Universal access to electricity in Burkina Faso: scaling-up renewable energy technologies

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Universal access to electricity in Burkina Faso: scaling-up renewable energy technologies

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Abstract

This paper describes the status quo of the power sector in Burkina Faso, its limitations, and develops a new methodology that through spatial analysis processes with the aim to provide a possible pathway for universal electricity access. Following the SE4All initiative approach, it recommends the more extensive use of distributed renewable energy systems to increase access to electricity on an accelerated timeline. Less than 5% of the rural population in Burkina Faso have currently access to electricity and supply is lacking at many social structures such as schools and hospitals. Energy access achievements in Burkina Faso are still very modest. According to the latest SE4All Global Tracking Framework (2015), the access to electricity annual growth rate in Burkina Faso from 2010 to 2012 is 0%. The rural electrification strategy for Burkina Faso is scattered in several electricity sector development policies: there is a need of defining a concrete action plan. Planning and coordination between grid extension and the off-grid electrification programme is essential to reach a long-term sustainable energy model and prevent high avoidable infrastructure investments. This paper goes into details on the methodology and findings of the developed Geographic Information Systems tool. The aim of the dynamic planning tool is to provide support to the national government and development partners to define an alternative electrification plan. Burkina Faso proves to be paradigm case for the methodology as its national policy for electrification is still dominated by grid extension and the government subsidising fossil fuel electricity production. However, the results of our analysis suggest that the current grid extension is becoming inefficient and unsustainable in order to reach the national energy access targets. The results also suggest that Burkina Faso's rural electrification strategy should be driven local renewable resources to power distributed mini-grids. We find that this approach would connect more people to power more quickly, and would reduce fossil fuel use that would otherwise be necessary for grid extension options.

1. Energy background at country level

1.1. Present electricity mix

The electricity production of Burkina Faso mainly relies on thermal-fossil fuel (about 70% of the total power generation capacity in the country) and hydropower [1]. The electricity production is based on 28 fossil fuel power stations and 4 hydropower stations. According to the national electricity company (SONABEL), the installed capacity in 2013 was 247 MW, with 215 MW supplied by thermal power [2]. Due to high production costs, fluctuating oil prices and a steadily increasing demand for electricity (see figure 1 and figure 2), Burkina Faso imports electricity (up to 20%) from its neighbours Ghana, Togo and Côte d'Ivoire. In rural areas of Burkina Faso, the main energy source is the utilisation of traditional biomass (i.e. fuelwood, charcoal, agricultural residues, and animal dung) [3, 4].

1.2. An alternative to the present energy mix

To ensure a substantial increase in the country's power supply that meets the fast-growing electricity demand and reduce the country's dependence on imported

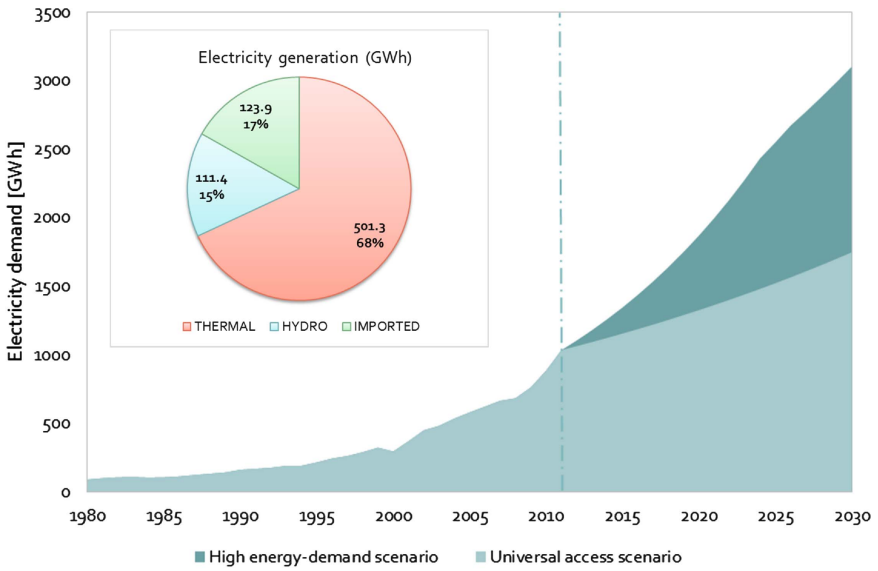


Figure 1. Electricity generation and projected electricity demand. Source: Joint Research Centre (JRC) compiled with data from EIA [5], United Nations, Department of Economic and Social Affairs [6] and World Bank's Development Indicator data [7].

fossil fuels for electricity generation, Burkina Faso may seriously consider an alternative energy mix [8]. The Department of Energy plans to establish the institutional and regulatory framework for the creation of a national renewable energy agency and to implement incentive mechanisms for a greater use of endogenous renewable energy resources [9–11].

Hydropower generation has limited potential mainly due to irregular and unfavourable hydro-meteorological conditions. Hydropower provides 10% of the total, with two hydropower plants of 22 MW and one small-scale of 3 MW, with an average production of 80 GWh (60–130 GWh yr^{-1} depending on rainfall).

In spite of the country's high solar energy potential [12], the installed photovoltaic (PV) capacity in 2014 was just around 400 kWp; 342 kWp on Solar Home Systems and three hybrid PV-diesel mini-grid, each with an installed capacity of 15 kWp [13]. In 2014, solar energy represented 0.1% of the total national energy consumption.

Wind energy is the least favoured form of renewable energy for Burkina Faso, given the low wind speeds [14].

