Screening of feasible applications of wind and solar energy in Mali:

Assessment using the wind and solar atlas for Mali

DANIDA contract 1711

Feasibility of renewable energy resources in Mali

December 2012

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Hybrid PV-diesel system in Ouélessébougou, Mali

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List of abbreviations

a.g.l	Above ground level
AMADER	Agence Malienne pour le Developpement de l'Energie Domestique et de l'Electrification Rurale
bbl	Barrel
BOOT	Build, Own, Operate and Transfer
CAPEX	Capital Expenditure
CNESOLER	Centre National de l'Energie Solaire et des Energies Renouvelables
DANIDA	Danish International Development Agency
DDO	Distillate Diesel Oil
DNE	Direction Nationale de l'Energie
DSSF	Down-welling Surface Short-wave Radiation Flux
DTU	Technical University of Denmark
EDM	Energie du Mali
ENI-ABT	Ècole Nationale d'Ingenieurs Abderhamabe Baba Touré
ESCOM	South African Utility
GRAS	Geographic Resource Analysis & Science A/S
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
HFO	Heavy Fuel Oil
IFC	International Finance Cooperation
IPP	Independent Power Producer
KAMM	Karlsruhe Atmospheric Mesoscale Model
MMEE	Ministère des Mines, de l'Energie et de l'Eau
MSG	Meterosat Second Generation
NASA	National (USA) Aeronautics and Space Administration
PV	Photovoltaique
SOGEM	La Société de Gestion de l'Energie de Manantali
SOSUMAR	Markala Sugar Company
SSE	Surface meteorology and Solar Energy
URC	UNEP Risø Centre
UTM	Universal Transverse Mercator coordinate system
WAsP	Wind Atlas Analysis and Application Program
WAPP	West African Power Pool
WB	World Bank
W_p	Watt peak effect
ZEM	Zones d'Electrification Multi - sectorielle

1 Preface

The supply of affordable, reliable and environmentally friendly energy services is an important precondition for the economic development of Malian society. Currently demand for electricity is increasing by about 10% per annum, and demand for fuel for transport is increasing at an even higher level (BAD 2010). This presents enormous challenges to the Malian government and to national operators in reducing imports of fossil fuels, as well as to the national electricity utility, EDM (Energie du Mali), and to private investors in providing sufficient electricity at reasonable prices.

A large part of electricity production comes from large-scale hydropower produced on the Senegal and Niger rivers, but small- and large-scale diesel generators are still providing about 20% of total production. While interconnectors are being planned and built to meet some of the demand with electricity produced from natural gas in Ghana and Ivory Coast, there are still good political and economic reasons to tap into abundant national renewable energy resources, such as hydro-energy, solar energy, wind energy, biomass residues from agriculture, and energy crops producing liquid biofuel.

Since the 1980s, in cooperation with various development partners, Mali has conducted a number of development projects and programmes focusing on the increased use of renewable energy sources, while the Ministry for Mines, Energy and Water has developed a strategy for the development of renewable energy in Mali, which was adopted by the Ministerial Council (Conseil des Ministres) on 26 December 2006 (MMEE 2007). This strategy combines the aims of reducing poverty, validating national energy resources and ensuring the long-term security and environmental sustainability of the energy supply. Given the rapid increase in prices for imported fuels such as diesel and gasoline, it is increasingly worthwhile to assess the potential for giving renewable energy resources a central role in the future energy system: environmentally friendly renewable energy resources are abundant in Mali and are becoming increasingly competitive.

For the purpose of planning future investment in the renewable energy sector, the Malian energy authorities, Energie du Mali, private operators and international cooperation partners have expressed their needs for a more precise assessment of the size and variety of renewable energy resources in Mali. The Danish International Development Agency (DANIDA) has therefore provided the finance to map renewable energy resources under the heading of the 'Feasibility of Renewable Energy Resources in Mali', or 'Faisabilité de Resources d'Energies Renouvelables au Mali'.

A first scoping phase of the project was conducted in 2007-2008. The project report, submitted in 2008 and entitled 'Provisional mapping of Renewable Energy Resources in Mali, or 'Carte provisoire de ressources renouvelables du Mali', was based entirely on satellite data and meteorological models.

The present project has taken the first study further by including ground measurements of wind and solar resources, and by including extensive field studies to assess the potential for using biomass waste for energy and to assess the socio-economic impacts of growing cassava for biofuel production. Not all renewable energy resources have been mapped, however. The most important exception is the stock of energy resources contained in Mali's woody vegetation, which is not easily assessed from satellite data but is being assessed by other on-going projects.

The present project is covered in five main reports:

1) Analyses of the potential for sustainable, cassava-based bio-ethanol production in Mali
2) Agricultural residues for energy production in Mali
3) Pre-feasibility study for an electric power plant based on rice straw
4) Estimates of wind and solar resources in Mali
5) Screening of feasible applications of wind and solar energy in Mali, using the wind and solar maps for Mali

The project is being carried out by a group of university departments, research institutions and consultants led by the UNEP Risø Centre (URC) at the Technical University of Denmark (DTU) and conducted in cooperation with Direction Nationale de l'Energie (DNE) and Centre National de l'Energie Solaire et des Energies Renouvelables (CNESOLER) in Mali. The subcontracted institutions comprise Geographic Resource Analysis & Science A/S (GRAS), Department of Geography and Geology (DGG), University of Copenhagen, Ea Energy Analyses, 3E, Ecole Nationale d'Ingénieurs Abderhamabe Baba Touré (ENI-ABT) and Mali Folkecenter Nyetaa.

The drafting of this report and the intensive research behind it has been led by Ivan Nygaard of URC, with input and support from the remaining authors.

2 Executive Summary

This report presents a first screening of feasible applications for the use of solar and wind energy in Mali. The report fulfils two important objectives. First, it increases the benefits of the mapping of solar and wind resources in Mali (Badger, Larsen *et al.* 2012) by presenting illustrative examples of project opportunities that project developers can take further towards implementation. Secondly, it serves as guidance to how the solar and wind maps can be used in the first phases of the planning and implementation of solar and wind technologies in Mali and elsewhere.

The feasibility of solar and wind applications is greatly dependent on the available resources, but as illustrated in the report a number of other factors, such as the current and planned structure of the energy system, the economic, institutional and legal framework, and the investment climate and political stability, may be even more important. The first elements to address here are the supply and price structures of the energy system into which solar and wind energy is to be integrated. This relates to the following questions: To what extent do solar and wind substitute for oil, natural gas and hydropower? What are the fuel costs, the conversion efficiencies and, consequently, the marginal prices for each of the production units? How do solar and wind profiles match current demand on both the daily and seasonal bases, and what are the regulatory opportunities in terms of flexible power from hydro or from interconnections? Finally, what are the expectations for the future in, for example, 2020 and beyond. These questions are addressed in Chapter 3 in relation to the coherent electricity system, the larger isolated grids and the mini-grids that are prevalent in Mali.

Wind

Chapter 4 presents a synthesis of the information in the wind mapping report, (Badger, Larsen *et al.* 2012), and gives further details of the daily and the annual variations in wind resources and the challenges of integrating large amounts of wind-generated electricity into the Malian grid. This chapter further illustrates the opportunities of downloading data files from a Google Earth-based web-application into the WaSP software for site-specific production estimates.

Chapter 5 describes four selected cases developed to illustrate the economic feasibility of wind energy under different conditions. The three cases in the North represent good wind resources, but also expensive grid connection opportunities. Case 4 from the South represents a site with local speed-up effects in a generally poor wind climate, but with cheap grid connection. Key data and results are presented in Table 2.1:

Table 2.1. Estimated production cost and avoided cost for electricity in the four cases

Region	Case study	Size	Production cost (CFA/kWh)		Avoided cost (CFA/kWh)		
					Thermal		Inter-connection
		MW	Option 1	Option 2	100 USD/bbl	125 USD/bbl	
North	1.Tombouctou	0.6	112	210	222	253	
	2.Kamango	8.5	51		222	253	
	3. Akle	170	85	112	103	119	65-100
South	4. Kay Hill	8.5	54		103	119	65-100

Overall the assessment indicates that in the southern part of Mali it will be possible to find a limited number of sites with local speed-up effects and situated close to the existing grid, at which there are options for making economically feasible medium-size wind power projects. The assessment also supports the findings from previous feasibility studies that smaller windfarms (around 1 MW) would be economically feasible if they were connected to isolated grids in Gao and Tombouctou (GTZ 2004, de Volder, Dewilde *et al.* 2009).

The assessment of large wind farms shows that in the current physical situation the logistics and grid-extension costs account for about 40% of the total investment costs. The good wind resource in the North does not compensate for the high investment costs, and consequently the application of wind energy in that region will only be feasible if the wind farm substitutes diesel-based electricity in existing plants, or if the infrastructure investments are covered by a larger investment plan for the North, for example, interconnections with other countries.

It is difficult to attract turbine manufacturers to isolated projects involving only a few turbines, as the costs of establishing an organization for the delivery of turbines and spare parts and for servicing the turbines will be relatively high. The above cost estimates are based on the assumption that a considerable market for the erection of wind turbines in Mali can be predicted, with the result that a reasonable degree of competition among turbine providers can be established.

Solar

Chapter 6 provides a synthesis of the information in the solar mapping report, (Badger, Larsen *et al.* 2012), while Chapter 7 describes the current application of solar energy in Mali, a number of projects in the making and estimates of the production costs of a smaller and a larger grid-connected PV system respectively.

Overall the opportunities for exploiting solar resources in Mali are promising. Not only has the country abundant resources, it has also space and has built up strong expertise in the field. Private companies and research centres such as CNESOLER are contributing significantly to the development of this sector in the country, and the tangible results are

more than 130,000 solar kits installed mainly for households, schools and health centres, 1300 solar pumps for pumping water, 700 off-grid installations for lighting and 400 mini-grid installations for telecommunications, offices, hospitals, etc.

The decline in the cost of PV solar panels and systems in recent years makes solar energy and solar PV an increasingly interesting option for electricity production. The cost of PV applications, however, is currently significantly larger in Mali than what we see in, for example, South Africa due to the high cost of transport, logistics and maintenance, and also because solar PV is still a niche market with poor competition.

The current cost level, illustrated by the estimated production cost for a 1 MW_p solar PV power plant under various assumptions, is presented in Table 2.2:

Table 2.2. Production costs (CFA/kWh) for 1 MW_p solar power plant under different assumptions

Solar radiation (kWh/m²/d)		**5.5**	**5.75**	**6.0**
Average production	MWh/y	1820	1893	1947
Maintenance cost **0.04 €/W_p**				
Total investment cost	**2.6 €/W_p**	173	166	162
Total investment cost	2.0 €/W_p	139	133	129
Total investment cost	1.4 €/W_p	104	100	97
Maintenance cost **0.02 €/W_p**				
Total investment cost	2.6 €/W_p	164	158	153
Total investment cost	2.0 €/W_p	129	124	121
Total investment cost	1.4 €/W_p	95	91	88

The calculation for the 1 MW_p system shows a production cost of 166 CFA/kWh in the base case, where the investment cost is 2.6 €/W_p. The calculation also shows that, if the specific investment costs in Mali can be brought down to 1.4 €/W_p and the maintenance costs can be reduced to the European level at 0.2 €/W_p, the production costs will be reduced to 91 CFA/kWh. Hence the cost will be lower than for electricity from existing large HFO-powered diesels, and close to the cost of imported electricity.

For a 100 kW_p PV system the estimated production costs are significantly higher than illustrated above, but in a number of cases still lower than the avoided cost in isolated grid systems, where they would be applied. This is due to the high costs of small diesel-based systems as a result of higher capital and maintenance costs, higher fuel costs and lower efficiency than larger diesel systems. This means that, if he investment costs can be slightly decreased, PV in smaller isolated grids will in general be economically feasible today.

Recent studies show that hybrid PV-diesel systems (10-75kW) in mini-grids are already economically feasible, but due to the high transaction costs in demonstration projects, the implementation of PV in mini-grids is likely be contingent on success in achieving

economies of scale, that is, in setting up a larger programme for PV-diesel systems and thereby reducing engineering, procurement and maintenance costs.

Wind and Solar

Both solar and wind energy have the potential to become cheaper in Mali in the very near future, but this will be contingent on political stability, continuing donor support to studies and cheap finance, and not least on the establishment of a clear legal framework for investors, including, for example, a Feed-in Tariff for grid-connected solar PV (Haselip 2011). Such measures could reduce prices as a result of reduced risk, increased competition and economies of scale.

It is necessary at this point to emphasize that cost calculations have been carried out for the chosen examples based on the best available data. Therefore all production costs should be considered indicative only. Likewise the avoided cost 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 purchase agreement with the utility or in a general Feed-in Tariff.

3 The electricity sector in Mali

The feasibility of solar and wind applications is strongly dependent on the current and planned structure of the energy system. This chapter therefore reviews the current and planned supply and price structures of the energy systems into which solar and wind are to be integrated. The chapter is structured according to three different markets for electricity: i) the integrated system, ii) large isolated grids owned by EDM, and iii) mini-grids, which are part of the rural electrification scheme under the responsibility of AMADER.

3.1 Demand forecast for electricity in the integrated system

The forecast for the demand for electricity in Mali in this study is mainly based on data from a Master Plan for Investment in the electricity sector in Mali conducted by SOGREAH Consults for the DNE in 2008 and finally published in 2009 (SOGREAH 2009; SOGREAH 2008a; SOGREAH 2008b; SOGREAH 2008c).Along with the regional study from the West African Power Pool (WAPP 2011c), the Master Plan is the most comprehensive planning document for the Malian electricity sector made available to the authors in February 2012, when this report was drafted.

3.1.1 Demand forecast

The demand forecast is based on the assumption that a number of non-grid connected towns or isolated grids (*centres isolées)* will be connected to the integrated system or *reseau interconnecté (RI)* according to the planning shown in *Figure 3.3*. This is especially related to the realisation of *la Boucle de Selingue*, which, according to the plan, will increase the demand significantly in 2011, 2012 and 2017. The interest of the non-grid-connected towns to connect to the grid is to replace thermal production with lower cost production such as hydro-power or imported electricity.

Table 3.1. Forecast of annual demand in the integrated system (from Master Plan)

GWh	Low scenario	Base scenario	High scenario
2007	835	835	835
2008	878	897	916
2009	932	963	994
2010	1 000	1 045	1 090
2011	1 207	1 275	1 343
2012	1 433	1 531	1 630
2013	1 506	1 628	1 751
2014	1 580	1 728	1 877
2015	1 712	1 894	2 077
2016	1 797	2 013	2 228
2017	2 026	2 297	2 568
2018	2 165	2 484	2 804
2019	2 258	2 623	2 988
2020	2 354	2 769	3 185

As shown in Table 3.1, the expected annual demand for electricity varies between 2,354 and 3,185 GWh at the end of the period, which is more than three times the demand in 2007. The demand forecast for the three scenarios is illustrated in Figure 3.1:

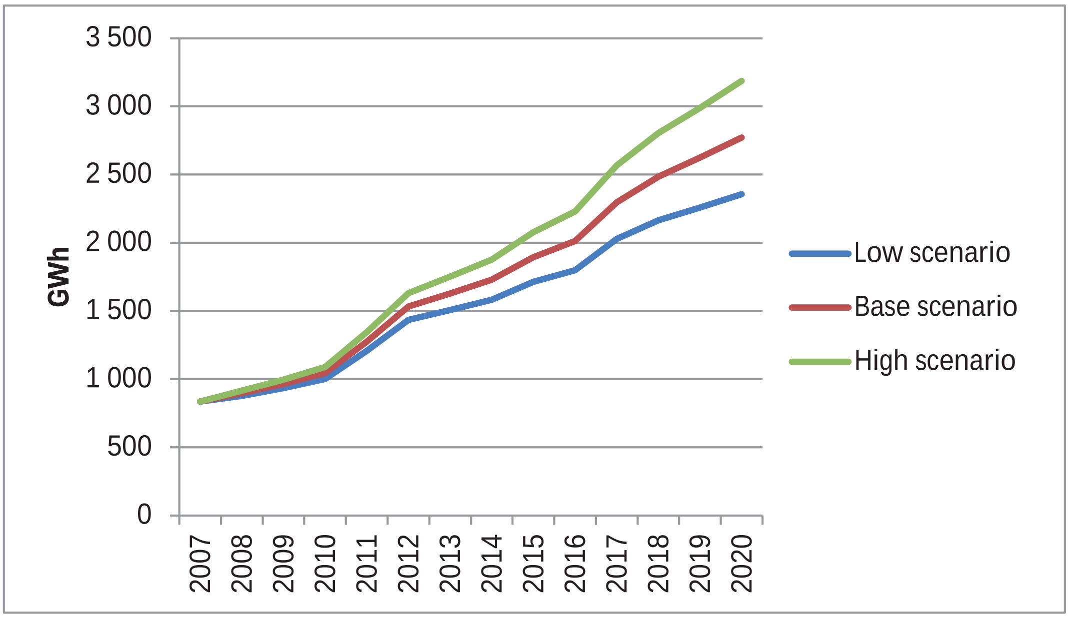

Figure 3.1. Annual demand for electricity in the integrated system (from Master Plan)

The Master Plan also forecast the peak load until 2020, as shown in Table 3.2 and graphically in Figure 3.2. In line with the annual demand, the peak load is expected to more than triple in 15 years.

Table 3.2. Projections of peak demand in the integrated system (RI)

MW	Low scenario	Base scenario	High scenario
2007	144	144	144
2008	154	154	154
2009	161	166	172
2010	173	180	188
2011	203	214	226
2012	235	251	268
2013	248	268	289
2014	261	286	310
2015	283	313	343
2016	298	334	370
2017	331	375	419
2018	355	408	460
2019	372	432	492
2020	389	457	526

Compared to the forecasts in « *La politique énergétique nationale* » from February 2006, the base scenario reaches the same level by 2020 (MMEE 2006). However, the SOGREAH scenario predicts a lower level in both 2010 and 2015. Comparison is made in Table 3.3 below:

Table 3.3. Comparison of demand forecasts in SOGREAH (2009) and MMEE (2006)

	Master Plan 2009 base scenario		National energy policy, 2006	
Year	**GWh**	**MW**	**GWh**	**MW**
2010	1 045	180	1310	230
2015	1 894	313	2110	370
2020	2 769	457	2680	465

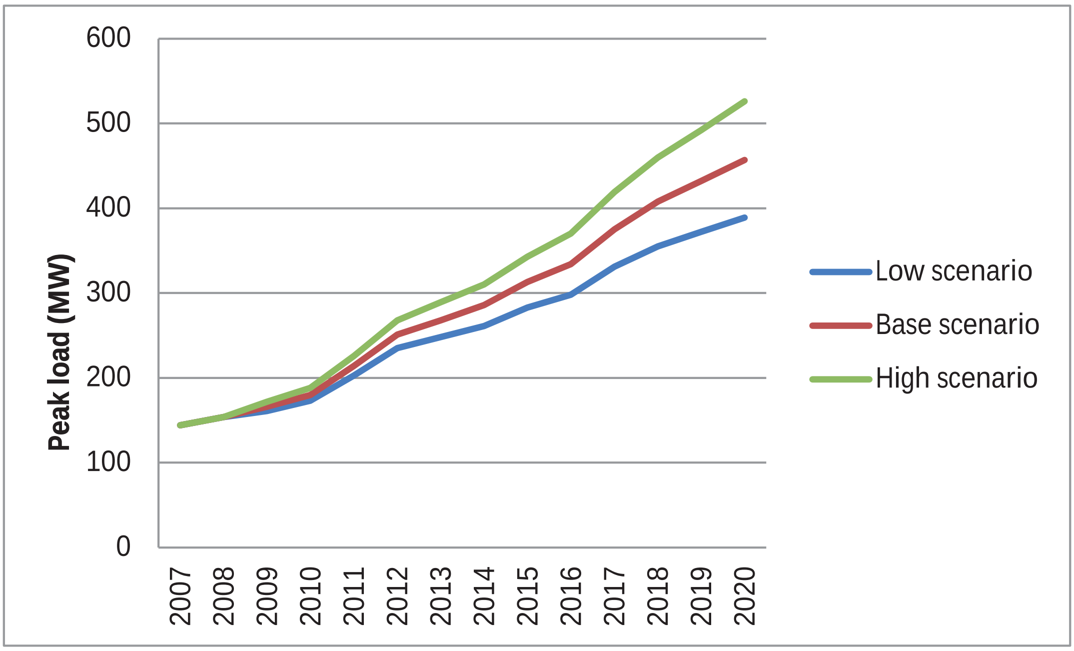

Figure 3.2. Forecast of peak demand in the integrated system (from Master Plan)

3.1.2 Extension of the integrated system

The long-term plan to extend the integrated system as presented in the Master Plan is shown in Figure 3.3 (SOGREAH 2009). The map provides information on two different issues.

The first issue is the connection of isolated grids to the integrated system. The exact timing may prove different, but this plan gives strong indications regarding which isolated grids will be connected in the near future and hence which will experience lower costs. This will be of importance in evaluating the feasibility of connecting solar, wind and biomass to the grid in existing isolated grids. This will be dealt with in more detail in section 3.2.

The second issue relates to the plans for transnational transmissions lines, or *interconnectors* from neighboring countries. As transnational transmission lines will lower the price for electricity in the integrated system, the first operational date for these transmission lines will be of importance for the feasibility of connecting solar, wind and

biomass-producing units to the integrated grids. This issue is dealt with in more detail in section 3.1.4.

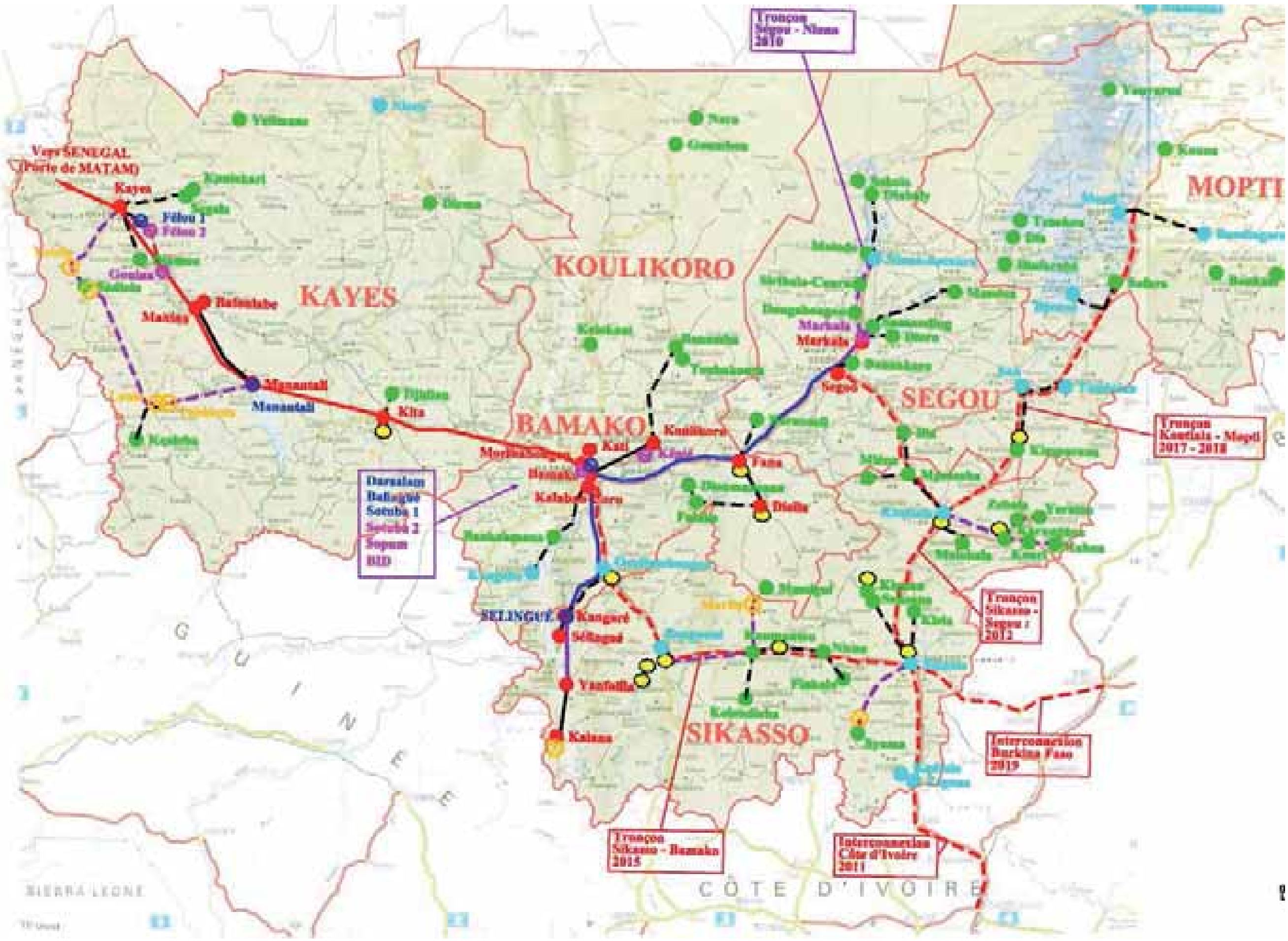

Figure 3.3. Long-term plan for interconnectors in the integrated system (from Master Plan)

3.1.3 and planned production units for electricity and planned imports

Installed thermal and hydro capacity in the integrated system by 2010 is shown in Table 3.4, and the prospective planned production units and interconnectors for imports of electricity are shown in Table 3.5. Besides installed capacity, the tables also provide estimated average production costs per kWh depending on the crude oil price in USD/bbl.

The relationships between crude oil price and fuel cost for diesel (DDO) and heavy fuel oil (HFO) are shown in Figure 3.4. Data are based on background information from the Master Plan (SOGREAH 2009).

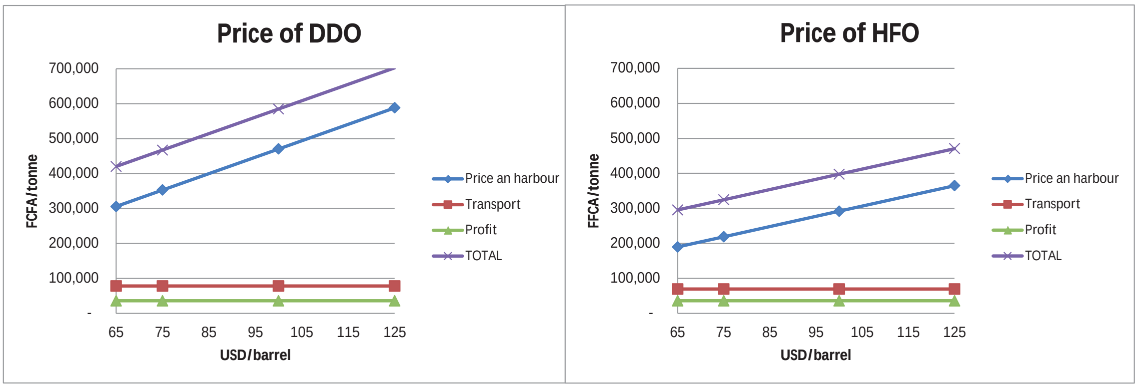

Figure 3.4. Relationship between crude oil price in USD/bbl and fuel cost in Bamako in FCA/tonne.

Table 3.4. Production capacity in the integrated system in 2010 and estimated production costs per unit

Crude oil price (USD per barrel)					**75 USD/b.**	**100 USD/b.**	**125 USD/b.**
Production unit	**Fuel type**	**Installed capacity**	**Specific consump.**	**Fixed costs**		**Total Costs**	
		MW	**g/kWh**	**CFA/kWh**	**CFA/kWh**	**CFA/kWh**	**CFA/kWh**
DarSalam_TAC	DDO	24.6	340	20	179	219	259
DarSalam_secour	DDO	0.7	260	20	141	172	203
DarSalam_MTU_G8 - G11	DDO	8.8	220	20	123	149	175
GPS Darsalam	DDO	18.0	220	20	123	149	175
Agreeko	DDO	30.0	220	20	123	149	175
Balingue_MWM_G1 - G4	DDO	23.7	216	15	116	141	167
Balingue_MTU_G5 - G8	DDO	8.8	215	15	115	141	166
SOPAM	HFO	56.0	210	20	88	103	119
BID	HFO	45.0	210	20	88	103	119
Thermal capacity		**215.6**					
Manantali	Hydro	104.0				24	
Sélingué	Hydro	46.2				36	
Félou	Hydro	0.6				37	
Hydro capacity		**150.8**					
Total capacity		**366.4**					

Source: Compiled based on EDM annual report 2010 (EDM 2011) and (SOGREAH 2008a) [1].

