DTU Library

Feasibility of wind power integration in weak grids in non-coastal areas of Sub-Saharan Africa: the case of Mali

Nygaard, Ivan; Kamissoko, Famakan; Nørgård, Per Bromand; Badger, Jake; Dewilde, Luc

Published in:
A I M S Energy

Link to article, DOI:
10.3934/energy.2017.3.557

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

http://www.aimspress.com/journal/energy

AIMS Energy, 5(3): 557-584.
DOI: 10.3934/energy.2017.3.557
Received: 05 February 2017
Accepted: 22 May 2017
Published: 27 May 2017

Research article

Feasibility of wind power integration in weak grids in non-coastal areas of sub-saharan Africa: the case of Mali

Ivan Nygaard [1,*] Famakan Kamissoko [2], Per Bromand Nørgård [3], Jake Badger [4], and Luc Dewilde [5]

[1] UNEP DTU Partnership, DTU Management Engineering, Technical University of Denmark, Marmorvej 51, 2100 Copenhagen Ø, Denmark
[2] Agence d'Energie Renouvelable, AER, Mali
[3] DTU Electrical Engineering, Technical University of Denmark, Frederiksborg-vej 399, 4000 Roskilde, Denmark
[4] DTU Wind Energy, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark
[5] Luc Dewilde, 3E, Quai à la Chaux 6, 1000 Bruxelles, Belgium

* **Correspondence:** Email: ivny@dtu.dk; Tel: +454-533-5297.

Abstract: Installed wind capacity in Africa has grown rapidly the last few years, and by late 2016 had reached about 4.8 GW. However, so far few investments have been made in inland localities due to the generally lower wind potential. This paper therefore explores if and to what extent it is possible to establish economically feasible wind-power plants in countries with lower wind potential. To address this question, the paper provides a combined wind resource mapping and a pre-feasibility study for grid integration of wind power at four specific sites in Mali. The study finds that Mali has generally poor wind conditions, with average wind speeds of below 5 m/s at 50 m above ground level in the south, while there are larger areas in the northern part with average wind speeds of above 7 m/s at 50 m above ground level. Overall the research shows that in countries with generally poor wind conditions, such as in the southern part of Mali, it is possible to identify a limited number of sites with local speed-up effects situated close to the existing grid, at which there are options for undertaking medium-size wind-power projects that would be economically feasible at current crude oil prices of 50 USD/barrel.

Keywords: wind resources; wind power; feasibility; non-coastal area; Mali; sub-saharan Africa

1. Introduction

In 2012 the UN Sustainable Energy For All (SE4All) initiative set the goal of universal access to energy for all by 2030, with the overall objectives of spurring economic growth and supporting improvements in education, health and gender equality [1]. Africa is the continent with the lowest electrification rates, with only 68% of the urban and 26% of the rural population having access to electricity [2]. At present, therefore, there is a high degree of focus on how high rates of electrification can be achieved in Africa.

A major challenge in this regard is to meet the demand for new power production capacity and to do so in a sustainable way. The lack of investment in the sector following the privatisation of utilities on the continent has led African utilities and governments to expand capacity rapidly through the use of emergency solutions, such as diesel barges and temporary generators [3].

To achieve the goal of universal access by 2030, a recent study by Bazillian et al. [4] projects a need for a tenfold increase in capacity, equivalent to an annual increase of about 13%. According to another study by IRENA [5], the African continent will need to add around 250 GW_p of new capacity (in addition to the existing 147 GW_p) between now and 2030 to meet the growth in demand. The study assumes two scenarios, a reference scenario and a renewable energy scenario. According to the renewable energy scenario, a large share of this, namely about 95 GW capacity from wind energy, should be installed between 2012 and 2030.

Some African utilities and governments have already started to consider the expansion of grid-connected wind farms. There are three main reasons for this. First, wind power has become competitive with diesel technologies, especially in coastal regions with good wind conditions. Secondly, wind has the advantage of faster installation times (compared, for example, to a large-scale coal-fired power plant). Thirdly, access to (green) financing for wind is easier than for environmentally questionable technologies such as coal and large-scale hydro.

While installed wind capacity worldwide reached 433 GW by the end of 2015 [6], installed capacity in Africa by late 2016 was only about 4.8 GW, mostly concentrated in coastal regions of South Africa (2122 MW), Morocco (896 MW), Egypt (745 MW), Kenya (343 MW), Ethiopia (325 MW), Tunisia (243 MW), Tanzania, (50 MW), Cape Verde (31 MW), Algeria (11 MW) and Nigeria (11 MW), with smaller projects in Eritrea, Gambia, Mozambique and Namibia.[1] One major exception that is not a coastal location is found in Kenya, where very specific wind conditions (avr. 11.8 m/s) at an inland locality close to Lake Turkana has resulted in installation of about 365 wind turbines of 0.85 MW each, representing about 90% of Kenya's installed wind capacity [7].

South Africa and Morocco have plans for significant investments in wind energy [8,9,10], and other countries situated along a coast, such as Ghana and Senegal, have also initiated serious investigations for the construction of the first grid-connected wind farms [11,12,13].

Global-scale wind assessments are available for Africa [14], and research into the wind potential of countries that lie on Africa's coasts are available for, e.g., Morocco [15], Tunisia [16], Egypt [17,18], Ethiopia [19], South Africa [20], Ghana [11] and Senegal [21], while wind mapping is

currently being conducted in inland countries such as Ethiopia and Zambia.[2] Inland countries in general have poorer wind conditions, but they are at the same time often dependent on using diesel and fuel oil for power generation, which could make wind power economically competitive even there. Nevertheless, only a few studies in countries such as Algeria [22] and Kenya [23,24] have assessed the wind resources under inland conditions on the African continent, and so far few if any research papers have combined a general wind assessment with an economic feasibility study of integrating wind into the grid under these conditions.

Against this background, this paper sets out to explore if and to what extent it is possible to establish economically feasible wind-power plants in African countries inland with lower wind potentials. To address this question, the study assesses the wind potential in Mali based on wind measurements and meso-scale modelling.[3] By means of an analysis of annual wind-power production at four sites, it conducts financial feasibility studies for integrating wind into the main grid and into mini-grids.

The following section describes the methodology used in the research. Section three presents the results of the wind assessment for Mali, section four the results of the economic feasibility studies for the four potential sites mentioned above. The options for integrating wind power into existing grids and the avoided cost of energy in these grids are analysed in section five, before reaching the conclusion in section six.

2. Research Design and Methods

This research is being carried out in collaboration between the Technical University of Denmark, the consultancy company 3E and the Renewable Energy Agency (AER) (formerly CNESOLER) in Mali as part of a wider assessment of opportunities for the integration of renewable energy into the energy system in Mali. The research is the result of a fruitful collaboration in which AER has been mainly responsible for the local measurement of wind conditions and the collection of data on local conditions, such as information on the energy system, while DTU and 3E have mainly concentrated on the various modelling work and the overall writing of the paper.

The research design includes two main modules. The first module comprises the modelling of a wind atlas for Mali, including information about the spatial, annual and daily variations in wind speed and wind-power density. The second module, which assesses the economic feasibility of the integration of wind power into the grid, includes: i) calculations of annual power production for each of the four cases; ii) the levelized cost of electricity (LCOE) for wind power for each case; iii) an assessment of the options for the integration of wind power into the grid; and iv) an assessment of the LCOE (avoided cost) for electricity in the system. A schematic illustration of the overall design is provided in Figure 1. Further details of the approach for the main elements will be described below.

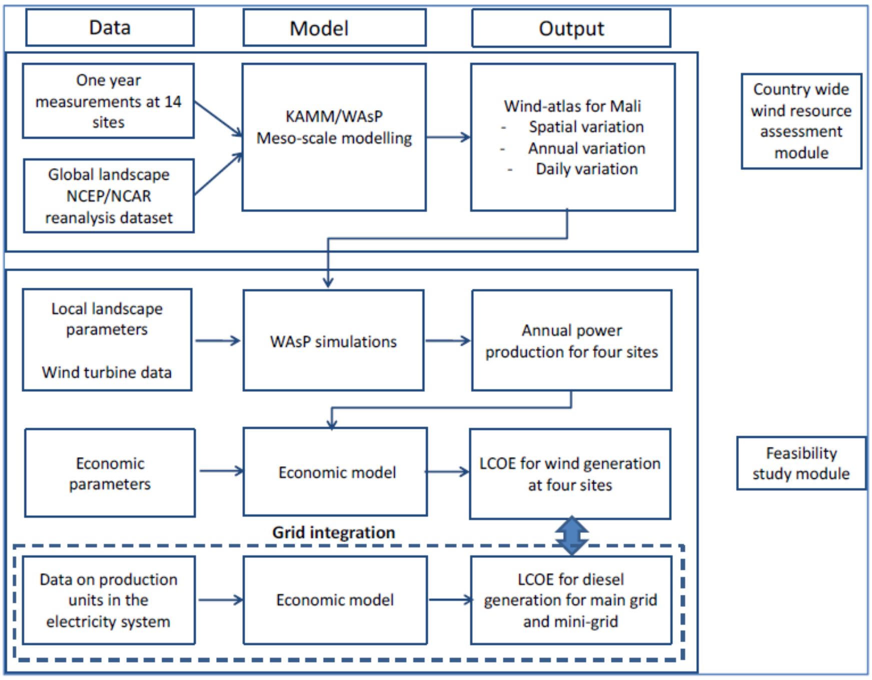

Figure 1. Illustration of the research design.

2.1. Wind atlas for Mali

The estimate of wind resources in Mali is based on meso-scale modelling using the KAMM/WAsP [25] statistical-dynamical downscaling methodology validated against local wind measurements at fourteen locations over the past few years.

The 'simulated wind atlas', based on a KAMM mesoscale modelling with input data from the NCEP/NCAR [4] reanalysis dataset, estimates wind resources at a specific height level. The 'generalized wind atlas', based on the simulated wind atlas in combination with maps containing information on topography and surface roughness, indicates resources at a specific height level, assuming flat land and homogeneous surface roughness. The purpose of the generalization is to isolate the wind conditions from the influence of the specific mesoscale model description of the terrain at any location, so that variation of generalized winds can be understood in terms of meteorological features rather than local terrain effects. The local terrain effects must be added at microscale modelling (see section 4.1) in order to get an accurate estimate of actual wind resources.

The local wind measurements serve a double purpose. First, they are used by WAsP to estimate local wind resources close to the measurement site. Secondly, they have been used to validate the generalized wind atlas in order to determine the confidence level of the KAMM/WAsP methodology for the area of interest.