1.3. Electricity strategy at national level

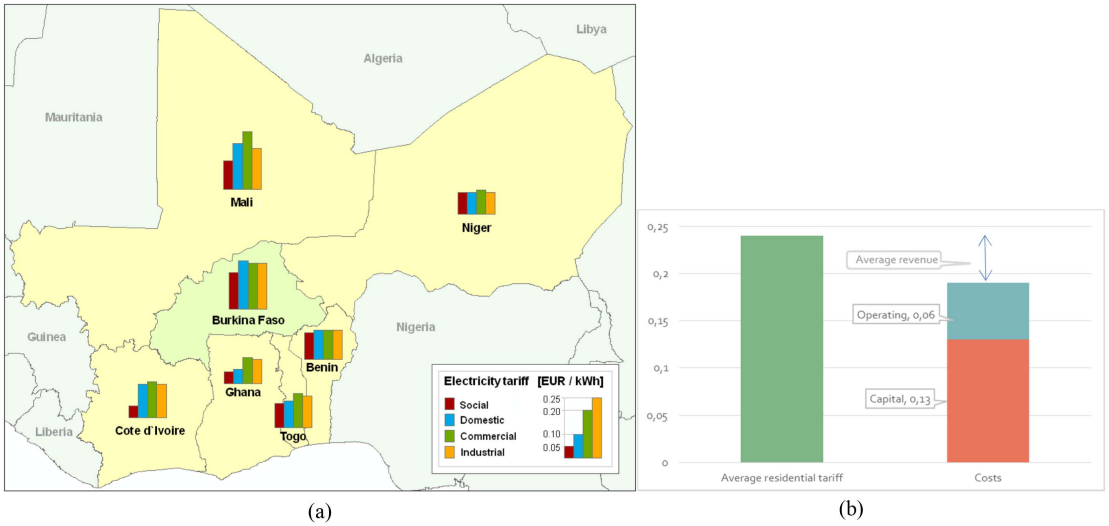
Electricity is important for rapid economic growth and poverty alleviation. With regard to the electricity sector, the country confronts an imminent challenge: the need to supply electricity to many more urban and rural localities, while improving the reliability and quality of the overall service. The country's electricity supply strategy is mainly based on establishing interconnections with neighbouring countries, and refurbishing and extending the existing network. Parallel to that, and in a much smaller proportion there is a policy support for the development of local generation capacity. The country's electricity supply is mainly handled by the national electricity company (SONABEL), which is a public company. SONABEL is fully responsible for the production, import and distribution of electricity in Burkina Faso. In 2014, there was no private producer of grid electricity. Nonetheless, Burkina Faso adapted an electricity law that allows the liberalisation of energy production without the privatisation of the national electricity company [15].

1.4. Specific regulatory framework for rural electrification

In the matters of new electrification the Rural Electrification Fund (FDE) is responsible for rural electrification programmes, whereas SONABEL electrifies peri-urban areas near the existing grid [17]. Rural electrification achievements in Burkina Faso are still very modest; in 2012 only 16% of population had access to electricity [13]. However, the national strategy for electricity access is not defined in one regulatory framework, but it is enclosed into several sustainable development policies [10, 15, 18–23]. An appropriate National Master Plan could support policy-makers set the policy direction, develop coordinated programmes and define the roadmap for rural electrification.

2. Electricity network in Burkina Faso

Planning and coordination between grid extension and off-grid electrification programmes are essential to reach a long-term sustainable energy model and avoid duplication of infrastructure investments. This



(a) (b)

Figure 2. (A) Electricity tariff for the national grid in Burkina Faso and neighbouring countries. (B) Electricity production costs for Burkina Faso. Source: JRC compiled with UPDEA data (2009) [16].

section analyses the status of the grid and its plans for extension. Section 4 will comparatively assess the competitiveness of the grid extension plans with off-grid strategies.

2.1. Quality of grid service

In the last years, interruptions in the interconnected areas have been increasing. The main causes for load sheddings are (1) power shortage (8% of the total services) caused by an important increase in demand mainly recorded during the hot season (April/May) and a massive connection of new customers to the Ouagadougou region; (2) disrupted supply from the interconnection with Ivory Coast (15% of the total services) [24]. On top of this, the status of the current grid is in a delicate situation [25, 26]: the percentage of assets older than 30 years is approximatively of 50% for the transmission lines (1161 km) and 32% for the distribution lines (6396 km) [27].

2.2. Policy of expansion and failure of the scheduling

SONABEL local development and interconnection policy is based on first creating the backbone of the grid and then expand the distribution network. Furthermore, since 2009 the two independent electricity networks are interconnected (the so-called Interconnected National Network). The pace of rural electrification by grid extension has been much slower than planned [10]. These facts reinforce the need to look for an alternative rural electrification approach: a tailored rural electrification option that gives stronger role to lower capital investments using reliable and indigenous sources.

3. Rural electrification planning tool: least-cost electricity option for Burkina Faso

The use of spatial analysis as decision support tools could support the definition of general rules for a more functional rural electrification plan at national level in Africa as other studies have demonstrated [28–34]. The georeferenced electrification tool aims to support the Burkina Faso government and development partners to define a coordinated planning for electrification, focusing on different technological choices.

3.1. Methodology: calculation of geo-referenced least-cost option

The methodology and the main steps used in this study are illustrated in the simplified logical framework (figure 3). The optimisation process detects the least-cost option for each settlement by comparing four electricity generation technologies (grid extension, diesel genset, PV and small-scale hydropower).

The developed methodology includes geospatial analysis and mapping, in a way that harmonises and integrates global and regional databases. The identified input data for the analysis and the corresponding sources are:

- Administrative areas, settlements location and distribution of population [35, 36].
- Transmission network: the existing and planned transmission networks have been compiled from several sources of information [36–38].
- Power stations: existing and planned [37, 38].
- Hydrological and solar resources [39–44].