[1] Specific consumption is based on (SOGREAH 2008a) and (EDM 2011). Fixed costs for Darsalam and Balingue are estimated based on financial information from 2006 and 2007 in SOGREAH background material. Fixed cost for SOPAM and BID based on (SOGREAH 2008a); fixed cost for Agreko and GPS Darsalam estimated roughly.

Table 3.5. Foreseen new thermal capacity in the integrated system

Crude oil price (USD per barrel)					75 USD/b.	100 USD/b.	125 USD/b.
Production unit	**Fuel type**	**Installed capacity**	**Specific consump.**	**Fixed costs**		**Total Costs**	
		MW	g/kWh	CFA/kWh	CFA/kWh	CFA/kWh	CFA/kWh
Centrale albatros	HFO	92.2	210	20	88	103	119
Extension of BID	HFO	20.0	210	20	88	103	119
Thermal capacity		**112.2**					

Source: Based on (SOGREAH 2008a) and (EDM 2011)

Table 3.6. Planned capacity from hydro and imports from neighbouring countries

Year	Production unit	Production type	Installed capacity (MW)	Cost CFA/kWh
2012	Interconnector Ivory Coast-Mali	Import from Ivory Coast. Capacity depending on availabiltiy in Ivory Coast or Ghana	100 150 200	45 - 50
2013	Félou	Hydropower	3 x 20	37
2014	Interconnector	Ghana-Burkina-Mali	160	65 - 100
2013	Markala	Hydropower	3 x 2,5	56
2014	Sotuba 2	Hydropower	2 x 2,5	64
2015	Kénié	Hydropower	3 x 14	46
2015	Talo	Hydropower	2	98
2018	Gouina	Hydropower	3 x 28,33	29
2021	Interconnector	Guinea	200	Not fixed

Source: Based on (EDM 2011) and (WAPP 2011b)

The planned future capacity from hydropower and from interconnectors to neighbouring countries is shown in Table 3.6. The interconnector from Cote D'Ivoire was under construction in February 2012. The hydropower project in Felou was also under construction, while the stage of development of Markala is unclear. According to (EDM 2011) and (WAPP 2011b) the Sotuba 2, Kénie and Talo projects are still at the planning stage.

The interconnectors with Ivory Coast and Ghana are part of a regional planning process led by the West African Power Pool (WAPP). The latest updated regional plan for the WAPP region was launched in 2011 and is documented in (WAPP 2011a; WAPP 2011b; WAPP 2011c). The objective of the WAPP is to reduce the cost of electricity in the region by interconnecting national grids and replacing expensive diesel generation by electricity from hydropower and from natural gas produced in countries such as Nigeria and Ghana.

Details of the three interconnectors to Ivory Coast, Burkina-Ghana and Guinea, planned to be in operation in 2012, 2014[2] and 2021 respectively, are shown in Table 3.5. They are all reflected in the regional plan from WAPP with minor differences in dates of operation.

Future costs of electricity in the WAPP will depend on specific contracts. According to WAPP, the interconnector Mali – Burkina – Ghana, which is expected to be in operation 2014 or 2015, will transport electricity from a new 400 MW combined cycle plant in Aboadze (Ghana) (WAPP 2011b; 51).

The combined cycle plant will be fuelled by natural gas from Nigeria transported through the West African Gas Pipeline. Recent problems in the delivery of gas from the West African Gas Pipeline to Ghana due to a shipping accident illustrates that, although from the outset a cheap alternative, imports from neighbouring countries may entail a certain risk in terms of prices and security of supply (Africa Report 2012).

The price per kWh will depend greatly on how this risk is shared among the parties. According to information from EDM issued in February 2012, the price is expected to be between 65-100 CFA kWh, which is higher than for hydropower but lower than for diesel generation.

Figure 3.5. High-voltage transmission networks and prospective interconnector projects (Source : WAPP 2011c)

[2] 2015 according to WAPP (WAPP 2011c).

3.1.4 Future avoided costs in the integrated system

For the cost-benefit analysis for EDM to include new production costs, it is necessary to estimate the future avoided cost, that is, the production cost for the most expensive unit which is running at a given time.

Figure 3.6 shows monthly production from the existing production units in 2010. The figure shows that the gas turbine at Darsalam, which is the most expensive unit, mainly produces from March to July, when demand is at its highest. During the rest of the year, for example, in September 2010, it will only cover the morning and evening peaks.

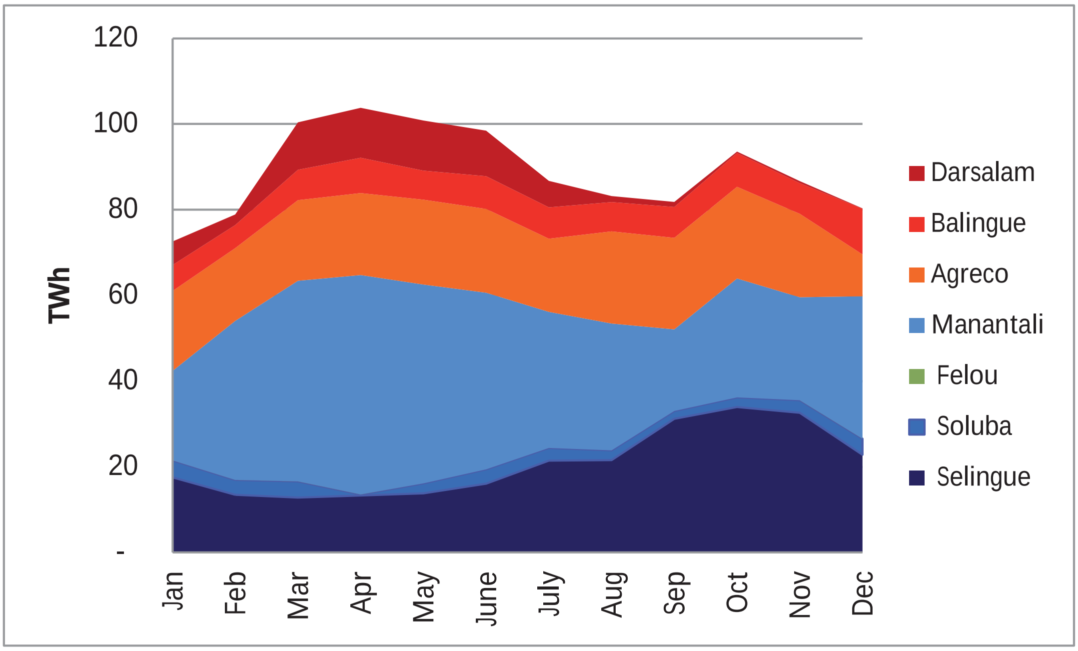

Figure 3.6. Monthly production from production units in 2010. Source: (EDM 2011)

This means that avoided costs depend on the time of year and the time of day. Given that the thermal units will mainly be applied using a least-cost approach, the avoided cost for thermal units depending on the actual thermal load is shown in Figure 3.7 for different oil price scenarios.

In the 100 USD/bbl scenario, avoided costs for the gas turbine in Darsalam is 219 CFA/kWh, while the avoided costs for the diesel units at DarSalam, Agreeko and Balingué are in the range of 141-149 CFA/kWh. Avoided costs for the SOPAM, BID and Albatros units are of the order of 103 CFA/kWh.

If the hydropower and interconnectors are established according to the above plans, the existing thermal units will only be used for peak loads and as a reserve.

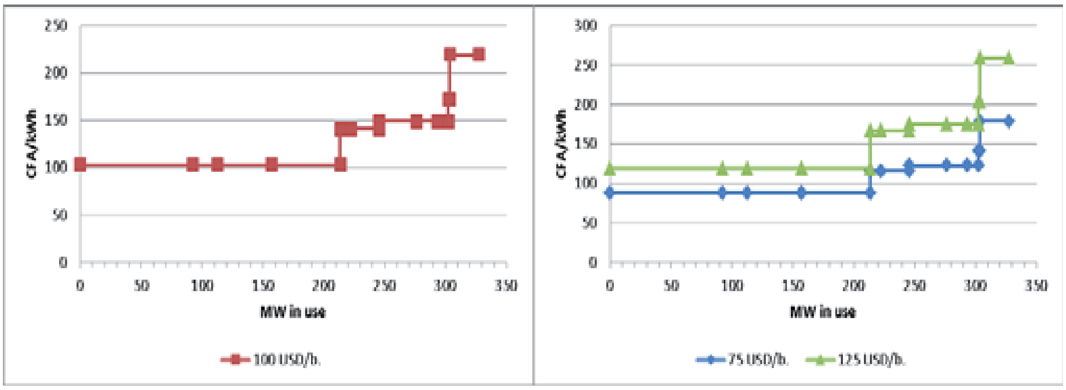

Figure 3.7. Costs curve for thermal production (based on Table 3.4 and Table 3.5)

In this case the marginal cost in the system will be the interconnector with the highest cost, namely 65-100 CFA/kWh, which is the expected cost for the Ghana–Burkina–Mali interconnector.

This situation is reflected in the DNE's planning, according to which the shares of electricity from hydro, thermal and interconnectors will develop as shown in Figure 3.8 (SOGREAH 2008b).

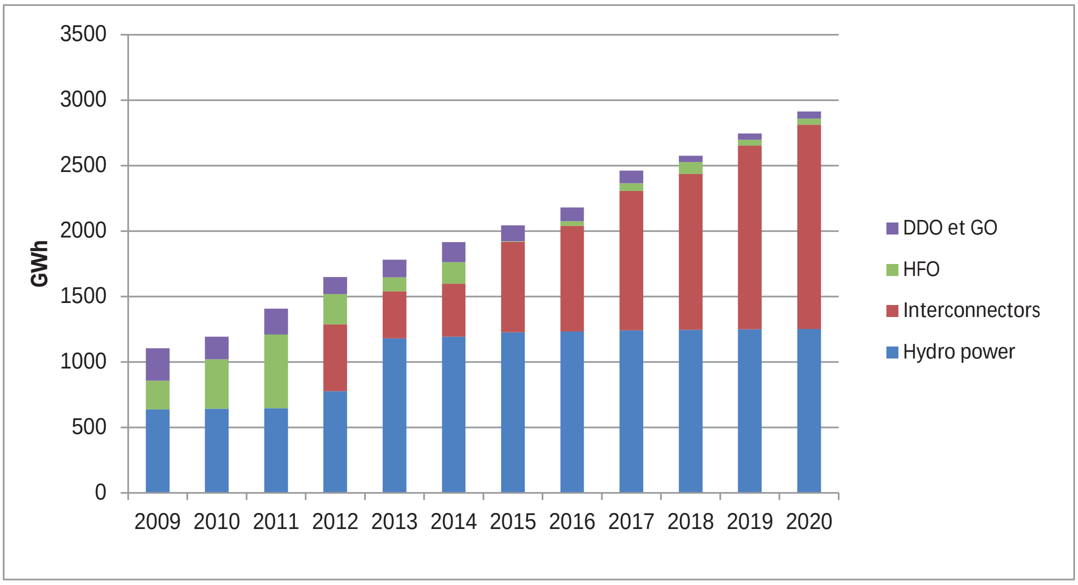

Figure 3.8. Electricity production according to the DNE's planning (SOGREAH 2008b)

Future avoided costs in the system will be thus be dependent on: i) the increase in future demand, and ii) the extent to which the planned interconnectors and hydropower plants will be commissioned on time and will be able to deliver the estimated amounts of power. Large projects dependent on international funding such as hydropower schemes and interconnectors are most often delayed when compared to the original plans. This is mainly due to i) difficulties in cooperation between one or several countries, ii) difficulties in bringing projects to financial closure, and iii) difficulties in finalising big infrastructure projects within the planned timeframe.

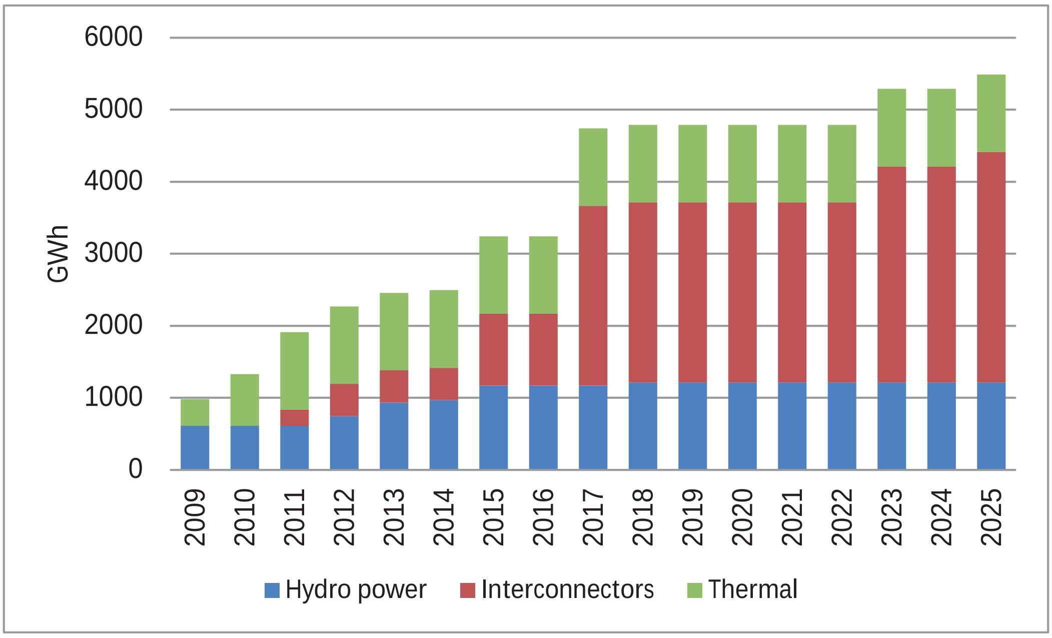

Figure 3.9. Energy mix in the integrated system according to predictions from the World Bank (WB 2009).

This is probably why the World Bank, in its appraisal report for the EDM support programme, is taking a more conservative approach in its prediction of future power supply (WB 2009). The World Bank prediction shows higher demand than the PLAN 2009 and maintains that 20% of the production will be delivered by thermal power plants, as illustrated in Figure 3.9.

The marginal costs in this case will hence be around 103 CFA/kWh in the 100 USD/bbl scenario and around 119 CFA/kWh for the 125 USD/bbl scenario.

3.1.5 Conclusion

Based on the load curves in 2010 and an oil price of 100 USD/bbl, the marginal production cost in the integrated system will vary between 201 and 141 CFA/kWh depending on the time of the year. This cost level will continue until the interconnector to Ferkessedou, Ivory Coast, is in operation in 2012.

According to the Master Plan, after 2015 marginal costs will be between 65 and 100 CFA (SOGREAH 2009). The exact cost will depend on the final outcome of negotiations of sales prices for electricity to the Ghana–Burkina Faso–Mali interconnector.

In case demand increases faster than predicted and in case of unforeseen delays in commissioning interconnectors and hydropower plants, there will still be demand for thermal power in the system in the range of 20%. In this case the marginal production cost will be around 103 CFA/kWh in a 100 USD/bbl scenario and 120 CFA/kWh in the 125 USD/bbl scenarios.

3.2 Demand forecast in the isolated grids (*Centres isolées*)

EDM is currently operating 19 isolated grids in Mali. The 19 centres are shown on the map in Figure 3.10 below.

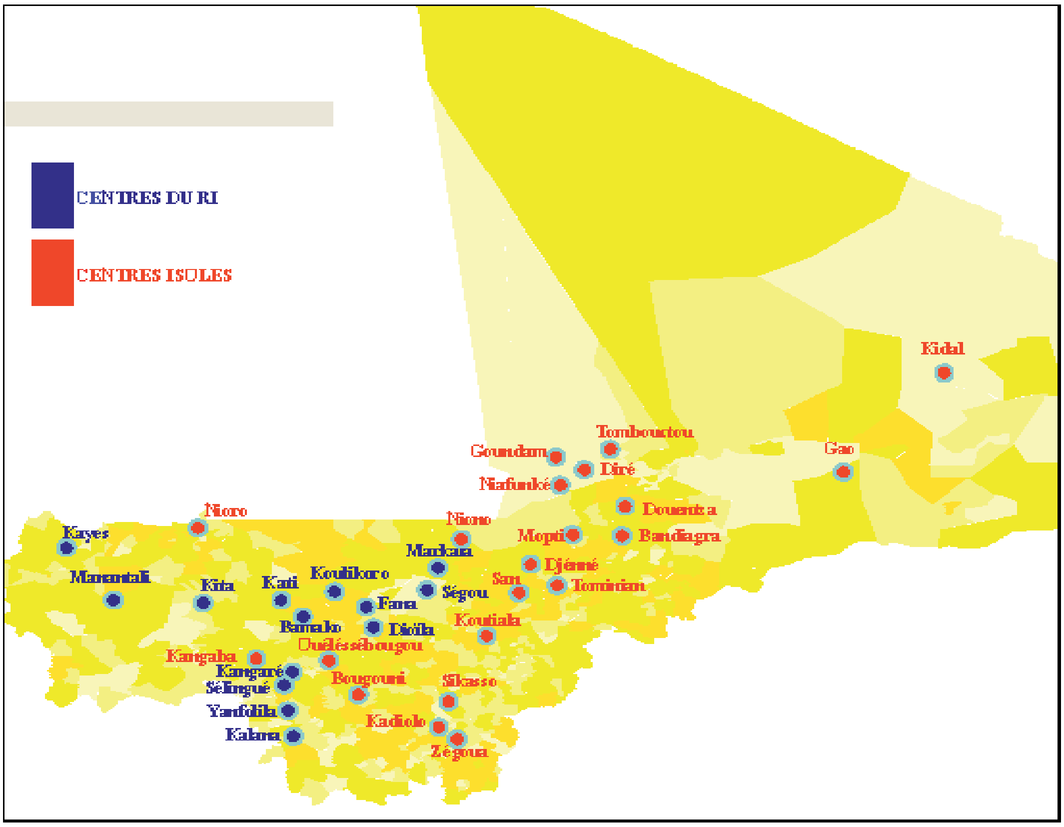

Figure 3.10. Map of Mali showing the current status of connection to the integrated systems (RI). (SOGREAH 2008c)

Sikasso, Koutiala and Niono will be connected to the integrated system in 2012. Data for the 16 centres are shown in Table 3.7 below.

Table 3.7. Installed capacity, peak load, annual production and production costs in isolated grids

Town	Installed capacity (1) MW	Peak load (1)			Annual Production (1) Mwh			Production cost (2) CFA/kWh		Estimated load (2) Mwh	Estimated peak load (2) MW
	2009	2005	2010	Increase	2005	2010	Increase	2006	2007	2020	2020
Mopti/sevaré	7.20	3.50	5.26	8.5%	19,302	28,436	8.1%	140	133	47,133	8.7
Gao	6.51	2.00	3.23	10.1%	11,180	16,805	8.5%	159	146	33,487	6.4
Tombouctou	4.61	1.18	2.21	13.4%	6,049	11,415	13.5%	186	174	24,533	4.7
Bougouni	2.46	0.91	1.43	9.5%	4,423	7,354	10.7%	151	129	17,135	3.3
San	3.66	0.81	1.59	14.4%	3,765	7,162	13.7%	162	159	20,105	4.5
Niono	2.61	1.07	1.53	7.3%	5,058	6,595	5.5%	166	156	Connected to RI in 2012	
Nioro	1.51	0.57	0.89	9.3%	2,727	4,697	11.5%	180	134	6,415	1.2
Kidal	2.96	0.46	0.99	16.5%	1,994	4,554	18.0%	187	129	7,283	1.6
Bandiagara	1.45	0.28	0.49	12.2%	1,067	2,248	16.1%	174	205	4,348	0.9
Douentza	0.88	0.21	0.41	14.0%	760	1,927	20.5%	249	181	3,484	0.7
Djenné	1.44	0.29	0.44	8.9%	1,028	1,860	12.6%	179	165	4,502	1.1
Dire	0.76	0.21	0.47	18.2%	781	1,702	16.9%	193	210	4,465	1.2
Goundam	0.72	0.20	0.35	12.2%	617	1,414	18.0%	265	192	4,837	1.2
Kangaba	0.45	0.14	0.23	10.7%	637	1,236	14.2%	192	190	1,765	0.3
Niafunke	0.66	0.18	0.26	7.3%	759	1,121	8.1%	196	207	2,662	0.6
Ouelessebougou	0.44	0.12	0.21	10.8%	544	947	11.7%	275	190	5,862	1.3
Tominian	0.24	0.14	0.17	4.1%	412	773	13.4%	212	210	1,595	0.4
Reseau Tombouctou	6.75	1.76	3.28	13.3%	8,206	15,652	13.8%	195	182	36,497	7.8

Note: 1) is based on EDM annual report (EDM 2011) and 2) is based on production costs from EDM available in background information for Master Plan (SOGREAH 2008b).

Ouélessébougou was equipped with a 220 kW_p solar PV system in 2011 as the first hybrid system operated by EDM. All the isolated grids are potential markets for hybrid systems for wind or solar PV.

3.2.1 Tombouctou grid

According to the Master Plan five centres, namely Tombouctou, Goundam, Dire, Tonga and Niafunke, should be integrated by a new 65 kV grid (Reseau Tombouctou) by 2016. Reseau Tombouktou could thus be a potential candidate for a larger hybrid solar or wind diesel system, as avoided costs for solar- and wind-produced electricity in this system will be higher than in the integrated system. Further details on the Tombouctou grid are provided in Figure 3.11 and Figure 3.12.

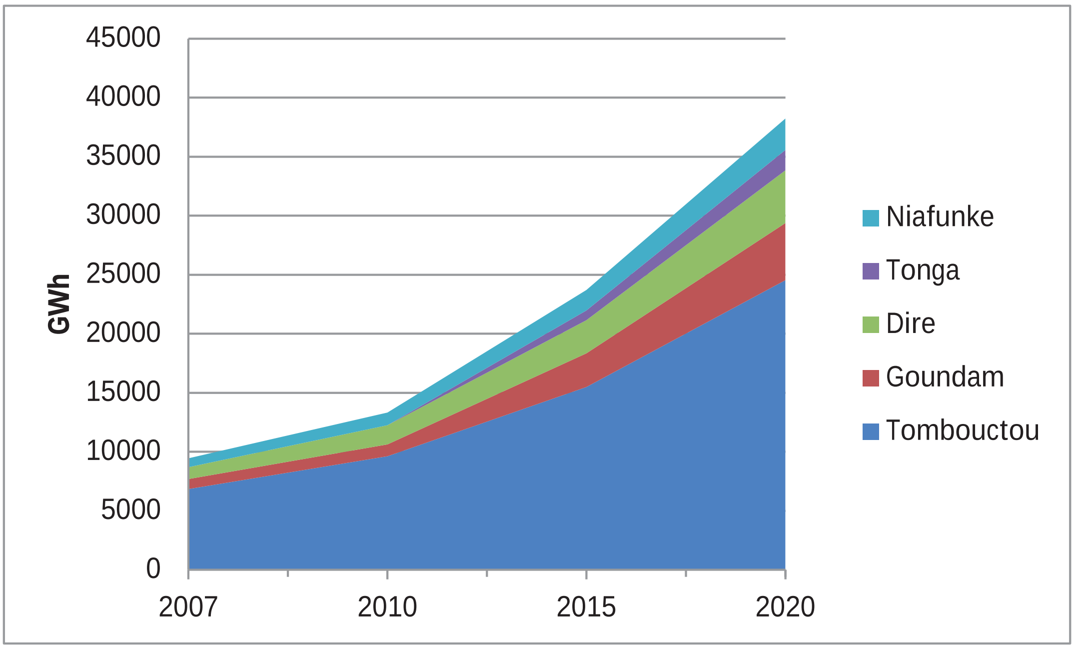

Figure 3.11. Forecast of annual demand in the Tombouctou grid

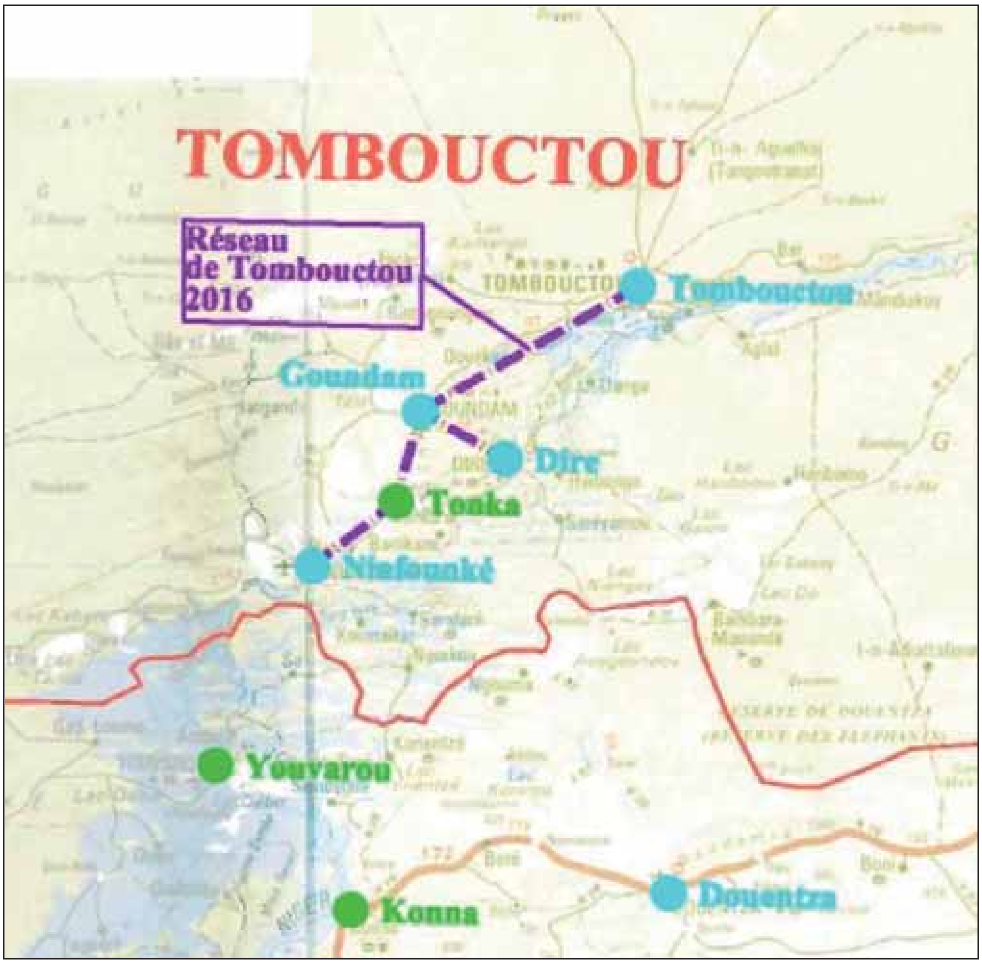

Figure 3.12. Map showing the potential grid between Tombouctou and neighbouring towns.

Besides the existing 19 centres, a number of smaller towns are expected to be electrified by EDM from 2012 onwards with grid extensions from the existing grid.

