Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension

Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension*

S Szabó[1,3], K Bódis[1], T Huld[1] and M Moner-Girona[2]

[1] European Commission Joint Research Centre, Institute for Energy, Renewable Energy Unit,
2749 via Enrico Fermi, TP450, 21027 Ispra (VA), Italy
[2] UNEP Energy Branch Division of Technology, Industry and Economics, 15 rue de Milan,
F-75441, Paris CEDEX09, France

E-mail: Sandor.Szabo@ec.europa.eu

Abstract

Three rural electrification options are analysed showing the cost optimal conditions for a sustainable energy development applying renewable energy sources in Africa. A spatial electricity cost model has been designed to point out whether diesel generators, photovoltaic systems or extension of the grid are the least-cost option in off-grid areas. The resulting mapping application offers support to decide in which regions the communities could be electrified either within the grid or in an isolated mini-grid. Donor programs and National Rural Electrification Agencies (or equivalent governmental departments) could use this type of delineation for their program boundaries and then could use the local optimization tools adapted to the prevailing parameters.

Keywords: rural electrification, economic analysis, developing countries, geographical information systems

1. Improving geographic information for rural Africa

1.1. Current status of electrification

Compared to the rest of the world, there is a general shortage of energy related information in Africa (on potential of energy sources, actual installed systems and current energy use). This lack of information is even more apparent for renewable energies [1]. It is indeed difficult to compare the potential for the different energy options due to the scattered validated information.

Despite a high total population figure—in Africa it exceeded one billion in 2009—United Nations estimates show that most parts of the African continent are sparsely populated, with almost 60% living in non-urban areas. This fact, coupled with the low per capita energy consumption and the high rate of non-electrified rural areas, creates a good opportunity for a sustainable energy development based on decentralized renewable energy sources (RES). When we combined available grid data with the population density and city layers, they showed that populous cities were already grid connected. For the remaining larger part of rural Africa, there is still not enough information on energy access [1].

From the 1950s onwards, diesel stand alone systems and grid extension have dominated the electrification of rural areas in Africa (with a few exceptions of mini hydro systems like Malawi) [2]. The dominance of these traditional energy systems for isolated areas—that is, a dominant part of today's installed capacity—is being challenged by solar, wind, micro

---

hydro and hybrid systems that can establish long-term plans of clean energy supply options for the electrification of areas with non-existing grid. Some argue that a shift in technology is the only way to create a sustainable energy market in Africa.

1.2. Key challenges

In Sub-Saharan Africa, where in 2008 more than 60% of the population was not connected to the grid, providing electricity access is a primary task [3–5]. Under certain circumstances, grid extension may prove to be the most economic solution. However, in other cases, a mini-grid or stand alone system could be the least-cost option. The underdevelopment of the grid infrastructure also means that mini-grids based on local renewable resources may prove to be more affordable in specific regions than grid extension. This is due to the excessive cost of grid building if the expected electricity load is relatively low. It is also relevant that some of the renewable energy technologies are much more productive in Africa than in regions where renewable energies are highly present in the national energy mix (e.g. the same photovoltaic panel can produce twice as much electricity in Africa as in Central Europe on average [6]). The fact that the transport cost of diesel is higher in remote areas with a sparsely developed road structure [7] helps to increase the competitiveness of diesel–renewable hybrid systems with a higher share of renewable energy technologies.

1.3. Options and opportunities

Renewable sources of energy, hydro, solar, biomass and wind in particular, can meet Africa's energy demands several times over [3]. The access of reliable information on renewable energy resources and their performance potential can stimulate renewable energy deployment [3] and help us to understand the potential of renewable energy options in off-grid areas in Africa.

There are two prevailing misconceptions over renewable energy technologies not only in developing countries but worldwide. First, renewable energies are usually seen as new competitors for conventional energies and electricity grid extension. Second, renewable energy technologies, mainly photovoltaic systems, are typically considered the most expensive technologies and therefore unaffordable for the rural areas of the developing world [8, 9]. These views do not take into account that in some areas of the developing world the operation and maintenance cost of the major rival technologies exceed the lifetime cost of photovoltaic (PV) electricity [10]. The renewable energy (RE) technologies should be seen as complementary options in places or situations where conventional energy is unavailable or the grid cannot be economically extended. RE technologies may become viable options in larger areas as their cost decreases and fuel prices get more volatile [11].

There is a widespread argument that the high up-front cost of most RE technologies renders them unaffordable to most rural inhabitants. Without a well-designed financial and support mechanism none of the rural electrification options will prosper in the Sub-Saharan rural regions. The ability

to pay for energy services of the rural population[4] has to be strengthened by providing initial support or by a continuous service support [9, 12]. Well-designed financial mechanisms that support the energy services (providing subsidy only if the system delivers the energy) to smooth out the cost burden for the whole lifetime play an important role in expanding RE technology in rural areas. As many of the renewable energy projects supported by initial investment subsidies have failed shortly after their start due to negligence, poor operation or misuse [9], it is critical for a successful sustainable energy plan to prioritize the support to the operation of the systems (generation of electricity) [13, 14].

The analysis presented in this paper is the first case of a series of analyses to identify the potential of RE options in rural electrification. In this first study PV technology is compared to the extension of grid and diesel generator potential options for rural electrification technologies. The present study is planned to be extended by incorporating other renewable energy options (biomass, hydro and wind) in the analysis.