2.2. Selection of cases

The case studies comprise a calculation of the power output and the LCOE for each of the four sites, as described further below. Cases were selected to illustrate how wind could be integrated into: i) the main grid, with a peak demand of about 400 MW; ii) a cluster of mini-grids, with a peak

demand of about 15 MW; and iii) an isolated system (mini-grid), with a peak demand of about 2 MW. Cases have been selected to illustrate how a combination of size, wind conditions, speed-up effects and distance to the grid influences the power output and the LCOE. An overview of the main parameters for the four cases is provided in Table 1.

Table 1. The four cases and the main varying parameters.

Grid Type	Case Name	Peak capacity	Wind conditions	Speed up effects	Distance to grid
Mini-grid	Timbuktu	0.675 MW	Relatively good	No	2 km
Cluster of mini-grids	Kamango	8.5 MW	Good	Yes	75 km
Main grid	Kay Hill	8.5 MW	Poor	Yes	15 km
Main grid	Akle wind farm	170 MW	Good	No	600 km

2.3. Annual power production at the four sites

The WAsP software is used to predict annual wind-power production at the sites based on the generalized wind resources for the region (available in grid points of 7.5 × 7.5 km) or on data from nearby wind measurement masts in case such data are available. The WAsP software further requests information on the local topography, surface roughness, local obstacles and power curves for the wind-turbines.

2.4. LCOE for wind-power generation

Based on assumptions concerning the financial parameters and available data on investment, as well as the operational and maintenance costs of similar power projects in Africa, the LCOE was calculated by means of a spreadsheet model developed for the purpose. The LCOE expresses the discounted lifetime cost divided by discounted lifetime generation.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+\mathrm{r})^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+\mathrm{r})}} \quad (1)$$

Where: I_t = investment expenditure in year t; M_t = operational and maintenance expenditure in year t; F_t = fuel expenditure in year t (not relevant for wind); E_t = electricity generation in year t; r = interest rate; n = life of the system.

2.5. System integration and LCOE for heavy fuel oil-based electricity production

Challenges to system integration are evaluated based on the energy system's production and consumption patterns described in [26] and supplemented by production data from the regional hydropower plant. The LCOE for heavy fuel oil (HFO)-fired generators is estimated based on

detailed background data on the fuel consumption and maintenance costs of existing power plants in Mali.

3. Wind Resource Assessment

3.1. Wind data

Measurements performed by CNESOLER since 2008 at fourteen locations are used in the validation of the wind atlas. The wind has been measured for at least one year at each site. Variations between the times of the measurements are given in Figure 2, while more detailed information about the measurements is provided in Table 2.

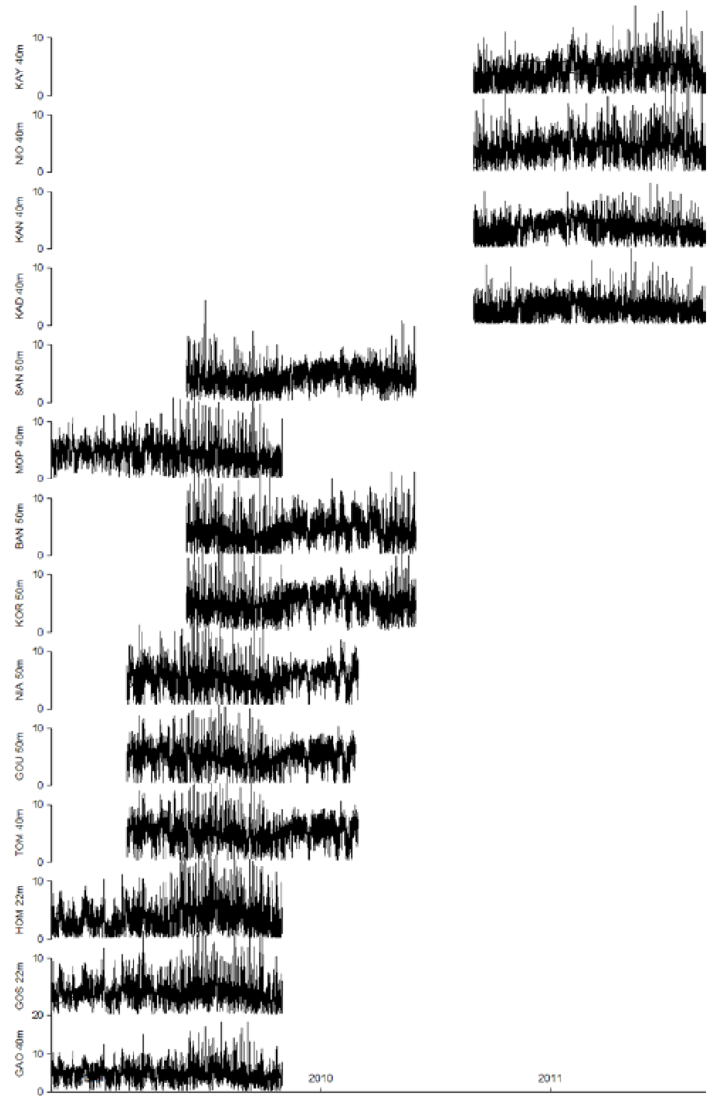

Figure 2. An overview of the wind measurements performed by CNESOLER at fourteen sites starting in 2008 (Data source: CNESOLER 2012).

Table 2. Measured mean and ten-minute maximum (in parentheses) wind speeds and calculated wind-power densities at measured height and at 50 m height (@ 1.225 kg/m^3 standard air density) for one year of data for fourteen stations during 2008–2011, sorted by the estimated generalized power density at 50 m and 3 cm surface roughness length (data source: CNESOLER, 2012).

Station	UTM29 (km)		Data from	Height (m)	Wind (m/s)	Power (W/m^2)	P@50 m (W/m^2)
Goundam	E 1072	N 1821	01-03-2009	50	5.5 (32)	160	185
Niafunke	E 1036	N 1768	01-03-2009	50	5.4 (37)	149	170
Timbuktu	E 1144	N 1859	01-03-2009	40	5.2 (33)	130	136
Koro	E 1139	N 1566	01-06-2009	50	5.1 (31)	125	136
Kayes	E 240	N 1602	01-09-2010	40	4.2 (24)	80	122
Gao	E 1464	N 1818	01-11-2008	40	4.8 (38)	112	119
Nioro	E 438	N 1685	01-09-2010	40	4.4 (25)	93	110
Bandiagara	E 1083	N 1595	01-06-2009	50	4.3 (36)	96	101
Mopti	E 1030	N 1610	01-11-2008	40	4.4 (43)	88	95
San	E 945	N 1473	01-06-2009	50	4.4 (35)	82	92
Hombori	E 1284	N 1704	01-11-2008	22	3.9 (37)	91	-
Gossi	E 1328	N 1765	01-11-2008	22	4.1 (37)	78	-
Kangaba	E 563	N 1321	01-09-2010	40	3.7 (18)	50	60
Kadiolo	E 855	N 1170	01-09-2010	40	3.1 (20)	33	51

Exactly one year of wind data has been extracted from each site and been screened for errors as input to WAsP to eliminate seasonal bias in the results. WAsP regional wind resource data files have been estimated for each site.

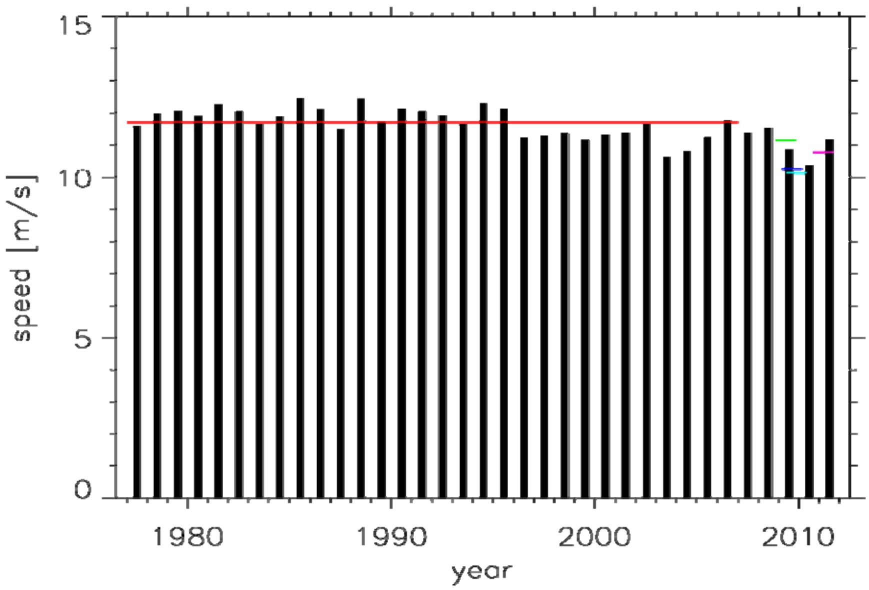

Figure 3. Variation of the annual large scale mean geostrophic wind speed from year to year (vertical bars) for Mali with indication of the thirty-year average value (red line) and the mean value for the different measurement periods (green, purple, blue and pink lines).

The variation in the annual mean for large scale geostrophic wind speed from year to year for Mali, with an indication of the thirty-year average value and the average values for the measurement periods, is shown in Figure 3. The figure shows that the measurement periods appear to have occurred during a period of slightly weaker large scale geostrophic wind speed. This may indicate that the measurement wind climates are slightly conservative relative to the long term wind climate, i.e. slightly underestimating the long term wind resources. For the validation of the windatlas presented in [27] this effect is accounted for by weighting of the modelling results appropriately for the measurement period as described in [25].

