel generator when demand is higher than 58 KWh/day with an equal escompte rate of 10%.

Similarly, Bugaje [11] carried out a feasibility analysis of the adoption of energy technologies in Nigeria. As with the former example, three technological options were considered. The first consisted in performing extension of the electricity grid so as to provide electricity services to remote rural areas. Moreover, the two remaining options (PV and diesel group) guaranteed the supply of energy services via a decentralized autonomous process. His analysis demonstrated the viability of the PV system compared to the two remaining options with a distance of 50 km including all selected villages. Finally, Bhuiyan et al. [10] analyze the feasibility of the adoption of PV technologies in Bangladesh. Using the net present value methodology, their conclusions are identical to that found by all of the above-mentioned authors; the levelized-electricity-cost of PV energy is lower than that related to conventional sources in zones where electrical grid is non-available.

5. Conclusion

According to World Bank [40], 1.6 million people in developing countries have not access to electricity. Anticipating the future, they predicted that a large portion of this population will lack electricity services if the same trends continue as exist now in terms of electricity distribution. While admitting a link between access to energy services and the improvement of living conditions, that means developing countries should wait long time before an improvement of their living conditions. Then one of the principal challenges facing developing countries can be summarized in two points:

- How could they increase electricity access particularly in remote rural areas
- Which electrification programme should they choose

The objective of this article is set within this background. We have attempted to compare two kinds of energy policy in one

[10] In fact these two regions make up part of the region of Saloum, located in the middle- west of the country, are very similar in terms of climatic conditions, in contrast to the Thies region, situated in the northwest of the country.

developing country (Senegal). The policy of autonomous decentralization via adoption of renewable energy technologies, and that of centralization leading to the extension of the electricity distribution network until the non-electrified zones. Three technological options were considered, namely a diesel generator with a capacity of 450 W representing the centralized option, a wind turbine with a capacity of 150 W and a PV module with a capacity of 130 Wc representing the decentralized scenario.

After a life-cycle analysis evaluation, our results show the viability of the decentralized option of PV technology. Moreover, for wind technologies, the viability is compromised when the demand estimated is higher than their maximum capacity offered 7.47 KWh/year for Thies and 7.884 KWh/year for the two regions of Kaolack and Fatick. Our results demonstrated that the decentralized option using PV technology remains currently the most competitive solution for the satisfaction of energy demand in the context of small villages within the microgrids project scheme. This latter aiming to bring energy services to remote rural areas can intended different approaches within which the energy supply can be discriminate according to village sizes. Building a micro-network can be quite important for villages with a high population density located in the selected areas. This conclusion emphasizes what we know earlier, network has to be built in areas with high population density [20].

However, wind technologies may certainly present high viability in zones where wind speed remains fairly high, such as in the north (St. Louis). In this paper the low wind speeds involved the low level of production. The implementation of a geographical information system (GIS) would be a worthwhile initiative to produce a map of the wind speed of the country, allowing researchers to pinpoint zones where wind energy is viable. However it is important to underscore that the results obtained depend heavily on a certain number of economic, technical hypothesis retained in this paper. For examples the rate of loss during electricity distribution, the structure of electricity distribution lines, and effectiveness of technologies utilized, escompte rate, and interest rate.

Beyond these technical and economic hypotheses, two important points have not been addressed in this article. First, we have clearly outlined that, only the demands of small villages have been retained. The capacities of the technologies studied have not allowed to addressing demands for other villages. A pertinent question that we might raise is that how electricity services could be provided to (medium-scale or large) villages displaying a level of demand greater than that of small villages and for which the centralized extension of the network remains economically non viable? Furthermore, it would be worthwhile to analyze how these technologies might be financed? Although these latter remain up to now very costly, despite important advances in R&D that have lower costs considerably. For a country with a limited budget, like Senegal, what might be suitable financing mechanisms for such costly technology? These preceding questions will be explored in the next following papers.

Acknowledgements

This paper is based on my PhD thesis in Energy and Environment Economics at University of Bordeaux under the GRETHA research team. I would like to thank my supervisors Mrs. Sylvie Ferrari (Assistant Professor) and Stéphane Becuwe (Director of research at CNRS) for comments and advices about this paper. I would like also to thank Jean-Jacques Malfait (Assistant Professor) for his reflexions and comments. I would like, also, to thank Kari Burman of the Energy Management and Federal Markets at National Renewable Energy Laboratory (NREL), Colorado U.S, for her second reading. Anonymous referees are also thanked to their comments. Any mistakes are my own.

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