1.4. Why spatial mapping?

The use of innovative research methodologies such as application of GIS and remote sensing technologies, spatial evaluation and interpolation of statistical and economic data will support and facilitate strategic energy decisions.

Spatial analysis and mapping can answer some of the key questions based on the limited information available using the global and regional databases derived by functions of remote sensing, GIS modelling, satellite image processing and processing of long-term meteorological data.

These results of the paper should be seen as a status report that gives a mid-2010 snapshot on the comparative cost of the selected technologies. Geo-referenced data have been uploaded onto the www.euei.net website in order to enable interested readers to carry out their own scenario using different assumptions.

2. Economic and geographical potential of different technologies for rural electrification

Through a combination of renewable energy resource information[5], geographical information, current fuel prices and travel distances, it becomes possible to map the economical potential of different technology options for rural electrification at the continental level.

Thereby an electricity generation cost-comparison can give some guidance about the economical viability of the different options. Our analysis compares several electrification technologies using a simple cash flow model. This model shows in a geographically explicit way how much the electricity would cost for each mini-grid option at each

---

[4] Finding the least-cost option for rural electrification in Africa is more important than in urban Africa or in the developed world. The population of those areas can hardly afford to pay more for energy services when even cooking fuel is expensive or scarce.

[5] The analysis presented in this paper had to rely on approximated input data as there is a huge uncertainty and general lack of reliable data on renewable energy in Africa [7].

location. The resulting spatial analysis offers support to key stakeholders, such as policy-makers, communities, NGOs and governmental agencies, to determine the most appropriate technologies for exploiting the indigenous resources that meet the specific energy demands.

Three technologies have been chosen to calculate their economical viability at a continental level as potential options for rural electrification: (i) photovoltaic systems, (ii) diesel generators and (iii) extension of the already existing electricity grid. The calculation attempts to find a comparable unit cost of output (Eurocent kWh^{-1}), focusing on the elements causing differences (such as fuel price, PV modules, with battery or generator) rather than the elements that are similar across the technology choices (distribution, metering, etc). While these last elements contribute to the overall cost of electrification, they are basically the same for all the options. The economic analysis compares the levelized cost of electricity generation for the three options. The levelized cost of electricity [11] allows for the quantification of the unitary cost of the electricity generated during the lifetime of the system; thus a direct comparison between the costs of different technologies becomes possible.

The relevant literature also confirms that PV electricity has the potential to be competitive with other electricity options in rural areas for many countries in Africa [15, 16] and Asia [17]. Additionally, the methodology may incorporate other renewable energy options (wind [18], mini hydro, small biogas) to extend the analysis as soon as reliable data are gathered.

2.1. Mapping the off-grid PV electricity production costs

PV electricity production depends primarily on the amount of solar radiation available. For grid-connected systems, the energy output can be approximated, being proportional to the total solar irradiation impinging on the PV modules. For off-grid systems energy output fundamentally depends on the installed capacity size of the RE resource conversion technology (i.e. PV, small hydro, wind, etc). The energy output will also depend on the size of the battery storage and on the consumption patterns. For the latter, it becomes useful to perform a simulation based on detailed time series of satellite solar irradiation data. This calculation was made using the photovoltaic geographic information system (PVGIS) database [6], which in turn is based on solar radiation data from HelioClim-1 [19]. The database contains daily global horizontal irradiation values for the period 1985–2004, with a spatial resolution of 15′ (∼30 km at the equator).

The levelized cost of electricity [11] (kWh^{-1}) was[6] calculated, assuming a certain daily shape of the electricity load pattern. The algorithm used in the calculations takes into account the daily PVGIS solar irradiation data (from 2002 to 2004), an optimized value of the PV array size and the battery size, and the calculation of the system performance ratio[7]. The assumptions used for the analysis are as follows.

---

[6] Conversion used at 2010 1.4 US$ = 1 €.

[7] The performance ratio is the ratio of the actual energy production to the energy production that would be obtained if the PV modules always performed at the nominal efficiency and there were zero losses in the other components of the system (such as inverters).
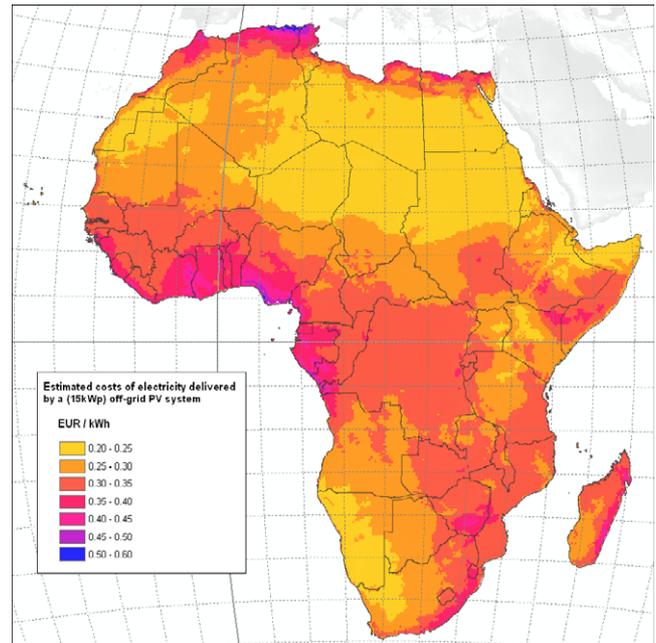

Figure 1. Estimated costs of electricity (€ kWh^{-1}) delivered by a (15 kWp) off-grid PV system. Source data based on [6].