3.2. Results

3.2.1. Average wind speed and wind-power density

The spatial distribution of average wind speed in Mali is illustrated in Figure 4. The figure shows the 'simulated wind speed' at 50 m a.g.l based on a KAMM modelling. The map has been created using a resolution of 7.5 km, which means that it does not take into account the actual, detailed local conditions of the topography (orography) or the surface roughness. It may therefore be possible to find local sites, for example, with local speed-up effects due to the local topography, thus providing a higher wind-energy potential than indicated by the maps. The results are also available as a set of generalized wind climate data files (WAsP wind climate input files) on a grid distributed over the country. These WAsP input files are available on the web.[5]

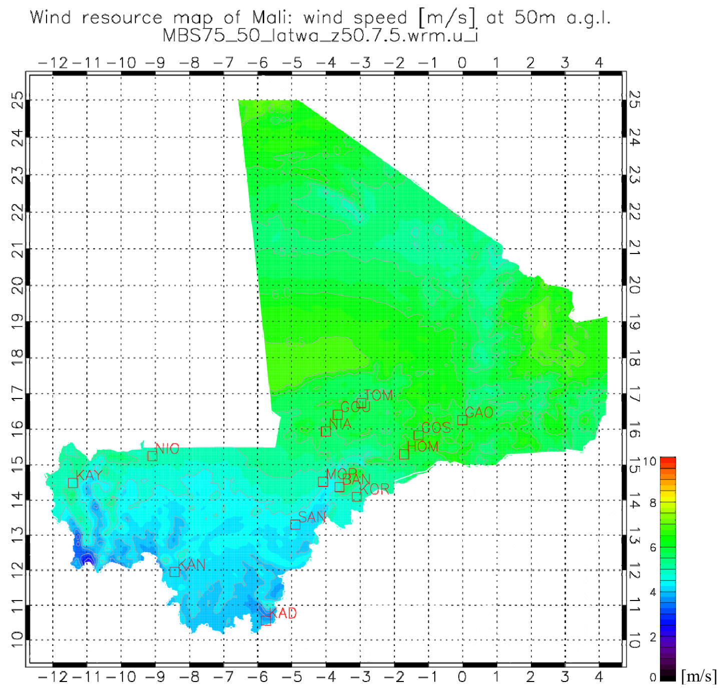

Figure 4. Annual mean simulated wind speed at 50 m a.g.l. The contour interval is 0.5 m/s and colour scale is in m/s [27].

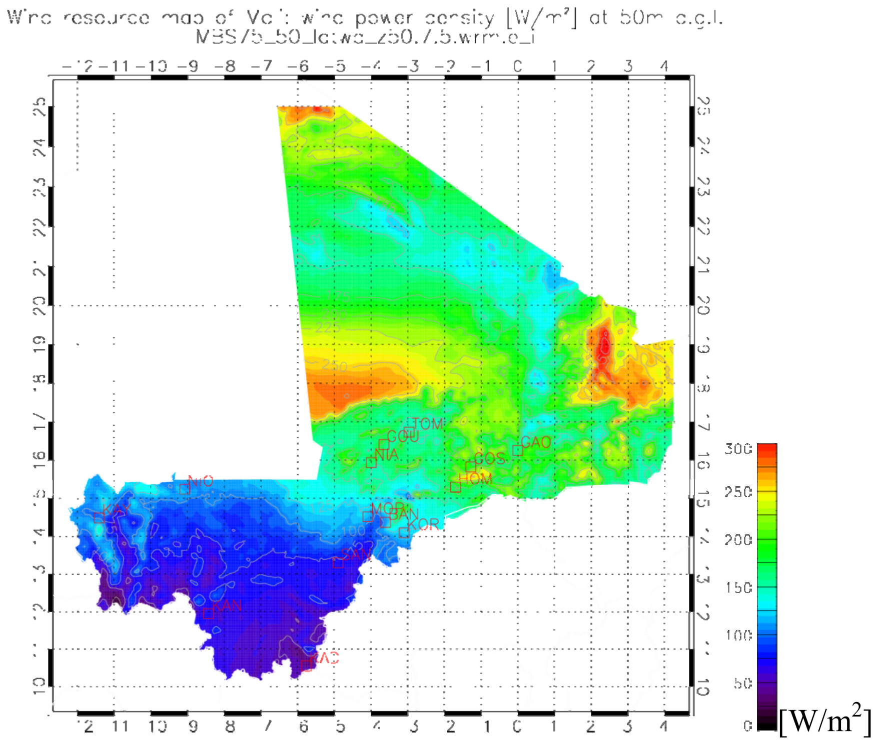

Figure 5. Simulated average wind power density for Mali (in W/m^2) at 50 m height level [27].

The resolution of the wind-speed map in Figure 4 and wind-power density in Figure 5 is 7.5 km. This means that local topography and roughness are not taken into account. It may thus be possible, as illustrated in section 4.1, to find local sites with, for example, local speed-up effects due to the topography, thus providing a higher wind energy potential than indicated by the maps.

3.2.2. Yearly and daily variations

The characteristic variations of the wind resources–and thus the variation in wind-power generation from possible wind turbines–from year to year, over the year, over the day and from minute to minute (the last indicated by the turbulence) are important in evaluating wind power and integrating it into the specific power system, as further noted in section 5 below.

Examples of the characteristics of the variations in wind resources over the year and over the day are illustrated for Kayes in Figure 6 and for Goundam in Figure 7. The upper parts of the figures show monthly averages of wind speeds, the turbulence intensities and wind-power densities for each month. The lower part of the figures show wind speed and wind-power densities for each hour of the day.

The examples show clear, systematic, but different characteristic variations in these resources over the year and over the day. Kayes shows maximum resources in spring and summer, and minimum in autumn and winter through to February. Kayes shows maximum resources at midnight and midday, and minimum resources during mornings and afternoons. Goundam shows maximum resources in summer and minimum in autumn. Goundam shows maximum resources during the morning and late evening, and minimum resources during the early morning and early evening. The variations should be seen as mainly indicative, as they are based on only one year of measurements.

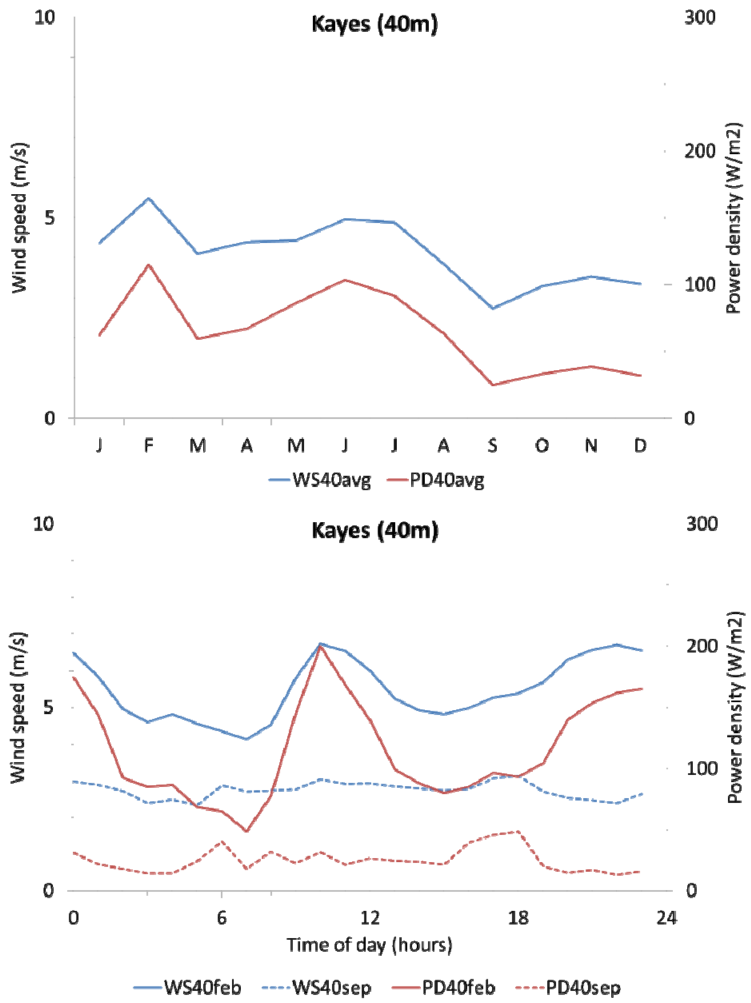

Figure 6. Example from Kayes of the variation of the wind resources (in terms of wind speed and corresponding power density at standard air density conditions, 1.225 kg/m^3) over the year and over the day, based on one year of measured data. Upper: monthly average wind speeds (WS) and wind-power densities (PD). Lower: hourly average wind speeds (WS) and wind-power densities (PD) over the day for February and September (CNESOLER, 2010/11).

In general, wind resources increase with latitude, from very little wind in the south (where the population and the load is) to better wind in the north (with sparse population): see Figure 4 and Table 2. With regard to annual variation, wind resources are higher during the dry season (from November to March), when the prevailing wind is from the north-east, than during the wet season (from April to October), when the prevailing wind is from the south-west.

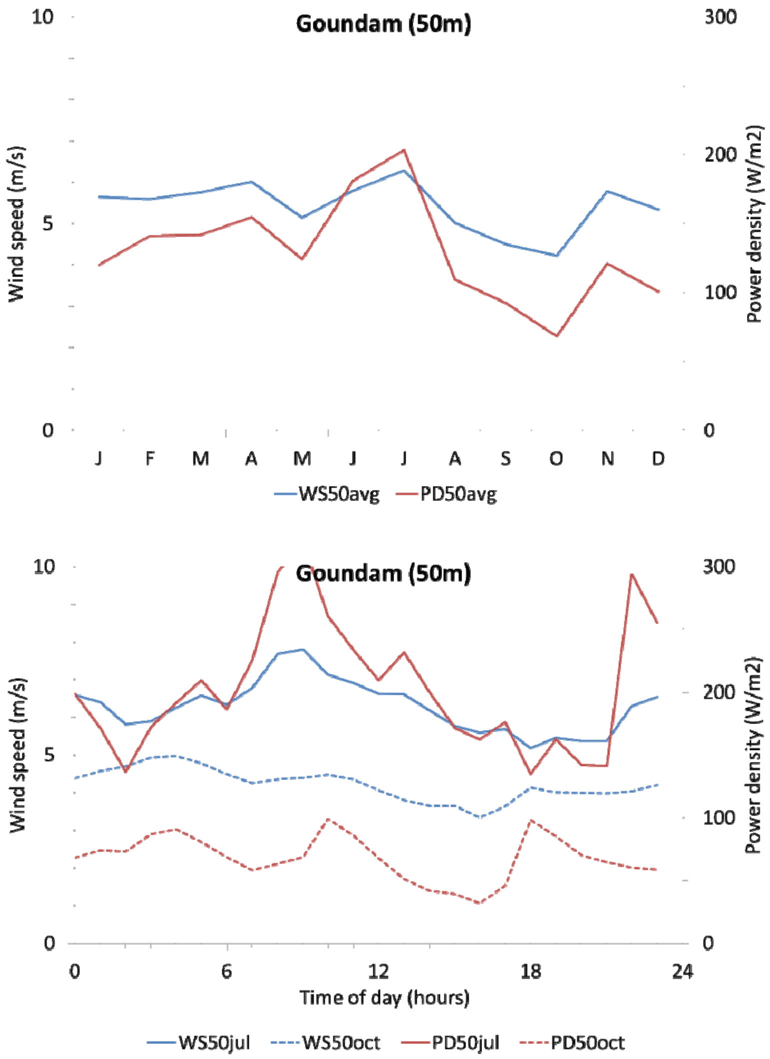

Figure 7. Example from Goundam of the variation in wind resources (in terms of the wind speed and the corresponding power density at standard air density conditions, 1.225 kg/m^3) over the year and over the day, based on one year of measured data. Upper: monthly average wind speeds (WS) and wind-power densities (PD). Lower: hourly average wind speeds (WS) and wind-power densities (PD) for July and October (dashes) (CNESOLER, 2009/10).