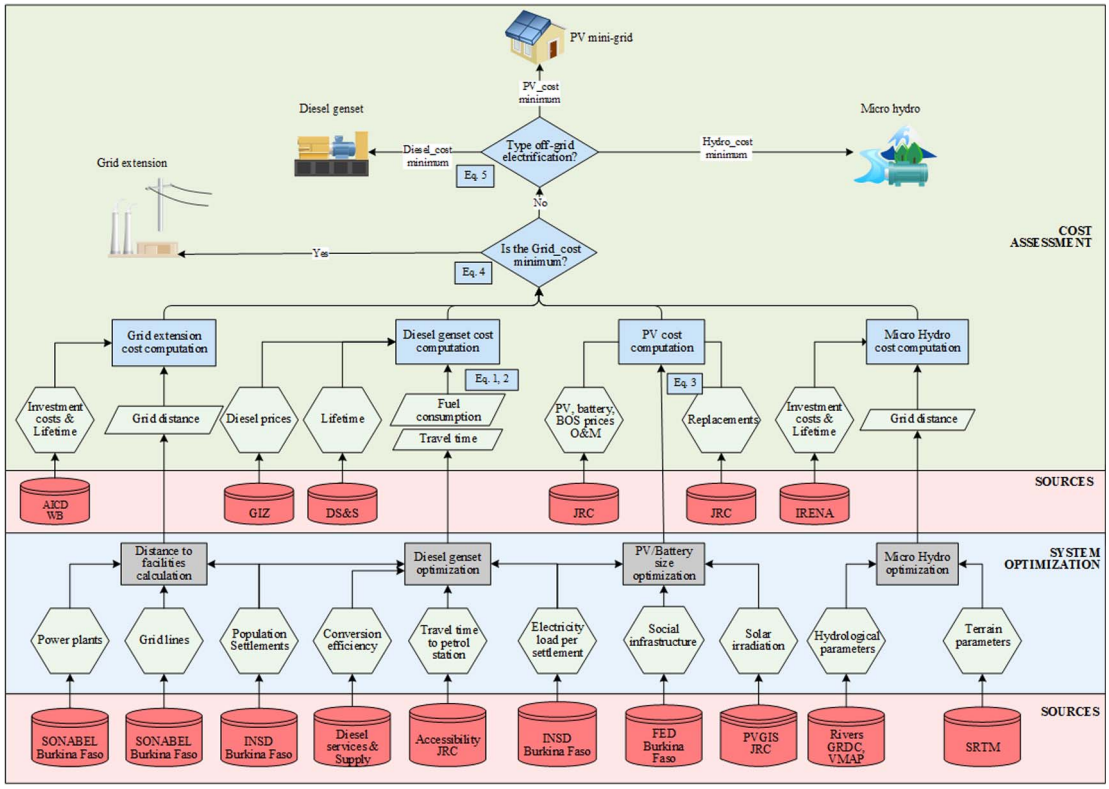


Figure 3. Logical framework of the developed methodology.

– PV, battery, balance of systems (BOS), operation and maintenance (O&M) prices, lifetimes and national diesel prices [40, 45–47].

– Travel time to main cities: dataset of accessibility [48].

– Electricity demand per settlement. There is a lack of detailed data on rural electricity demand in Burkina Faso. The electricity demand projection (figure 1) is based on population estimations provided by the United Nations [6] for Burkina Faso, in combination with average household's population and electricity consumption data from INSD [35, 49] and IMPROVES [36]. The daily profile of the electricity load is estimated considering the data available in government records (FDE 2014 and [35] for settlements at rural areas and energy use in social infrastructure [50, 51] and population for each location (see table 1 for assumptions considered).

The elaborated geoprocessing builds on spatial numerical operations within Geographic Information Systems (GIS) environment and also applies functions of remote sensing and satellite image processing, through the evaluation of long-period meteorological data [39, 53, 54]. For each settlement, starting from the geospatial analysis, the cost of each electrification technology is evaluated with a specific cost model. In the final step of the developed algorithm the least-cost technology among the four studied options is detected and represents the optimal option.

3.1.1. Hydropower

The suitability mapping of potential small-scale hydropower plants focused on run-of-the-river technologies that do not require construction of dams [54]. Hydropower potential can be defined using different approaches. The '*technical*' hydropower potential gives the potential electric power 'that could be, or have been developed, considering current technology, regardless of economic and other restrictions' [55]. The site-selection procedure is based on evaluation of hydro-geographical circumstances, including drainage properties derived from the digital terrain model, climatic conditions and river regimes (discharge variability, perennial or intermittent watercourses). In the initial phase of the modelling the physical constrains of potential locations have been delineated using a continental scale data set [56]. Based on the hydrographical characteristics and detailed description African river data, river segments and suitable area fulfilling the following criteria had been selected as potential locations of mini hydro systems:

– Permanent river (from VMAP0) [41].

– River gradient or surface gradient along the river >1% (derived from SRTM30) [42].

Table 1. Parameters for optimisation modelling.

General parameters	
Population growth rate (country average)	2.8% [6]
Number of inhabitants per household	8 in rural areas 5 in urban areas
Percentage of scattered households	50% (30% for Sahel region)
Households	
Electricity consumption (2015)	40 kWh per capita per year
Rate of increase in consumption	4% yr^{-1}
The daily energy consumption pattern for households (figure 7)	1/3 of the energy is consumed during daytime and 2/3 during evening and night
Average ability to pay	220 FCFA kWh^{-1}
Infrastructures	
Load assumptions for social structures	2 kW Social centre 5 kW Health centre 15 kW Hospital
Rate of increase in consumption	4% yr^{-1}
The daily energy consumption pattern for social infrastructure and productive uses (figure 7)	2/3 of the energy is consumed during daytime and 1/3 during evening and night

Source: [6, 18, 42, 50–52].

– Catchment size $>100\,km^2$ (calculation based on HydroSHEDS) [43].
– Mean annual stream flow $>4\,m^3\,s^{-1}$ (GRDC) [44].

The processed and combined GIS data resulted in a binary map of suitable and non-suitable areas. Distance analysis and cost estimation have been performed to estimate '*economic*' and '*exploitable*' potentials and thus, mapping potential locations of run-of-river hydropower generation [54, 55].

The estimation of the electricity production cost was based on our previous studies [53] (0.15 EUR kWh^{-1}) combined with the additional costs due to distance from the closest suitable river section. The lifetime production costs have been calculated taken into account the average life time, the investment and operation cost of the hydropower plants projects in Africa [53, 57]. The grid extension cost from the closest permanent river to a local grid has been set at 0.025 EUR $kWh^{-1}\,km^{-1}$ [53].

3.2. Diesel genset

The cost of electricity from diesel gensets is calculated following the methodology developed described in [58]. For diesel gensets, fuel consumption is the major portion of the costs. To estimate the location specific operating costs for diesel gensets, the national diesel price has been combined with the transport cost of diesel (the travel time data was derived from the accessibility map in [48]).

The computations are performed in three main steps.

Step 1. Transport costs for diesel:

$$P_t = \frac{2P_d ct}{V}, \quad (1)$$

where:

– p_t is the transport costs (EUR).
– p_d is the national market price for diesel (EUR) .
– c is the diesel consumption per hour ($l\,h^{-1}$).
– t is the transport time (h).
– V is the volume of diesel transported (l) .

Step 2. Production cost for electricity is calculated as

$$p_p = (p_d + p_t)\eta, \quad (2)$$

where:

– p_p is the production cost for electricity (EUR kWh^{-1}).
– η is the conversion efficiency of the generator ($l\ kWh^{-1}$).