- The size of the system is minimized for a given electricity consumption to guarantee a certain availability of power; i.e. in this analysis, the system was designed not to run out of energy on more than 5% of days.
- The daily energy consumption pattern is such that 1/3 of the energy is consumed during daytime and 2/3 during evening and night.
- The PV array size is calculated for a nominal desired daily consumption, with both PV array size and battery size varying geographically so as to satisfy this consumption.
- The performance ratio is assumed to be 70%, a little lower than typical grid-connected systems, due to the additional losses in the batteries.
- The battery discharge depth is 70%; this assumes specialized solar system batteries (AGM).
- PV lifetime is 20 years, battery lifetime is 5 years.
- The price of the PV modules is taken as 2500 €/kW$_p$ + 40% of this cost for installation and balance-of-system (BOS) components. Battery prices are estimated as 1.5 € A^{-1} h^{-1} for 12 V AGM-type lead-acid batteries. The assumed operation and maintenance costs are assumed to be 2.5% of the price of the PV and BOS for each year of operation.
- Cash flow: 5% discount factor.

The electricity production cost calculated for local mini-grid PV systems in Africa (figure 1) ranges from 0.2 up to 0.55 € kWh^{-1}. Large geographical differences can be observed: some of the most favourable regions with low costs have very low population density (e.g. Sahara with 0–15 persons km^{-2}), while other regions are relatively densely populated [6] (e.g. Tanzania, South Africa with 30–100 persons km^{-2}).

2.2. Mapping the off-grid diesel generator electricity costs

Diesel generators have been the traditional solution to decentralized electrification needs. For off-grid applications, they present lower up-front capital costs per kilowatt installed; however, the dramatic increase of fuel costs in recent years and the cost of transport to remote areas greatly diminish the low capital cost advantage of the diesel option.

The analysis quantifies the levelized cost of electricity in order to attain a direct comparison between the costs for diesel-based electricity and the different technologies during the lifetime of the systems. For diesel gensets, fuel consumption is the major portion of the levelized costs, as opposed to PV systems, where the up-front costs are dominant. Specific consumption varies, but a modern diesel genset of a similar size will consume between 0.28 and 0.4 l of fuel per kWh. This gives a fuel cost of 11 c€–16 c€ kWh^{-1} (using diesel price at 40 c€ l^{-1}), although the fuel cost would double considering the prevailing oil prices. Lifetime engine maintenance is about 1 c€ kWh^{-1}. Information regarding the travel time to major cities [7] was used as a proxy to establish the diesel price for various locations differentiated from the countries' average. Thus, the farthest villages would probably be the most favoured for renewable energy installations. The database of international diesel prices for 2008 in African countries [20] was used (see figure 5): depending on national taxes/subsidies, national average values range between 8 c€ l^{-1} (Libya) and 113 c€ l^{-1} (Malawi).

The other decisive component we had to take into account in the cost calculation of diesel electricity is closely related to the haulage costs. In Africa the transport infrastructure is underdeveloped which has a severe consequence: the transport costs faced by African countries are almost twice as high as the world average [21].

A global map of accessibility developed by the JRC [7] formed this second component for the genset electricity cost calculations. The accessibility is defined as the travel time to a location of interest using land- (road/off road) or water- (navigable river, lake and ocean) based travel. The accessibility is computed using a cost–distance algorithm which calculates the 'cost' (time) of travelling between two locations on a regular raster grid.

To estimate the location specific operating costs for diesel gensets, the country-based diesel prices have been combined with the travel time data (derived from the accessibility map) integrating the transport costs[8]. The computations were performed in three main steps.

Step 1—Transport costs (€), P_t, for diesel are estimated using the following equation:

$$P_t = 2P_d ct/V$$

where P_d (€) is the national market price for diesel, c (l h^{-1}) is the diesel consumption per hour, t (h) is the transport time, and V (l) is the volume of diesel transported.

[8] As an example, for a small van of 300 l, the price is calculated as 0.01 € kWh^{-1} one way, with 12 l consumption in 1 h (it can cover different distances during the same period assuming approximately the same consumption per hour depending on the roughness of the surface).
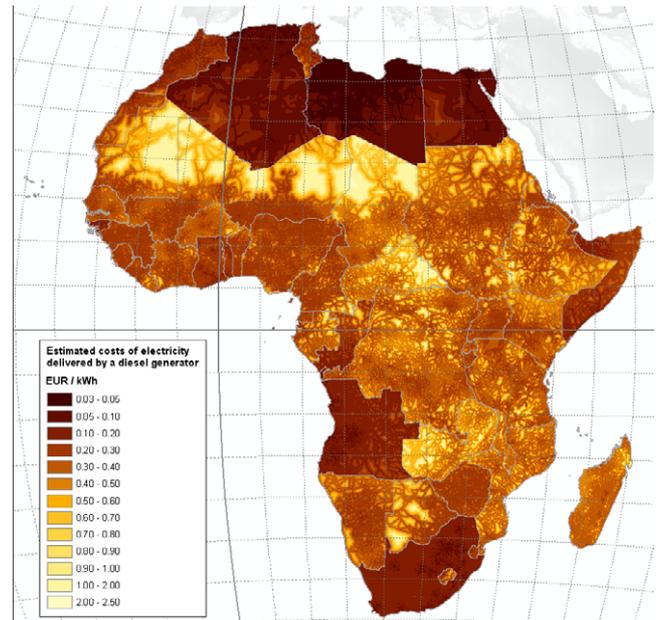

Figure 2. Estimated costs of electricity (€ kWh^{-1}) delivered by a diesel generator using the diesel price for each country and taking into account the cost of diesel transportation.