3.2.2 Monthly variations

The integration of solar and wind into small systems will be more feasible from an economic point of view if load variations over the year are similar to the production patterns for wind and solar. As examples, this section shows monthly variations in demand from the Tombouctou grid in Figure 3.13, from smaller towns in the grid in Figure 3.14 and from Tombouctou itself in Figure 3.15. The load variations are from the EDM annual report in 2010 (EDM 2011):

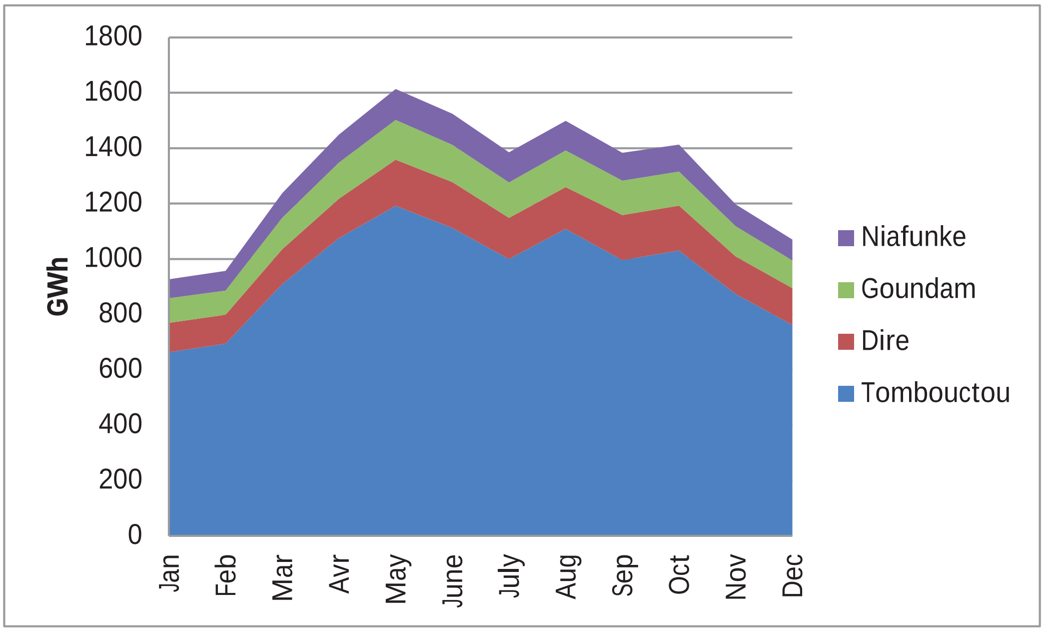

Figure 3.13. Monthly variation in the Tombouctou grid (EDM 2011)

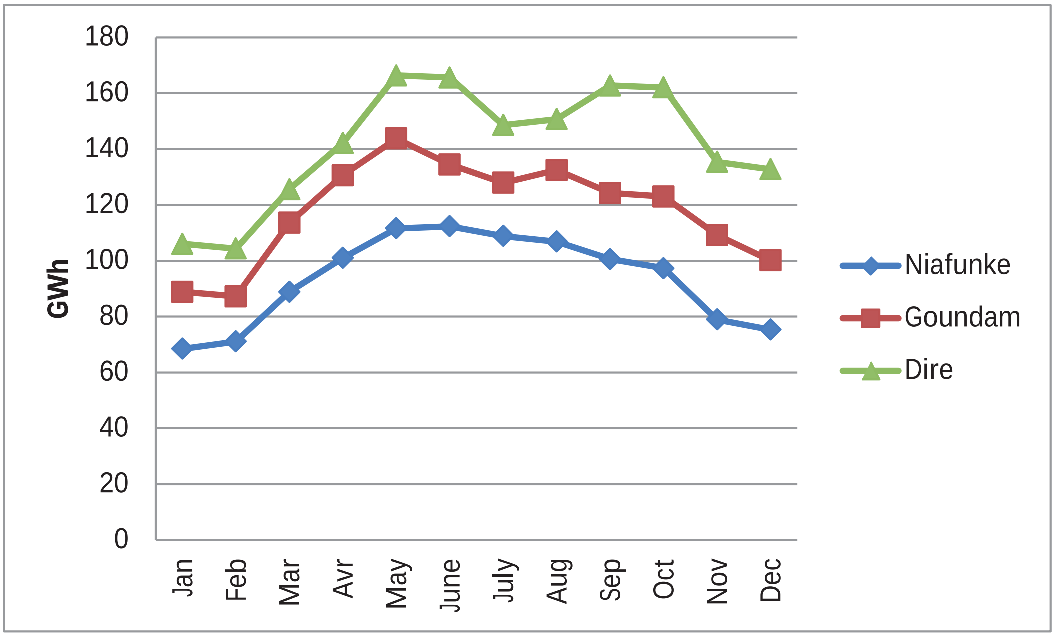

Figure 3.14. Monthly load variations in three smaller towns in the Tombouctou grid (EDM 2011)

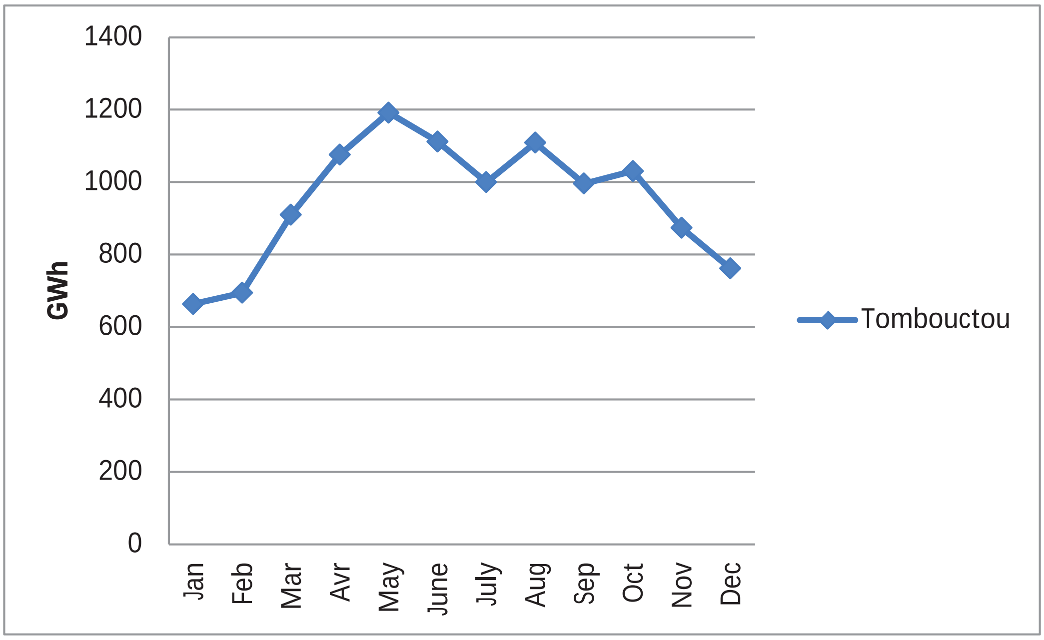

Figure 3.15. Monthly load variations in the town of Tombouctou (EDM 2011)

3.2.3 Diurnal variations

In the isolated grids, the daily load curve varies according to the mix of consumers connected to the grid. This means that load curves will vary significantly from one grid to another. As an example, daily load curves for the week with maximum load and from the week with minimum load are shown in Figure 3.16 and Figure 3.17.

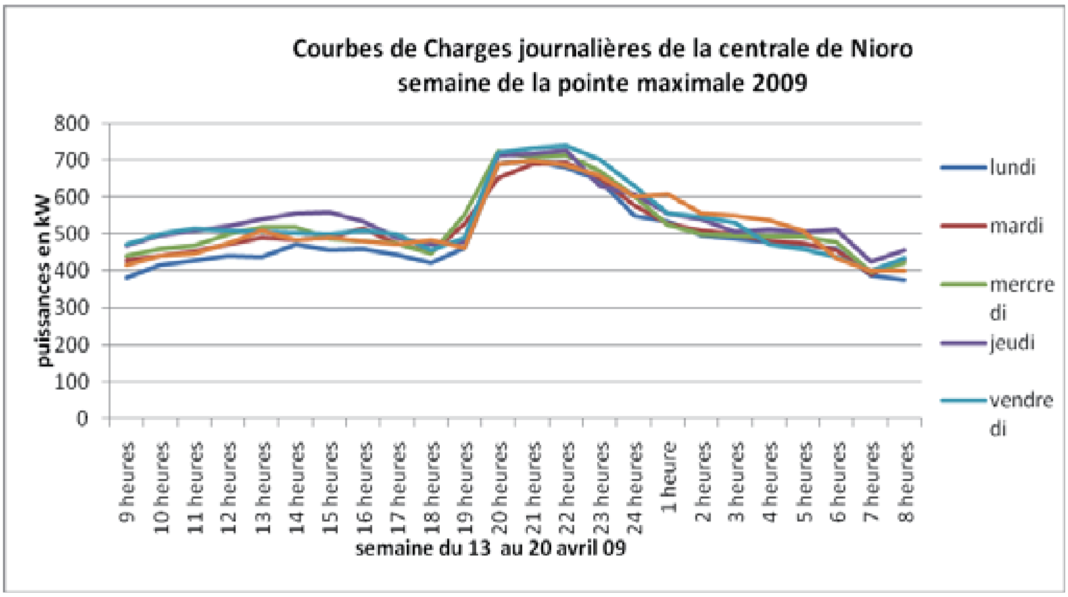

Figure 3.16. Daily load curves for Nioro in the week with maximal load in 2009

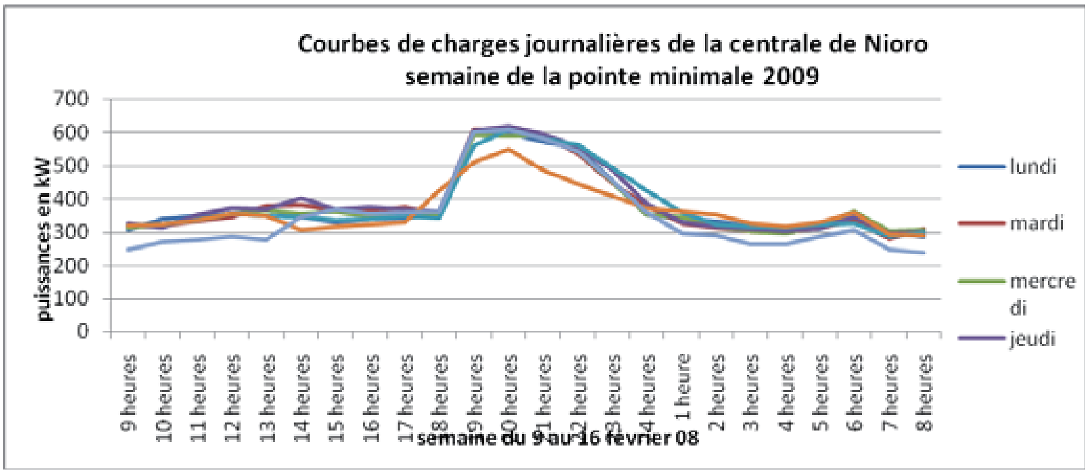

Figure 3.17. Daily load curves for Nioro in the week with minimal load in 2009.

3.2.4 Avoided costs for electricity in isolated grids

The production cost for electricity in the isolated grids is considerably higher than in the integrated area. The production costs in 2006 and 2007 are shown in Table 3.7. Based on the average production costs for 2006 and 2007, and given that the oil price in those two years was about 65 USD/bbl, production costs have been estimated for fuel costs of 75, 100 or 125 USD/bbl. These cost estimates are shown in Table 3.8.

Table 3.8. Estimated production costs for isolated grids based on 2006 and 2007 production costs.

Town	Specific consump.	Fuel independent costs	Total production cost (CFA/kWh) depending on crude oil price			
	g/kWh	CFA/kWh	65 USD/b.	75 USD/b.	100 USD/b.	125 USD/b.
Mopti/sevaré	246	33	137	148	177	206
Gao	241	51	152	164	192	220
Tombouctou	260	71	180	192	223	253
Bougouni	256	33	140	152	183	213
San	206	74	161	170	195	219
Niono	272	47	161	174	206	238
Nioro	232	59	157	168	195	222
Kidal	239	57	158	169	197	225
Bandiagara	259	81	190	202	232	263
Douentza	245	112	215	226	255	284
Djenné	282	54	172	185	218	251
Dire	259	93	202	214	244	275
Goundam	300	102	228	243	278	313
Kangaba	264	80	191	203	234	265
Niafunke	269	89	202	214	246	278
Ouelessebougou	272	118	233	245	277	309
Tominian	272	97	211	224	256	288

The estimated production costs for electricity (100 USD/bbl) at isolated grids are shown in Figure 3.18.

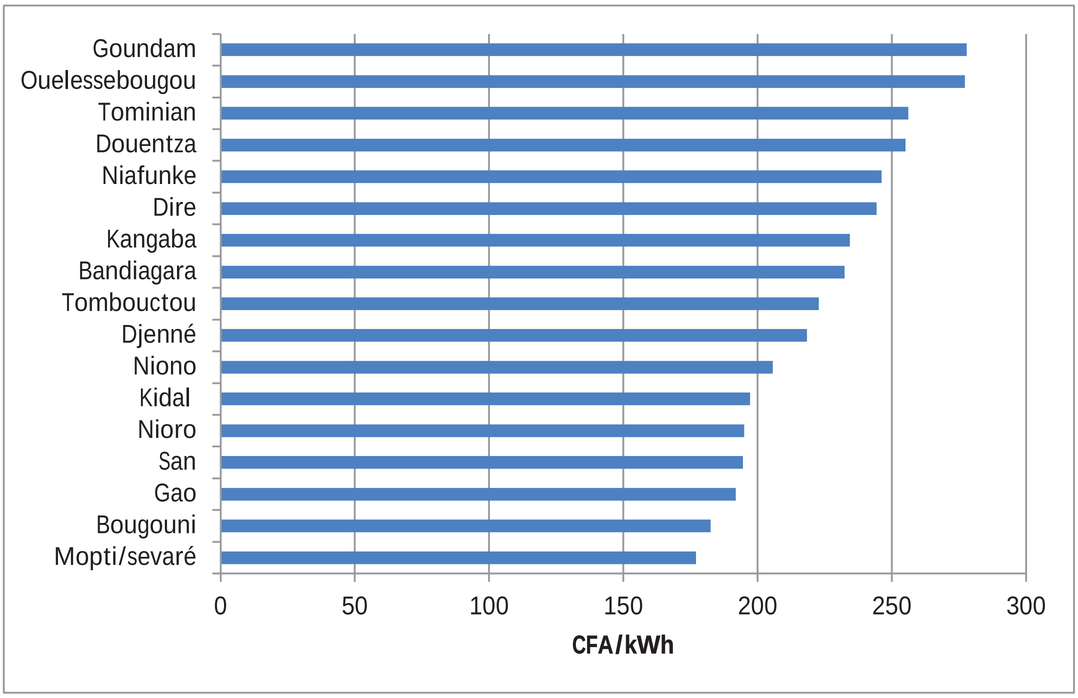

Figure 3.18. Estimated production costs for electricity at isolated grids with a fuel cost of 100 USD/bbl

Table 3.8 and Figure 3.18 show that the avoided costs at the isolated grids are significantly higher than in the integrated system. This is mainly because the smaller systems have lower efficiency (higher spec. consumption) and higher operation and maintenance costs. Therefore smaller installations of solar and windpower in hybrid with existing diesel may be economically feasible in these grids. Further details will be provided in Chapters 5 and 7.

3.3 Rural electrification (mini-grids)

In Mali, smaller towns outside the existing and planned grid are categorized as included in the rural electrification programme under the responsibility of l'Agence Malienne pour le Développement de l'Energie Domestique et de l'Electrification Rurale (AMADER).

Two different approaches to rural electrification were planned in Mali:

1) *A concession approach*, according to which concessions for rural electrification should be attributed to private operators after a tendering process. For the concessions, the country is divided into 8 *Zones d'Electrification Multi - sectorielle* (ZEM). The process has been under way for some years, but in spite of a high level of subsidies it has proved difficult to attract private operators that can mobilize sufficient equity funding to implement the zonal plans. According to information from AMADER issued in February 2012, this process has come to a halt.

2) *An application approach*, according to which private operators are asked to submit proposals for the electrification of a specific smaller town or groups of towns. This approach is called ‘Projets à Candidatures Spontanées’. The projects are eligible for an investment subsidy (up to 80% of the initial investment) depending on the feasibility of the project. 111 smaller towns, with a total of 32,000 customers, had achieved access to electricity through this programme by the end of 2010 (AMADER 2011).

A full list of the 111 smaller towns already electrified is provided in Annexe 2, along with a list of planned projects. The towns are mainly electrified through mini-grids fuelled by diesel. Due to the high prices for diesel and the reduced cost of solar PV panels, this market seems interesting for hybrids combining solar PV and diesel. This option is further explored in section 7.2.

3.4 Power purchase agreements

A number of African countries have implemented or are in the process of implementing general power-purchase agreements for renewable energy, such as solar and wind sold to the grid. Experiences from Africa and elsewhere show that a well-prepared power-purchase agreement can be an important factor for larger scale implementation of renewable energy sources to the grid (Haselip, Nygaard *et al.* 2011; Haselip 2011; Pegels 2011)

The first individual power-purchase agreement in Mali was apparently made between EDM and the sugar factory SOSUMAR. According to an interview with SOSUMAR management, they are planning a bagasse-fired power plant of 30 MW_{el} to be established for their own consumption of process energy and electricity (27 MW_{el}) and for electricity to the grid (3 MW_{el}). According to the interview, a power-purchase agreement has been concluded with EDM, but no details were revealed (SOSUMAR 2012).

4 Wind resources in Mali

This chapter provides a summary of the resource assessment . in the report ‘Estimation of wind and solar resources in Mali’ (Badger, Larsen *et al.* 2012), and adds valuable information on the annual and . daily variations in wind speed and wind power density. The chapter ends . discussing the opportunities for the large-scale integration of wind with existing hydropower capacity.

4.1 Introduction

The estimate of wind resources in Mali is based on a combination of global meteorological data for the past 30 years[3] and local wind measurements at 14 locations over the past few years. The two sources of data have been combined using KAMM / WAsP analyses, the results of which are presented in graphical form as wind resource maps.

The ‘simulated wind atlas’, based on a KAMM analysis of data from the global data base, indicates the estimated wind resources at a specific height level. The ‘generalized wind atlas’, based on the simulated wind atlas in combination with maps with information on the topography and surface roughness, indicates resources at a specific height level assuming flat land and homogeneous surface roughness. The actual wind resources for a specific site can then be estimated based on the generalized wind resources for that region in combination with actual information of the local topography and surface roughness.

The local wind measurements serve a double purpose. First, they can be used by WAsP to estimate the local wind resources close to the measurement site. Secondly, they have been used to evaluate and calibrate the generalized wind atlas.

Based on a set of wind speeds and wind directions at a given site and height (either from local measurements or from a KAMM analysis) and detailed information on the local topography and surface roughness, the computer programme WAsP can be used to estimate the generalized local wind resource as well as the actual wind resource at any given site and height in the local region where the local generalized wind resource is valid (typically within a distance of 50-100 km, depending on the local conditions).

4.2 Local measurements

An overview of wind measurements performed since 2008 by CNESOLER at 14 locations is given in Table 4.1 and Figure 4.1. The wind has been measured for at least one year at each site. The measurements are not directly comparable, since the measurement heights vary from 22m to 50m (Table 4.1) and since the wind resources vary from year to year, as illustrated in Figure 4.1later in this chapter.

3. http://www.cdc.noaa.gov/cdc/reanalysis/

The maximum recorded 10-minute average wind speeds are indicated in the table for each site. None exceeds 45 m/s.

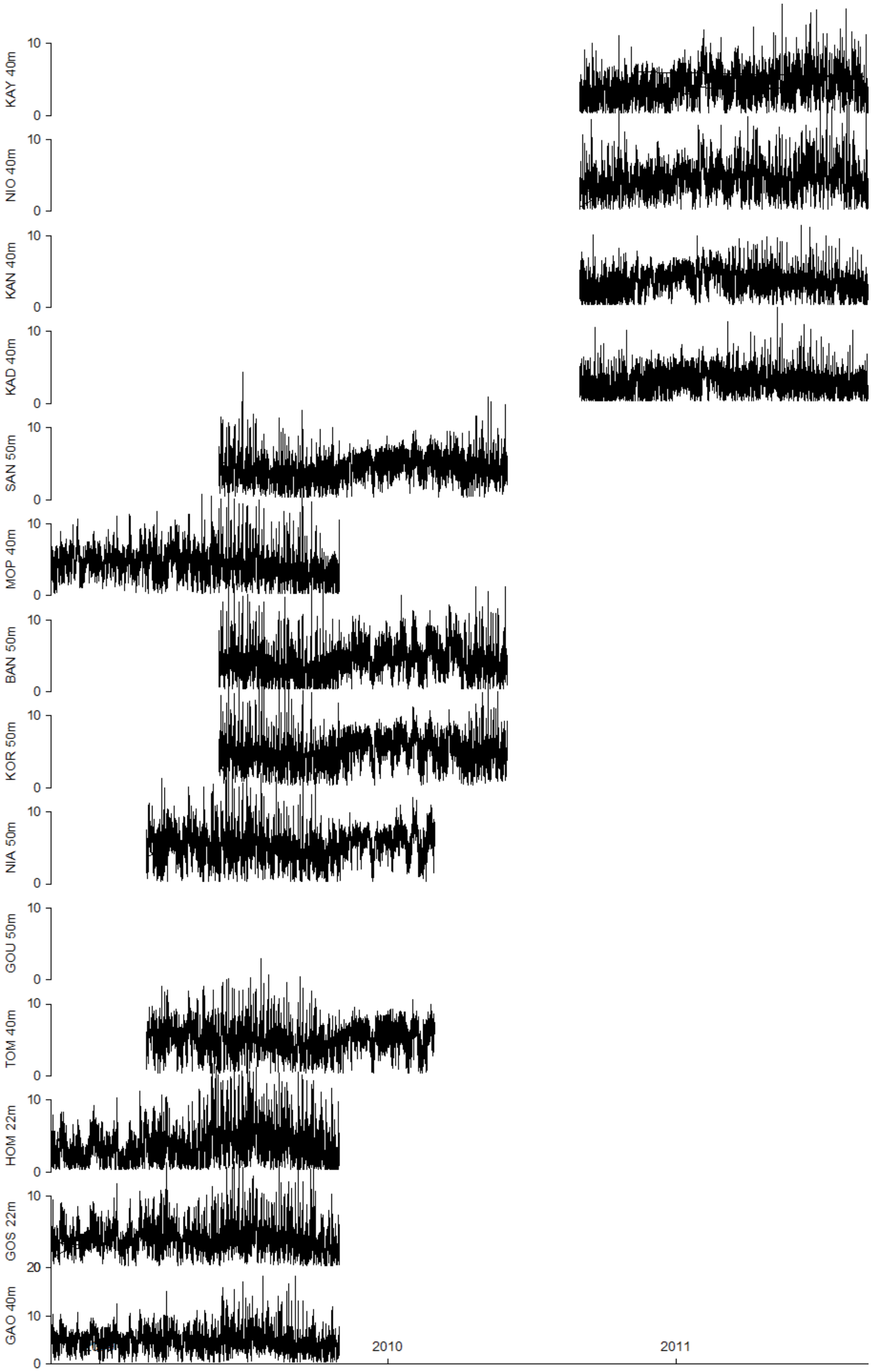

Figure 4.1. An overview of the wind measurements performed by CNESOLER at 14 sties started in 2008 (Data source: CNESOLER 2012

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

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

Table 4.1. Measured mean and 10-minutes 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 14 stations during 2008-2011, sorted by the estimated generalized power density at 50 m and 3 cm surface roughness length. (Data source: CNESOLER, 2012)

4.3 Annual wind resources

4.3.1 Wind speed

The spatial distribution of average wind speed in Mali is illustrated in Figure 4.2. The figure shows the 'simulated wind speed' at 50 m a.g.l based on a KAMM analysis of data from the global data base. The map has been created using a surface description at 7.5 km resolution, 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 topography, thus providing a higher wind energy potential than indicated by the maps.

The results are also available as a set of local wind resource data files (WAsP wind resource input files) at geographically distributed grid points. WAsP input files are available on the web, as described in section 4.4. Examples of estimates of annual power generation from cases of wind farms at specific locations using WAsP are given in section 5.2.

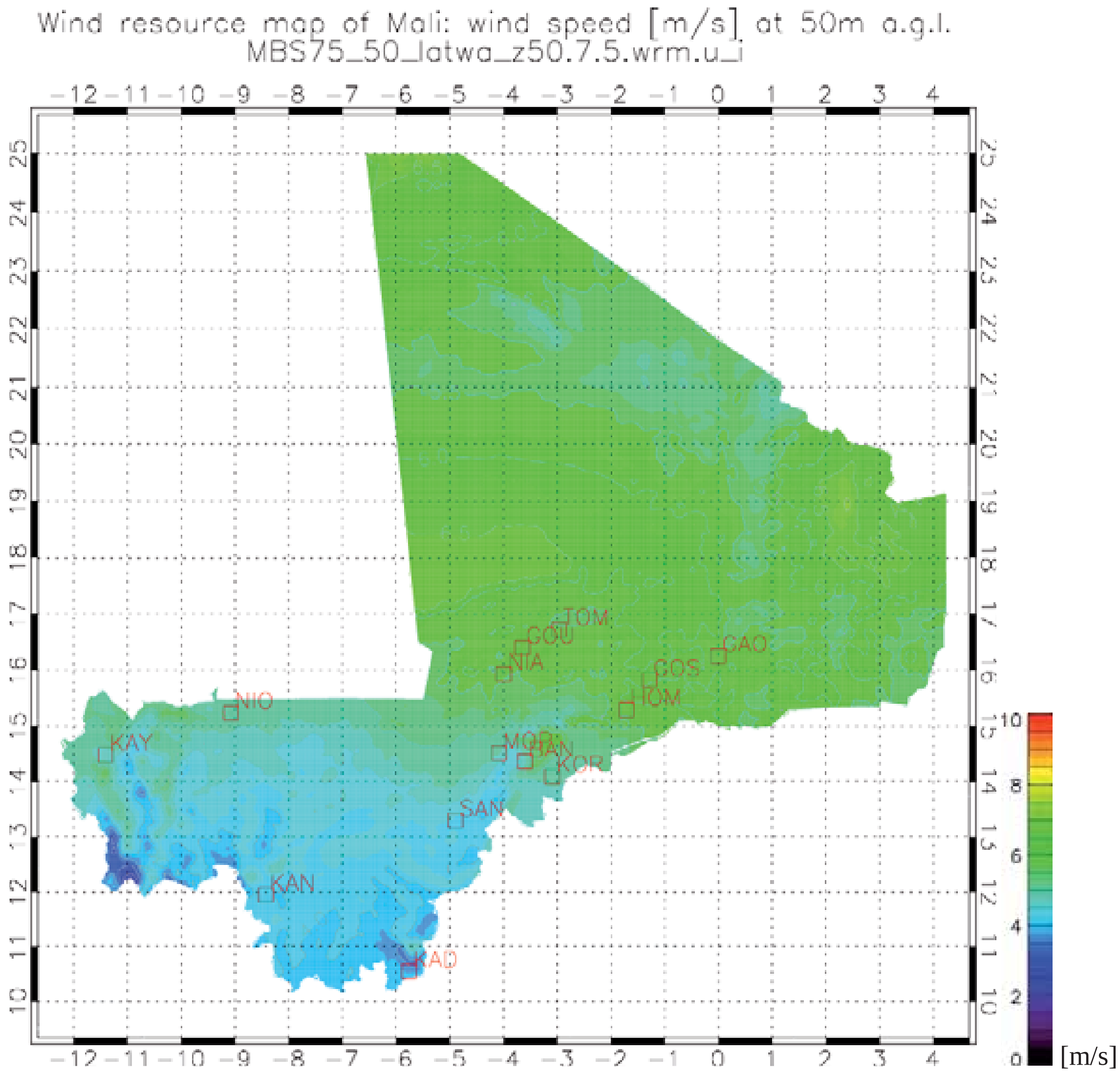

Figure 4.2: Annual mean simulated wind speed at 50 m a.g.l. The contour interval is 0.5 m/s and colour scale is in m/s. (Badger, Larsen et al. 2012)

4.3.2 Surface roughness and height

In general, wind resources increase with height above ground, depending on surface roughness. As a first-order approximation in the lower surface layer, relevant for wind power, a logarithmic vertical wind-speed profile can be assumed:

$$u_2/u_1 = \ln(z_2/z_0)/\ln(z_1/z_0)$$

where

- u is the wind speed
- z is the height
- z_0 is the roughness length (see Table 4.2)

Class	z_0 (m)	
3	0.4	Open forest
2	0.1	Farmland with shelters
1	0.03	Open farmland
0	0.0002	Sand / water

Table 4.2. Surface roughness length (Frank, Rathmann et al. 2001)

4.3.3 Wind power density

The most useful way to describe the wind resource available at a potential site is by using the concept of wind power density. This is measured in watts per square meter and indicates how much energy is available at the site for conversion by a wind turbine.