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

The input parameters for the electricity costs of diesel genset are:

- Lifetime of the diesel genset: 10 000 h. As an average generators would last from 1 to 5 years [59], with most of them ranging in the lower lifetime line.
- National retail diesel price: 1.00 EUR l^{-1} (2011) range between 2008 and 2016: 0.94–1.04 EUR l^{-1}.
- Fuel consumption of the genset with a conversion efficiency of 0.286 (l kWh^{-1}) [60].

3.2.1. Solar PV

Solar energy production is modelled using hourly solar radiation data derived from satellite observations [61, 62] as the number of solar irradiation field measurements in Burkina Faso is limited [63]. The optimisation algorithm is applied at each location using the hourly solar irradiance data from PVGIS [39], the calculation of the system performance ratio, the calculation of the PV system/battery size ratio and load demand profile (figure 7) for each settlement (considering the existing social infrastructure and domestic consumption for each settlement). The input parameters for the calculation of the off-grid PV electricity costs are:

- PV module price: 0.83 EUR Wp^{-1} (2014); BOS components: 1.0 EUR Wp^{-1}.
- Batteries lifetime: 5 yr; battery price: 122 EUR kWh^{-1}.
- System is optimised so that energy delivery will fail due to empty batteries on less than 5% of days.
- O&M annual costs: 2% of the capital expenditure.
- PV system lifetime: 20 years.
- 70% system performance ratio for the PV systems, considering also the losses in charging and discharging o batteries.
- Capital cost of construction of the minigrid including replacements of BOS.
- Cost of capital as discount rate: 5%; depreciation: 5%/year[1]. The Atlantic Bank Burkina is assuming conservative discount rates between 5% and 10% for PV systems [64, 65].

Based on above assumptions the PV system costs can be defined by the following equation:

$$\begin{aligned} \text{PV\_COST} = (1 + 0.02_{*}N1)[&\mathcal{P}_{\text{PV}*}\text{PV\_price} \\ &+ \mathcal{P}_{\text{PV}*}\text{BOS\_price} + \sum_{n=0}^{n=N1/N2} \text{BAT\_size} * \\ &\text{BAT\_price}(1 - 0.05)^{n*N2}], \end{aligned} \quad (3)$$

where:

- $\mathcal{P}_{\text{PV}}$ is the estimated PV system peak capacity (kW_p) depending on solar radiation and consumption profile of the community
- BAT_size is the total battery array size (kWh) optimised per each location
- PV_price is the module price (EUR kW_p^{-1}).
- BOS_price is the BOS price (EUR kW_p^{-1}).
- BAT_price is the module price (EUR kW h^{-1}).
- N1 lifetime (years) of the PV system.
- N2 lifetime (years) of the battery.

3.2.2. Calculation of least-cost option for each settlement

Grid extension might not be the most appropriate option for scattered population even at medium distance to grid. We define a 'dynamic criterion' that favours grid connections where population is concentrated and at relatively in short distance to the existing distribution lines (33 kV). When grid extension is not feasible, as determined by the 'dynamic criterion', off-grid solutions are assessed taking into account the specific electricity loads for each settlement. Grid extension is likely to be a viable alternative compared to decentralised systems in each settlement i when:

$$(\text{Cost}_{\text{off-grid}})_{i*}(P_{\text{off-grid}})_i > (\text{Cost}_{\text{grid}})_{i*}D_i\,. \quad (4)$$

D is the distance from the rural community to the main grid (km).

$\mathcal{P}_{\text{off-grid}}$ is the estimated peak capacity (kW_p).

$\text{Cost}_{\text{off-grid}}$ is the calculated cost of decentralised system (EUR kW_p^{-1}).

$\text{Cost}_{\text{grid}}$ is the cost of grid extension (EUR km^{-1}). Grid extension costs in Sub-Saharan Africa can certainly reach 30 000 EUR km^{-1} or more [26]. In addition, as Burkina Faso experiences constant capacity shortage in the transmission system and power shortage in generation [15] the grid extension may trigger investments in the centralized power system that may more than double the costs of electrification [66]. The unit price for grid extension under this criterion has been set to relatively high cost (40 000 EUR km^{-1}), which is realistic if compared to the field costs in Burkina Faso [18, 67].

Suitability mapping and generation costs estimation have been completed in 1 km × 1 km resolution in Burkina Faso for all competitive technologies (extension of the grid from the closest existing network, hydropower including the extension of a local grid from the closest permanent river section, off-grid PV system and stand-alone diesel generator). Based on the generation cost of each studies technology, the following formula defines the minimum cost for each geographic location (i):

[1] Influences the price of future battery replacements.