The factor 2 is due to the fact that the vehicle has to drive back to the origin point (assuming dedicated transport for the fuel in the generators). For the calculations, we assumed average values of $V = 300$ l and $c = 12$ l h^{-1}.

Step 2—Production cost for electricity (€l kWh^{-1}) is calculated as

$$P_p = (P_d + P_t)\eta$$

where P_d is the national market price for diesel, η is the conversion efficiency of the generator, with a value of $\eta = 0.286$ l kWh^{-1} [22].

Step 3—The final costs of electricity consist of the production costs and the costs of labour, maintenance and amortization. For this, 1 c€ kWh^{-1} unit costs are calculated using the commercial price and the average lifetime for the 4–15 kW diesel generators.

The resulting map (figure 2) shows the spatial variance of the electricity costs per kWh delivered by a diesel generator. The electricity cost ranges between 0.30 € (dark brown) and 2.4 € (light yellow).

2.3. Boundaries of grid extension: the off-grid potential for rural electrification in Sub-Saharan Africa

One of the main concerns for rural electrification planning agencies and policy-makers is how and when off-grid investments should complement grid-extension projects. A spatial-analysis approach that defines the boundaries of the least-cost electrification option can support the planning to meet the national and rural access targets of the various governments.

In a challenging and extensive data mining exercise, the available, geographically explicit information on the existing
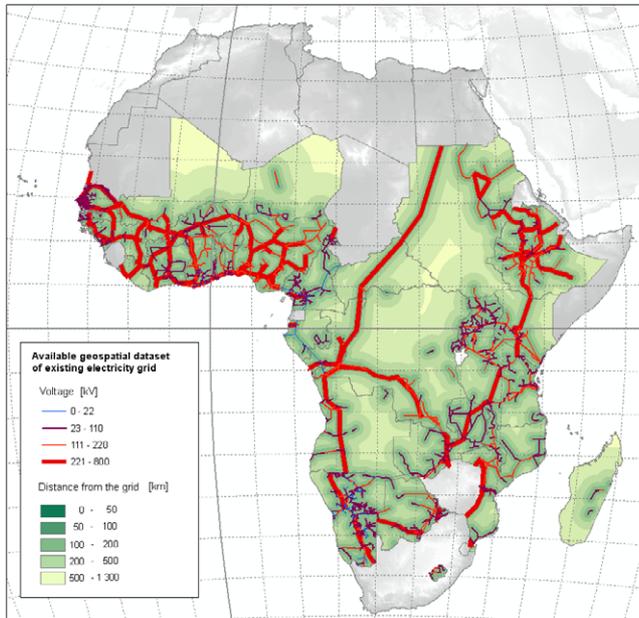
Figure 3. Available geospatial dataset of existing electricity grid in Sub-Saharan Africa and distance from the grid.
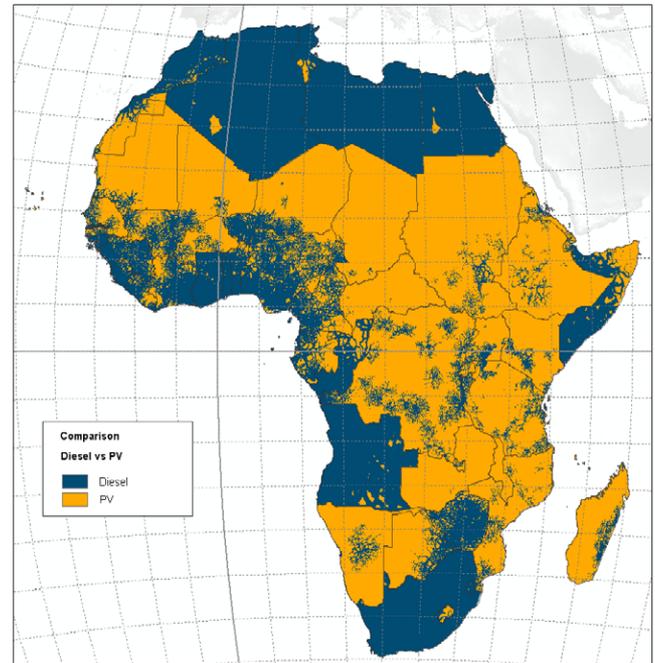

Figure 4. Off-grid options: economic comparison of diesel versus PV.

electricity lines for transmission and distribution in Sub-Saharan Africa was collected (figure 3). The information was gathered from freely available web sources [23], from databases of regional institutes or from individual experts [24, 25]. However, after the data integration, the digital dataset of the electricity grid is still not complete, covering unevenly 33 of the 48 countries. The costs of electricity, when considering grid extension, are determined by the load density (measured in households km^{-2}), the number of households connected and line length among others [17, 26]. For most of the Sub-Saharan African rural areas, this information is still available unevenly.