4. Case Studies of Wind Applications in Mali

This section will illustrate the economic feasibility of the integration of wind into Mali's electricity grid by estimating the electricity production and the LCOE for wind power at four different wind-power configurations and sites in the country. The selection of cases and variations of parameters are described in section 2 (above).

According to the wind map in Figure , potential areas for the development of larger wind farms can be found 300 km north-west of Timbuktu and 400 km north-east of Gao. Unfortunately these areas, though suitable for large wind farms, are far from the integrated electricity grid. The existing grid ends at Segou, though an extension to Mopti was planned for 2017–2018 [26], but due to the

current political instability in the area its present status is unknown. The distances from the areas mentioned above to Mopti are 400 km and 500 km respectively. Figure 8 maps the wind-power density along with existing and planned transmission lines.

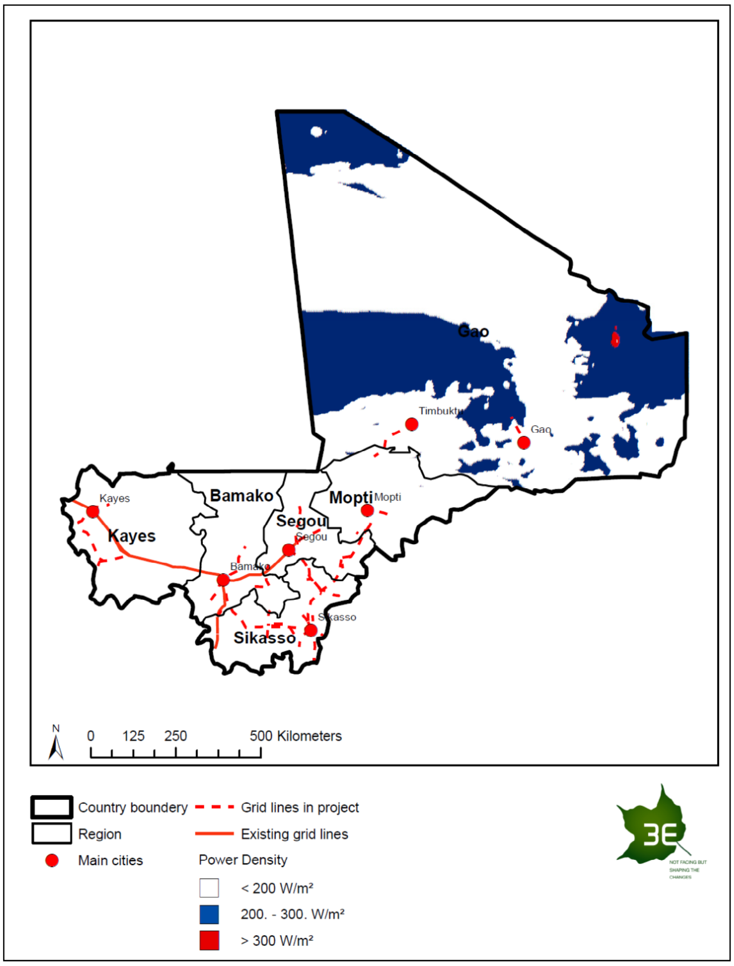

Figure 8. Wind-power density and existing and planned transmission lines.

4.1. Estimates of electricity production

This section estimates the annual productions from the four case studies (see section 2) by the WAsP tool, based on the measured wind data for a full year at the nearby measurement stations, the height contours and the surface roughness.6 The maps in Figure 9–12 indicate the locations of the measurement masts and the wind turbines. The wind power density at 50 m height level, estimated by the WAsP tool, is indicated for an area around the wind farms. The left maps give and overview, while the right maps zoom in on the wind farms.

4.1.1. Timbuktu

As an example of a small-scale wind farm for isolated diesel-based power systems, a 675 kW wind farm is assumed to exist north of Timbuktu town (see Figure 9). The wind farm consists of

3 × 225 kW Vestas V29-225 wind turbines designed for low wind conditions with a 29 m rotor diameter and corresponding to a generator capacity / swept area ratio of 340 W/m^2.

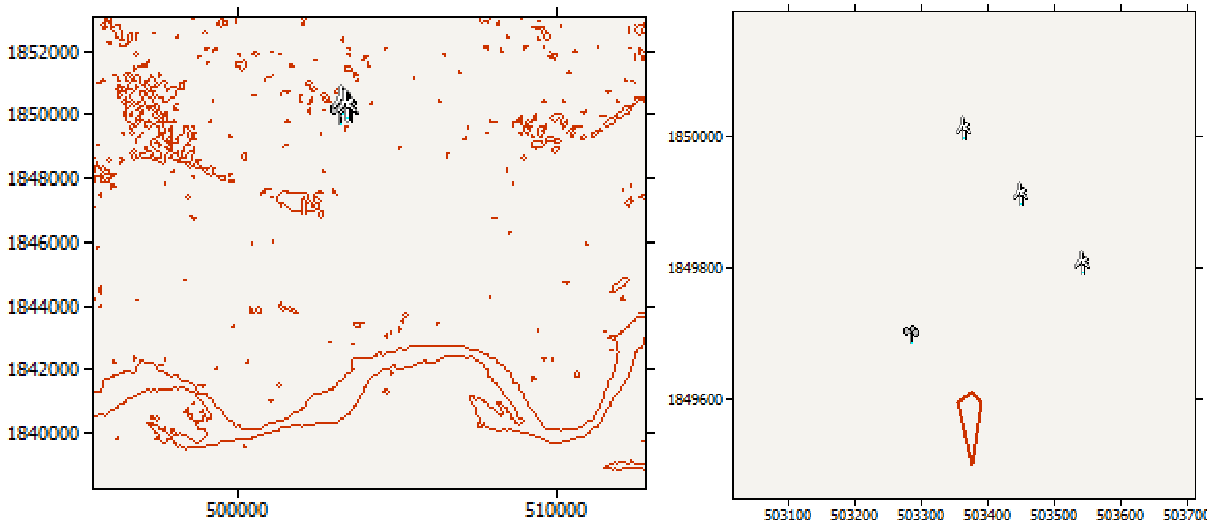

Figure 9. WAsP topographic maps indicating the 675 kW Timbuktu Wind Farm north of Timbuktu town and the Timbuktu measurement station at the airport. X and Y axis are the UTM coordinates in metres. The left map gives an overview, the right map zoom in on the wind farm an the measurement station. Local landscape 10 m hight contour lines are seen on the map to the left, but almost absent on the close up of the site shown at the map to the right. illustrating a fairly flat landscape.

A WAsP calculation based on the wind atlas estimates annual energy production from the wind farm at 700 MWh, corresponding to a load factor for the wind turbines of 12%.

An earlier feasibility study conducted by one of the authors presents calculations for another technology based on tilting windmills (MP275 Vergnet), which have an output of 275 kilowatts and a tower height of 55 m [28]. This alternative, consisting of four turbines, produces 1850 MWh. The load factor is 19%, mainly because the hub height is increased from 32 meter for the Vestas turgines to 55 meter for the Vergnet. For three wind turbines, potential annual energy production would be 1350 MWh.

4.1.2. Kamango wind farm

As an example of the integration of wind power into a cluster of mini-grids, an 8.5 MW wind farm is assumed to exist at Kamango, 75 km west of Timbuktu and 60 km north of Goundam, making use of the wind speed-up effect from a 100 m north-south oriented hill, and connected to the Goundam–Timbuktu cluster system (see Figure 10).

The wind farm consists of 10 × 850 kW wind turbines (Vestas V60-850) designed for low wind conditions, with a 60 m rotor diameter corresponding to a generator capacity / swept area ratio of 300 W/m^2, and relatively high surface roughness, with a 60 m hub height. Annual energy production from the wind farm is estimated by WAsP at 28 GWh, corresponding to a load factor of 38% and based on measured data at Goundam.

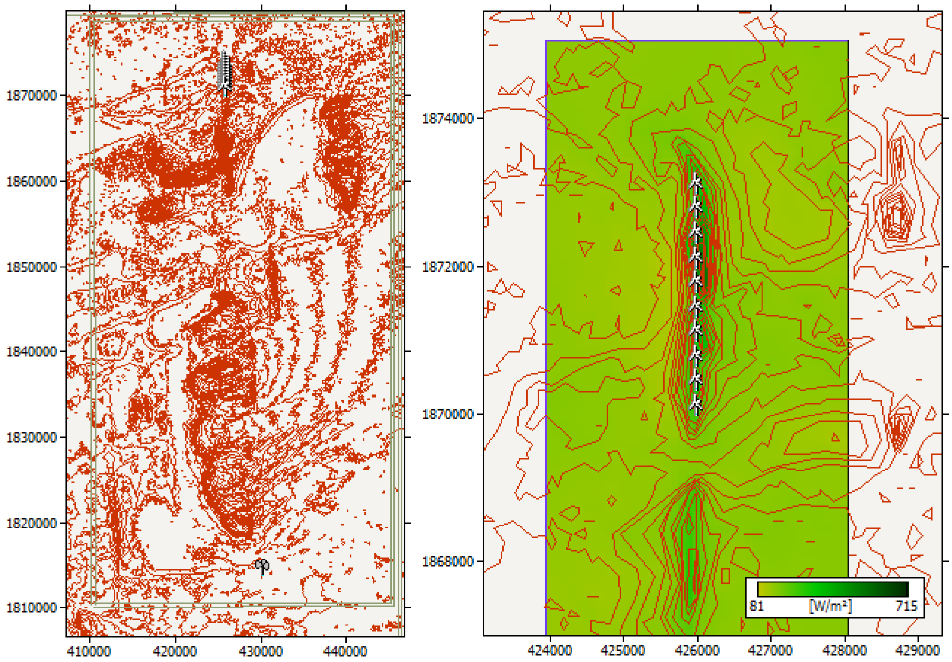

Figure 10. WAsP topographic maps indicating the 8.5 MW Kamango Wind Farm at a 100 m north-south oriented hill and the Goundam measurement station at the bottom of the left map. Power density distribution for the wind farm site is illustrated on the right map. X and Y axis are the UTM coordinates in metres. The left map gives and overview, the right map zoom in on the wind farm. The maps show the 10 m height contour lines. As the measurement station is placed in relative non-complex terrain, the data form a good basis for the calculation of the wind resources in the area. The WAsP model calculates the wind speed-up effects where the wind turbines are indicated. The power density distribution (W/m^2) is calculated and show for an area around the wind farm.