The relationship between the wind speed and the power in the wind is:

$$P = \frac{1}{2} q A u^3$$

where

- P is the power flow
- q is the air density
- A is the swept area
- u is the wind speed

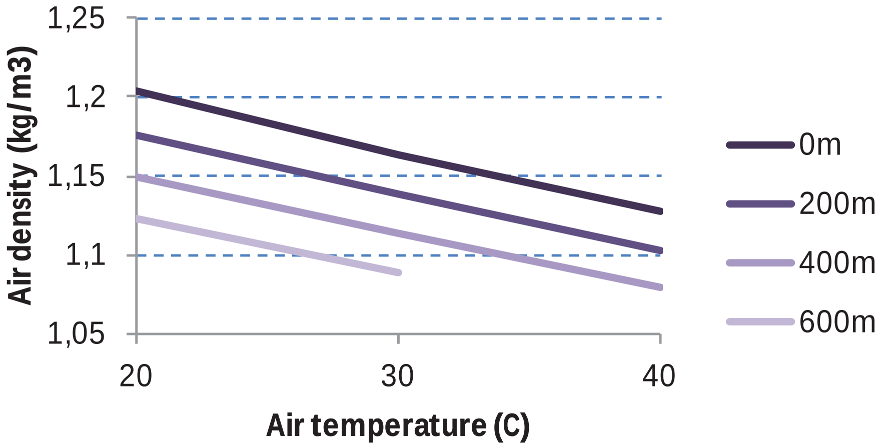

Figure 4.3 Air density as function of the air temperature and the height level for standard air pressure at sea level

This means that the power density (P/A) is proportional to the air density (see Figure 4.3) and to the cube of the wind speed. Consequently a 10% change in wind speed corresponds to a 30% change in power density.

In the literature, sites are classified according to wind power density as shown in Table 4.3. The wind resource map, showing the spatial distribution of annual *simulated* wind power density, is produced in Figure 4.4. This map is the most illustrative map for the visual identification of potential sites.

Table 4.3. Wind power classes

Wind power class	Power density W/m² at 10 m	Indicative wind speed	Power density W/m² at 50 m	Indicative wind speed
1	0-100	0-4.4	0-200	0-5.6
2	100-150	4.4-5.1	200-300	5.6-6.4
3	150-200	5.1-5.6	300-400	6.4-7.0
4	200-250	5.6-6.0	400-500	7.0-7.5
5	250-300	6.0-6.4	500-600	7.5-8.0
6	300-400	6.4-7.0	600-800	8.0-8.8
7	400-1,000	7.0-9.4	800-2,000	8.8-11.9

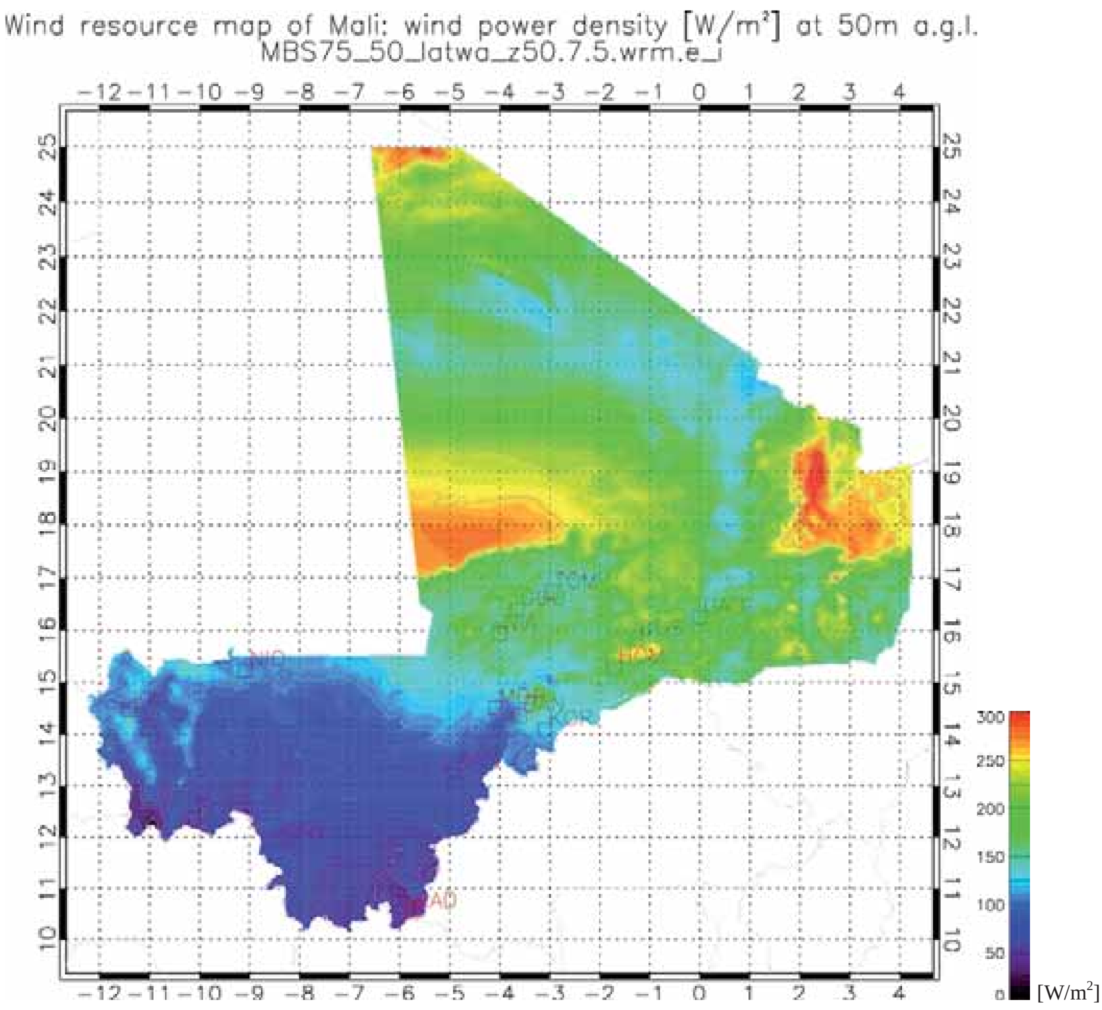

Figure 4.4. Simulated average wind power density for Mali (in W/m²) at 50 m height level (Badger, Larsen et al. 2012)

However, the resolution of the wind speed map in Figure 4.2 is 7.5*7.5 km. This means that local topography and roughness are not taken into account. It may thus be possible, as illustrated in section 5.2, 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.

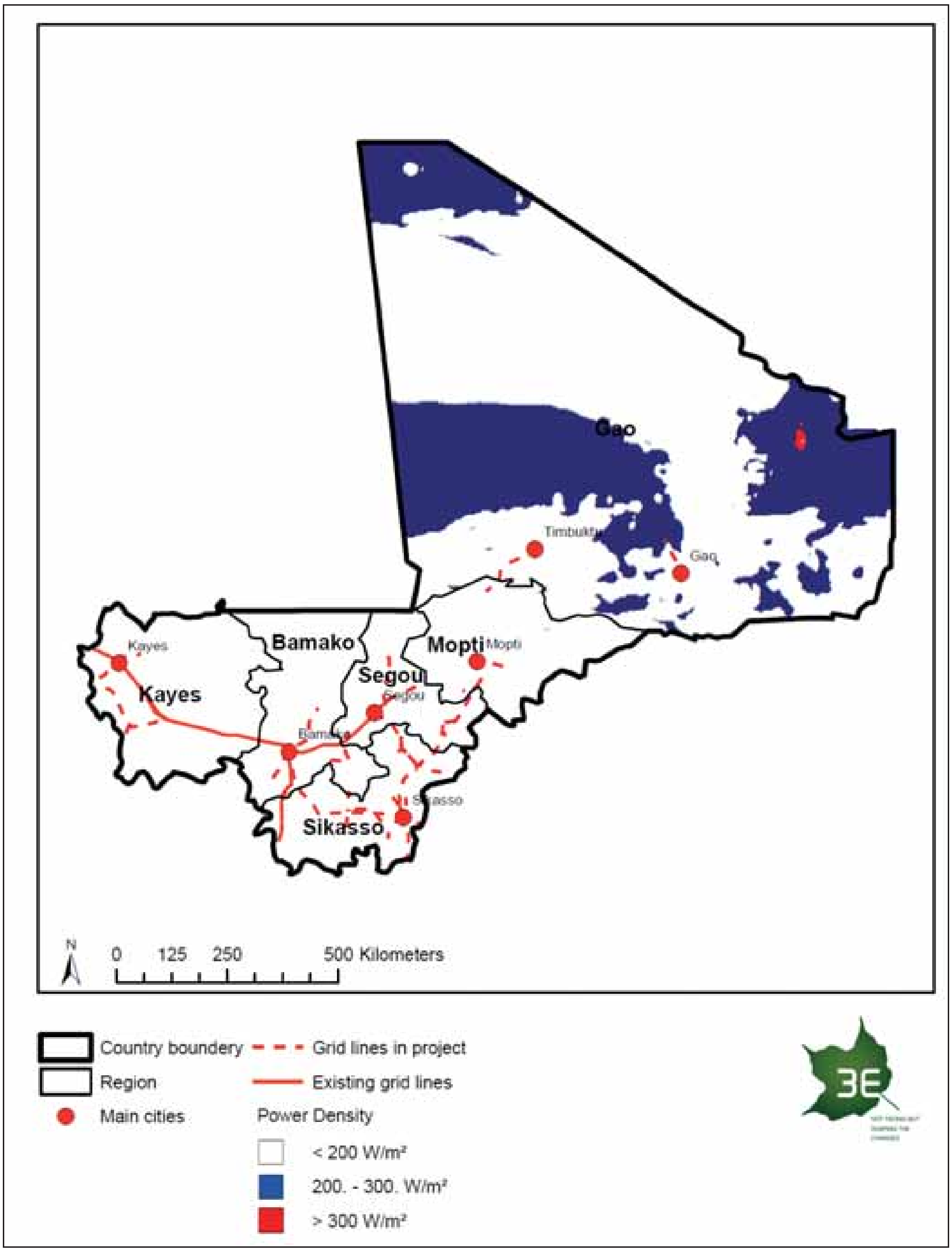

Figure 4.5. Wind power density and existing and planned transmission lines

According to the wind map, 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, which are suitable for large wind farms, are far from the integrated electricity grid, as shown in Figure 3.6. The existing grid ends at Segou, though an extension to Mopti is planned for 2017-2018. The distance from the areas mentioned above to Mopti is

400 km and 500 km respectively. Figure 4.5 shows wind power density along with existing and planned transmission lines.

4.4 Application of data using WAsP

The real added value element of the KAMM/WAsP numerical wind atlas methodology is the ability to apply the derived generalized wind atlas data at the microscale using the WAsP software. This allows the WAsP user to make pre-feasibility calculations for any location covered by the numerical wind atlas, and to make estimates for annual energy production given specific turbine type and characteristics. This section gives a demonstration of this application.

First the user must assess the correct generalized wind climate data for a given location. These data are contained in a so-called lib-file. Mali is covered by a grid of lib-files with 7.5 km spacing, making up tens of thousands of lib-files.

There are two methods of accessing generalized wind climate data for Mali.

Method 1

For offline access, to assist the user a simple program is provided for download from the project website (www.frsemali.org). By running this program, the user is prompted for the location of interest's longitude and latitude, and the program copies the relevant lib-file containing the generalized wind climate data into a convenient folder. A screenshot of this application is shown in Figure 4.6. The project website also includes a guide to using the offline lib-selection tool.

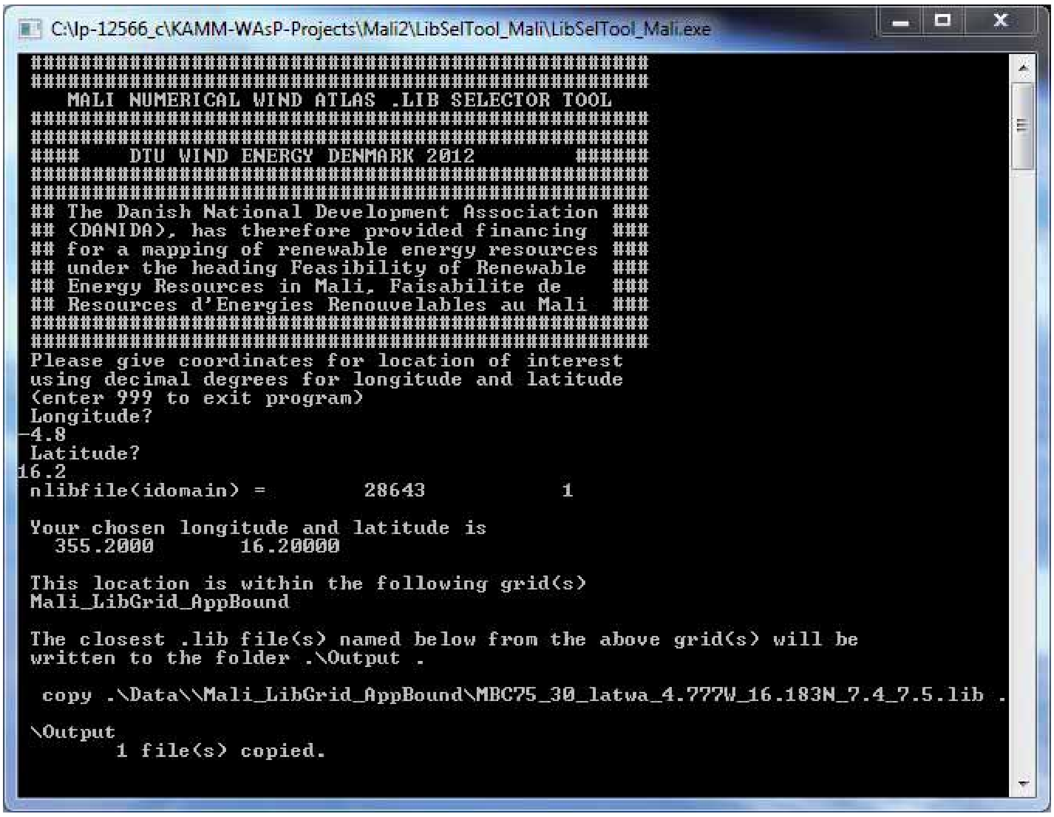

Figure 4.6. Screen shot of the lib-file selection tool

Method 2

For online access, an alternative lib-file selector is available. This is called Tadpole and uses a Google Earth plug-in to allow the user to navigate, select a location of interest and download the generalized wind climate data. A link to the Tadpole server will be given on the project website (www.frsemali.org). A screen shot of Tadpole is given in Figure 4.7. The project website also includes a guide to using Tadpole.

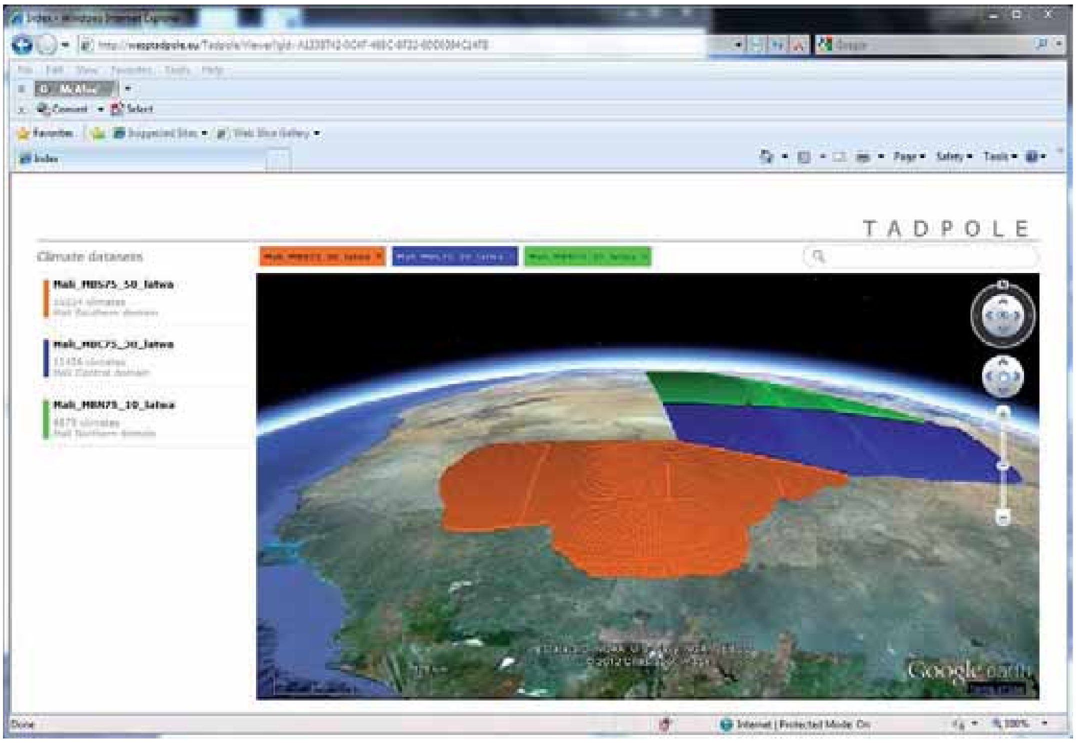

Figure 4.7. Screen shot of the lib-file selection tool Tadpole over Mali. Orange, blue and green dots indicate lib-file locations. The user can navigate, zoom and search the map, and by clicking on a dot the user can download the lib-file so that it can be applied in WAsP.

WAsP

Once downloaded, the lib-file can be used in the WAsP software to carry out microscale modelling. Figure 4.8 shows a screen shot of the WAsP results displayed in Google Earth. This display functionality is part of WAsP. The application shown has been used to calculate the variation in the annual energy production over terrain south of Kayes. The software is very powerful as a tool to locate potential sites for wind turbines away from the measurement locations and to estimate the annual energy production of particular wind turbines by combining the information about directional wind speed distribution with the wind turbine power curve.

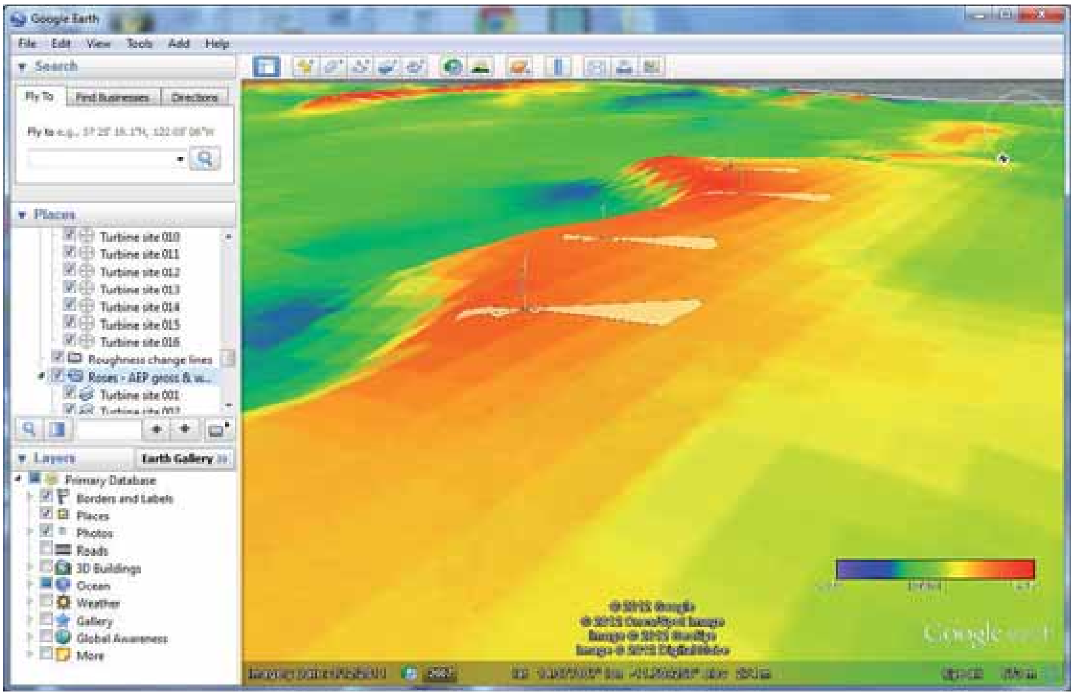

Figure 4.8. Screen shot showing the WAsP software being used to calculate annual mean wind speed at 70 m a.g.l for a 4.5 km by 4.5 km area at 100 m resolution. The area includes the measurement station (near western edge) and a hypothetical wind turbine site (north-eastern corner). A predicted wind climate can be calculated for any location, and a estimate of the annual energy production of a wind turbine can be obtained using WAsP. The input data are generalized wind climate data from the KAMM/WAsP numerical wind atlas calculation. This calculation is an example only. Surface roughness is assumed to be 0.02 m everywhere. A site survey is needed to add more topographical detail to the calculation map.

4.5 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 for the value and integration of wind power into the specific power system, as further noted in section 4.6 below.

The variation in the annual mean for geostrophic wind speed from year to year for Mali, with an indication of the 30-year average value and the values, is shown Figure 4.9.

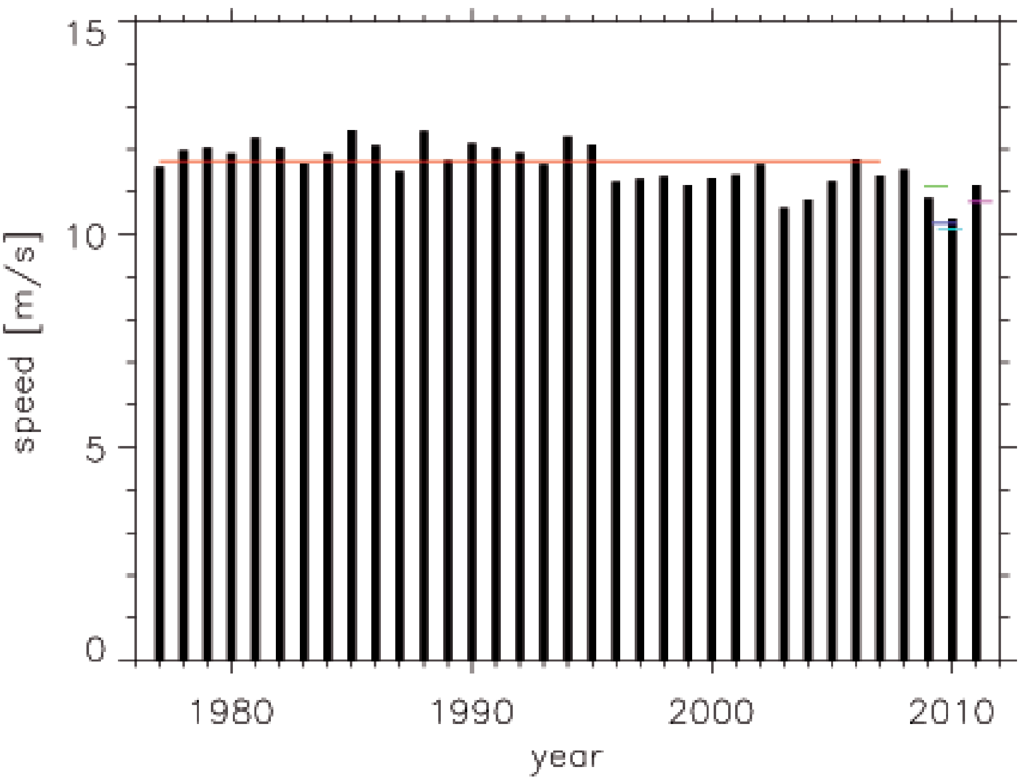

Figure 4.9. Variation of the annual mean geostrophic wind speed from year to year for Mali with indication of the 30-year average value and the values

Examples of the characteristics of the variations in wind resources over the year and over the day are illustrated for Kayes in Figure 4.10 and for Goundam in Figure 4.11.

The figures show monthly averages of wind speeds, the turbulence intensities and wind power densities for each month, and monthly averages of wind speed and wind power densities for each hour of the day for the month with the highest and lowest average wind power densities respectively.

The examples show clear, systematic, but different characteristic variations in the resources over the year and over the day. Kayes shows maximum resources in spring and summer, and minimum in autumn through to February. Kayes shows maximum resources at midnight and mid-day, 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.

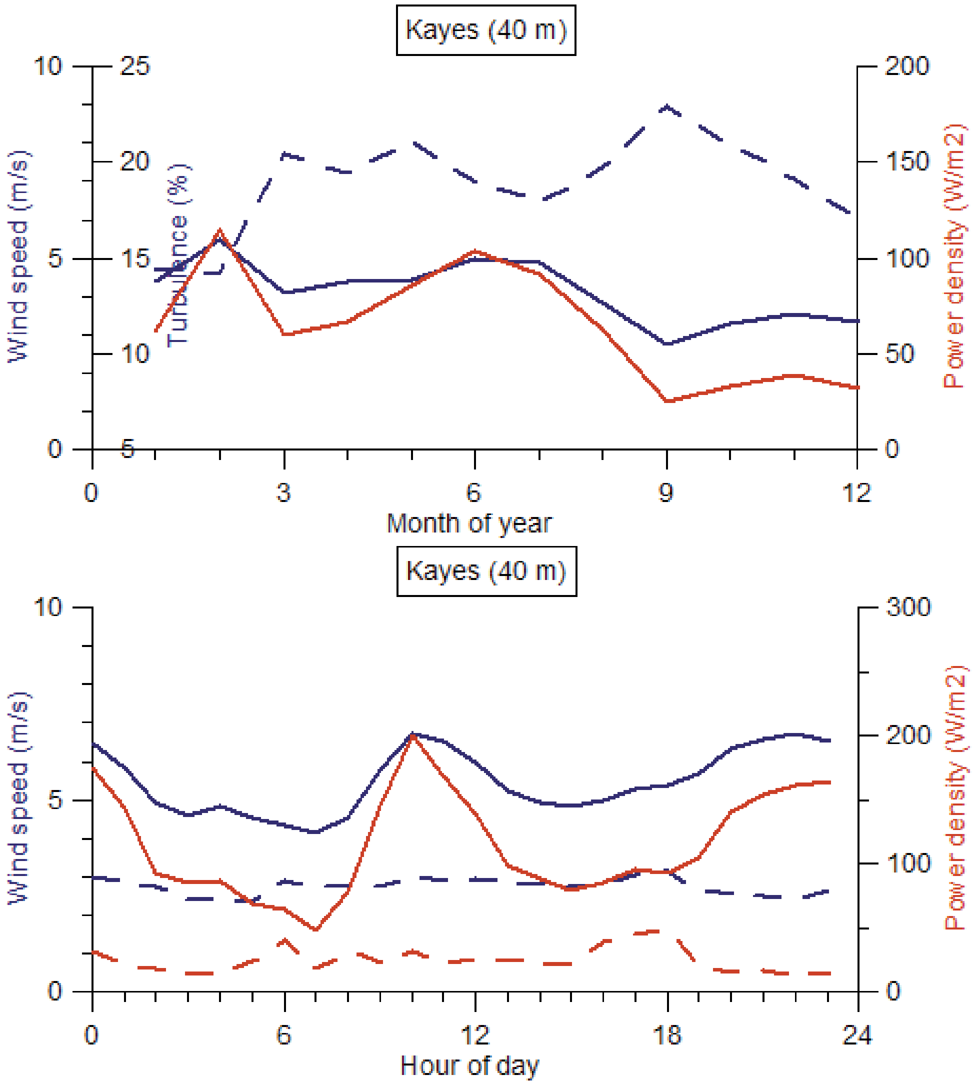

Figure 4.10. Example from Kayes of the variation of the wind resources over the year and over the day, based on one year of measured data. Upper: monthly average wind speeds, turbulence intensities and wind power densities. Lower: monthly average wind speeds and wind power densities for February and September (dashes) (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 4.2 and Table 4.1; and
- 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.