When planning for network extension, in addition to the geographical location of the grid, it should be taken into account how sensitive the market prices of grid electricity are to global fossil fuel prices. As an example, a recent analysis shows that the levelized cost of electricity for the industrial sector has gone up from 8.00 to 15.00 Kenyan Shilling kWh^{-1} on average [27] (approximately from 0.08 to 0.15 € kWh^{-1}), which shows that the current rises of fossil fuel prices accentuate its affordability limitations. Steep price increases can be observed in many countries of the continent due to the oil price increase and the removal of existing energy subsidies. Nigeria and Egypt have started to remove oil subsidies. The electricity price has been raised by 25% in South Africa and the National Energy Regulator plans to increase it two times at the same rate [4]. When planning for grid extensions in cities where the grid already exists, the cost of a connection may start at €140, while in areas where there is no grid, construction and connection costs can exceed €1050 [28] and the extension cost km^{-1} can be ten times these values [16, 29].

Regarding the current situation of the electricity grid in the 48 Sub-Saharan African countries, the International Monetary Fund reported that 30 countries suffered 'acute' energy shortages in recent years [30]. Regardless of the establishment of new energy support policies to keep electricity prices affordable to the low income population, still 550 million people—almost 75% of the population of Sub-Saharan Africa—remain without access to electricity[9] [4].

3. Mapping decentralized options for rural electrification: diesel versus solar

The broad variety of energy resources and existing energy infrastructure in the African regions require quite a wide range of policy approaches and rural electrification options to meet the different conditions. A good example of this variety is West Africa. Many countries of this region have already developed extensive grid infrastructures which may render rural electrification as a complementary task in policies concerning the extension of energy access. In contrast, in many of the other Sub-Saharan countries, where the grid is in an embryonic phase and so the dominant part of the population is not connected, off-grid solutions can prove to be more important than grid extension.

The following map (figure 4) illustrates an economic comparison of the two off-grid options (diesel or PV): the most economically viable option is geographically identified. The colour blue shows the location where diesel is more economically advantageous, while the colour orange indicates where PV options are cheaper.

It is interesting to see the effect of the different policies prevailing in the various African countries on the fuel taxation/fuel subsidies (see figure 5). The diesel versus PV

---

[9] In 2004 in East Africa, fewer than 3% of rural people and 32% of urban residents were connected to their national grids.
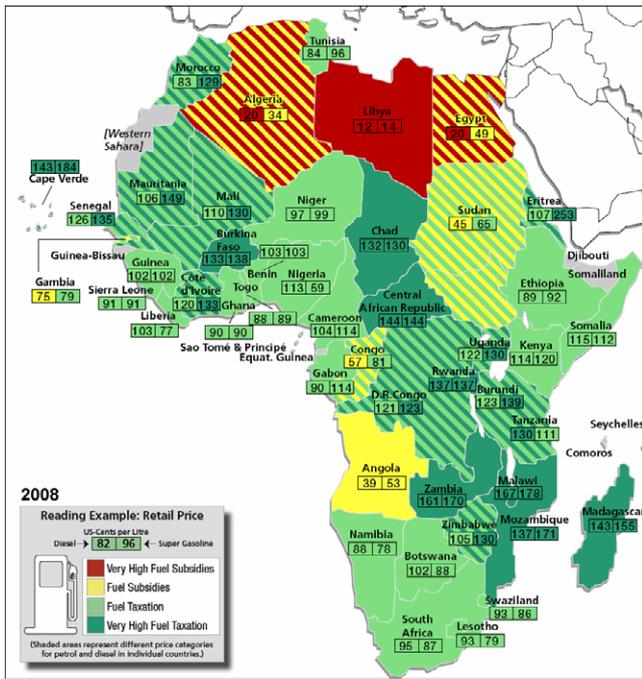
Figure 5. Retail fuel prices in Africa as of November 2008 (in c\$ l^{-1}). At the time of writing, the spot-market price of crude oil is about 53 c\$ l^{-1} = 38 c€ l^{-1} [20].

map reveals that the effects of fuel subsidies play a crucial role: they change the picture of the most economically viable option dramatically (note the huge colour variation in neighbouring countries).

The economic analysis was extended to include the grid-extension option at continental level.

This visual analysis identifies the areas where the decentralized options (diesel or PV) deliver electricity below 25 c€ kWh^{-1} (figure 6(a)) and 30 c€ kWh^{-1} (figure 6(b)). The green areas in figures 6(a) and (b) represent the territory where the electricity delivered by the two technologies is higher than the electricity cost threshold (25 or 30 c€ kWh^{-1} respectively). The yellow areas indicate the regions where PV is the most competitive option, while the dark brown ones show where diesel gensets are the competitive options. The red regions are those where both rural electrification options are cheaper than the electricity cost threshold (25 or 30 c€ kWh^{-1}).

The orange regions show where the extension of the grid is the most economical option, while, in contrast, the different blue coloured parts of the buffer zone indicate the regions where, depending on grid-extension cost, the other rural electrification options might be viable despite the closeness of the existing grid. The green areas show where none of the assessed options can deliver electricity with lower cost than the threshold. In these regions, other rural energy service options might improve the energy access for the rural population, making it more important to extend the economical analysis to other options (see introduction, e.g. biomass or hydro).