4.1.3. Kayhill wind farm

As an example of a small wind farm near and connected to the central power system, an 8.5 MW wind farm is assumed to exist 15 km south of Kayes, making use of the wind speed-up effect from a 100 m NNW-SSE oriented hill (see Figure 11).

The wind farm consists of 10 × 850 kW wind turbines (Vestas V60-850) designed for low wind conditions, with a 60 m rotor diameter corresponding to a generator capacity/swept area ratio of 300 W/m^2, and relatively high surface roughness, with a 60 m hub height. Annual energy production estimated by WAsP from the wind farm is 25 GWh, corresponding to a load factor of 34%, and based on the measured data at Kayes. For comparison, the estimated annual production for a similar wind farm next to the measurement station is 10 GWh, corresponding to a load factor of 13%.

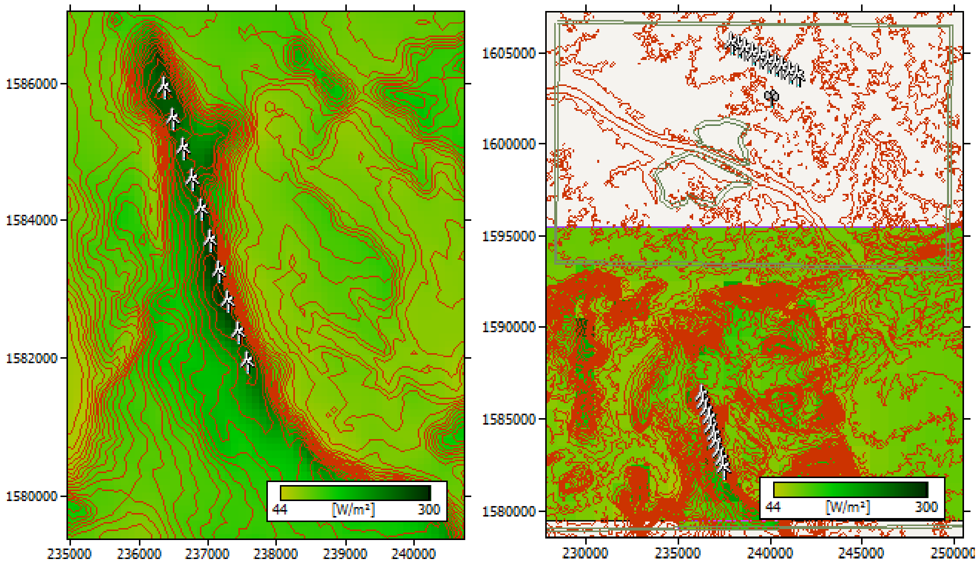

Figure 11. WAsP maps indicating the 8.5 MW Kayhill Wind Farm at a 100 m NNW-SSE oriented hill, the Kayes. X and Y axis are the UTM coordinates in metres. The left map gives an overview, while the right map zoom in on the wind farm, both with 10 m height contour lines. The measurement station is located in a relative non-complex terrain 15 km north of the wind farm (the left map). The right map indicates the power density distribution (W/m^2) and the positions of the wind turbines. The power density distribution has only been calculated for mountain area with potential wind speed-up effects (the lower part of the left map).

4.1.4. Akle wind farm

As an example of a large-scale wind farm far from, but connected to, the integrated power system, a 170 MW wind farm is assumed to exist in the desert 300 km NW of Timbuktu, 600 km from the main grid (see Figure 12).

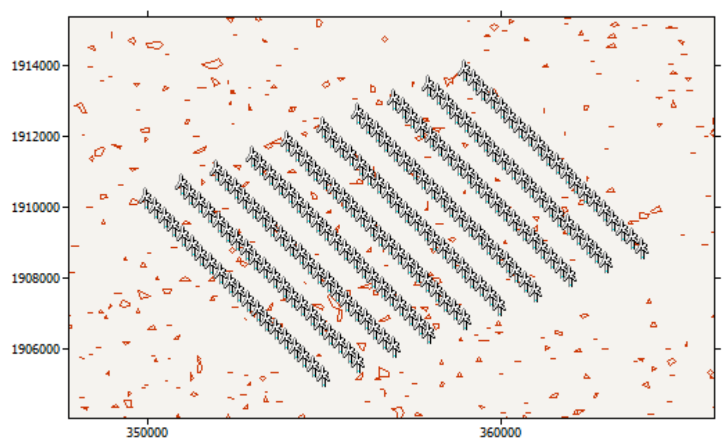

Figure 12. WAsP topographic maps indicating the 170 MW Akle Wind Farm in the desert west of Timbuktu. X and Y axis are the UTM coordinates in metres.

The wind farm consists of 200 × 850 kW Vestas V60-850 wind turbines arranged in 10 NW-SE oriented rows, each of 20 units. The distance between the rows is 1000 m (17 times the rotor diameter), while the distance between the units in a row is 500 m (8 times the rotor diameter), an area of 10 × 10 km in total.

The WAsP analysis indicates wake losses in the area of 10% and a total annual energy production of 340 GWh (corresponding to a load factor for the wind turbines of 23%).

4.1.5. Summary of wind power production in the case studies

An overview of the annual power generation estimated by WAsP and the corresponding wind turbine load factors for the four sites and for different models of the two wind turbines, used as examples, is presented in Table 3.

Table 3. Illustration of the impact of the type of wind turbine on estimated annual production (with the corresponding load factors in parentheses) at the four selected wind farm sites.

Wind farm	Elev. (m)	No.	V27	V29	Vergnet	V52	V60
Timbuktu	260	3	0.6 GWh (10%)	0.7 GWh (12%)	1.9 Gwh (19%)	-	-
Kamango	350	10	5.7 GWh (29%)	6.2 GWh (31%)		23 GWh (31%)	28 GWh (38%)
Kayhill	350	10	5 GWh (25%)	5.5 GW (28%)		20 GW (27%)	25 GWh (34%)
Akle	280	200				255 GWh (17%)	340 GWh (23%)

Turbine	Generator	Rotor	Hub height
V27-225/32	225 kW	27 m	32 m
V29-225/32	225 kW	29 m	32 m
Vergnet HP 275/55	275 kW	32 m	55 m
V52-850/55	850 kW	52 m	55 m
V60-850/60	850 kW	60 m	60 m

The impacts of the rotor diameter and hub height are illustrated for the Timbuktu wind farm: with a rotor diameter of 27 m and a hub height of 32 m, the load factor is estimated at 10%. Increasing the rotor diameter by 7% to 29 m increases the load factor by 20% to 12%. Increasing the hub height by 70% to 50 m increases the load factor by 40% to 17%.

The impact of the speed-up effect of the topography is illustrated by the two similar wind farms at Kayes–increasing the load factor by 150% from 13% to 34%. It must be stressed that WAsP calculations are rather uncertain in very complex terrain, as is the case for the Kayhill and Kamango wind farms. The actual wind resources must be confirmed by local measurements at the sites.

4.2. Levelized cost of electricity

The assessment of LCOE comprises investment cost and maintenance cost and depends on a number of financial preconditions. These costs and conditions are presented in the following based on the authors' experience of similar projects in sub-saharan Africa.

4.2.1. Financial assumptions

In practice, a number of financial assumptions, such as inflation, subsidies, tax reductions, the cost of borrowed capital, equity capital, and project lifetime, will determine the LCOE. For the sake of simplicity and transparency, in this paper we use the weighted average cost of capital (WACC) as interest rate (r) for calculating LCOE in equation (1). WACC is calculated based on the share of the investment covered by equity, soft loans (e.g. from the World Bank) and other bank finance following the equation below.

$$r = WACC = f_e \times r_e + f_s \times r_s + f_b \times r_b \qquad (2)$$

Where: f_e = Equity fraction of capital, r_e = Interest rate on equity, f_s = Fraction of capital met by softloans, r_s = Interest rate of softloans, f_b = Fraction of capital requirement met by other bankloans, r_b = Interest rate of other bankloans.

In this case WACC is 7%, based on the following financial assumptions: [7]

f_e = 20%, f_s = 60%, f_b = 20%, r_e = 17.5%, r_s = 2.5% r_b = 10%.

Life time 20 years

4.2.2. Capital expenditure (CAPEX)

Applications in emerging countries require robust technology. This includes: i) a power-electronic grid interface that can cope with large variations in voltage frequency and voltage amplitude; ii) a grid interface that can withstand dips and interruptions to grid voltage due to short-circuits in the grid; iii) an extended temperature range for applications in extremely hot, cold or humid environments; iv) increased protection against dust or mechanical particle infiltration for installations near mines or sandy areas; and v) enhanced controllability of output power and limitation of rotational speed for applications in smaller grids or wind-diesel systems. These requirements mean additional costs compared to projects in Europe, and the cost figures for the wind turbines are therefore taken either from quotes for the same type of wind turbine for equivalent projects in Europe and South Africa, or from other projects in Africa. The price of the SCADA control system is stable across all markets and does not depend on the price of the wind turbines. Cost estimates are at 2012 price levels, and based on [6] it is anticipated that investments and operational and maintenance costs have remained at the 2012 nominal level due to general cost reductions for wind turbine investments and operations.

Table 4 sets out the assumptions used in the model. This cost includes the tower, the complete nacelle, the hub, the three blades and the 690 V/20 kV transformer.

The costs of installation and commissioning are also taken from quotes for projects of this size in South Africa. For example, for Gamesa G52, with a hub height of 55 and 65 m, a 600-tonne lattice crane is required, and the cost of mobilization/demobilization (€140,000) is based on a crane from Europe or North Africa. Examples in Africa (Lake Turkana) show that such large turbines require a lot of logistical preparation. For these reasons, we excluded the use of wind turbines with a nominal power greater than 1 MW.

Table 4. Unit costs for wind turbines.