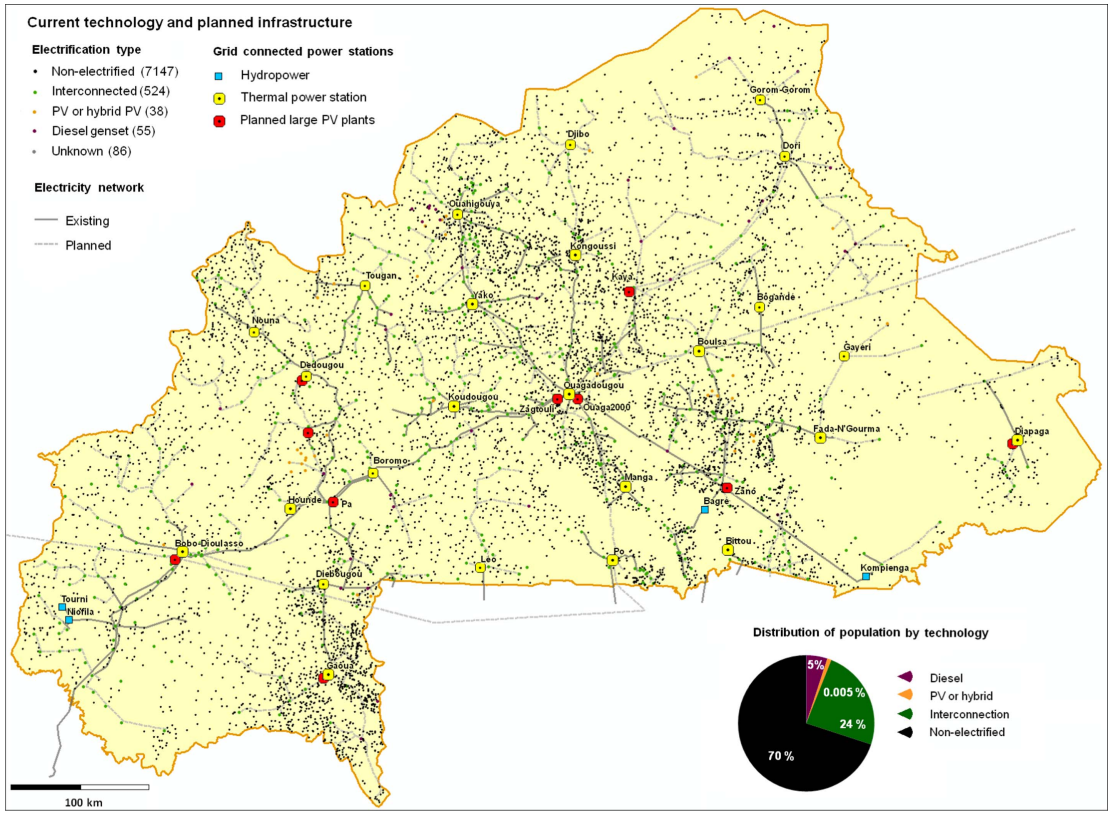


Figure 4. Existing technology per community. Data source: SONABEL, FDE (2014). GIS processing and map: JRC.

$$[\text{MINIMUM\_Cost}_{\text{off-grid}}]_i = [\text{minimum} \times (\text{Diesel\_COST}, \text{Hydro\_COST}, \text{PV\_COST})]_i. \quad (5)$$

4. Results

4.1. Current tendencies for grid extension

In Burkina Faso, 95% of the electricity is consumed in urban areas, while electricity needs in peri-urban and rural areas remain almost uncovered [64]. The national policy for electrification is dominated almost exclusively by slow grid extension supported by the government subsidising fossil fuel electricity production. Nevertheless, a high proportion of the rural population is not connected to the grid even for communities located relatively close to the existing transmission lines (around 1500 non-electrified communities with a total of 2.5 million people are within 5 km of distribution lines). Figure 4 identifies the settlements within the country based on the current mode of electricity supply.

The eligibility criteria for the selection of grid extension can be based on either social considerations, cost-effectiveness criteria or a combination of both. Burkina Faso policy prioritises grid extension when feasible accordingly to distance criterion [18]. The distance criterion to the grid is based on the assessment of the operating constraints of the electricity network and the analysis of options for power supply to priority localities. The grid extension approach does not take into consideration the needs of refurbishment of the existing grid. If refurbishment costs are taken into consideration, they would probably minimise the prioritisation for grid extension option [68].

According to the Energy Ministry feasibility study [18, 17], SONABEL established the minimum criterion of extending the grid to communities located within 25 km from the nearest 33 kV line and to localities with over 6000 people as well as smaller ones located along the transmission route ($D < 1$ km). A revised feasibility study [18] updates the minimum size of the to be connected to localities with population over 1500 inhabitants.

Figure 5 illustrates the location of the communities classified following a combination of size of communities (more than 6000, between 1500 and 6000, less than 1500 inhabitants) and the minimum distance criteria along four corridors.

As illustrated in figure 5, 77% of the population in Burkina Faso still resides in rural areas. Only 1% of the communities are located farther from the grid than 25 km and almost all of them retain a population of fewer than 6000, the size limit for urban settlement in

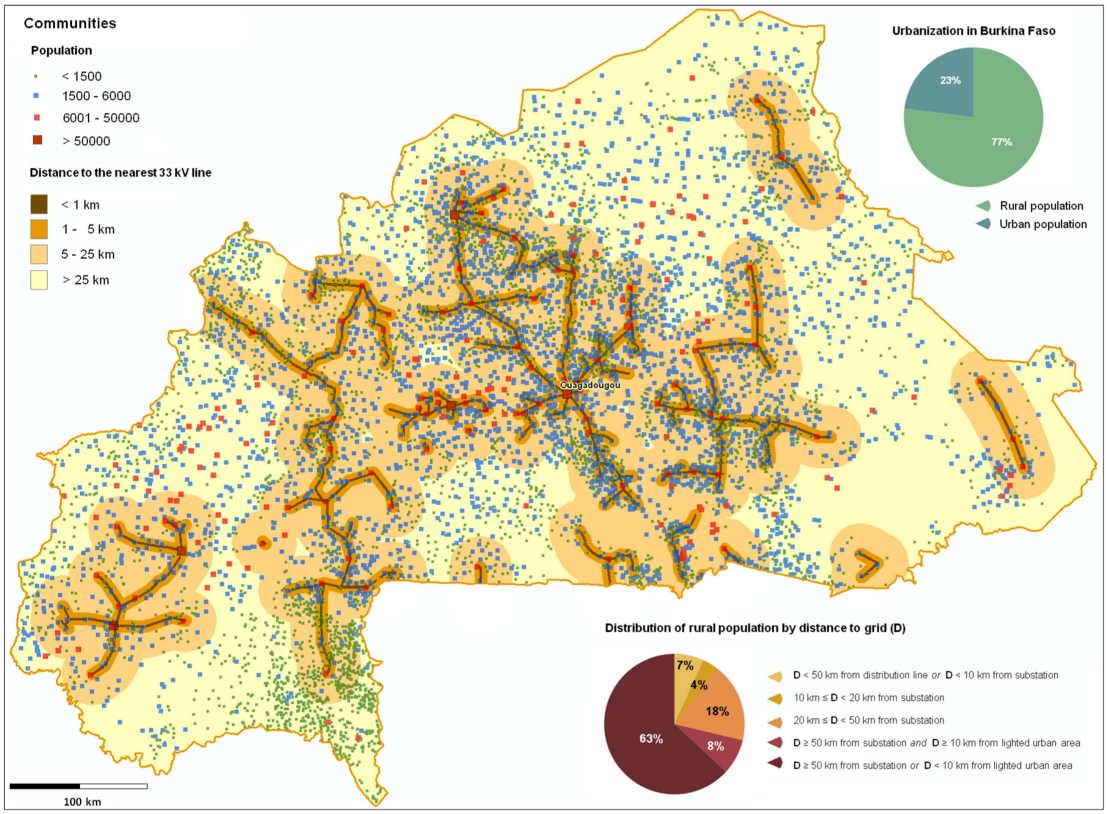


Figure 5. Distribution of communities according to size and the distance to 33 kV line. Data source: [27, 35, 36, 69]. GIS processing and map: JRC.