The present analysis uses a conservative estimation[10] (significant distance to the existing grid) to delineate where the

---

[10] To attain a more adjusted and realistic buffer zone, the analysis needs reliable detailed population density, settlement and consumption data.
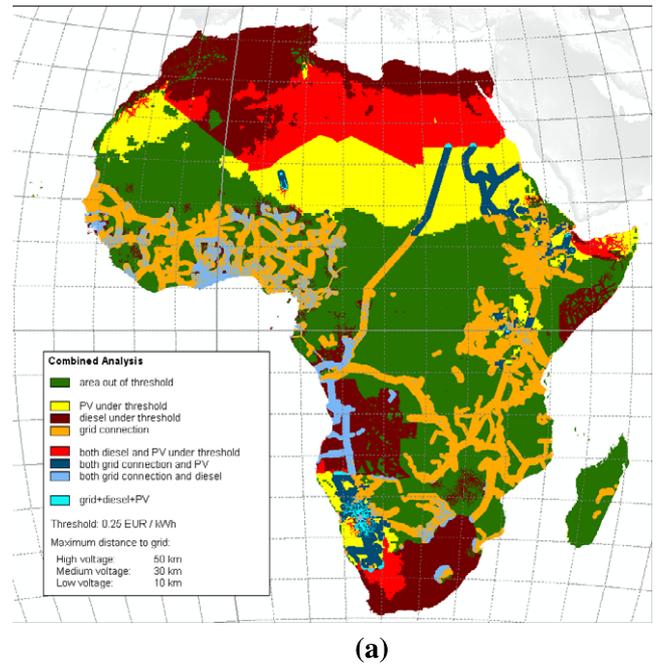
(a)
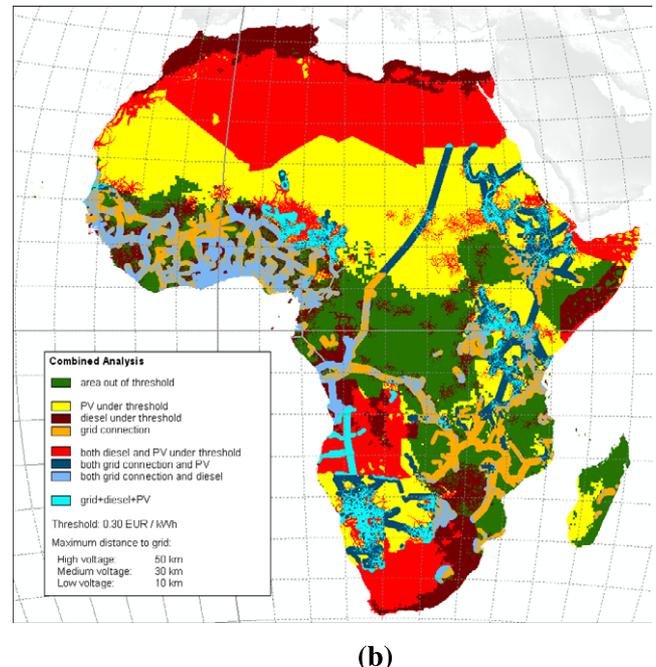
(b)

Figure 6. (a) Geographical distribution of technologies with electricity costs lower than 25 c€ kWh^{-1} and conservative assumption on grid extension. (b) Geographical distribution of technologies with electricity costs lower than 30 c€ kWh^{-1} and conservative assumption on grid extension.

grid is the economically prevalent option denoted by the orange and blue belts in figures 6(a)/(b). The boundaries for grid extension delineate the distance where a potential extension of the grid would be reasonable, as exact calculations of the levelized cost of electricity would depend on the particular conditions of each geographical area. The boundaries estimated for high, medium and low-voltage lines are 50, 30 and 10 km respectively. For low-voltage distribution lines,

Table 1. Potential rural population served by different energy service options, considering a higher and a lower ability to pay, ATP (0.25 and 0.30 € kWh^{-1}).

Energy service options	Potential population (millions) served by the energy service cheaper than the ATP		Per cent change when consumers can pay 0.05 € kWh^{-1} more for energy service (%)
Ability to pay =	0.25 € kWh^{-1}	0.30 € kWh^{-1}	
All energy service costs higher than ATP	179.6	91.3	−50
PV costs under ATP	19.8	55.4	180
Diesel costs under ATP	194.7	192.4	−1
Both diesel and PV costs under ATP	10.9	65.9	500
Grid connection costs under ATP	320.6	115.8	−64
Both grid connection and PV costs under ATP	23.3	62.2	170
Both grid connection and diesel costs under ATP	118.2	191.9	63
Three energy option costs (grid, diesel and PV) under ATP	1.5	93.8	6153

the boundaries are the technical limit distances, above which the transmission cost becomes overwhelming (even in highly populated rural sites) [17]. High-voltage transmission lines extended beyond the boundary limits can be economically favourable only if a large number of end-use consumers with relatively high load are connected (higher costs can be shared among more consumers). So the boundaries are multiplied for higher-voltage lines, keeping in mind that this distance is certainly lower in low population density and low consumption areas.