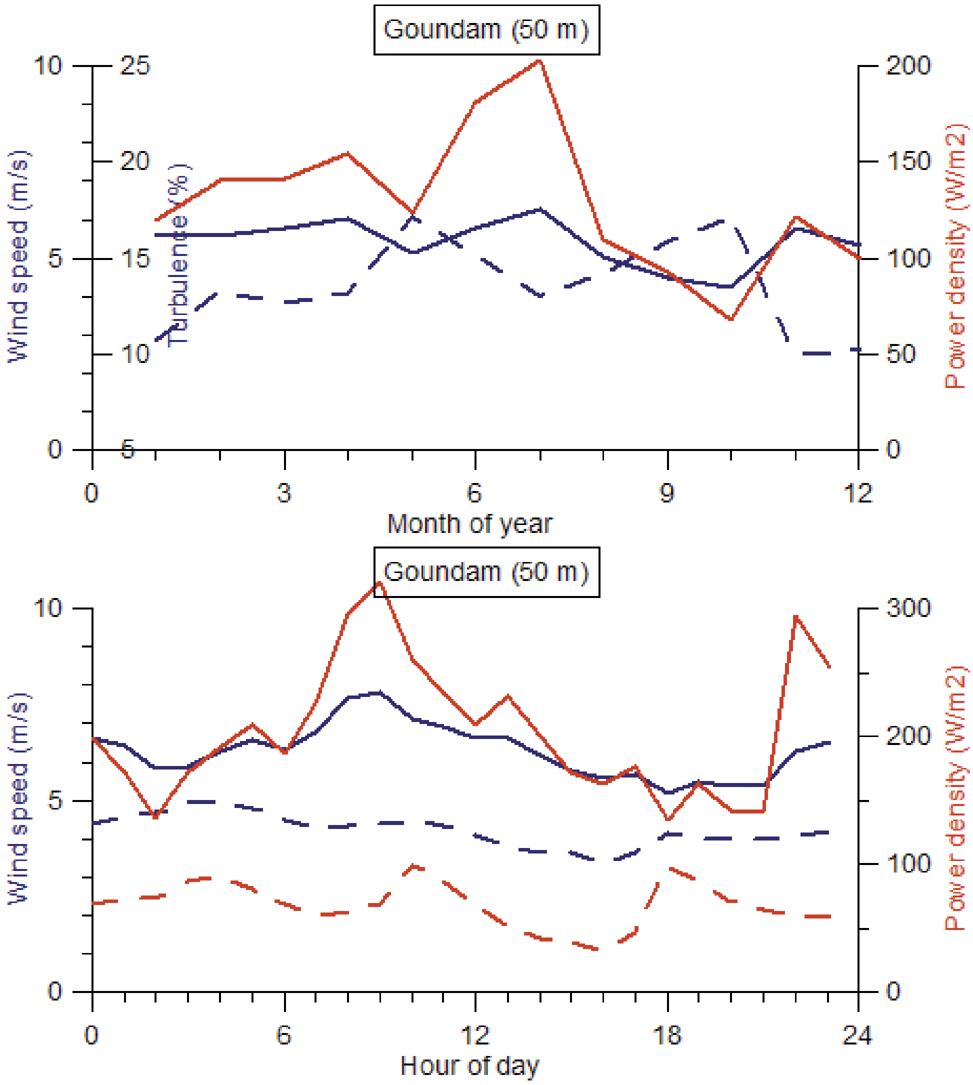

Figure 4.11. Example from Goundam of the variation in wind resources over the year and over the day, based on one year of measured data. Upper: monthly average wind speeds, turbulence intensities and wind power densities. Lower: monthly average wind speeds and wind power densities for July and October (dashes) (CNESOLER, 2009/10)

4.6 Integration with hydropower

The water level in the hydropower dams – and thus the hydropower potential – is at its lowest at the beginning of the rainy season in July and August. This is illustrated in Figure 4.12, which shows the water level in the Manantali dam on the Senegal river. The Mananteli power project is a joint project between Senegal, Mauritania and Mali, and the power produced is shared among the partners.

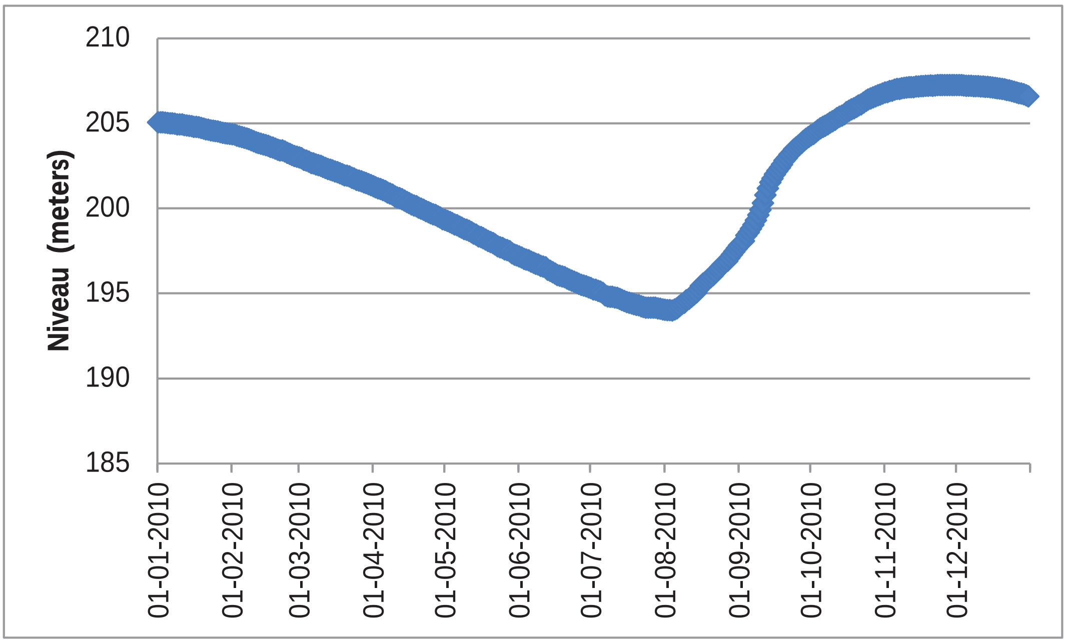

Figure 4.12. Variation in water level in the Manantali dam in 2010 (SOGEM)

Due to seasonal rainfall in a few months from July to October, water remains a limiting factor for the operation of the hydropower scheme for most of the year. In 2010 the Manantali dam, with a rated output of 200 MW, was operating at a yearly average load of 97 MW, due to a lack of water inflow.[4] However, this low load factor implies that the hydropower schemes have a high regulating capacity.

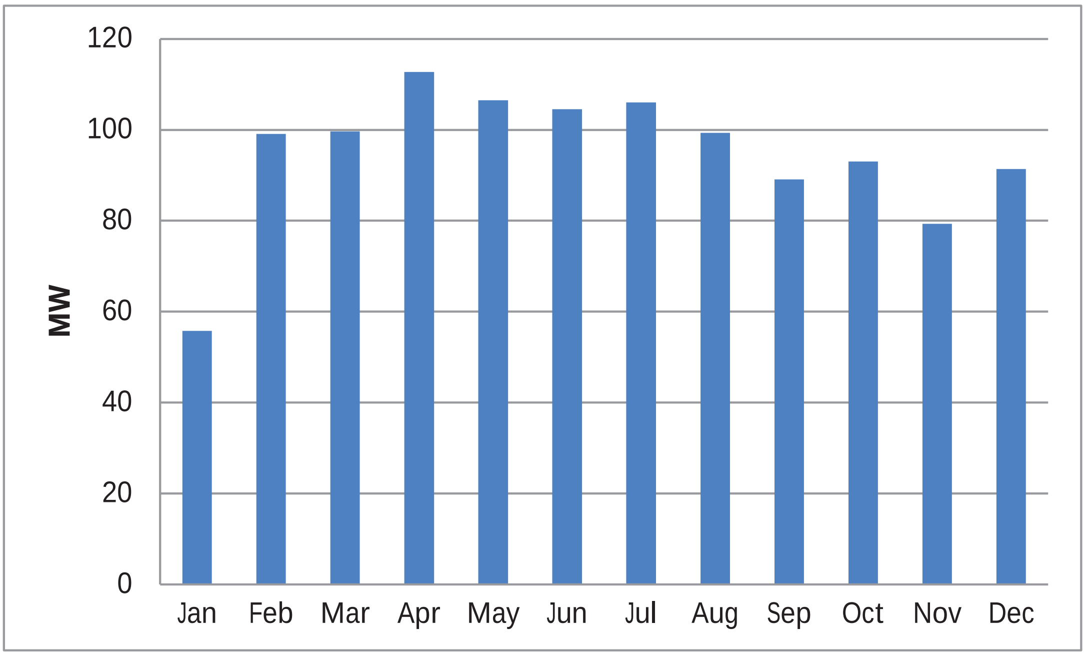

Figure 4.13. Average monthly power output for Manantali in 2010 (SOGEM)

4. In the Manantali case, the dam has never been filled to the maximum. This means that the efficiency per m^3 of water is lower than maximum, but also that water is not wasted, not even at the end of the rainy season. Interview with Seybou TOURE, SOGEM, February 2012.

This regulation capacity can be used throughout the year. Figure 4.13 shows how production is held at a low level in autumn to save water, with the result that production can increase in the spring months, where power demand in the integrated system is at its highest, as shown in Figure 3.6:

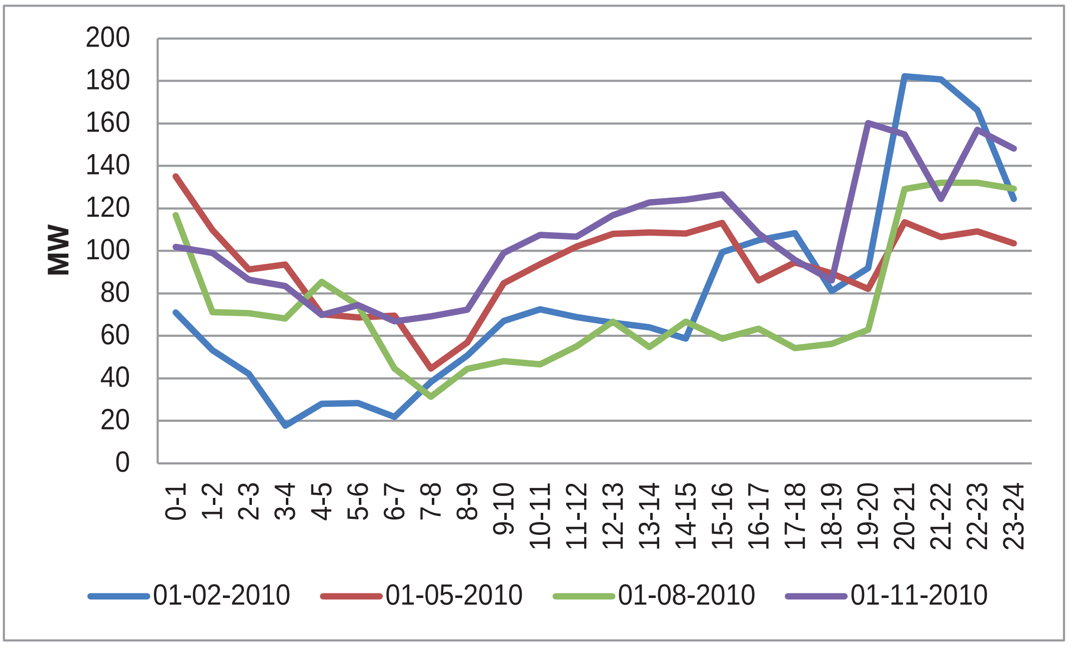

Figure 4.14. Average power output per hour for Manantali in 2010 (SOGEM)

The regulating capacity can also be used to comply with the daily load patterns. Figure 4.14 shows how the Manantali hydropower scheme is used to follow the daily load patterns in February, May, August and November.

This regulating capacity means that a large amount of wind (and solar) power can be integrated into the central power system, even without the need for transnational interconnector power lines. Dynamic regulation of the hydropower can be used to balance the fluctuating wind power, and the wind power can be used to provide a seasonal delay in utilization of the hydropower. A geographical distribution of the wind power plants will reduce the short-term fluctuations of the aggregated wind power generation.

5 Applications for wind energy in Mali

As described in detail in Chapter 3, power systems in Mali can be classified into:

- The integrated grid, with a peak load of around 1000 MW
- Isolated systems, with peak loads of around 1 MW
- Hybrid systems, with peak loads of around 100 kW

For the small-scale hybrid systems, wind power is assessed at not being feasible.

As there is no obvious candidate for the type of wind power application in Mali, three types of wind power application have been studied further:

- Small-scale wind farm for the isolated power systems
- Medium-scale wind farm close to and connected to the central power system
- Large-scale wind farm far from, but connected to the central power system

Tombouctou has been selected for the first type, Kayes for the second, and the desert west of Tombouctou for the third. In general, for the wind farms connected to the central power system, the larger the wind farm, the longer the distance from the grid that may be economically feasible.

Figure 5.1. Example of a wind farm in Spain with 7 Gamesa 850 kW wind turbines (Gamesa, 2012)

5.1 Examples of wind turbines and characteristics

The important parameters and characteristics for a wind turbine in relation to conversion of the wind into electricity are:

- the generator capacity,
- the rotor diameter,
- the hub height, and
- the efficiency (or power) curve.
-

The 'same' wind turbine may be offered (at different prices) with different hub heights and different rotor diameters – see Figure 5.2. At high wind speeds, the efficiency of the wind turbine must be limited so as not to overload the drive train and the generator. For most large-scale wind turbines, power generation at high wind speeds is limited through pitching of the blades. The economically optimum set of parameters is site-specific. In general, the lower the wind resources the larger the rotor diameter, and the higher the surface roughness the higher the hub height.

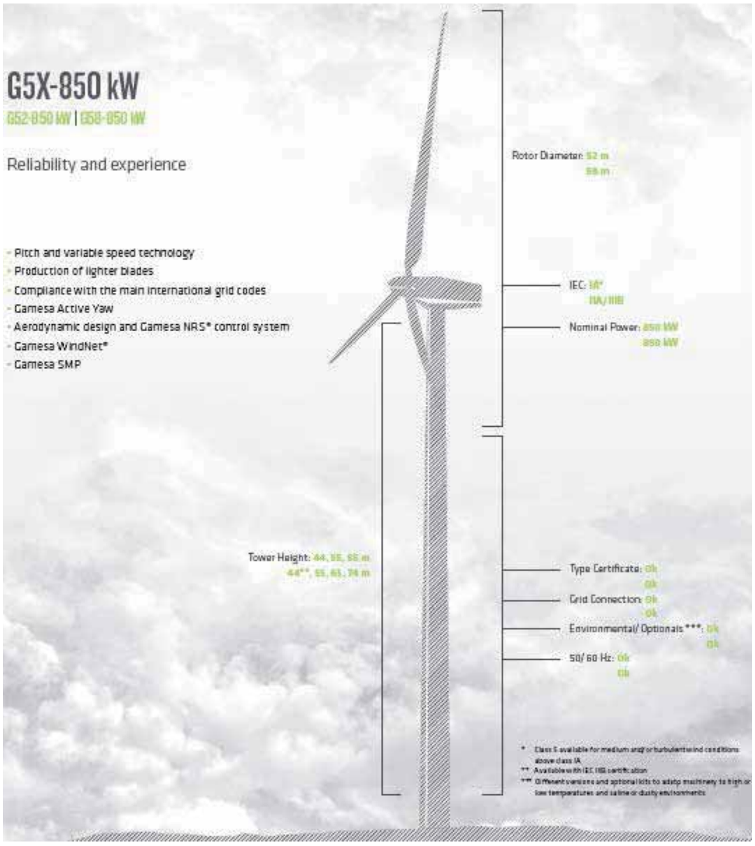

Figure 5.2. Example of the different models offered of the Gamesa 850 kW wind turbine (Gamesa, 2012)

An example of the power in the wind, the efficiency curve and the power curves for a specific wind turbine is given in Figure 5.4. The efficiency is 0 at low wind speed and maximum (around 50%) around 7 m/s. The combination of relatively low energy in the wind and relatively low efficiency of the wind turbine at 5 m/s wind speed results in very

low power generation by the wind turbine. The maximum power generation is reached at 12-15 m/s, depending on air density.

Figure 5.3. Vergnet turbines 275 kW with tiltable tower

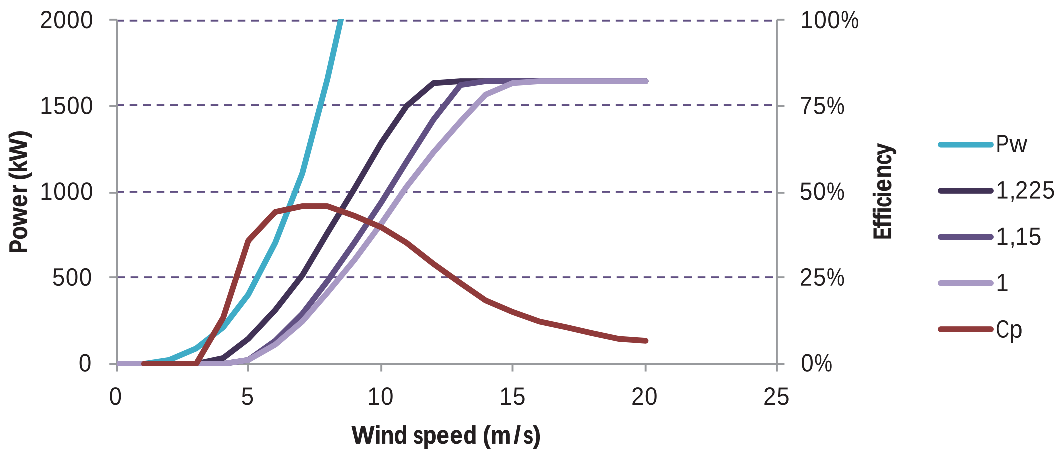

Figure 5.4. Example of the power in the wind (P_w) and the efficiency curve (C_p) (at 1,225 kg/m^3 air density), and the power curves for different air densities for a specific wind turbine (Vestas V82-1650). (Data source: Vestas)

5.2 Case studies of wind applications

5.2.1 Tombouctou

As an example of a small-scale wind farm for the isolated diesel-based power systems, a 675 kW wind farm is assumed to exist north of Tombouctou town – see Figure 5.5. 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.

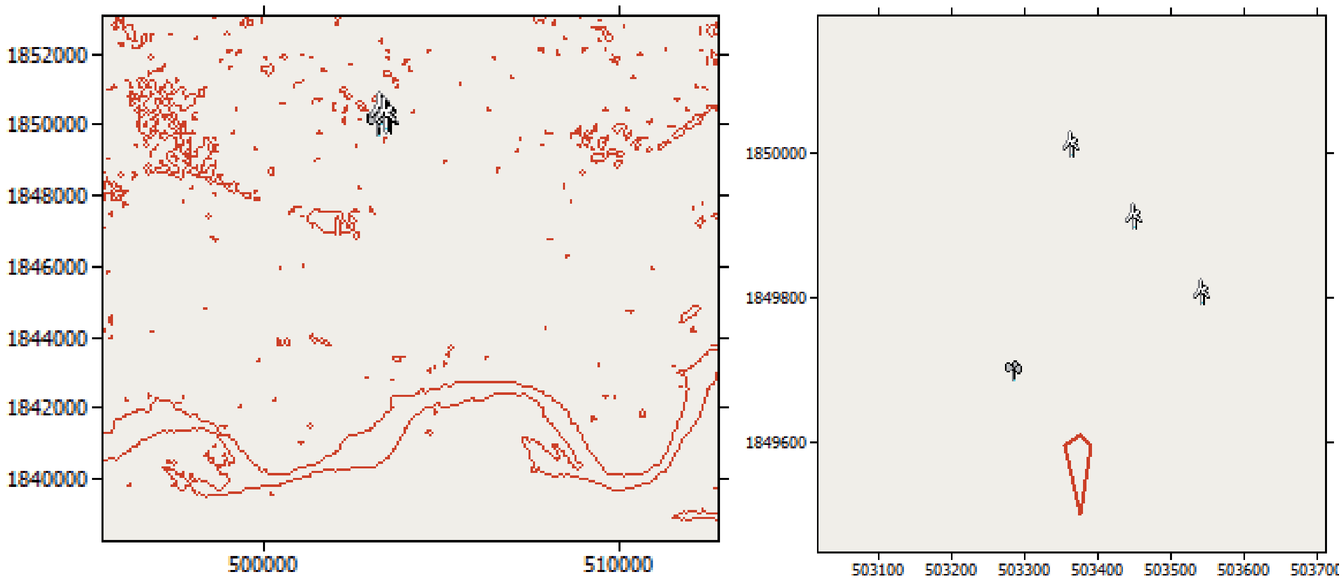

Figure 5.5. WAsP maps indicating the 675 kW Tombouctou Wind Farm north of Tombouctou town

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

Volder, Dewilde et al. (2009) present calculations for another technology based on tilting windmills (MP275 Vergnet), which have 275 kilowatt output and a tower height of 55 m. This alternative consisting of four turbines produces 1850 MWh. The capacity factor is 19% mainly because the hub height is higher. For three wind turbines, the potential annual energy production would be 1350 MWh.

5.2.2 Kamango wind farm

As an example of the integration of wind power into one of the isolated power systems, an 8.5 MW wind farm is assumed to exist at Kamango, 75 km west of Tombouctou 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–Tombouctou integrated power system – see Figure 5.6.

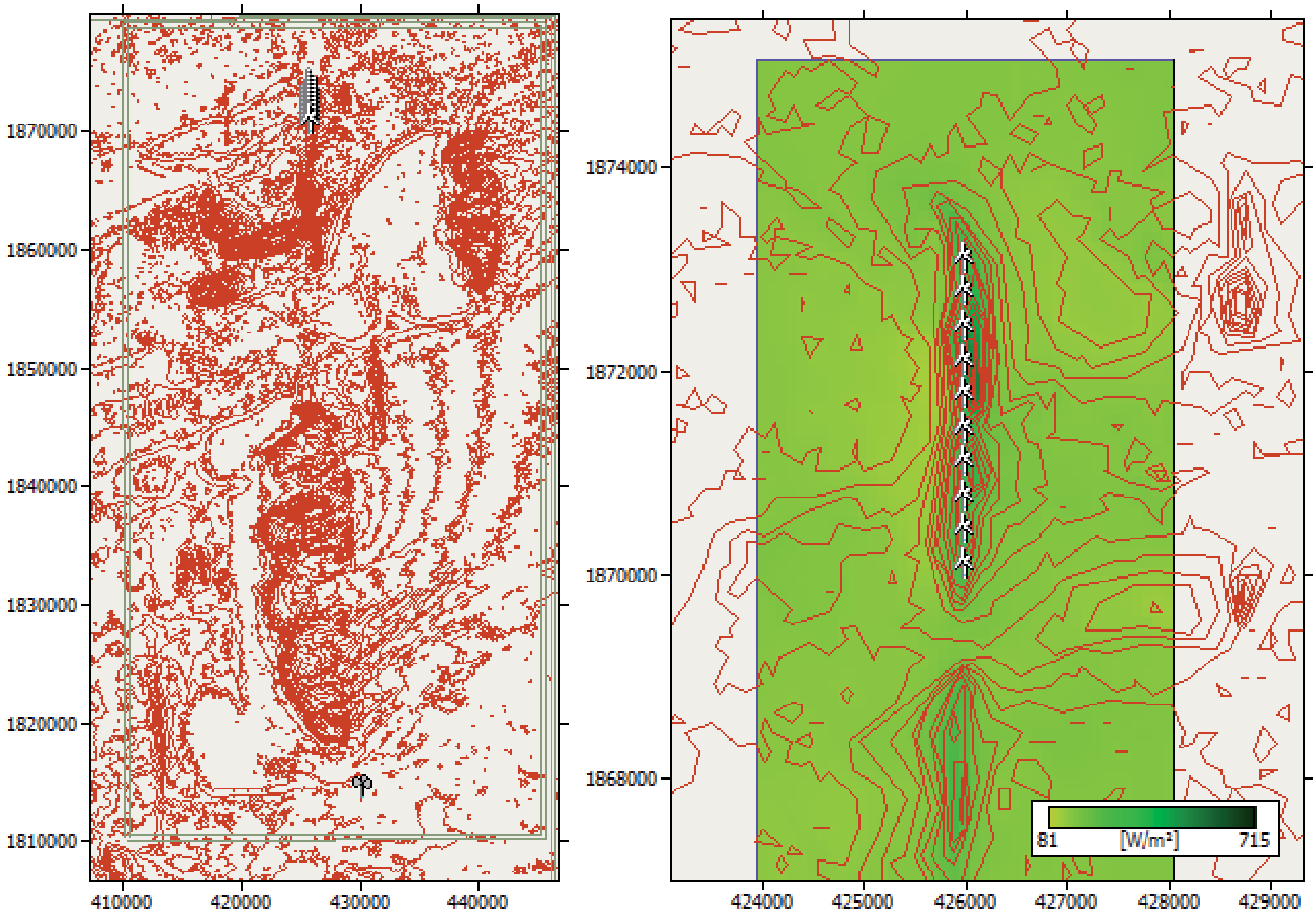

Figure 5.6. WAsP maps indicating the 8.5 MW Kamango Wind Farm at a 100 m north-south oriented hill, the Goundam measurement station (the left map), and the power density distribution (the right map)

The wind farm consists of 10 × 850 kW wind turbines (the 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. The annual energy production from the wind farm is estimated by WAsP at 28 GWh (corresponding to a capacity factor of 38%), based on measured data at Goundam.

5.2.3 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 5.7.