	Gamesa 52 850 kW 55 m	Vestas- 850 kW 60 m	Vestas- 225 kW 29 m	Vergnet HP 275 55 m
Wind turbine (€/wind turbine)	800,000	870,250	210,000	450,000
Discount for large quantities	10%	10%		
SCADA System (€)	40,000	40,000	22,000	included
Installation and commissioning (€/wind turbine)	80,000	80,000	30,000	10,000
Mobilization/demobilization of main crane (€)	140,000	200,000	60,000	
Daily rate for main crane (€) estimated at 3 days per project	5000	5000	3000	
Sea transport (€/wind turbine)	25,000	25,000	15,000	15,000
Road transport (€/wind turbine)	80,000	80,000	25,000	15,000

Table 5 below shows the unit costs for calculating the total cost of civil and electrical engineering for the project. There is no grid available in a large part of Mali, and consequently overhead lines have to be constructed. The maximum voltage level in Mali is 225 kV, ending in Mopti. In the case of the large wind farms, this figure is certainly above 100 MW, so a 220 KV line will be needed. For the smaller wind farms, a 33 kV extension would be feasible as well [29].

Table 5. Unit costs for civil and electrical engineering.

	Gamesa52- 850 kW 55 m	Vestas 850 kW 60 m	Vestas 225kW 29 m	Vergnet HP 275 55 m
High-voltage network (€/km)	100,000	100,000	100,000	100,000
Medium-voltage network (€/km)	25,000	25,000	25,000	25,000
Roads/tracks/crane operation areas (€/wind turbine)	40,000	40,000	40,000	10,000
Wind turbine foundation (€/wind turbine)	100,000	100,000	34,000	10,000

4.2.3. Operational and maintenance costs

The financial model is based on the data and assumptions shown in Table 6:

Table 6. Assumptions of operation and maintenance costs.

	Vestas	Gamesa	Vergnet
Annual maintenance contract, first 10 years	5%	5%	5%
Annual maintenance contract, years 11–20	6%	6%	6%
Duration of initial contract (availability guarantee, in years)	10	10	10
Annual indexation (%)	3	3	3
Insurance	0.5%	0.5%	0.5%

Wind turbines are normally guaranteed for continuous availability with a maintenance contract. In Europe this availability reaches 97%. However, for remote locations, especially where the market for wind turbines is rather low, manufacturers are not willing to guarantee such a high level of availability. Consequently higher maintenance costs and lower availability levels might be expected.

The services and guarantees provided by the maintenance contracts are difficult to estimate at this stage, as they strongly depend on the strategy chosen for Mali: Vestas, Gamesa or Vergnet. If the wind farm is the manufacturer's only wind farm in the country, the manufacturer will probably train local sub-contractors and offer quite a low level of guarantee, which should bring down the costs of the maintenance contracts. On the other hand, if the manufacturers are seeking to establish themselves in the country, they will offer more expensive contracts with better levels of guarantee and services provided by their own staff. The cost of the annual maintenance contracts factored into the model corresponds to a high price level for contracts offering relatively low guarantees (92–95%). All insurance costs and expenses are values observed by 3E in Europe and South Africa for projects of equivalent size.

4.2.4. Assessment of levelized cost of energy

Based on the economic assumptions above, the LCOE for each of the four cases is set out in Table 7. Detailed calculation of LCOE for the four cases utilising different types of wind turbines.. For purposes of technological comparison, the LCOE figures are calculated for up to two selected turbine manufacturers for each site.

Table 7. Detailed calculation of LCOE for the four cases utilising different types of wind turbines.

	AKLE		**TIMBUKTU**		**KAYHILL**	**KAMANGO**
	Gamesa 52-850 kW 55 m	**Vestas V60 850 kW 60 m**	**Vestas V29 225 kW 29 m**	**Vergnet HP 275 55 m**	**Vestas V60 850 kW 60 m**	**Vestas V60 850 kW 60 m**
Number of turbines	200	200	3	3	10	10
Capacity [kW]	850	850	225	275	850	850
Total capacity of wind farm [kW]	170,000	170,000	675	825	8500	8,500
Wind turbine [€/wind turbine]	720,000	783,225	235,000	450,000	870,250	870,250
Scada system [€]	40,000	40,000	22,000	included	40,000	40,000
Foundations	100,000	100,000	34,000	10,000	100,000	100,000
PRICE FOR WIND TURBINE+FOUNDATION [€]	860,000	923,225	291,000	460,000	1,010,250	1,010,250
TOTAL PRICE [€]	**172,000,000**	**184,645,000**	**873,000**	**1,380,000**	**10,102,500**	**10,102,500**
Installation and commissioning [€/wind turbine]	80,000	80,000	30,000	10,000	80,000	80,000
Mobilization/demobilization main crane [€]	140,000	200,000	60,000		200,000	200,000
Rate for main crane [€]	15,000	15,000	5,000		15,000	15000
Sea transport [€/wind turbine]	25,000	25,000	15,000	15,000	25,000	25,000
Road transport [€/wind turbine]	80,000	80,000	40,000	25,000	100,000	60,000
Roads and crane tracks	40,000	40,000	15,000	10,000	40,000	40,000
COST OF LOGISTICS [€]	**48,140,000**	**48,200,000**	**375,000**	**180,000**	**2,800,000**	**2,400,000**
High voltage network [€/km]	100,000	100,000	25,000	25,000	25,000	25,000
Distance [km]	600	600	5	5	20	60
Cost of interconnector [€]	60,000,000	60,000,000	125,000	125,000	500,000	1,500,000
Cost of Transfo+BOP [€]	5,000,000	5,000,000			100,000	100,000
INTERCONNECTOR INVESTMENT [€]	**65,000,000**	**65,000,000**	**125,000**	**125,000**	**600,000**	**1,600,000**
TOTAL INVESTMENT [€]	**285,140,000**	**297,845,000**	**1,373,000**	**1,685,000**	**13,502,500**	**14,102,500**
INVESTMENT/KW [€]	**1,677**	**1,752**	**2,034**	**2,042**	**1,589**	**1,659**
Operation and maintenance, first 10 years [%]	5	5	5	5	5	5
Operation and maintenance, years 11–20 [%]	6	6	6	6	6	6
Insurance [% of investment]	0.5	0.5	0.5	0.5	0.5	0.5
POTENTIAL WIND POWER P50 [GWh]	**255.0**	**344.0**	**0.7**	**1.3**	**25.0**	**28.0**
LCOE PER KWH [€/kWh]	**0.17**	**0.13**	**0.32**	**0.17**	**0.083**	**0.078**
LCOE PER KWH [CFA/kWh]	**112**	**85**	**210**	**112**	**54**	**51**

5. Wind Energy Integration

This section will discuss the challenges of integrating wind into the main grid and into mini-grids and mini-grid clusters, as well as estimating the avoided cost of electricity in the three grid sizes. The section concludes with an assessment of the economic feasibility of wind-produced electricity compared to existing alternatives in the four cases.

5.1. Dynamic integration into the main grid

In 2012 about 150 MW of hydropower was in operation, and another 60 MW was planned to be in operation before 2015. A high-voltage interconnection line to the Ivory Coast of up to 200 MW was under construction, and another interconnection of 160 MW to deliver electricity from Ghana was planned to be in operation from 2014. The remaining demand would be delivered by 215 MW of diesel generators [26]. In Mali, the available water in the main hydropower schemes is the limiting factor for electricity production throughout the year. For example, the Manantali hydropower scheme, which has been in operation since 2001, has never reached its full operational level. In 2010 the Manantali dam, with a rated output of 200 MW, was operating at an annual average load of 97 MW, due to low water level in the dam.[8] The low load factor means that the hydropower schemes can be used as dynamic regulators to balance the fluctuating wind power on an hourly basis, and the wind power produced can be used to 'save water' and provide a seasonal delay in utilization of the hydropower. To illustrate the regulation potential, Figure 13 shows the seasonal water level in the Manantali dam on the Senegal River, while Figure 14 shows how production is held at a low level in the autumn to save water, with the result that production can increase in the spring months, where the power demand in the main grid is at its highest [26]. Figure 15 shows how the Manantali hydropower scheme is used to follow the daily load patterns in February, May, August and November respectively.

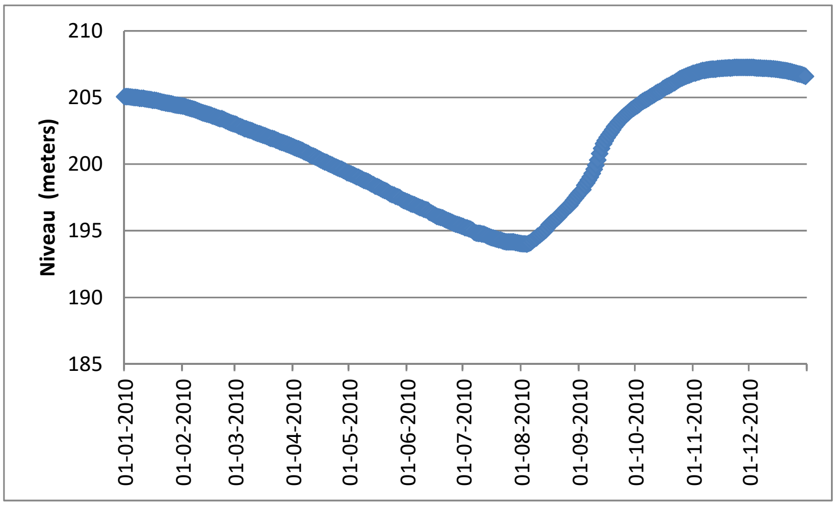

Figure 13. Variation in water level in the Manantali dam in 2010 (SOGEM).[9]

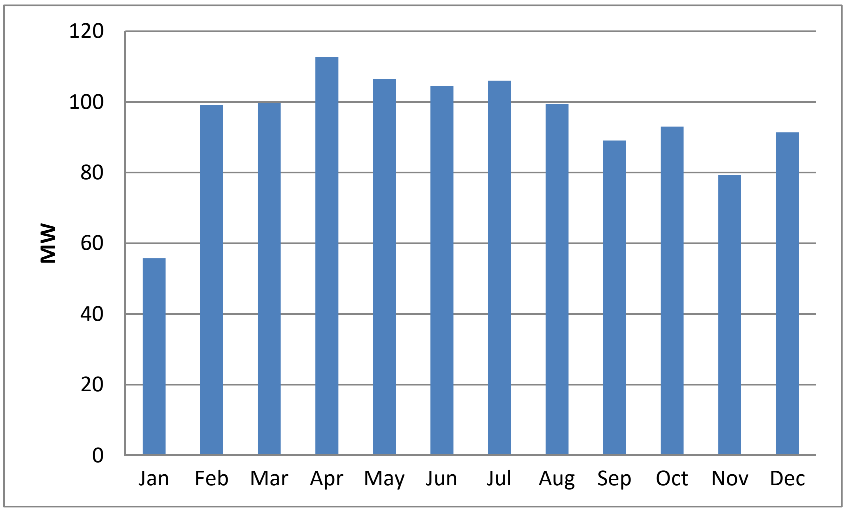

Figure 14. Average monthly power output for Manantali in 2010 (SOGEM).[9]