The model used could be applied to local country-specific situations where such detailed data are available. To compare the grid levelized cost of electricity (€ kWh^{-1}) with the other options, it would be necessary to make the calculations with real load data. Instead, the economical analysis was made by comparing how territorial distribution changes the prevalent least-cost option following a slight shift in the threshold of the ability to pay for electricity (from 0.25 to 0.30 € kWh^{-1}). The sensitivity is clearly shown by the change between the two distribution maps (figures 6(a) and (b)). As is visible from the maps, the area where PV can be the cheaper option becomes much larger when the threshold is increased by 5 c€ kWh^{-1}.

4. Discussion and conclusions

The next summarizing table gives a good insight into the potential of PV and diesel decentralized rural electrification options. Clearly, only 5 c€ difference in ability to pay would significantly expand the proportion of regions where PV can play the central role in rural electrification. In addition, the population benefiting from these decentralized systems would also increase noticeably. It highlights the importance of any financial mechanism that could reduce the burden of paying for the improved energy services on the rural population. On the other hand, the rapid change in the potential area shows how many potential consumers can be gained with only small cost change (see the final conclusion). PV shows much larger dynamism than the diesel option in this respect.

The different electrification options have to be studied simultaneously. For example the diesel option decreases slightly with the higher ability to pay because the combined options (grid + diesel, all three options) increase a great deal.

Over large regions, neither diesel genset nor PV (shown by green colour on the maps, figures 6(a) and (b)) offers affordable solutions for rural areas (considered <0.30 € kWh^{-1}). These are the places where the various biomass production, micro hydro, wind and efficient fuel use options have to be analysed in order to determine whether these can serve as potentially viable answers to the challenges of rural energy services in Africa. From the dynamics presented in table 1, it is visible that the 25 and 30 c€ threshold is the range where the PV option becomes the most attractive rural electrification technology. As grid extension delivers low-cost options only if a high number of consumers can be connected in a small area, sparsely populated regions can become target areas for PV- or hybrid-based rural electrification development with a proper financial scheme put in place.

The analysis also revealed how sensitive the rural electrification costs are to diesel prices. As certain African governments have decided to subsidize diesel due to other social factors, it could also be considered to support PV (for example in the form of feed-in-tariff) in order not to distort the emerging rural electrification market.

Finding out the level that is affordable for the population is therefore of key importance. 80% of the population lives on 2.5 \$ day^{-1} or less in Sub-Saharan Africa [4]. The typical household consumption is 1–3 kWh day^{-1} for users already connected [16]. Even if we consider mini-grid options where more families use the grid, the proportion of their income that would be spent on energy would constitute a much higher proportion than in most of the world. However, in some cases the inhabitants of rural areas already pay much higher amounts (e.g. 50 c€) [14, 31] for diesel electricity; therefore, the willingness and ability to pay for energy services is still an important factor to be determined. Consequently, financial mechanisms to share and flatten the burden of mini-grid investment through the lifetime of the system play a vital role [13, 32].

Taking the above described information and analyses into account and using a combination of already available optimization tools (renewable energy datasets, empirical and analytical resource mapping methods, satellite and terrestrial measurements, and numerical models), it is possible to design

the optimal generation scheme for small off-grid systems. Even if in some African countries a policy and legislative framework for RE has already been established, there is still a lot to do in the arena of policy decision-makers and other high-level stakeholders. This letter provides a basis at continental level for determining the least-cost electrification option for off-grid areas with attractive renewable energy resource potential. However, the model would only be applicable in local country-specific situations when detailed data become available. The strategic directions for further research and policy discussion can be summarized as follows.

- Collection of the regional and national master plans for grid extension in order to delineate more accurately the population that is going to be served by the grid.

- Socio-economic data integration. In this respect, collection of systematic information on the ability and willingness to pay for improved energy services in the different countries is the primary task, complementing social data (settlement size, energy use profiles) with population density distribution.

- Complementing the data collection on the potential load profile/consumption. A collaboration between the JRC and a network of African research centres [25] aims at the collection of data on public consumption centres (hospitals, schools, municipal centres). As they are operated by public institutions, it is easier to collect data on their location and size [24], and their load profile can be more accurately estimated.

- The analysis shows where the solar renewable option may be the most attractive in comparison to diesel or grid extension. Subsequent analyses should explore the other existing RES options in the delineated areas where PV and grid connection are not the prevalent options (in green).

From the rapid increase of the area where the PV mini-grid option is estimated to be the cheapest option (see the difference between the 25 and 30 c€ kWh^{-1} threshold maps, figures 6(a) and (b)), the final conclusion of the analysis can be formulated as follows.

For decentralized options, PV electricity is at the margin to become competitive with diesel and also with grid electricity in large remote areas where the extension costs would increase the electricity price by around 10–15 c€ kWh^{-1}. It is hardly possible to collect comparable electricity prices for grid electricity as there are so many different subsidies and rates (for most of the countries for which there is information, it is around 12–18 c€ kWh^{-1}). With RES incentives of 15 c€ kWh^{-1}, a feed-in-tariff specifically designed for mini-grids [32], PV electricity would reach grid parity. That would mean that PV could become an economically feasible option even for the rest of the 500 million rural population who live within the 100 km boundaries of the existing grid. Therefore, to result in a long-term sustainable energy supply and to decrease the dependence on oil prices, a well-designed financial support scheme, combined with the relevant international aid programs, will play a key role.