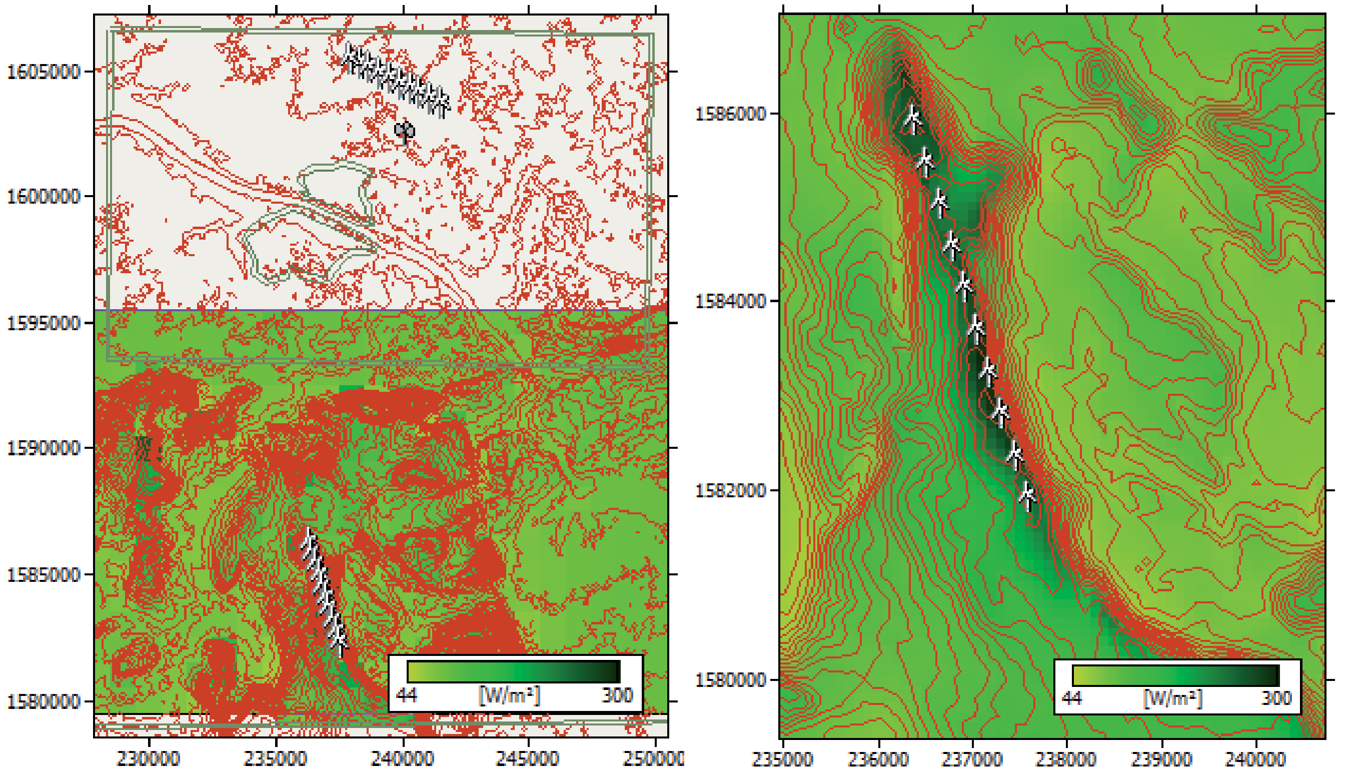

Figure 5.7. WAsP maps indicating the 8.5 MW Kayhill Wind Farm at a 100 m NNW-SSE oriented hill, the Kayes measurement

The wind farm consists of 10 × 850 kW wind turbines (the 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. The annual energy production estimated by WAsP from the wind farm is 25 GWh (corresponding to a capacity factor of 34%), based on the measured data from 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%.

5.2.4 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 Tombouctou, 600 km from the integrated grid.

The wind farm consists of 200 × 850 kW Vestas V60-850 wind turbines arranged in 10 NW-SE oriented rows 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.

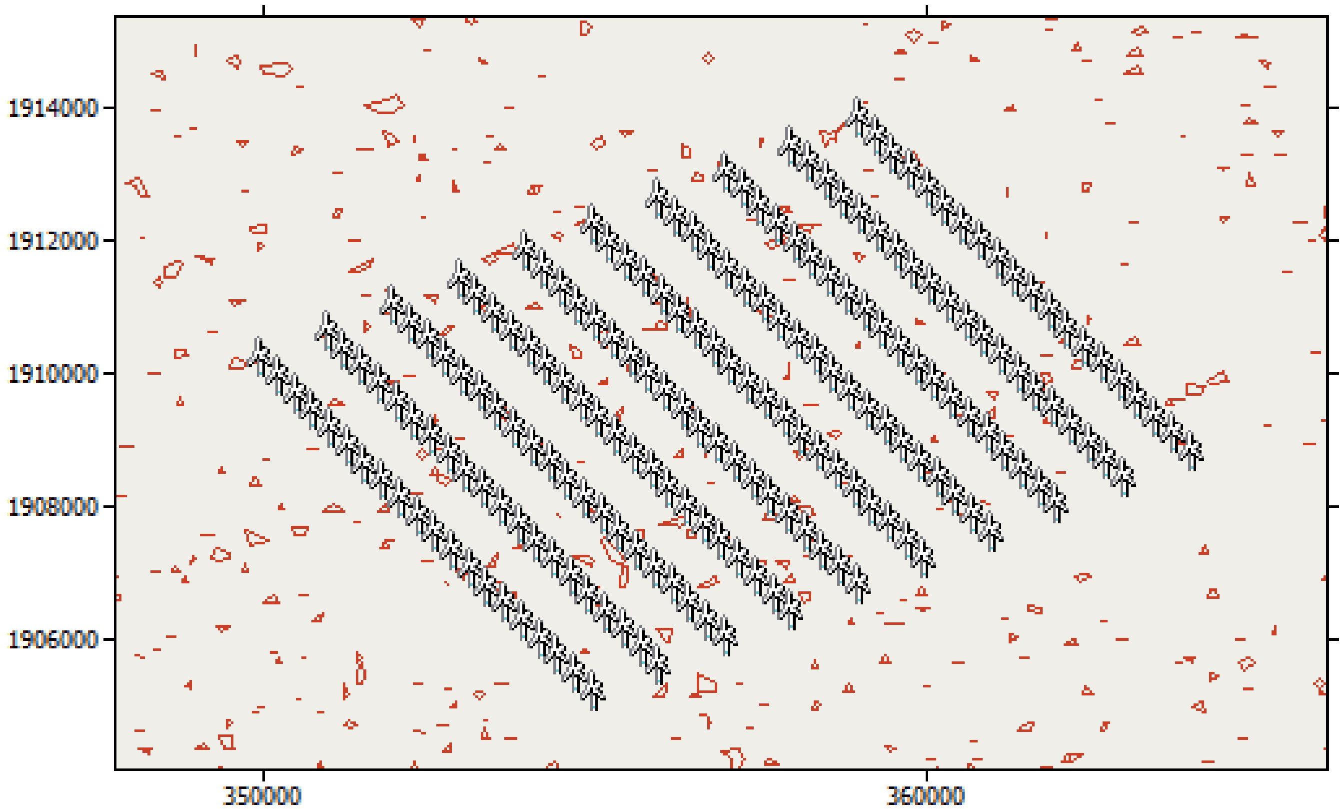

Figure 5.8. WAsP maps indicating the 170 MW Akle Wind Farm in the desert west of Tombouctou

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%).

5.2.5 Summary of case studies

An overview of the annual power generation estimated by WAsP and the corresponding wind turbine load factors for the five sites and for different models of the two wind turbines, used as examples, is presented in Table 5.1.

The impact of the rotor diameter and hub height is illustrated for the Tombouctou 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 the WAsP calculations are rather uncertain in very complex terrain, as for the Kayhill and Kamango wind farms. The actual wind resources must be confirmed by local measurements at the sites.

Wind farm	Elev	Nos	V27	V29	(50m)	V52	V60
Tombouctou	260 m	3	0.6 GWh (10 %)	0.7 GWh (12 %)	1 GWh (17%)		
Kamango	350 m	10	5.7 GWh (29 %)	6.2 GWh (31 %)		23 GWh (31 %)	28 GWh (38 %)
Kayes	60 m	10					10 GWh (13 %)
Kayhill	350 m	10	5 GWh (25 %)	5.5 GW (28 %)		20 GW (27 %)	25 GWh (34 %)
Akle	280 m	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
V29-225/50	225 kW	29 m	50 m
V52-850/55	850 kW	52 m	55 m
V60-850/60	850 kW	60 m	60 m

Table 5.1. Illustration of the impact of the type of wind turbine on estimated annual production (with the corresponding capacity factors in parentheses) at the five selected wind farm sites

5.3 Main technical challenges in building wind farms in developing countries

5.3.1 Logistics

The installation of large turbines requires consideration of the implications of the transport of turbines with tower heights of 55m and turbine diameters of 60m (850 kW range) or even 80m with a rotor diameter of 90m (2 MW range). Typical characteristics of the components of such turbines are summarised below:

Table 5.2 Typical characteristics of wind turbine components

Component	Rotor diameter 60m	Rotor diameter 90m
Transport frame with three blades		
Length	30m	45m
Width	2.5m	2.5m
Height	2.9m (TH: 4.1m) *	3.5m (TH: 4.7m) *
Mass	14 tonnes	25 tonnes
Tower:		
No. of sections	2	3
Length	29m	29m
Width	2.5m	4.2m
Height	3.3m (TH: 4.5m)	4.2m (TH: 5.4m)
Mass	35 tonnes	45 tonnes
Nacelle:		
Length	6.8m	10.4m
Width	2.3m	3.4m
Height	3.1m (TH: 4.3m)	4m (TH: 5.2m)
Mass	23 tonnes	70 tonnes

*TH : The total height to be transported is calculated as the height of the component plus 1.2m for the height of the low-bed trailer.

Examples in Africa (Lake Turkana) shows that such large turbines requires a lot of logistics preparation. An example of blade transport is given below.

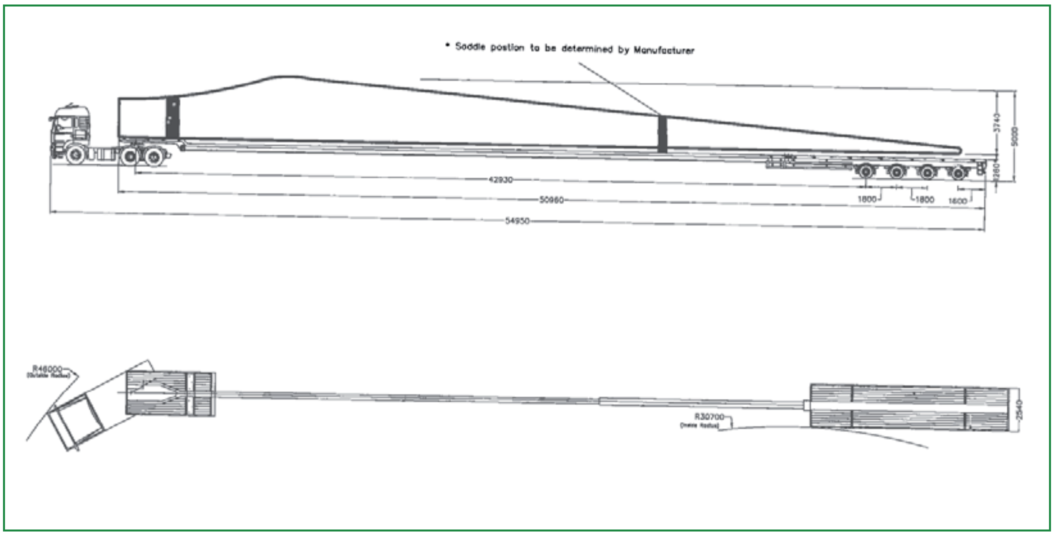

Figure 5.9. Example of blade transport by road

For these reasons, we excluded the use of wind turbines with a nominal power greater than 1 MW.

5.3.2 Grid issues

Integrated grid

There is no grid available in a large part of Mali, and consequently overhead lines have to be constructed. The max voltage level in Mali is 225 kV, ending in Mopti.

In the case of the large wind farms, this is certainly >100 MW, so a 220 KV line will be needed. For the smaller wind farms a 33 kV extension would be feasible as well. (Karhammer, Sanghvi *et al.* 2006)

Isolated grids

In general very little technological innovation is happening in this product segment. The wind turbines will operate in hybrid mode with the existing power plant (mostly diesel).

Applications in emerging countries require robust technology

- Power-electronic grid interface that can cope with large variations in voltage frequency and voltage amplitude
- Grid-interface that can withstand grid voltage dips and interruptions due to short-circuits in the grid
- Extended temperature range for applications in extremely hot, cold or humid environments
- Increased protection against dust or mechanical particle infiltration for installations near mines or sandy areas

- Enhanced controllability of output power and limitation of rotational speed for applications in smaller grids or wind-diesel systems

There are different levels of the penetration of renewables into weak grids.

- 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)
- Mid-penetration systems: renewable energy becomes a major part of the power system. Additional components and limited automated control is required to insure that power quality is maintained. Little operational control is required, though it may be used (20-50% renewable fraction)
- High-penetration systems: completely integrated power system with advanced control. Limited operational control of system by plant staff (50-100%).

5.3.3 Maintenance Issues

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.

5.4 Assessment of production costs in the four cases

5.4.1 Financial parameters

- Investment costs:
    - Site preparation and infrastructure
    - Foundations
    - Connection to grid
    - Roads
    - Study costs
    - Development costs

- Maintenance costs:
    - Maintenance, first 10 years per turbine
    - Maintenance, years 11-20 per turbine
    - Annual insurance premium
    - Lease of land
    - Project management (per annum)

- Financial parameters
    - Inflation
    - Subsidies
    - Tax deductions
    - Borrowed capital
    - Equity capital
    - Borrowing rate
    - Equity cost
    - Profit tax
    - Depreciation period
    - Loan term
    - Project lifetime

- Annual Energy yield for 20 years lifetime
- Retail price
- Income from carbon trading

5.4.2 Capital expenditure investment (CAPEX)

Table 5.3 shows the assumptions used in the model. The cost of the wind turbines was 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. This cost includes the tower, the complete nacelle, the hub, the three blades and the 690V/20kV transformer.

Table 5.3. Assumptions used in the model

	Gamesa 52 850kW 55m	Vestas-850kW 60m	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
Mobilisation/demobilisation 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

The costs of installation and commissioning are also taken from quotes for projects of this size in South Africa. For example: Gamesa G52, with a hub height of 55 and 65m: a 600t lattice crane is required, and the cost of mobilisation/demobilisation (€140,000) is based on a crane from Europe or North Africa.

5.4.3 Civil and electrical engineering

Table 5.4 below shows the unit costs for calculating the total cost of civil and electrical engineering.

Table 5.4. Unit costs for civil and electrical engineering

	Gamesa52-850kW 55m	Vestas 850 kW 60m	Vestas 225 kW 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

5.4.4 Operation and maintenance costs

The financial model is based on the following data and assumptions:

Table 5.5. General assumptions

	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 (€/wind turbine)	0.5%	0.5%	0.5%

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%).

5.4.5 General data of the model

The following data was also factored into the model:

- The percentages are expressed on the basis of the total investment
- All insurance costs and expenses are values observed by 3E in Europe and South Africa for projects of equivalent size.
- A contingency rate of 7%, which reflects the highest uncertainty for an installation in a new market such as Mali.

5.4.6 Assessment of production costs

Based on the economic preconditions above, the production costs for electricity in the four cases are described in Table 5.6. For purposes of technological comparison, the production costs are calculated for up to two selected turbine manufacturers for each of the sites.

Table 5.6. Detailed calculation of production costs for the four cases utilising different types of wind turbines

	AKLE		TOMBOUCTOU		KAYHILL	KAMANGO
	Gamesa 52-850kW 55m	**Vestas 850kW 60m**	**Vestas V29 225 kW 29 m**	**Vergnet HP 275 55 m**	**Vestas V60 850kW 60m**	**Vestas V60 850kW 60m**
Number of turbines	200	200	3	3	10	10
Capacity [Kw]	850	850	225	275	850	850
Total capacity of windfarm [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
Mobilisation/demobilisation 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, 10-20 years %	6	6	6	6	6	6
Insurance	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**
COST PER KWH [€/kWh]	**0.17**	**0.13**	**0.32**	**0.17**	**0.083**	**0.078**
COST PER KWH [CFA/kWh]	**112**	**85**	**210**	**112**	**54**	**51**

5.5 Feasibility considerations

The wind map clearly shows that the most interesting wind resources can be found in the northern part of the country far from the integrated grid and in only few larger isolated grid systems, such as Gao and Tombouctou.

To visualize the options for exploiting the wind resources in the north, three cases have been assessed:

1) **Tombouctou:**
   Small-scale windfarm (625 kW) connected to the isolated grid at Tombouctou
2) **Kamango:**
   Medium-scale windfarm (8.5 MW) connected to the future enlarged grid connecting Tombouctou, Goundam, Dire, Goundam and Niafunke.
3) **Akle:**
   Large-scale windfarm (170 MW) connected to the integrated grid through a high-voltage transmission line

In the southern part of Mali, where the general wind climate is relatively poor, there are a limited number of sites, where the speed-up effects from hills may make good wind conditions for smaller windfarms, which are located close to the integrated grid. To illustrate this opportunity, a fourth case has been assessed.

4) **Kayhill:** Medium-size windfarm placed on a hill 15 km outside of Kayes in the western part of Mali.

The energy yield calculations have been made with WAsP and generic power curves for some types of wind turbine. Production costs for the four cases have been estimated based on the information provided by the team members and experiences in other African countries and are shown in detail in the section 5.4 above.

The estimated production costs and the avoided cost in the systems to which the wind farms are connected (see section 3.1.4. and 3.2.4) are summarized in Table 5.7 below:

Table 5.7. Estimated production cost and avoided cost for electricity in the four cases

Region	Case study	Size	Production cost (CFA/kWh)		Avoided cost (CFA/kWh)		
					Thermal		Inter-connecti on
		MW	Option 1	Option 2	100 USD/bbl	125 USD/bbl	
North	1.Tombouctou	0.6	112	210	222	253	
	2.Kamango	8.5	51		222	253	
	3. Akle	170	85	112	103	119	65-100
South	4. Kay Hill	8.5	54		103	119	65-100

The table shows that small-scale projects, such as the Tombouctou wind farm, have relatively high production costs (112-210 CFA/kWh), mainly due to high fixed costs for project development, site preparation, transport and crane support, while the costs for medium-size wind farms at sites with good wind conditions (e.g. local speed-up effects) are the lowest at 51-54 CFA/kWh. The production costs for the large-scale wind farm with the best wind condition is in the range of 85 to 112 CFA/kWh, mainly due to the large investment in high-voltage transmission lines.

The feasibility of the investment depends on the avoided costs in the systems to which the turbines are connected. The avoided cost in the integrated system is assessed in detail in section 3.1.1. According to the Master Plan for the electricity sector the marginal cost in the system may be in the range of 65 to 100 CFA depending on the outcome of contract negotiations with regard to imports from Ghana through Burkina Faso. If the commissioning of planned interconnectors and hydropower schemes are delayed, the marginal cost in the system will be the average cost for large HFO-powered diesels, which is between 103 and 120 CFA/kWh, corresponding to a crude oil price of 100 and 125 USD/bbl.

This means that the Kayhill wind farm (54 CFA/kWh) will be financially viable under the condition that the Master Plan is followed, while the Akle wind farm (85-112 CFA/kWh) will only be viable under the condition that it will replace thermal power.

According to the assessment in section 3.2.4, the avoided cost in the isolated system of Tombouctou will be in the range of 220-250 CFA/kWh, assuming a crude oil price of 100 and 125 USD/bbl. Although the production cost in this case is between 112 -220 CFA/kWh, the higher level of avoided cost still makes this case economically feasible under certain conditions.

The avoided cost in the Tombouctou enlarged grid will be at the same level, but slightly lower than in the isolated Tombouctou system due to a moderate economy of scale. If the enlarged grid materializes, this option seems to be the most feasible, as it has low production costs due to good wind conditions and a medium size of wind farm, while at the same time facing high avoided costs due to the substitution of fuel oil-based power.

5.6 Conclusion

Overall the assessment indicates that in the southern part of Mali it will be possible to find a limited number of sites with local speed-up effects situated close to the existing grid, at which there are options for undertaking a medium-size wind power project which will be economically feasible. The assessment also supports the findings of previous feasibility studies, namely that smaller windfarms (around 1 MW) will be economically feasible if they are connected to isolated grids in Gao and Tombouctou (GTZ 2004, de Volder, Dewilde *et al.* 2009).

The assessment of large wind farms shows that, in the current physical situation, the logistics and grid extension costs take up about 40% of total investment costs. The wind resource in that region does not compensate for the high investment costs, and consequently the application of wind energy in that region will only be feasible if the wind farm replaces diesel-based electricity in existing plants, or if the infrastructure investments are covered by a larger investment plan for the north, for example interconnections with other countries.

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 all costs of production have to be regarded as indicative. Likewise the avoided cost 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.

It is difficult to attract turbine manufacturers to isolated projects involving only a few turbines, as the costs of establishing an organization for the delivery of turbines and spare parts and for servicing the turbines will be relatively high. The above cost estimates are based on the assumption that a considerable market for the erection of wind turbines in Mali can be predicted, with the result that a reasonable level of competition can be established among turbine providers. This implies political stability and clear market signals, such as a general feed-in tariff or a general power-purchasing agreement for wind-produced electricity.

6 Solar resources

6.1 Solar atlas

The solar atlas for Mali provides a modeled spatial distribution of solar irradiation for Malian territory for a three-year period from 2008 to 2011 (Badger, Larsen *et al.* 2012). This chapter provides a brief extract of the solar atlas. Detailed maps can be downloaded from www.frsemali.org.

The model producing the spatial map is based on an analysis of satellite data (MSG DSSF estimates)[5] for the three-year period, and calibrated by measurement at 5 measurement stations in Mali, shown on the map in Figure 6.1:

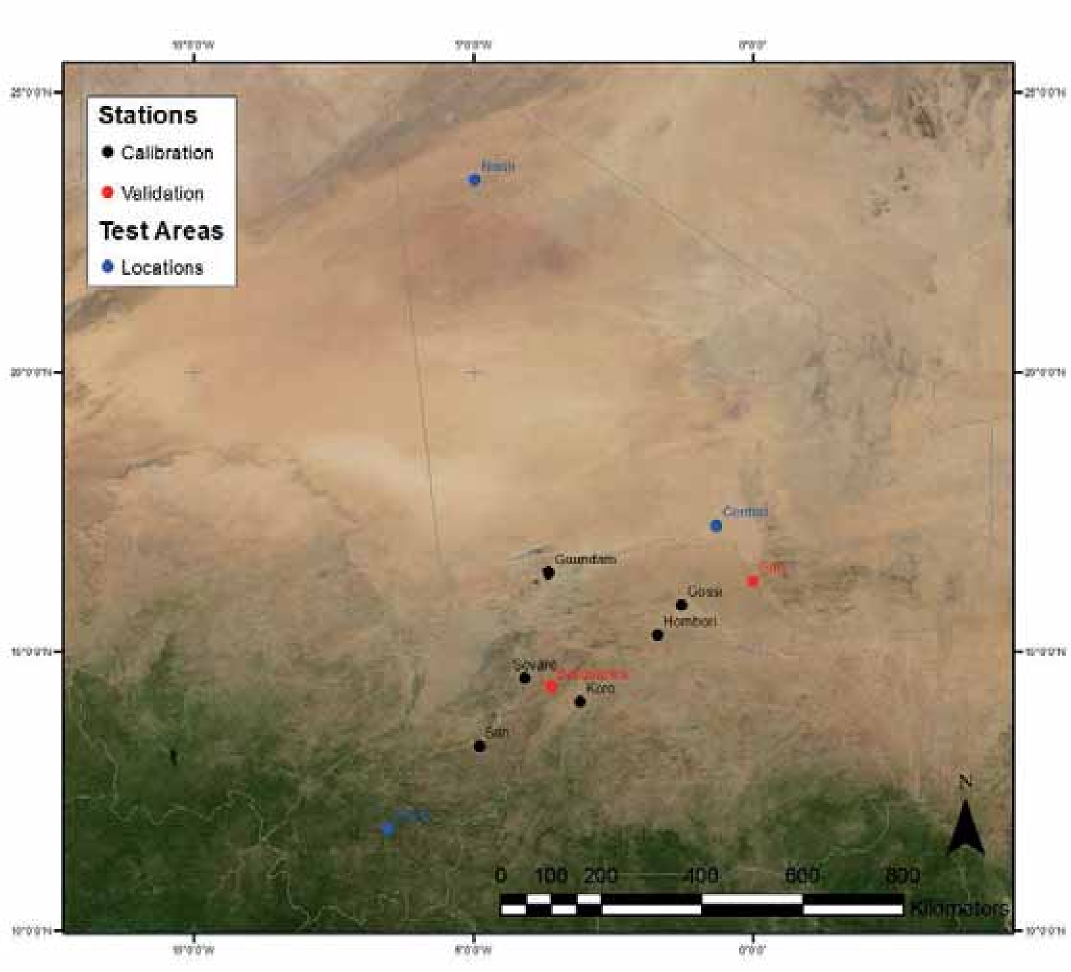

Figure 6.1. Location of the 8 field stations for which in situ measurements of incoming shortwave radiation was available. The blue locations show the location of the northern, the central and the southern locations referred to below.

5. This study relies on satellite-based estimates of the available solar energy at the surface by using the Down-welling Surface Short-wave Radiation Flux (DSSF) product produced by the Land Surface Analysis – Satellite Applications Facility (LSA-SAF).

Figure 6.2 shows mean solar radiation for the years 2008 to 2011.

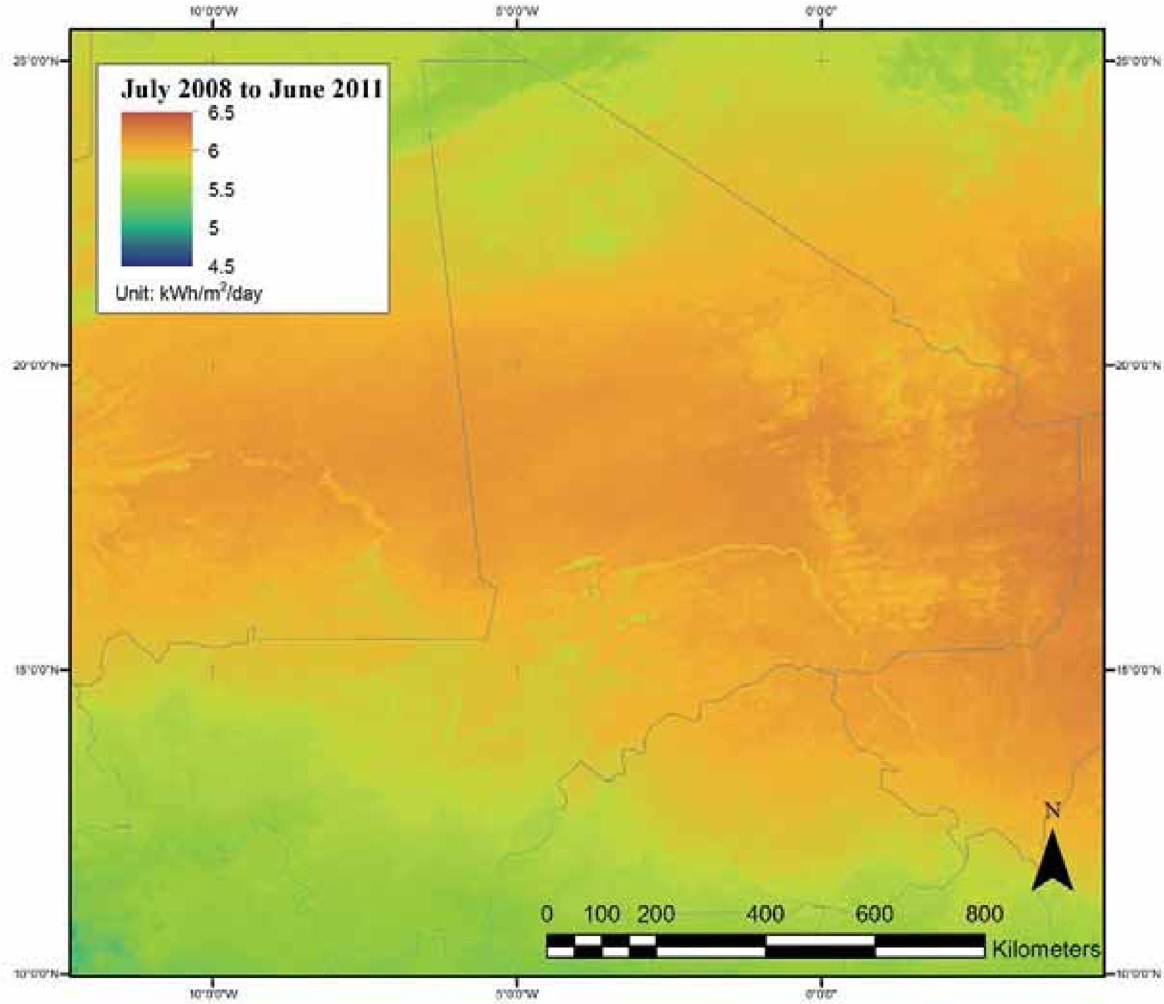

Figure 6.2. Average daily solar radiation for the period between July 2008 and June 2011

Figure 6.3 shows the information from Figure 6.2 in a 1 degree resolution (110*110 km). The three years of average solar radiations are indicated in kWh/m^2/day. The figures above show that there is substantial variation from north to south in Mali, due to the seasonal differences in cloud cover and the position of the sun. We extracted the time-series of daily radiation estimates for three sites representing the northern, central and southern parts of the country (see Figure 6.1 for locations).