Burkina Faso. Most of the large communities are located along a 5 km corridor from the existing or planned lines.

4.2. Least-cost technology according to dynamic criterion

Figure 6 shows the geographical distribution of the least-cost technology when using the dynamic criterion including electricity loads per settlement, and the distance of load centres to grid.

Along the same line as other studies [13, 70, 71], the least-cost spatial planning results show a clear preference for decentralised RE technologies when low electricity demand does not justify the high investments of grid extension. The techno-economic results under a universal electricity access target suggest distributed generation options to 60% of population living in non-electrified communities. The results show the same tendency even under conservative assumptions with higher module PV prices and lower grid extension costs (see sensitivity analysis sub-section).

Although hydropower has been mapped as the optimal electricity source also in Burkina Faso at some remote locations [53]; close to southern tributaries of Black Volta and Komoe River (south-west) and Pendjari River (south-east), there were no settlements within economically feasible distance. As a result, due to geographic, hydrogeographic and climatic conditions of the country [72], the run-of-the-river based small or mini hydropower electricity generation does not seem to be competitive nor optimal electricity source for communities in Burkina Faso.

The oil price has experienced a very volatile market in the last 2 years and the national diesel prices partially followed. The comparative analysis of the two major distributed electricity generation option therefore has also shown quite a changing picture [53, 73]. While the decrease of PV module prices have steadily favoured the PV based options in the last decade as the high oil prices prevailed, the sharp decrease of oil prices had the opposite effect. The price drop during 2014/15 in oil prices could make the diesel option much more competitive than the presented model results suggest. As investment in electricity generation assumes at least 5 years of operation, probably the most adequate approximation for the fuel cost would be a 5 year moving average price of the given fuel so the short-term fluctuation is excluded. The input parameters used for diesel reflect these longer-term price trends.

The results show that 8.3 million people distributed in 2300 communities would be covered by grid electricity services, including the already 620

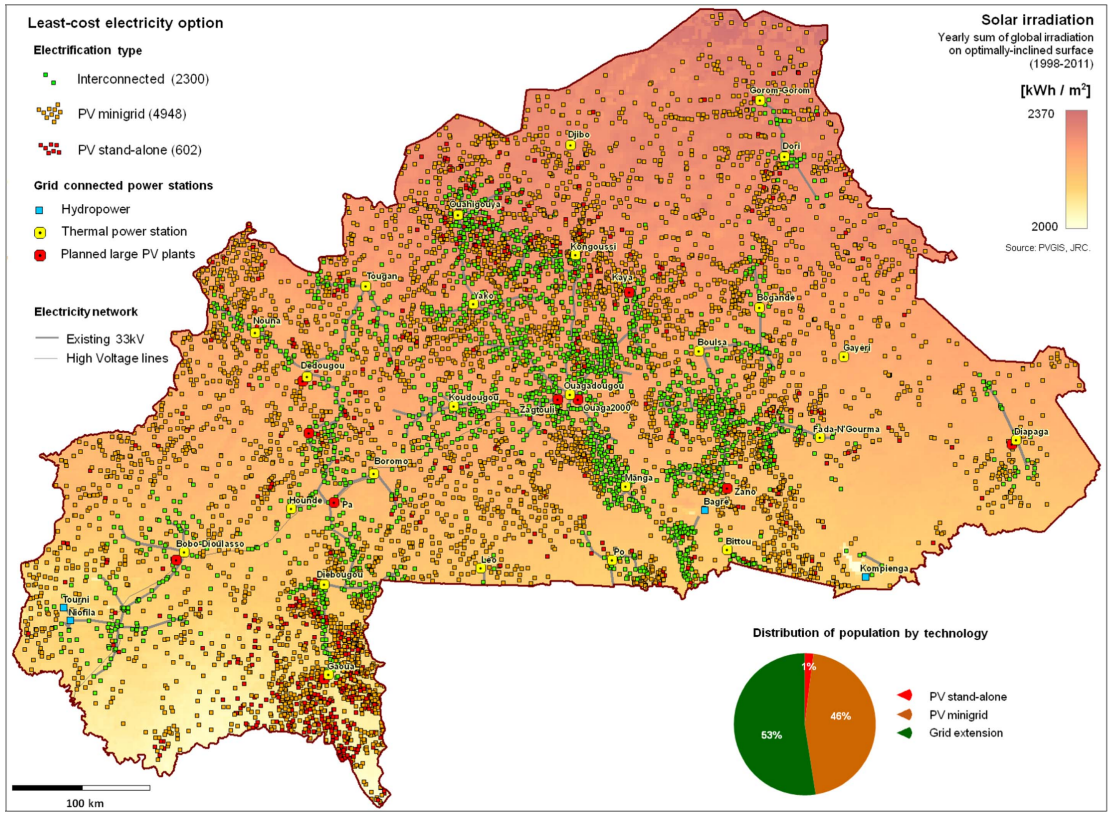


Figure 6. Least-cost electricity option for Burkina Faso.

electrified communities (see table 2). The results of the developed spatial electricity model clearly demonstrate the remarkable photovoltaic potential in Burkina Faso (with a suggested total installed capacity of 350 MWp under the baseline scenario). In a second step, the PV technology option is further processed to distinguish between PV minigrid ($\mathcal{P}_{PV} > 15$ kW$_p$) and PV stand-alone systems ($\mathcal{P}_{PV} < 15$ kW$_p$). The PV minigrid is a prime candidate to provide service to 7.2 million population (for 4948 small and medium-size remote villages) and PV stand-alone systems cover 115 000 people (0.7% of population). It should be stated that due to lack of demographic and geographical information, our study does not include highly dispersed population where PV stand-alone system might be considered a better solution.

The average cost of electrification per inhabitant for grid and PV are 52 and 180 EUR/capita respectively. The total capital cost of connecting 13 million new customers in the baseline scenario is approximately 1.7 billion EUR (table 2). According to ODI [74]. Burkina Faso has subsidised almost 200 EUR millions of fossil-fuel, that would translate on bringing electricity by decentralised technologies to 1 million rural people. Due to the volatility of oil prices and the subsidising of fossil fuel electricity production, it is becoming unsustainable that the government continue supporting fossil fuel electricity production in order to be able to provide universal access to electricity [64].