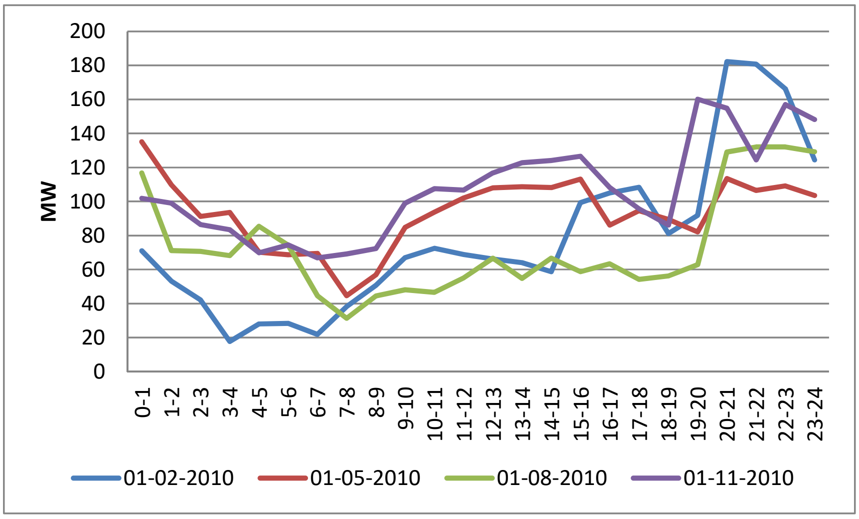

Figure 15. Average power output per hour for Manantali in 2010 (SOGEM).[9]

The descriptive statistics above show that there was a high regulatory capacity in the grid by 2012, which would be sufficient for a number of smaller wind projects in the range of 10 to 20 MW. By 2012, it was unrealistic to integrate 170 MW of wind power into the 400 MW of existing capacity, but with planned future interconnections to the Ivory Coast and Ghana of 160 MW and 200 MW capacity respectively, large-scale wind power could be an option within a time frame of five to ten years.

5.2. Integration into mini-grids and clusters of mini-grids

In the mini-grids and clusters, wind turbines will operate in hybrid mode with the existing diesel power plant. Three different levels of the penetration of renewables into weak grids are normally considered:

(1) Low-penetration systems: renewable energy acts as a negative load, and very little control of or integration of wind turbines into the power system is needed (20% renewable fraction).
(2) Mid-penetration systems: renewable energy becomes a major part of the power system. Additional components and limited automated control are required to ensure that power quality is maintained. Little operational control is required, though it may be used (20–50% renewable fraction).
(3) High-penetration systems: completely integrated power system with advanced control. Limited operational control of system by plant staff (50–100%).

In this case, we have assumed wind fractions of up to 50%, corresponding to a mid-penetration system, which means that little operational control is required.

5.3. Value of wind electricity in existing grids

Given that hydropower schemes have the regulatory capacity to balance wind production, the value of wind electricity (avoided costs) in the main grid equals the marginal cost of firm power delivered either by large heavy fuel oil (HFO)-powered diesel power plants, or at best by the 200 MW planned interconnection to Ghana [26]. According to the Master Plan for the electricity sector from SOGREAH (2009), the marginal cost for the interconnection to Ghana is in the range of 9.9 to 15.2 $€_{cent}$/kWh, contingent on price negotiations. By late 2016 price negotiations are still ongoing and commissioning of the interconnector to Ghana is postponed to 2020. Most likely interconnections and hydropower schemes will continue to be delayed, which implies that the marginal cost in the system will consist rather of the LCOE for large HFO-powered diesel generators, which is highly contingent on fuel costs.

From 2010 to 2014 crude oil prices were relatively stable, varying between 100 and 125 USD/bbl, but since 2014 they have dropped to their current level of about 50 USD/bbl.[10] Based on [26], the LCOE produced by large HFO-powered diesel generators is estimated at between 11.1 to 15.7 €cent/kWh, reflecting crude oil prices of 50 and 100 USD/bbl respectably. According to the assessment in [26], the LCOE in the Timbuktu mini-grid will be in the range of 24.7 to 34 €cent/kWh, assuming a crude oil price of 50 to 100 USD/bbl. The LCOE in the Timbuktu mini-grid cluster will be at the same level, but slightly lower than in the Timbuktu mini-grid, due to a moderate economy of scale.

In 2015, contracts for two large-scale solar plants of 33 and 50 MW_p respectively were concluded assumingly at a price of 13.7 $€_{cent}$/kWh (90 CFA/kWh).[11] Given the continuing decrease in the costs of large-scale solar plants, this figure can be seen as an upper limit for avoided costs in the main grid.

5.3.1. Economic feasibility of wind integration

The LCOE for wind electricity in the four cases and the avoided cost in the systems to which the wind farms are connected are summarized in Table 8 below:

Table 8. LCOE for wind and avoided cost for electricity in the four cases.

Grid system	Case study	Size MW	Wind LCOE €$_{cent}$/kWh	Avoided cost (€$_{cent}$/kWh)		
				Thermal		Inter-connection
				50 USD/bbl	100 USD/bbl	(2009 estimates)
Mini-grid	1. Timbuktu	0.6	17.1	24.7	34.0	Not
Mini-grid cluster	2. Kamango	8.5	7.8	24.7	34.0	relevant
Main grid	4. Kayhill	8.5	8.2	11.1	15.7	9.9–15.2
Main grid	3. Akle	170	13.0	11.1	15.7	9.9–15.2

The table shows that small-scale projects, such as the Timbuktu wind farm, have a relatively high LCOE (17.1 €$_{cent}$/kWh), mainly due to the high fixed costs of project development, site preparation, transport and crane support, while the LCOE figures for Kamango and Kayhill, being medium-size wind farms at sites with good wind conditions (e.g. local speed-up effects), are the lowest at 7.8–8.2 €$_{cent}$/kWh. The LCOE for the large-scale wind farm with the best wind conditions is in the range of 13.0–17.1 €$_{cent}$/kWh. This relatively high LCOE is mainly a result of the long road transport of wind turbines and large-scale investments in long high-voltage transmission lines.

Comparison between the LCOE for wind and the avoided costs in the Timbuktu mini-grid shows that, although the LCOE in this case is 17.1 €$_{cent}$/kWh, the high level of avoided cost (15.7–34.0 €$_{cent}$/kWh) makes it economically feasible even at the low crude oil price of 50 USD/bbl. The provision of electricity to the mini-grid cluster by Kamango seems to be the most feasible of the four cases, as it has a low LCOE (7.8 €$_{cent}$/kWh) due to its good wind conditions, medium-size wind farm and moderate length of transmission lines, while at the same time having high avoided costs (24.7–34.0 €$_{cent}$/kWh) due to the substitution of fuel oil-based power.

Comparison between the LCOE for wind electricity and the avoided costs in the main grid shows that the Kayhill wind farm (8.2 €$_{cent}$/kWh) will be financially viable under the condition that the interconnection predicted in the master plan is in operation (9.9–15.2 €$_{cent}$/kWh), while the Akle wind farm (13.0 €$_{cent}$/kWh) will be viable only under the condition that it will replace large-scale diesel power at a crude oil price of 75 USD/bbl (13.1 €$_{cent}$/kWh).

The assumptions above are based on the wind mapping and not on on-site measurements. For wind farms, on-site measurements will always be necessary to refine the energy yield calculation and determine the uncertainties. Therefore the costs of production must be regarded as indicative only. Likewise the figure for the avoided costs in the system is based on a cost estimate seen from the perspective of the utility. For projects to be financially viable, these avoided costs will need to be reflected in a power-purchasing agreement with the utility or in a general feed-in tariff. Land-tenure issues and environmental concerns relating to noise and other disturbances to local communities have not been assessed in this paper, but experience from Europe and lately from the Lake Turkana wind project shows that such concerns need to be taken into account at an early stage of project development.

6. Conclusion

Overall the research in this paper finds that, even under the assumption of current low oil prices, it is possible to establish economically feasible wind-power plants in inland African countries with lower wind potentials. In southern Mali, the research has identified a limited number of sites with local speed-up effects situated close to the existing grid at which there are options for undertaking

economically feasible medium-size wind-power projects. The research project hence sustains the findings of a recent study of the feasibility of inland wind power in Kenya [30]. The research also supports the findings of previous feasibility studies, namely that smaller wind farms (around 1 MW) will be economically feasible if they are connected to isolated grids in Gao and Timbuktu [28,31].

The case study of large wind farms in the north of Mali shows that, in the current physical situation, the logistics and grid extension costs account for about 40% of the total investment costs. The Lake Turkana wind farm in Kenya, which has extraordinary good wind conditions, has signed a power purchasing agreement at a price of 7.5 $€_{cent}$ /kWh.[12] In the present case, however, the wind resource in the north of Mali is not good enough to compensate for the high investment costs, and the LCOE is as high as 13 $€_{cent}$/kWh, which equals the cost of electricity from recently established solar PV plants. Consequently the introduction of wind energy in the north will only be feasible if the infrastructure investments in transmission lines are covered by a larger investment plan for the north, involving, for example, interconnections with other countries. However, due to the political unrest that has affected northern Mali since 2012, this scenario may be unrealistic for the next few years [32].

It is difficult to attract investors to isolated projects involving only a few turbines, as the costs of arranging the delivery of turbines and spare parts and the servicing of the the turbines will be relatively high. The above cost estimates are based on the assumption that a regional market for wind turbines in West Africa can be expected to develop, with the result that competition can be established among turbine providers. The recent commissioning of the two large grid-connected solar PV plants, mentioned above, shows that it is possible to attract foreign investors in spite of the currently unstable political situation [32].

Experience with successive competitive bidding for onshore wind and solar PV in South Africa from 2011–2015 has demonstrated how important competition, economies of scale and political stability are in driving prices down. According to Eberhard and Kåberger [33], four successive bidding rounds totalling 6327 MW have reduced prices for onshore wind and solar PV by 46% and 71% respectively, reaching a low of 3.4 $€_{cent}$ /kWh for wind and 4.7 $€_{cent}$/kWh for PV in 2015. While this development provides hope for further decreases in prices for wind-produced electricity in Mali, we suggest that relatively low wind resources, limited market size and a low level of political stability will maintain prices at a higher level, although still being competitive with diesel-based generation.