The northern location is situated almost on the Tropic of Cancer, where the sun is at its zenith at the summer solstice, and we would therefore expect the largest amplitude in the solar radiation time-series for this position as it experiences the largest variation in solar zenith angle. In addition to the differences in sun–earth geometry for the three locations, the cloud cover and atmospheric aerosol content also induce large temporal variations in solar radiation. The monsoon season starts in May-July in the south, slowly progressing northwards. The differences in cloud cover and the timing of the cloud cover (together with the temporal changes in solar position) also causes the time-series for the three points to be out of phase. The southern area sees the largest values of solar radiation in

April, when the sun is almost at its zenith and before the monsoon sets in. For the central and northern areas, the peak appears later in May or July

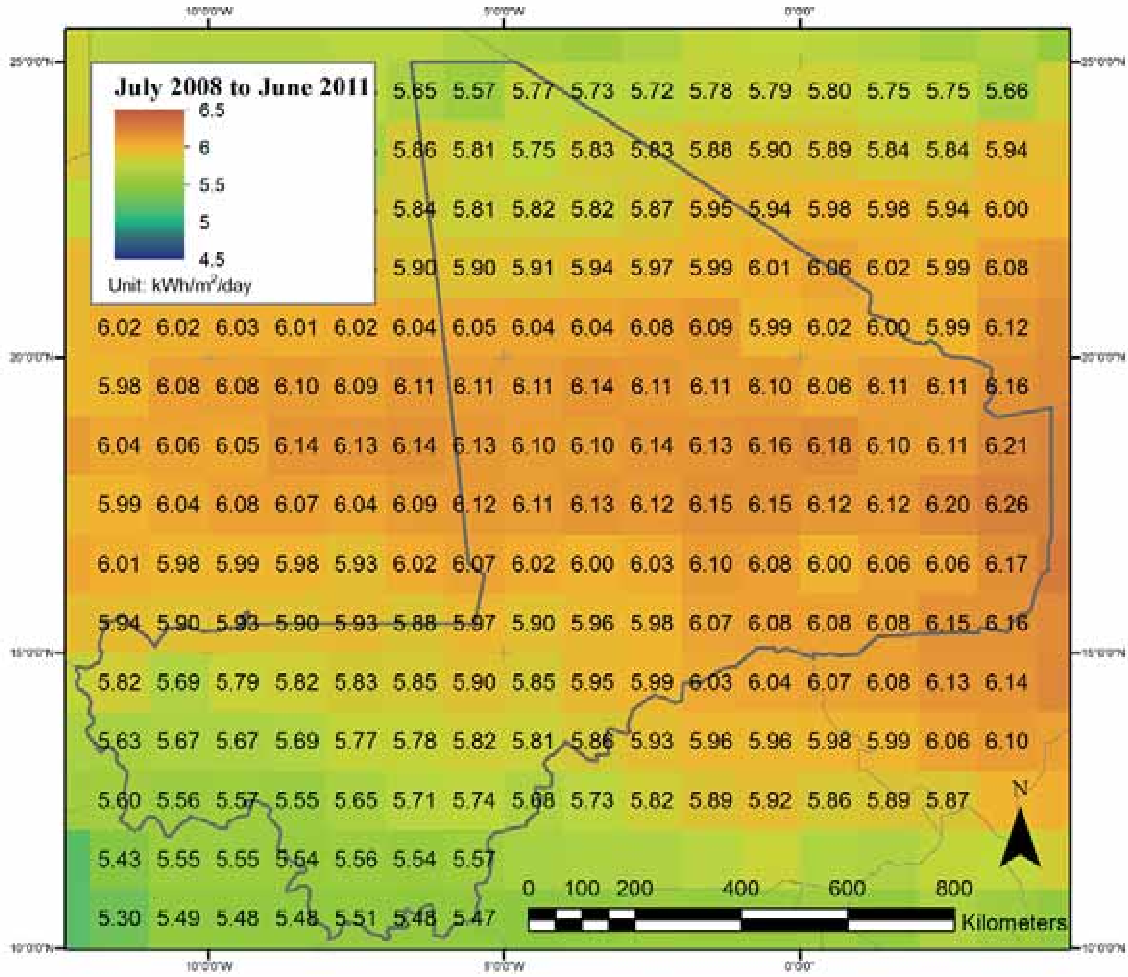

Figure 6.3. Average daily solar radiation for the period between July 2008 and June 2011

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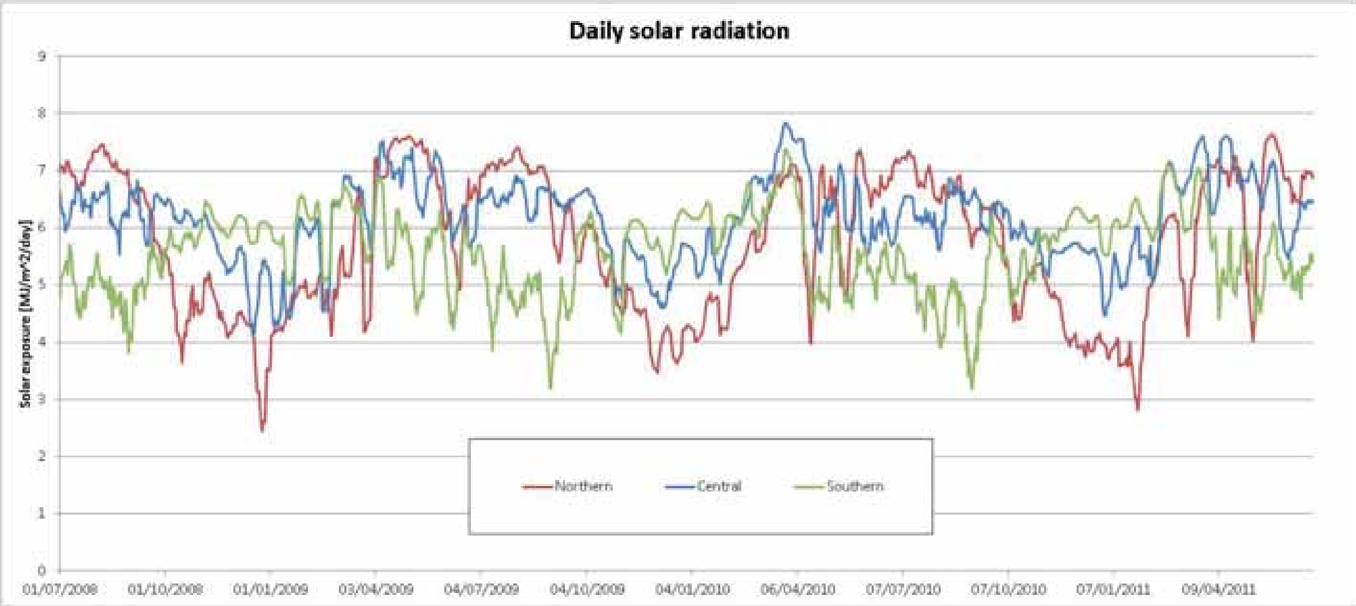

Figure 6.4 Time series of the three areas shown in Figure 6.1 represent the north-south differences in solar radiation in Mali. Note that the time-series have been smoothed out by showing a 9-day moving average.

6.2 Annual variation in solar radiation

It is also clear from Figure 6.4 that there is substantial inter-annual variation, due to the differences in the weather and cloud cover from year to year. In Figure 6.5, Figure 6.6 and Figure 6.7, the yearly variation in the solar radiation is shown for the three sites respectively, as well as the average (by month) for the three-year study period analyzed here. For comparison data are included from the NASA POWER/SSE database,[6] which shows the monthly average values for the period between 1983 and 2005. Generally, the matches between the MSG DSSF estimates and the NASA estimates are good, although MSG DSSF shows smaller values during spring and summer for the "central" location.

[6.] http://wosweb.larc.nasa.gov/sse/

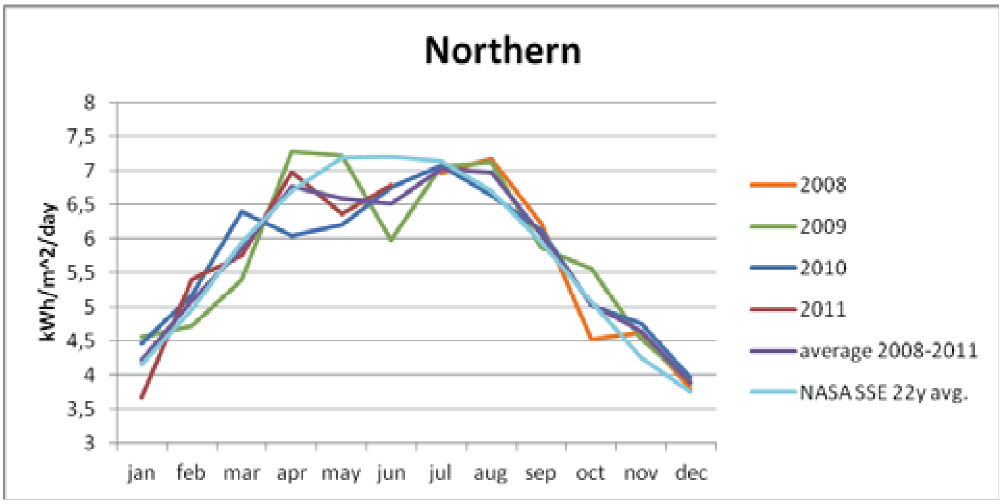

Figure 6.5. Comparison between the 3 years of data from the MSG DSSF product and the historic NASA SSE (1983-2005) data series for the "North" location (see Figure 6.1 for location)

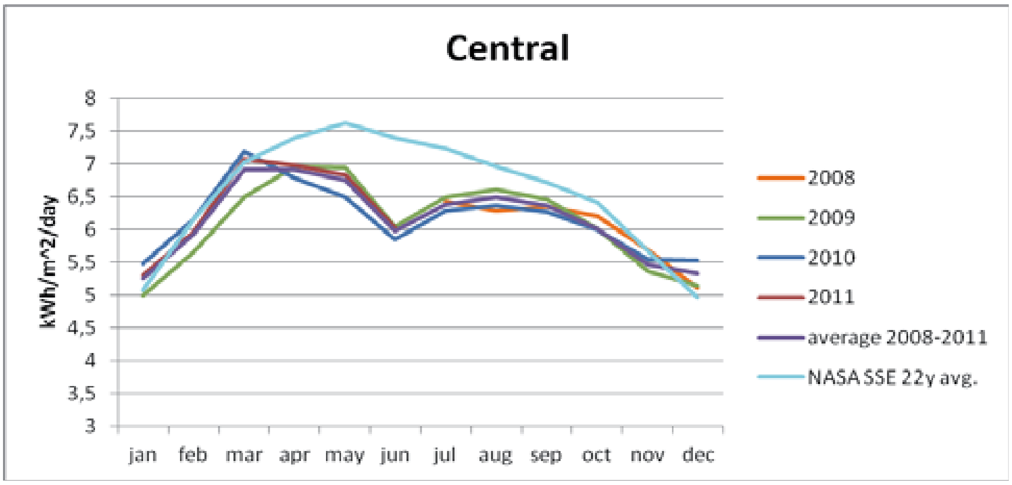

Figure 6.6. Comparison between the 3 years of data from the MSG DSSF product and the historic NASA SSE (1983-2005) data series for the "Central" location (see Figure 6.1 for location)

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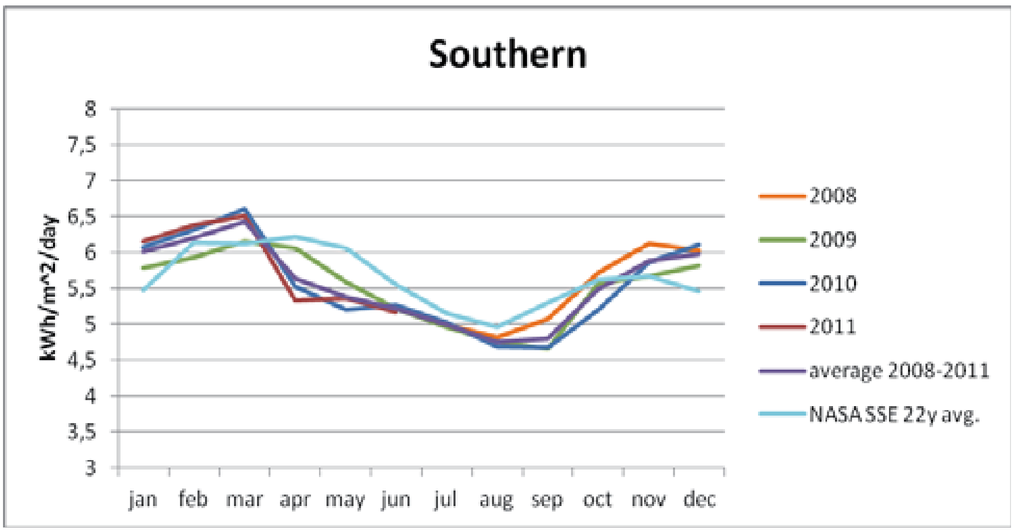

Figure 6.7. Comparison between the 3 years of data from the MSG DSSF product and the historic NASA SSE (1983-2005) data series for the "South" location (see Figure 6.1 for location)

Table 6.1. Comparison between the average of 3 years of data from the MSG DSSF product and the historic NASA SSE (1983-2005) data series for the three locations (see Figure 6.1 for location).

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Northern												
Average 2008-11	4.23	5.10	5.85	6.77	6.60	6.50	7.03	6.98	6.07	5.04	4.64	3.89
Nasa SSE	5.08	6.16	7.02	7.39	7.62	7.39	7.23	6.96	6.72	6.42	5.68	4.96
Center												
Average 2008-11	5.25	6.16	7.02	7.39	7.62	7.39	7.23	6.96	6.72	6.42	5.68	4.96
Nasa SSE	4.15	4.97	5.95	6.70	7.19	7.21	7.14	6.71	5.94	5.07	4.26	3.75
Southern												
Average 2008-11	6.00	6.21	6.42	5.65	5.38	5.22	4.99	4.76	4.80	5.50	5.89	5.98
Nasa SSE	5.48	6.14	6.13	6.22	6.06	5.56	5.16	4.96	5.30	5.63	5.68	5.46

6.3 Diurnal variation of solar radiation

The average diurnal cycle of solar radiation on a monthly basis is shown in Figure 6.8 for the three sites. Note that the time is given in UTC, and the small horizontal shifts in the curves are at least partly due to the seasonal changes in the timing of local solar noon, while the difference in the timings of the maximum values between the three sites can also be related to their absolute positions.

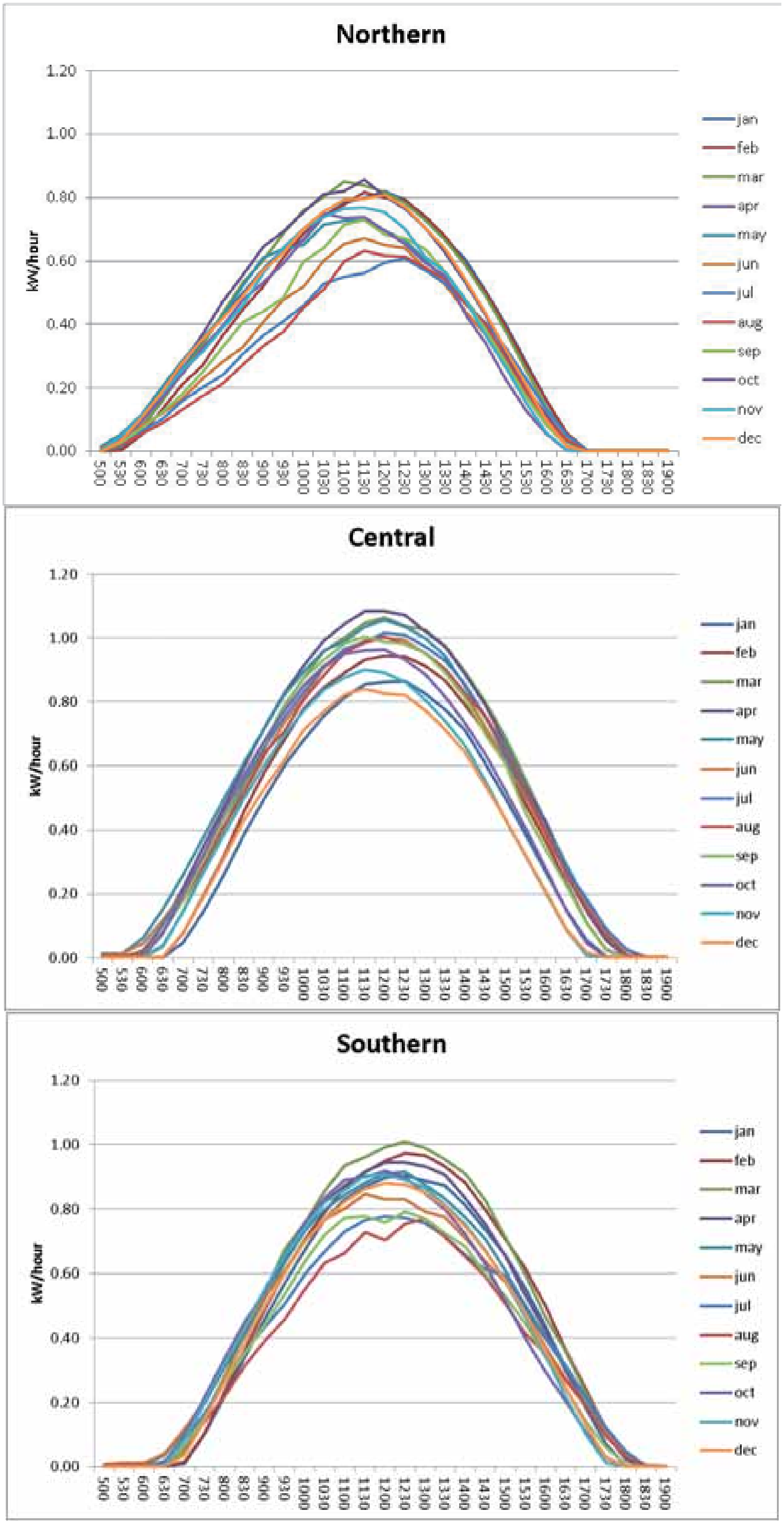

Figure 6.8. Monthly mean diurnal variation in solar radiation (calculated as the mean for each specific time of day for all three years) for the three sites shown in Figure 6.1

7 Applications for solar energy in Mali

Based on the resource map and the previous experiences in Mali with photovoltaic solar (PV) technology, the future for solar energy in Mali is promising. The applications for PV are diverse and include solar lanterns, public lightning projects, the cold chain for medical products, solar water pumping, hybrid systems with and without storage and large integrated PV arrays.

According to the investment plan for "Scaling up renewable energy in Mali" (SREP) programme launched in 2011, currently 130,000 solar kits have been installed, mainly for households, schools and health centers. In addition there are 1300 solar pumps for pumping water, 700 off-grid installations for lighting and 400 mini-grid installations for telecommunications, offices, hospitals etc. There are so far no large-scale grid-connected installations (DNE 2011b).

This chapter will illustrate the opportunities for grid-connected solar applications, focusing especially on applications in the integrated electricity network and local networks (mini-grids) in hybrid installations with diesel. The chapter will briefly introduce the system configurations for the two application areas before providing cost estimates for two typical PV installations in Mali.

7.1 Large-scale solar energy in the integrated grid

There are currently two technologies used to exploit solar resources for large power plants:

- CSP (Concentrated Solar Power) use mirrors or lenses to concentrate solar light on to a small area. Electrical power is produced when the concentrated light is converted to heat (traditional steam cycle), which drives a heat engine (usually a steam turbine) connected to an electrical power generator. Units from 50 MW to 500 MW are being deployed in countries with high direct irradiation (DNI). This technology is an interesting option for larger solar power plants delivering firm power due to the heat-storage capacity and controllability of CSP.
- PV power plants comprise large arrays of solar panels feeding into the integrated grid. Such systems, which are widespread in Europe, are currently being installed in a number of countries in SSA. In South Africa, for example, PV power plants of 75 MW_p are now under development.

In this report we only address the PV power systems.

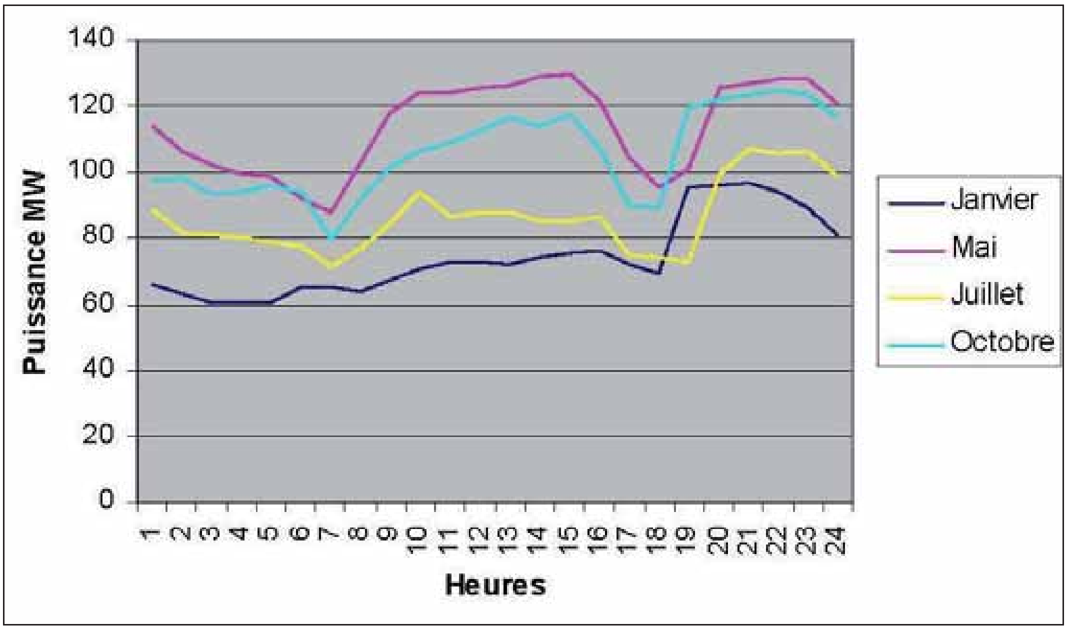

Figure 7.1. Load curves (monthly average for workdays) for the integrated grid in 2006 (SOGREAH 2008c)

The daily load curves for the integrated grid presented in Figure 7.1 show that there is a relatively high load during the daytime, especially in May and October, following the demand for air-conditioning (SOGREAH 2008c). This load corresponds well to the production pattern for solar PV, with the consequence that PV plants feeding into the integrated grid can replace electricity normally produced by diesel. The solar-based production will further be balanced with hydropower from the dams thanks to the controllability of the hydropower stations, as already described in section 4.6. For more information on production capacity in the integrated grid, see Chapter 3.

There are as yet no larger grid-connected PV plants in operation in Mali, but the recent decrease in the cost of PV panels opens up new opportunities for implementing this technology, and grid parity[7] is now close to reality. Today PV panels are offered in Europe at 0.6 €/W_p, whereas in 2009 they still cost 2€/W_p.

In February 2012, the CNESOLER and EDM had received an overwhelming number of feasibility studies, project proposals and expression of interest for grid-connected PV projects coming from project developers, IPPs and donors. An extract of information from a couple of these feasibility studies is presented in section 7.4 below. Based on these experiences, the SREP investment plan assumes the opportunity to establish IPPs for large-scale grid-connected solar PV plants (DNE 2011a).

[7.] Grid parity occurs when an alternative energy source can generate electricity at a levelized cost (LCoE) that is less than or equal to the price of purchasing power from the electricity grid.

7.2 PV in the local isolated grids

A large number of isolated grids run by EDM are currently powered by diesel generators, as described in section 3.4. These isolated grids constitute an interesting market for PV in combination with diesel in hybrid systems, mainly because electricity in the isolated grids is produced at much higher costs than in the integrated system, but also because the production of electricity by solar is relatively predictable and stable in the daytime in most of the year.

Load patterns for larger isolated grids are similar to the one shown above for the integrated grid, with relatively stable consumption during the day and night, but with a high evening peak from 1900 to 0100 in the morning due to evening activities (TV, lighting etc.). Load curves for Nioro, a relatively large isolated grid with an installed diesel capacity of 1.5 MW, are shown in section 3.4.3. To match this load pattern best economically, a hybrid solution comprising battery backup and 75% PV capacity and 25% diesel capacity could be used. There is so far limited experience with these larger systems in Mali. The Ouélessébougou plant (250 kW_p), put into operation in 2010, is currently the only plant run by EDM, but according to interviews with EDM in February 2012, more plants of this kind are envisaged. A schematic view of such as system is shown below:

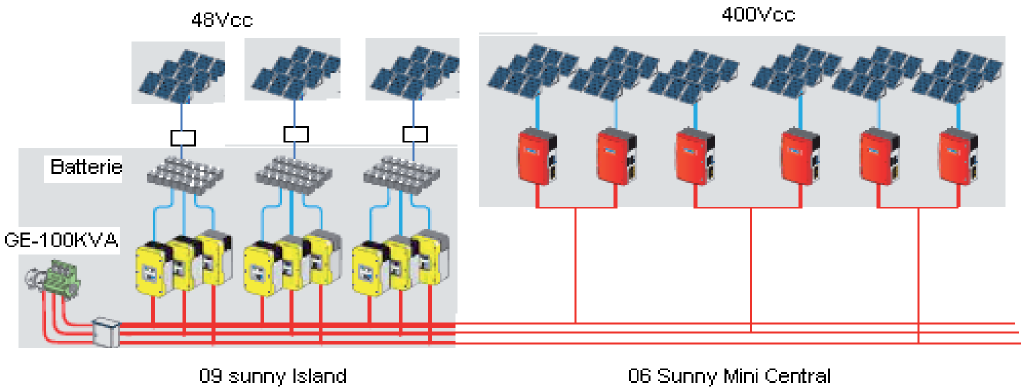

Figure 7.2. Schematic view of a hybrid system with battery storage (Semega 2011)

Smaller towns outside the existing and planned grids are categorized as being included in the rural electrification programme under the responsibility of AMADER. For more information, see section 3.5. Until 2010 AMADER had electrified 111 smaller towns mainly with diesel generators, of which a great number are currently only used for a few hours (4-6 hours a day). For a full list of these towns, see Annexe 2.

There are currently a few smaller hybrid PV–diesel systems in operation in smaller towns such as Kimparana (72.5 kW_p), Ansongo (35 kW_p), Kolondiéba (150 kW_p) and Ouroukila (50 kW_p). The economic feasibility of hybrid plants compared to diesel plants has been shown in a number of studies, for example, in the annex to the SREP programme launched in 2011 (DNE 2011b). Based on these experiences, the SREP

investment plan assumes the opportunity to establish 35 hybrid systems combining, PV, diesel and biofuels (DNE 2011a).

7.3 Estimate of the production cost of PV electricity

Due to the falling cost of the PV panels, electricity generated from this source is becoming the most interesting renewable option in many countries. Especially in Africa, in a number of countries grid parity is becoming a reality. A clear example of this is the request for qualification and proposals for new generating capacity under the IPP procurement programme in South Africa (Planting 2012).

In this programme, independent power producers propose projects for electricity generation based on renewable energy. Contracts are awarded based on the proposed selling price of electricity generated to ESKOM, the state utility.

Table 7.1 below shows the result of first and second bidding rounds for grid connected PV systems in sizes of 10-75 MW_p. Recent projects in India have likewise been offered in a BOOT scheme at 0.108 €/kWh.[8]

Table 7.1. Bidding price for PV produced electricity by IPP's in South Africa (Planting, 2012)

Bidding rounds	Dates	Average Bidding Price €/kWh
First Bid Submission Date	4 November 2011	0.24
Second Bid Submission Date	5 March 2012	0.14

Solar resources in South Africa are in the same range as in Mali, but the cost of PV in Mali will be higher due to the logistics. To illustrate the feasibility of applications for solar PV in Mali, the production cost has been estimated for two cases:

- 1 MW_p PV system feeding into the integrated grid
- 100 kW_p PV system connected to a diesel-powered local grid with battery storage.