References

[1] REN-21 (http://www.ren21.net)
[2] Core International Inc. 2003 Issues and options for rural electrification in southern Africa power pool member countries *Submitted to Energy and Environment Training Program Global Bureau and The US Agency for International Development* (http://pdf.usaid.gov/pdf_docs/PNADD466.pdf)
[3] SWERA: Solar and Wind Energy Resource Assessment (http://swera.unep.net/)
[4] IEA 2009 *World Energy Outlook 2009* (Paris: IEA)
[5] Karekezi S and Kithyoma W 2004 *AFREPREN: Improving Access of Modern Energy Use in Rural Africa* (Nairobi: African Renewable Energy Policy Network)
[6] Huld T, Šúri M, Dunlop E, Albuisson M and Wald L 2005 Integration of HelioClim-1 database into PVGIS to estimate solar electricity potential in Africa *PVGIS: Proc. 20th European Photovoltaic Solar Energy Conf. and Exhibition (Barcelona, June 2005)* (http://re.jrc.ec.europa.eu/pvgis)
[7] Nelson A 2008 Estimated travel time to the nearest city of 50,000 or more people in year 2000 *Global Environment Monitoring Unit—Joint Research Centre of the European Commission (Ispra, Italy)* (http://bioval.jrc.ec.europa.eu/products/gam)
[8] Kanagawa M and Nakata T 2008 Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries *Energy Policy* **36** 2016–202
[9] Lemaire X 2009 Fee-for-service companies for rural electrification with photovoltaic systems: the case of Zambia *Energy Sustain. Develop.* **13** 18–23
[10] Munoz J, Navarte L and Lorenzo E 2007 Experience with PV–diesel hybrid village power systems in southern Morocco *Prog. Photovolt. Res. Appl.* **15** 529–39
[11] Szabó S, Jäger-Waldau A and Szabó L 2010 Risk adjusted financial costs of photovoltaics *Energy Policy* **38** 3807–19
[12] Hamilton K 2010 Scaling up Renewable Energy in Developing Countries: Finance and Investment Perspectives *Chatham House Energy, Environment and Resource Governance Programme Paper 02/10*
[13] 2010 Deutsche Bank Global Energy Transfer Fit for Developing Countries
[14] Solano-Peralta M, Moner-Girona M, van Sark W G J H M and Vallvè X 2009 'Tropicalisation' of feed-in tariffs: a custom-made support scheme for hybrid PV/diesel systems in isolated regions *Renew. Sustain. Energy Rev.* **13** 2279–94
[15] Broesamle H, Mannstein H, Schillings C and Trieb F 2001 Assessment of solar electricity potentials in North Africa based on satellite data and a geographic information system *Sol. Energy* **70** 1–12
[16] 2011 Alliance for Rural Electrification—USAID: Hybrid Mini Grids for Rural Electrification: Lessons Learned
[17] Nguyen K Q 2007 Alternatives to grid extension for rural electrification: decentralized renewable energy technologies in Vietnam *Energy Policy* **35** 2579–89
[18] Wisse J A and Stigter K 2007 Wind engineering in Africa *J. Wind Eng. Indust. Aerodyn.* **95** 908–27
[19] Rigollier C, Lefévre M and Wald L 2004 The method Heliosat-2 for deriving shortwave solar radiation from satellite images *Sol. Energy* **77** 159–69
[20] Ebert S, Metschies D G P, Schmid D and Wagner A 2009 International Fuel Prices 2009 *Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH* (Eschborn: Federal Ministry for Economic Cooperation and Development (BMZ))
[21] United Nations University 2007 The Significance of Transport Costs in Africa *Policy Brief n.5* (http://archive.unu.edu/publications/briefs/policy-briefs/2007/pb05-07.pdf)
[22] Fuel consumption rate at rated capacity (www.freepatentsonline.com)

[23] AICD 2009 Africa Infrastructure Country Diagnostic (AICD)
[24] Kaijuka E 2007 GIS and rural electricity planning in Uganda *J. Clean. Prod.* **15** 203–17
[25] Szabó S, Bódis K, Girbau-García Z, Huld T, Moner-Girona M and Pinedo Pascua I 2010 Building the African renewable energy platform integrating support tools for a sustainable energy development in Africa *Proc. 25th European Photovoltaic Solar Energy Conf. and Exhibition* pp 5256–62
[26] Parshall L, Pillai D, Mohan S, Sanoh A and Modi V 2009 National electricity planning in settings with low pre-existing grid coverage: development of a spatial model and case study of Kenya *Energy Policy* **37** 2395–410
[27] API/Source. East African Business Week (Kampala)

[28] Kimani M 2008 Electricity: Keeping the lights on in Africa, African news and analysis from the United Nations (http://www.un.org/ecosocdev/geninfo/afrec/newrels/electricity-2008.html)
[29] UNDP-ESMAP 2000 Reducing the Cost of Grid Extension for Rural Electrification
[30] IMF: Regional Economic Outlook: Sub-Saharan Africa, April 2008
[31] Chaurey A and Kandpal T C 2010 Assessment and evaluation of PV based decentralized rural electrification: an overview renewable and sustainable *Energy Rev.* **14** 2266–78
[32] Moner-Girona M 2009 A new tailored scheme for the support for renewable energies in developing countries *Energy Policy* **37** 2037–41