4.2.1. Sensitivity analysis on electricity load profiles and demand projections

We have performed a sensitivity analysis to determine how a variation in the load profile or a change in the electricity demand would influence the selection of the least-cost technology option in each settlement. The different load profiles (figure 7) investigated assuming universal electricity access are:

- Household profile. The electricity load per settlement follows the assumption that households are the dominant costumer group (current average household consumption is 40 kWh/year/capita).
- Social profile. The electricity load per settlement is calculated assuming that the households are the dominating costumer group and incorporating 10% of total load due to social infrastructure.
- Productive profile. The electricity load per settlement is calculated incorporating productive uses and potential commercial activities (40% of productive use, 10% due to social infrastructure and 50% to households).

The total peak demand for each settlement is estimated by summing up all household and social

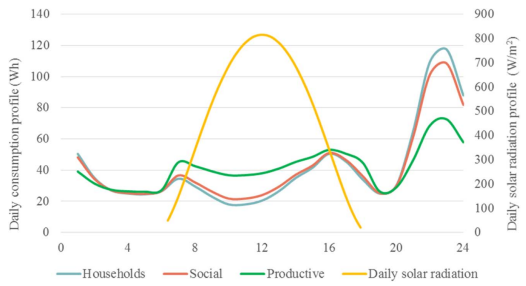


Figure 7. Solar radiation and consumption profiles.

infrastructure demands and a coincidence factor of 70%. In order to investigate the effect of energy demand projections on least-cost rural electrification technologies two different electricity demand projections are investigated under the social load profile:

- Universal electricity access (reach universal electrification by 2030). Full coverage scenario assumes all households (in rural and urban areas) will be electrified over a 20 year period beginning at 2012 and ending in 2032. The increase in demand is applied only in non-electrified settlements (from nothing to 40 kWh/year/capita).
- High-energy demand scenario: Independent increase of electrified and non-electrified settlements. Increase in total demand is due to an increase to 110 kWh/year/capita in electrified settlements by 2032 and increase to 40 kWh/year/capita for settlements without access to electricity. For population already living in electrified areas there is a distinction between rural and urban areas.

The sensitivity analysis shows that changing the load profile to productive use, increasing the share of day consumption, results in a slight shift from grid extension to distributed technologies (table 3). These findings indicate that an increased share of PV systems favours productive activities. At the same time moving from the universal access scenario towards a higher energy-demand scenario, increases the share of grid extension from 53% to 59% (table 3).

4.2.2. Sensitivity analysis on PV and diesel costs

The analysis of the diesel cost parameters on its competitiveness for electricity production has been based on the 2008–2016 data of diesel price development in Burkina Faso from [45] and from Global Petrol Prices [75]. Burkina Faso needs to import all fossil fuels, most of this from trade partner countries that have lately experienced turbulent disruptions (Ivory Coast, Mali). Due to the energy security problems and to the high prevailing subsidies already funded, Burkina Faso is amongst the group of countries that did not follow the decreasing trend of oil prices in the national diesel prices. These prices stayed quite stable with the decrease between 2012 and 2016 below 5%. Therefore, the sensitivity analysis has shown negligible changes in settlements where diesel generators was potentially the most economic option for electricity generation.

Table 2. Costs of universal electrification.

	Population (million)	Costs (million EUR)
NON-electrified settlements	10.8	1529
Grid extension	4.4	345
Urban	0.4	18
Rural	4	327
PV technologies	6.5	1184
Urban	0.2	34
Rural	6.3	1150
Electrified settlements	4.7	214
Grid extension for population gaining access to electricity[a]	3.9	90
Urban	3.1	22
Rural	0.8	68
PV for population gaining access to electricity	0.8	124
Urban	0.2	18
Rural	0.6	106
Total		**1745**

[a] 54% of urban population with electricity access and 2% of rural population with electricity access.

Sensitivity analysis on the cost of PV technology suggests that lowering the cost of PV components would have a significant impact on reducing the costs of universal electrification, decreasing module cost from 1 to 0.8 EUR Wp^{-1} reduced the total investment costs by almost 10%. But taking into account the slow grid electrification progress in Burkina Faso, a large part of the population is not going to be connected in the near future, (still 7.9 million people are living in non-electrified communities farther away than 5 km corridor). Therefore, there is a big opportunity for a large proportion of these communities to get electricity from a different solution to that of grid extension.

5. Conclusions

In Burkina Faso, the problem of low electrification rates is severe [70, 76]. Up to date government rural electrification policies are still based on the 'status quo' path of grid extension. Accordingly, Burkina Faso progress falls substantially short of what is required to attain the SE4All objectives by 2030 [76]. The results of the present study underline the need for a new national approach which will emphasise the opportunities for long-term sustainable options, and increase access to electricity on an accelerated timeline. While the existing plan gives poor prospects for the expansion of

Table 3. Share of population to be covered by different technologies. Model results for the three load profiles and the two demand scenarios.

	Household load profile	Social load profile	Productive load profile	Universal access scenario	High energy-demand scenario
PV stand-alone (%)	1	1	1	1	1
PV minigrid (%)	46	46	52	46	40
Grid extension (%)	53	53	47	53	59

decentralised technologies, the results from a least-cost analysis indicates a preference for distributed renewable energy systems, even stronger when the low level of consumption does not justify the high investments of grid extension. Taking into account the upfront investment needs and the related risks, the planning, regulation and authorisation capacities in Burkina Faso, the central grid extension option may not be feasible (as shown by the halted grid implementation of the last decade), giving priority to the modularly implementable off-grid solution.

KEY COST FIGURES

MEPRED (study by ministry of mines and energy)

Additional communities electrified by interconnections: 1528

Number of covered people = 5.5 million

Refurbishment needs for power production = Hydro (63 MW) and thermal (117 MW)

Refurbishment costs for national network = 100 million EUR [26]

Total investments costs = 200 million EUR

JRC under universal access to electricity scenario

Additional communities connected by interconnection and PV: 7149

Number of additional covered people = 15.5 million

Total PV installed: 374 MW

Cumulative investment = 1.7 billion EUR

Source: JRC with the interpolation from MEPRED [18].
1 EUR = 656 FCFA (2012).