Notes

[1] http://www.thewindpower.net/country_list_en.php (Accessed 06.04.17).

[2] http://www.esmap.org/re_mapping_ethiopia; http://www.esmap.org/re_mapping_zambia (Accessed 06.04.17).

[3] The paper thus refines a preliminary assessment of the wind potential in Mali solely based on meso-scale modelling [34].

[4] Downloadable from htttp://www.cdc.noaa.gov/cdc/reanalysis (accessed Jan 2011).

[5] http://wasptadpole.eu/Tadpole/Viewer?gid=A133B742-0C4F-468C-8F32-6DD0394C14FB (Accessed 06.04.17).

[6] For the four cases, the selected sites were very close to a wind measurement mast, and therefore measurement data was considered to be more accurate than the lib files generated for the wind-atlas. While this approach is more precise given its closeness to the measurement mast, it gives a concervative estimate of the electricity production, as the annual wind speed in the year of measurements were below average (see figure 3).

[7] For comparision, in the lake Turkana project, WACC is 7.5% [35], with a equity share, fe = 20% [7]. In the 33 MW solar project in Segou, Mali, fe = 25%, Concessional loan from climate investment fund, fc = 30% and other loans (partly provided by IFC Infraventures, 56 %), fb = 45%. http://www.agenceecofin.com/enr/1107-30583-scatec-solar-awarded-33mw-solar-plant-contract-in-mali (Assessed 28.03.17).

[8] In the Manantali case, the dam has never been filled to the maximum. This means that the electricity production per m^3 of water is lower than maximum, but also that water is not running over the spillway, not even at the end of the rainy season. Interview with Seybou TOURE, SOGEM, February 2012.

[9] Data made available by Seybou TOURE, SOGEM, February 2012.

[10] http://oil-price.net/dashboard.php?lang=en (Assessed 12.10.2016).

[11] This price is not official and has not been verified by any of the involved partners.

[12] The negotiated price is 7.52 € cents per kWh (8.42 US cents where €1 = US$1.12) [35].

Acknowledgement

This research has been supported by the Danish institute for development cooperation, DANIDA, as part of the project 'Feasibility of Renewable Energy Resources in Mali', DANIDA contract no. 1711.

Conflict of interest

All authors declare no conflicts of interest in this paper.

References

1. UN (2012) International Year of Sustainable Energy for All, 2012, Report of the Secretary-General; United Nations General Assembly, Sixty-seventh session, Item 20 of the provisional agenda. Available from: http://www.se4all.org/sites/default/files/l/2015/08/A-67-314-2012-Report-of-the-Secretary-General-to-the-General-Assembly-on-the-Year-of-Sustainable-Energy-for-All.pdf.
2. IEA (2014) World Energy Outlook 2014 Electricity Access Database Available from: http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/.
3. Eberhard A, Foster V, Briceño GC, et al. (2010) Catching Up. In: Foster V, Briceño-Garmendia C, *Africa's Infrastructure: A time for transformation*; IBRD/WB: Washington DC, 181–202.
4. Bazilian M, Nussbaumer P, Rogner HH, et al. (2012) Energy access scenarios to 2030 for the power sector in sub-Saharan Africa. *Util Policy* 20: 1–16.
5. IRENA (2012) Prospects for the African Power Sector; International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates. Available from: https://www.irena.org/DocumentDownloads/Publications/Prospects_for_the_African_PowerSector.pdf.
6. GWEC (2016) Global wind energy outlook; Global Wind Energy Council (GWEC). Available from: http://www.gwec.net/publications/global-wind-energy-outlook/global-wind-energy-outlook-2016/.
7. Tarnoy H (2014) Lake Turkana Wind Power Project (LTWP); Presentation at Seminar on Sustainable Energy Investments in Africa-Engaging the Private Sector UN City, Copenhagen, 25 June 2014. Available from: http://www.unepdtu.org/PUBLICATIONS/Workshop-Presentations/Workshop-Presentations-Sustainable-Energy-Investments-in-Africa.

8. Msimanga B, Sebitosi AB (2014) South Africa's non-policy driven options for renewable energy development. *Renew Energ* 69: 420–427.
9. Alhamwi A, Kleinhans D, Weitemeyer S, et al. (2015) Moroccan national energy strategy reviewed from a meteorological perspective. *Energy Strateg Rev* 6: 39–47.
10. GWEC (2014) Global Wind Energy Outlook 2014; Global Wind Energy Council (GWEC). Available from: http://www.gwec.net/publications/global-wind-energy-outlook/global-wind-energy-outlook-2016/.
11. Adaramola MS, Agelin CM, Paul SS (2014) Assessment of wind power generation along the coast of Ghana. *Energ Convers Manage* 77: 61–69.
12. Ahiataku TW (2014) Perspectives on Sustainable Energy Investment in Ghana; Presentation at Seminar on Sustainable Energy Investments in Africa-Engaging the Private Sector UN City, Copenhagen, 25 June 2014. Available from: http://www.unepdtu.org/PUBLICATIONS/Workshop-Presentations/Workshop-Presentations---Sustainable-Energy-Investments-in-Africa.
13. Dodd J (2014) West Africa's largest project moves closer; *Wind Power Monthly*, 6 January 2014. Available from: http://www.windpowermonthly.com/article/1226020/west-africas-largest-project-moves-closer.
14. Mentis D, Hermann S, Howells M, et al. (2015) Assessing the technical wind energy potential in Africa a GIS-based approach. *Renew Energ* 83: 110–125.
15. Kousksou T, Allouhi A, Belattar M, et al. (2015) Renewable energy potential and national policy directions for sustainable development in Morocco. *Renew Sust Energ Rev* 47: 46–57.
16. El Alimi S, Maatallah T, Dahmouni A, et al. (2012) Modeling and investigation of the wind resource in the gulf of Tunis, Tunisia. *Renew Sust Energ Rev* 16: 5466–5478.
17. Ahmed AS (2012) Potential wind power generation in South Egypt. *Renew Sust Energ Rev* 16: 1528–1536.
18. Mortensen NG, Said SU, Badger J (2006). Wind Atlas for Egypt. In Proceedings of the Third Middle East-North Africa Renewable Energy Conference (on CD-ROM). Available from: http://orbit.dtu.dk/files/52612711/Wind_Atlas_for_Egypt_paper.pdf.
19. Asress MB, Simonovic A, Komarov D, et al. (2013) Wind energy resource development in Ethiopia as an alternative energy future beyond the dominant hydropower. *Renew Sust Energ Rev* 23: 366–378.
20. Ayodele TR, Jimoh AA, Munda J, et al. (2012) Wind distribution and capacity factor estimation for wind turbines in the coastal region of South Africa. *Energ Convers Manage* 64: 614–625.
21. Bilal BO, Ndongo M, Kebe CMF, et al. (2013) Feasibility study of wind energy potential for electricity generation in the northwestern coast of senegal. *Energ Procedia* 36: 1119–1129.
22. Boudia SM, Benmansour A, Ghellai N, et al. (2013) Temporal assessment of wind energy resource at four locations in Algerian Sahara. *Energ Convers Manage* 76: 654–664.
23. Kamau JN, Kinyua R, Gathua JK (2010) 6 years of wind data for Marsabit, Kenya average over 14 m/s at 100 m hub height; An analysis of the wind energy potential. *Renew Energ* 35: 1298–1302.
24. Mukulo BM, Ngaruiya JM, Kamau JN (2014) Determination of wind energy potential in the Mwingi-Kitui plateau of Kenya. *Renew Energ* 63: 18–22.
25. Badger J, Frank H, Hahmann AN, et al. (2014) Wind-climate estimation based on mesoscale and microscale modeling: statistical–dynamical downscaling for wind energy applications. *J Appl Meteorol Clim* 53: 1901–1919.

26. Nygaard I, Nørgård P, Dewilde L, et al. (2012) Screening of feasible applications of wind and solar energy in Mali: Assessment using the solar and wind atlas for Mali; UNEP Risoe Centre, Technical University of Denmark. Available from: http://www.frsemali.org/reports/00%20final%20reports/Screening%20of%20applications.pdf .
27. Badger J, Kamissoko F, Rasmussen MO, et al. (2012) Estimation of wind and solar resources in Mali; UNEP Risø Centre, Technical University of Denmark. Available from: http://www.frsemali.org/reports/00%20final%20reports/Estimation%20of%20solar%20and%20 wind%20resources.pdf.
28. de Volder G, Dewilde L, Diallo M, et al. (2009) Systéme éolien-diesel á Tombouctou: etude de faisabilité; Coopération technique Belge, CNESOLER, Mali.
29. Karhammer R, Sanghvi A, Fernstrom E, et al. (2006) Sub-Saharan Africa: Introducing Low Cost Methods in Electricity Distribution Networks; ESMAP technical paper 104/06. Available from: http://documents.worldbank.org/curated/en/home.
30. SOGREAH (2009) Etude de la demande et du plan directeur d'investissement optimaux dans le secteur de l'électricité au Mali: Synthese et recommenda-tions; Ministére de l'Energie, des Mines et de l'Eau - Direction Nationale de l'Energie et SOGREAH.
31. GTZ (2004) Feasibility Study for a 900-kW Wind Farm in Gao, Mali. Wind-Diesel systm. Final report; Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH: Available from: http://www.gtz.de/de/dokumente/en-windenergy-mali-feasibility-study-gao-2004.pdf.
32. Cold-Ravnkilde SM (2013) War and Peace in Mali: Background and perspectives; Danish Institute for International Studies, Denmark.
33. Eberhard A, Kåberger T (2016) Renewable energy auctions in South Africa outshine feed-in tariffs. *Energ Sci Eng* 4: 190–193.
34. Nygaard I, Rasmussen K, Badger J, et al. (2010) Using modeling, satellite images and existing global datasets for rapid preliminary assessments of renewable energy resources: the case of Mali. *Renew Sust Energ Rev* 14: 2359–2371.
35. Pueyo A, Bawakyillenuo S, Osiolo H (2016) Cost and Returns on Renewable Energy in Sub-Saharan Africa: A comparison of Kenya and Ghana; Institute of Development Studiess, UK. Available from: https://opendocs.ids.ac.uk/opendocs/bitstream/handle/123456789/11297/ER190_CostandReturnsofRenewableEnergyinSubSaharanAfricaAComparisonofKenyaandGhana.pdf;jsessionid=F5B7F647B177FA09989CD5399849283E?sequence=1.