The key costs figures compares the total investment cost calculated by our least-cost model for universal electricity access (1.7 billion EUR) with the estimations of the Energy Ministry study [18], where 5.5 million people (1528 additional communities) will be electrified by grid extension with a total investment cost of 200 million EUR. The grid extension figures does not include the costs of fossil fuel consumption at the generation sites, neither the capacity shortage in the transmission system, or energy shortage in generation. It should be noticed that the results of the MEPRED study corresponds to a scenario with a national electricity access target of 45% and a rural electricity access target of 36% without adding the 100 million EUR needed for the refurbishment of the existing network [26]. On the other hand, our model results are based on the assumption of providing electricity to all the communities with a 100% coverage; including those already living in already electrified settlements and without access to electricity (in the case of Burkina Faso 46% of urban population and 98% of rural population).

It should be noted that the present study has an additional characterisitic compared to our previous work [53, 58]. It considers energy-related geospatial information by taking into account the variation of electricity load for each location and considers the current electrification status and the rate of electrification (urban/rural). To our view this is important because it responds better to the status quo of the country and adapts to the modular nature of PV technology (with PV size per settlement ranging from 400 Wp to 567 kWp).

The national level modelling has to be complemented in the implementation phase with a local-level modelling like HOMER [77] or the RETScreen [78] micro-power optimisation models. The presentation of these approaches goes beyond the scope of the analysis.

6. Recommendations and future developments

6.1. Concrete and unified action plan for rural electrification

6.1.1. Scattered Plan

(A) Rural electrification achievements in Burkina Faso are very modest, still less than 5% of the rural population have access to electricity. The rural electrification plan for Burkina Faso is scattered in several policies for electricity sector development. There is a need to define a concrete and single action plan as those existing in other Sub-Saharan countries and successfully supporting rural electrification (e.g. Cape Verde, Kenya). The use of the presented spatial analysis at an early development stage can be influential to overcome the deficiencies of the current scattered national planning and to increase the probability of achieving the national goals.

(B) Furthermore, most of the neighbouring countries from which Burkina imports electricity most of have experienced turbulent disruptions (Ivory Coast, Mali). Besides, the Burkina government is

also exposed to instability. Therefore, smaller local projects are expected to be more feasible than centralized planning in the long-term.

(C) Burkina Faso has to import all fossil fuels, mostly from countries under political instability (Ivory Coast, Mali). This raises energy security issues and considering the already high subsidies, it explains why Burkina Faso is amongst the few countries that national diesel prices did not follow the decreasing trend of oil prices.

6.1.2. Stronger support institutions

(A) The institutional development must be considered when undertaking an assessment of the sustainability and risk factors of a proposed rural electrification planning. The Rural Electrification Fund (FDE) was developed with international institutions to manage their direct subsidies or concessional loan transfers. In the case of implementing a rural electrification plan with a high percentage of PV distributed technologies, the Fund should become a full-fledged financial institution due to the higher complexity of financing many smaller local projects which requires higher installation costs of PV but lower running costs [11, 15, 70].

(B) Burkina Faso should develop a clear renewable energy financing strategy capable of securing resources to cover the financial needs to implement the use of renewable energy technologies while gaining universal access to electricity [76, 79]. Therefore, there is a need of coordinating the resources coming from a variety of institutions: international lenders, investment funds, energy operators, and national and international markets. Specific literature on this topic implies a stronger consistency for renewable energy funds allowing a centralized management of the national or international subsidies [11, 70, 80].

(C) The establishment of a renewable energy agency to strengthen the development of a specific programme for renewable energy technologies at national scale (with involvement of the influential ECREEE the Renewable energy centre of the West African Economic Community).

The rural electrification planning tool can help to revise the national priorities and support the coordination with other programmes [15]. The next stage of this study is to proceed with the discussion and consultation with main stakeholders of the results of the mapping and extension of the rural electrification master plan.

6.2. Stronger integration of renewable energy sources

This paper highlights the substantial photovoltaic potential in Burkina and shows results that may increase the willingness of the government and international organisations to develop renewable energies in its territory. For the economic aspects, the paper shows one potential approach on how to reduce the marginal cost by the deployment of additional 374 MW solar photovoltaic capacity in Burkina Faso.

The optimisation of least-cost technology option is based on the available local resources (small hydropower and solar PV), or imported fossil fuel resources (diesel generator or grid extension). The results strongly suggest an increase on the integration of renewable energy in the overall electricity supply and a decrease on the current dominance of fossil fuels.

(A) Currently, the common national policy for electrification is grid extension. The national portfolio might strongly consider more profitable projects such as minigrids using local resources, as the economic burden to develop and maintain the national grid will be very high and not necessarily the least-cost option. Our results suggest up to 65% of the non-electrified settlements would be covered by decentralised technologies.

(B) The cumulative investment to reach universal access to electricity by 2030 is 1.7 billion EUR, according to our model. However, defining the source of capital/funds extends the scope of the present study. Specific literature on this topic implies several financial and incentive schemes to support the deployment of decentralised energies [11, 70, 80].

(C) The diesel generator option is strongly decreased due to the high dependency on fuel imports and the increasing costs due to transportation.

(D) Due to geographic, hydrogeographic and climatic conditions of the country [56], run-of-the-river hydropower electricity generation does not seem to be feasible nor optimal electricity source for communities in Burkina Faso.

(E) SONABEL studies indicate that wind resources are very low and hydropower potential is not high. Accordingly it has already recommending the use of solar resources (PV and thermal), but at the moment there is not a specific master plan for development at country level (apart from some general indication from ECOWAS) [81].

6.3. Identified opportunities for the extension of the planning tool

The developed model resulted to a collaboration with the Africa-based research institution ECOWAS-ECREEE and the development of a similar tool

(ECOWREX) [82]. Linking the Burkina electrification plan more tightly to such tools could help attract more international support to the electrification projects of the country.

In order to integrate social and environmental aspects [83, 84, 85] in our rural electrification planning tool the following cross-cutting aspects of the UN Sustainable Development Goals could also be considered: (i) identification of potential significant adverse impacts on the environment and resettlement issues (such as on rural-urban migration patterns, urbanisation and rural planning), (ii) roles and priorities of men and women in the electrification planning and possible mechanisms to ensure equal participation, (iii) links between electricity services and educational, health and productive sectors.

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