8. Oral communication from Solaire Direct, Green Power Conference, 22-23 May 2012, Casablanca.

7.3.1 The 1 MW_p PV system grid connected

The cost calculation of kWh produced has been based on the assumptions in Table 7.2 below:

Table 7.2. Assumptions for cost estimations for 1 MW_p grid-connected PV system

Item	**€/W_p**	**Comments**
PV panels	1.6	Actual Price in Europe is 0.6 €/W_p, but in Mali as a land locked county 1€W_p is added for transport
Support structures	0.3	
Invertors	0.3	Ref: Photon - Das Solar Strom Magazin
Cabling and protection	0.2	
Installation works	0.2	
Total Investment cost	**2.6**	**Variables 2.0, 1.4**
Maintenance	0.02	Twice the cost compared to Europe
Insurance	0.02	
Total Maintenance cost	**0.04**	**Alternative 0.02**
Interest rate	5%	
Replacement of invertors		After 10 years

Production costs for the solar power plant with battery storage is shown in €/kWh in Table 7.3 and in CFA/kWh in Table 7.4:

Table 7.3. Production costs (€/kWh) for 1 MW_p solar power plant under different assumptions

Solar radiation (kWh/m²/d)		**5.5**	**5.75**	**6.0**
Average production	MWh/y	1820	1893	1947
Maintenance cost **0.04 €/W_p**				
Total investment cost	**2.6 €/W_p**	**0.264**	**0.254**	**0.247**
Total investment cost	2.0 €/W_p	0.212	0.203	0.198
Total investment cost	1.4 €/W_p	0.159	0.153	0.148
Maintenance cost **0.02 €/W_p**				
Total investment cost	2.6 €/W_p	0.250	0.241	0.234
Total investment cost	2.0 €/W_p	0.198	0.190	0.185
Total investment cost	1.4 €/W_p	0.145	0.139	0.135

Table 7.4. Production costs (CFA/kWh) for 1 MW solar power plant under different assumptions

Solar radiation (kWh/m²/d)		**5.5**	**5.75**	**6.0**
Average production	MWh/y	1820	1893	1947
	Maintenance cost **0.04 €/W$_p$**			
Total investment cost	**2.6 €/W$_p$**	173	166	162
Total investment cost	2.0 €/W$_p$	139	133	129
Total investment cost	1.4 €/W$_p$	104	100	97
	Maintenance cost **0.02 €/W$_p$**			
Total investment cost	2.6 €/W$_p$	164	158	153
Total investment cost	2.0 €/W$_p$	129	124	121
Total investment cost	1.4 €/W$_p$	95	91	88

7.3.2 The 100 kW$_p$ PV system with battery storage

The calculation of cost per kWh produced has been based on the assumptions and variables presented in Table 7.5 below. For comparison it should be noted that the system set up by EDM in Ouélességbougou in 2011 had an investment cost of 8.56 €/W$_p$, which is about 60% more than in the assumptions below. Detailed information on investment costs for this plant is available in Annexe 1.

Table 7.5. Assumptions for cost estimations for 100 kW$_p$ system with battery storage

Item	**€/W$_p$**	**Comments**
PV panels	1.6	Actual price in Europe is 0.6 €/W$_p$, but in Mali as a land-locked county 1€W$_p$ is added for transport
Support structures	0.4	0.4 is an averaged price in Africa for smaller systems
Invertors	0.3	Ref: Photon - Das Solar Strom Magazin[9]
Cabling and protection	0.2	
Battery storage	2.5	300€/kWh
Installation works	0.2	
Total Investment cost	**5.2**	**Variables 4.6, 4.0**
Maintenance	0.02	Twice the cost compared to Europe
Insurance	0.02	
Total Maintenance cost	**0.04**	**Alternative 0.02**
Interest rate	5%	
Replacement of invertors		After 10 years

Production costs for the solar power plant with battery storage is shown in €/kWh) in Table 7.6 and in CFA/kWh in Table 7.7:

9. http://www.photon.de/

Table 7.6. Production costs (€/kWh) for 100 kW_p solar power plant with battery storage under different assumptions

Solar radiation (kWh/m²/d)		**5.5**	**5.75**	**6.0**
Average production	MWh/y	182	189	194
Maintenance cost **0.04 €/W_p**				
Total investment cost	**5.2 €/W_p**	**0.490**	**0.474**	**0.462**
Total investment cost	4.6 €/W_p	0.442	0.424	0.413
Total investment cost	4.0 €/W_p	0.389	0.373	0.363
Maintenance cost **0.02 €/W_p**				
Total investment cost	5.2 €/W_p	0.481	0.461	0.449
Total investment cost	4.6 €/W_p	0.428	0.410	0.399
Total investment cost	4.0 €/W_p	0.375	0.359	0.350

Table 7.7. Production costs (CFA/kWh) for 100 kW_p solar power plant with battery storage under different assumptions

Solar radiation (kWh/m²/d)		**5.5**	**5.75**	**6.0**
Average production	MWh/y	182	189	194
Maintenance cost **0.04 €/W_p**				
Total investment cost	**5.2 €/W_p**	**321**	**310**	**303**
Total investment cost	4.6 €/W_p	289	278	270
Total investment cost	4.0 €/W_p	255	244	238
Maintenance cost **0.02 €/W_p**				
Total investment cost	5.2 €/W_p	315	302	294
Total investment cost	4.6 €/W_p	280	268	261
Total investment cost	4.0 €/W_p	246	235	229

7.4 Recent initiatives under development

As described above, EDM and CNESOLER have received a number of feasibility studies, project proposals and expression of interests for grid-connected PV projects from project developers, IPPs and donors. An extract of information from a couple of these feasibility studies is presented below. It should be noted that the two studies have been carried out as proposals to BOOT and turn-key projects by the respective companies. This means that the production prices should be seen as inputs to a negotiation rather than as final bids.

7.4.1 Scatec Solar at Mopti

The Norwegian-based Scatec Solar is a supplier of photovoltaic (PV) solar energy solutions worldwide. International Finance Cooperation (IFC), a member of the World Bank Group, and Scatec Solar have recently signed an agreement to develop solar power projects that will supply renewable energy to address electricity needs in parts of West and Central Africa. In May 2011 they prepared an initial feasibility study for a 10 MW_p

PV power plant in Mopti, Mali (Scatec 2011). According to the study, the power plant will produce 15,070 MWh annually or 50% of current power production in Mopti. A battery back-up of 2 MW_p could be installed to cope with variations and switching between the different power sources, but based on the characteristics of the existing network, it was decided that no battery back-up system will be used.

Table 7.8. Investment cost, maintenance cost and selling price for 10 MW_p PV plant in Mopti

Investment cost (05/2011)	18 368	M CFA	28	Mill. €
Investment cost per W_p	1837	CFA/W_p	2.8	€/W_p
Maintenance cost	35.1	CFA/W_p	0.053	€/W_p
Selling price	**160**	**CFA/kWh**	**0.24**	**€/kWh**

The main economic figures are shown in Table 7.8 The selling price of 160 CFA/kWh is based on the following assumptions: depth ratio, 70%; interest rate, 9%; loan period, 15 years; IRR, 18%; indexation, 4%, lifetime, 25 years.

In the framework of a 60 MW_p solar development plan, another group of cities have been listed as potential sites for solar PV: Segou, Koulikor, Fana (integrated), Mopti, San, Tombouctou, Diré, Goundam, Gao, Nioro and Bougouni (isolated grids) (Scatec 2011).

7.4.2 Hybrid PV-diesel system in Douentza

SPEC, based in Senegal, is the first manufacturer of PV modules in West Africa, aiming at a production capacity of 25 MW_p every year. SPEC has prepared a feasibility study for a PV power plant of 1 MW_p in Douentza, which is currently supplied by three diesel units with a combined capacity of 900 kW. In this case a battery back-up system is planned with a capacity of 3 * 700 kWh. Production from the PV units is estimated at 1580 MWh annually (SPEC 2011a).

Total cost of the power plant (diesel engines not included) is estimated at 3780 M CFA (or 5.7 Mill. €). The selling price of the electricity is estimated at 174 CFA/kWh.

Table 7.9. Investment cost, maintenance cost and selling price for 1 MW_p PV plant in Douenza (SPEC, 2011)

Investment cost (01/2011)	3780	M CFA	5.7	Mill. €
Investment cost per W_p	3780	CFA/W_p	5.7	€/W_p
Maintenance cost	N/A	CFA/W_p	N/A	€/W_p
Selling price	174	CFA/kWh	0.27	€/kWh

Similar propositions from SPEC have been made for TENEKOU (350 kW_p) and SOKOLO (350kW_p) (SPEC 2011b; SPEC 2011c).

7.5 Conclusions

The opportunities for exploiting solar resources in Mali are very promising. Not only does the country have abundant resources, it also has space and has built up strong expertise in the field. Private companies and research centers such as CNESOLER contribute greatly to the development of this sector in the country, and the tangible results are the more than 130,000 solar kits installed, mainly for households, schools and health centers, the 1300 solar pumps for pumping water, the 700 off-grid installations for lighting and the 400 mini-grid installations for telecommunications, offices, hospitals etc.

The decline over the last few years in the costs of PV solar panels and systems make solar energy and solar PV an increasingly interesting option for electricity production. The cost of PV applications is currently significantly higher in Mali than in what we see, for example, in South Africa due to the high costs of transport, logistics and maintenance, but also because solar PV is still a niche market with poor competition. Solar energy has the potential to become cheaper in Mali in the very near future, but this will be contingent on political stability, continued donor support to studies and cheap finance and not least on the establishment a clear legal framework for investors, including, for example, a Feed in Tariff for grid-connected Solar PV (Haselip 2011). Such measures would reduce prices as a result of reduced risk and increased competition and economies of scale.

Besides the production costs, the feasibility of investments in solar PV depends on the avoided costs in the systems to which the PV plants are connected. The avoided cost in the integrated system is assessed in detail in section 3.3.4. According to the Master Plan for the electricity sector, the marginal cost in the system is expected to be in the range of 65 to 100 CFA depending on the outcome of contract negotiations with regard to imports from Ghana through Burkina Faso. If the commissioning of planned inter-connections and hydropower schemes are delayed, the marginal cost in the system will be the average cost for large HFO-powered diesels, which is between 103 and 120 CFA/kWh, corresponding to a crude oil price of 100 and 125 USD/bbl.

This chapter has presented calculations of the costs of a kWh produced by PV systems for two types of applications, namely large PV systems connected to the integrated grid and smaller systems in isolated diesel grids.

The calculation for the 1 MW_p system shows a production cost of 166 CFA/kWh in the base case, where the investment cost is 2.6 €/W_p, but the calculation also shows that if the specific investment costs in Mali can be brought down to 1.4 €/W_p and the maintenance cost can be reduced to the European level of 0.2 €/W_p, the production cost will be reduced to 91 CFA/kWh and hence be lower than for electricity from existing large HFO-powered diesels, and close to the cost of imported electricity.

For the 100 kW_p system, the estimated production costs are significantly higher. The production cost is 310 CFA/kWh in the base case, where the investment cost is 5.2 €/W_p, while a reduction in the investment cost to 4.0 €/W_p will reduce the production cost to 235 CFA. According to the assessment in section 3.4.4, the avoided cost in the smaller

isolated system run by EDM is in the range of 230-280 CFA/kWh in the case of a crude oil price of 100 USD/bbl. This means that, if investment costs can be brought down slightly, these systems will be economically feasible today.

For the smaller hybrid PV–diesel system (mini-grids) established through the rural electrification programmes, avoided costs as well as production costs for PV are higher than for the larger EDM systems. Recent studies show that hybrid PV–diesel systems (10-75 kW_p) in mini-grids are already economically feasible, but due to the high transaction costs of demonstration projects, implementation of PV in mini-grids is likely be contingent on success in achieving economies of scale, that is, setting up a larger programme for PV–diesel systems and thus reducing the engineering, procurement and maintenance costs.

It is necessary at this point to emphasize that cost calculations have been carried out for two case examples based on the best available data. Therefore all the costs of production must be considered as indicative. Likewise the avoided cost 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.

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Annexe 1: The case of Ouélessébougou

This presentation of the power plant of Ouélessébougou is based on a cost evaluation by Sangaré (2011).

The power plant is composed of two diesel generators, of 220 and 240 kW (275 & 300 KVA). The average monthly consumption is between 50 and 60 MWh. A PV array of 175 kWp was installed.

N°	DESIGNATION	U	QTE	PU F.CFA	MONTANT F.CFA	MONTANT €
				(HT/HD)	(HT/HD)	
1.10	Module Photovoltaïque 160Wp / 24V	u	1100.00	450000	495000000	754573
1.20	Ensemble support de deux modules	ens.	550.00	136364	75000000	114329
1.30	Coffret de champ avec protection parafoudre	ens.	14.00	171429	2400000	3659
1.40	*	ens.	2.00	115000000	230000000	350610
1.50	Onduleur Chargeur de 100 kW- 220 Vcc	u	2.00	35000000	70000000	106707
1.60	Unité de contrôle et de commande système	ens.	1.00	840000	8400000	12805
1.70	Inverseur normal/secours	ens.	3.00	900000	2700000	4116
1.80	Onduleurs réseaux triphasés 100 kW - 300 V	u	2.00	25000000	50000000	76220
1.90	Jeux de câbles et accessoires d'installation	ens.	1.00	20000000	20000000	30488
1.10	Main d'oeuvre d'installation et déplacement	ff		30000000	30000000	45732
TOTAL FOURNITURE ET POSE GENERATEUR PHOTOVOLTAÏQUE F.CFA (HT/HD) et €					**983500000**	**1499237.80 * [Or 8.56 €/Wp]**

*The cost is based on prices early 2011

Annexe 2: List of rural electrification projects

Liste des Projets d'Electrification Rurale 2010

Source : Rapport annuel d'activités 2010, Amader

1.1 Liste des localités avec PCASER

N°	Opérateur	Localité	Région	Clients ayant Accès	Date de mise en service
1	ACCESS	Garalo	Sikasso	680	10-janv-07
2	ALBARKA YERKOYE	M'Bouna	Tombouctou	-	nov-10
3	CHARBEL	Siby	Koulikoro	-	août-10
4	CTEXCEI-GNETA	Barouéli	Ségou	703	20-juin-10
5	DIEKA ELECTRIC	Siribala	Ségou	824	01-janv-08
6	DJENNE PROXI	Yangasso	Ségou	300	déc-09
7	EDS	Sokolo	Ségou	200	22-sept-08
8	EES	Nara	Koulikoro	727	10-févr-07
9	EGB	Diéma	Kayes	575	02-juin-07
10	ELECTRIMAX	Yorobougoula	Sikasso	310	12-mars-10
11	ENORD	Léré	Tombouctou	795	01-août-07
12	EOK	Kanadjiguila	Koulikoro	-	nov-10
13	EOK	Ouézindougou	Koulikoro	-	nov-10
14	EOK	Mamaribougou	Koulikoro	-	nov-10
15	EOK	Samaya	Koulikoro	-	nov-10
16	EPRODED-DIORO	Dioro	Ségou	755	22-sept-07
17	ERD	Sanankoroba	Koulikoro	846	01-févr-07
18	ERD	Banankoro	Koulikoro	-	oct-10
19	ERD-KALANA	Kalana	Koulikoro	-	oct-10
20	FINTEL	Gangafani	Mopti	-	juin-10
21	FINTEL	Yerendourou	Mopti	-	juin-10
22	FINTEL	Douary	Mopti	-	juin-10
23	FINTEL	Dinangourou	Mopti	-	juin-10
24	GES	Konna	Mopti	944	01-janv-08
25	GTE	Konobougou	Ségou	1 421	20-sept-07
26	GTE-NIORO	Gourel	Kayes	182	31-janv-09
27	GTE-NIORO	Awoiny	Kayes	100	25-déc-09
28	GTE-NIORO	Madina	Kayes	100	25-déc-09
29	GTE-NIORO	Loumbougana	Kayes	182	25-déc-09
30	HORONYA	Toubacoura	Koulikoro	826	21-févr-07
31	KAMA	Diakon	Kayes	184	01-nov-07
32	KAMA	Sibendi	Kayes	152	01-nov-07
33	KAMA	Kembé	Kayes	152	01-nov-07
34	KAMA	Bendougou	Kayes	176	01-nov-07
35	KAMA-KENIEBA	Kéniéba	Kayes	929	20-mai-08
36	KAMA-SADIOLA	Sadiola	Kayes	746	29-sept-09
37	KAMA-SANDARE	Sandaré	Kayes	232	28-juil-08
38	KNEM	Markacoungo	Koulikoro	100	déc-09
39	MAIRIE TONKA	Tonka	Tombouctou	-	oct-10
40	MECOF	Lani	Kayes	245	30-sept-08
41	MECOF	Gabou	Kayes	245	20-oct-08
42	MECOF	Sobougou	Kayes	245	30-sept-08

43	MECOF	Digokory	Kayes	246	20-oct-08
44	MOYERE SB	Téninkou	Mopti	1 003	06-juil-09
45	NEMABAT	Loulouni	Sikasso	-	mars-11
46	PGE	Nara	Koulikoro	652	2007
47	SAFEELEC	Sanankoro Djitoumou	Koulikoro	147	31-janv-08
48	SAFEELEC	Kafara	Koulikoro	147	31-janv-08
49	SAFEELEC	Sougoula	Koulikoro	147	31-janv-08
50	SAFEELEC	Tinkélé	Koulikoro	147	31-janv-08
51	SAFEELEC	Digan	Koulikoro	149	31-janv-08
52	SDD CINZANA	Cinzana	Ségou	650	01-janv-08
53	SDD SEKORO	Dougoukouna	Ségou	300	20-sept-07
54	SDD SEKORO	Ségoukoro	Ségou	625	20-sept-07
55	SEER	Dia	Mopti	560	19-mars-08
56	SEKB-BANKASS	Bankass	Mopti	842	01-janv-08
57	SEKB-KORO	Koro	Mopti	997	01-janv-08
58	SGEI	Baguineda		-	oct-10
59	SOGEP	Badinko	Kayes	250	31-déc-07
60	SOGEP	Djidjan	Kayes	200	31-déc-07
61	SOGEP	Kourounikoto	Kayes	200	29-mai-08
62	SPGE	Sofara	Mopti	705	25-déc-09
63	SSD KURAYE KURUMBA	Koniakary	Kayes	242	15-févr-09
64	SSD KURAYE KURUMBA	Ambidedikoré	Kayes	153	01-janv-00
65	SSD KURAYE KURUMBA	Dogofiry	Kayes	119	14-mars-10
66	SSD KURAYE KURUMBA	Koméoulou	Kayes	242	01-déc-09
67	SSD KURAYE KURUMBA	Maréna Diombougou	Kayes	242	15-févr-09
68	SSD KURAYE KURUMBA	Tringa Maréna	Kayes	150	01-déc-09
69	SSD KURAYE KURUMBA	Sambaga	Kayes	92	01-déc-09
70	SSD KURAYE KURUMBA	Yélimané	Kayes	292	01-janv-00
71	SSD KURAYE KURUMBA	Diongaga	Kayes	337	15-févr-09
72	SSD KURAYE KURUMBA	Dialaka	Kayes	-	nov-10
73	SSD KURAYE KURUMBA	Gagny	Kayes	-	nov-10
74	SSD KURAYE KURUMBA	Gakoura	Kayes	-	nov-10
75	SSD KURAYE KURUMBA	Kersignané Diafounou	Kayes	127	20-déc-09
76	SSD KURAYE KURUMBA	Kersignané Kaniaga	Kayes	252	12-déc-09
77	SSD KURAYE KURUMBA	Kirané	Kayes	288	10-nov-09
78	SSD KURAYE KURUMBA	Kodiè	Kayes	-	nov-10
79	SSD KURAYE KURUMBA	Krémis	Kayes	229	17-oct-09
80	SSD KURAYE KURUMBA	Lakanguemou	Kayes	163	01-janv-00
81	SSD KURAYE KURUMBA	Sambakanou	Kayes	96	12-déc-09
82	SSD KURAYE KURUMBA	Ségala	Kayes	-	oct-10
83	SSD KURAYE KURUMBA	Somankidi	Kayes	246	16-oct-09
84	SSD KURAYE KURUMBA	Yaguiné	Kayes	360	12-nov-09
85	SSD KURAYE KURUMBA	Dioncoulane	Kayes	228	15-oct-09
86	SSD KURAYE KURUMBA	Dramanekoré	Kayes	310	15-févr-09
87	SSD KURAYE KURUMBA	Gory	Kayes	-	
88	SSD KURAYE KURUMBA	Tambacara	Kayes	179	01-janv-00
89	SSD YEELEN KURA	Yorosso	Sikasso	369	21-sept-07
90	SSD YEELEN KURA	Koury	Sikasso	813	01-janv-08
91	SSD YEELEN KURA	Kimparana	Ségou	615	21-sept-07
92	SSD YEELEN KURA	Ourikila	Sikasso	291	21-sept-07
93	SSD YEELEN KURA	Kolondièba	Sikasso	490	01-déc-08
94	SSD YEELEN KURA	Bla	Ségou	770	20-sept-07
95	SSD YEELEN KURA	Baramba	Sikasso	80	12-mai-03
96	SSD YEELEN KURA	Blindio	Sikasso	55	23-mai-03
97	SSD YEELEN KURA	Finkolo	Sikasso	75	23-mai-03
98	SSD YEELEN KURA	Karangana	Sikasso	65	23-mai-03

99	SSD YEELEN KURA	Kiffosso	Sikasso	52	23-mai-03
100	SSD YEELEN KURA	Kléla	Sikasso	80	23-mai-03
101	SSD YEELEN KURA	Konséguéla	Sikasso	65	23-mai-03
102	SSD YEELEN KURA	Koumantou	Sikasso	66	23-mai-03
103	SSD YEELEN KURA	Molobala	Sikasso	85	23-mai-03
104	SSD YEELEN KURA	M'Pessoba	Sikasso	70	23-mai-03
105	SSD YEELEN KURA	Nièna	Sikasso	100	21-sept-07
106	SSD YEELEN KURA	Sanso	Sikasso	120	01-mai-03
107	SSD YEELEN KURA	Sincina	Sikasso	100	01-mai-03
108	SSD YEELEN KURA	Sanzana	Sikasso	80	01-mai-03
109	Til GAZ ANSONGO	Ansongo	Gao	-	nov-10
110	TIL GAZ BOUREM	Bourem	Gao	509	01-janv-08
111	TIL GAZ MENAKA	Menaka	Gao	817	01-janv-08
Total				**31 957**	

1.2 Liste des projets en cours de réalisation

N°	Opérateurs	Total clients	Nombre localités	Localités
1	Service Energétique Falémé /SEF sarl	507	1	Diboly
2	Société Général d'Energie SGE-sarl	800	3	Baboundié1, Baboundié2, Wabaria
3	SBNIF SARL	509	1	Kolokani
4	ERD- SARL	522	2	Banankoro-Sanankoroba
5	GTE	512	5	Werekela, Danzenibougou-Dounamakebougou- Marabougou-Konobougou-
6	HOROYA TOUBA sarl-	556	2	Touba-Kérouane
7	EPRODED-Sarl	754	1	Kominé
8	GOURMA TRAVAUX SARL	533	1	Gossi
9	GIE YELEEN BA	873	1	Djalakorodji
10	CATERES SARL	200	2	Tienfala Gare, Tienfala Village; Djingoni
11	SKY BLUE	626	2	Sero Et Melo
12	BLUE SKY	308	1	Goumera-
13	ENERGETIC SARL	309	1	Dioumera
14	ACCESS-SARL	667	1	Manankoro
15	ACCESS-SARL/ZANTEBOUGOU-OURE	659	2	Zantiébougou Et Ouré
16	GIE DJEYASSO	134	2	SABOUGOUCIRE- LOGO Et KAKOULOU
17	SAKHO ENT.BECI	630	1	Didiéni
18	BOURE INTERNATIONAL	538	1	Madiga Sackho
19	GIE FITINE	604	2	Bodie Et Kamb
20	LES BOULONNERIES BOUNE INDUSTRIES SARL	590	1	Trouncoumbe
21	GIE KALAOU	502	2	Kalaou+ Mouline
22	MOHA sarl	526	2	Selinkegny, Oussoubidiagna
23	ENTREPRISE TOURE LASSANA SARL	621	1	Tabakoto-
24	KAMA sarl	570	5	Douale, Koury, Kembele, Loumbama, Trantimou
25	KAMA sarl	502	1	Kéniéba
26	KAMAsarl	505	1	Diafarabe
27	KAMAsarl	596	1	Sadiola
28	KAMA sarl	232	1	Sandare
29	ESE2	500	1	Sebekoro
30	REXMETAL	528	1	Toukouto-
31	COOPERATIVE MULTI-FONCTIONNELLE-HAOUKOUNA	562	1	Korienze
32	ABIS DISTRIBUTION	500	1	Lambidou
33	KAGNELA –BTP	525	1	Diancounte Camara-
34	ETS ALASSANE TOUNKARA	401	1	Lobougoula
35	EES-SARL	513	1	Nara
36	YELEEN KURA	825	5	Bla, Yorosso, Kouri, Kolondieba, Kimparana
37	SSD KKRUMBA	650	4	Yélimané, Tambakara, Ambidékoré, Lakanguémou
38	GTE-SA	315	1	Hombori
39	ACESS-sarl	185	1	Koloni
40	DENTAL- SA	763	4	KAMBILA, Daral, Fanafiècoura, Fanafiè Coro, N'Gorokondji
41	GIE BELDOHORE	255	1	Diondiori
42	GIE BEESAGO	400	1	Kokry
43	Mairie de Bintagoungou	390	1	Bintagoungou
44	EGEC	203	1	Sagabari
45	AFRIMPEX-MALI	315	1	Madina Sacko
	TOTAL GENERAL	**23216**	**75**	

1.3 Situation des protocoles d’accord et conventions sur la gestion des réseaux électriques et PTF

N°	Localités	Région	Opérateur	Protocole	Convention	Observations
1.	Diataya	Kayes	Kama sarl		Signée	Exploitation assurée par l’Opérateur. Plan d’Affaires et étude d’exécution déposés.
2.	Batama	Kayes	Kama sarl		Signée	Population opte pour une gestion communautaire
3.	Diabadji	Kayes	Kama sarl	Signé		Exploitation assurée par l’Opérateur. Plan d’Affaires et étude d’exécution déposés. Projet en attente de signature de convention de financement.
4.	Diandioumbéra	Kayes	Association des ressortissants	Signé		Contrepartie en cours de mobilisation
5.	Troun	Kayes	Pas d’Opérateur	Signé		Contrepartie en cours de mobilisation
6.	Sido	Sikasso	EMK	Signé		Contrepartie en cours de mobilisation
7.	Sotien	Sikasso	EMK	Signé		Contrepartie en cours de mobilisation
8.	Dembela	Sikasso	EMK	Signé		Contrepartie en cours de mobilisation
9.	Ouré de Keleya	Sikasso	Pas d’Opérateur	Non Signé		Recherche de gestionnaire en cours
10.	Dioliba	Koulikoro	EMS-Electric		Signée	Exploitation assurée par l’Opérateur. Plan d’Affaires et étude d’exécutions déposées pour passage en PCASER.
11.	Farakala	Segou	Niger Sahel Energie	Signé		Contrepartie en cours de mobilisation
12.	Kokofata	Kayes	Et Jean DAKOUO	Signé		Contrepartie en cours de mobilisation
13.	Sirakoro	Kayes	Et Jean DAKOUO		Signée	Contrepartie en cours de mobilisation
14.	Ouattagouna	Gao	Pas d’Operateur	Signé		Recherche d’un repreneur en cours
15.	Bentia	Gao	TILGAZ	Signé		Contrepartie en cours de mobilisation
16.	Labbezanga	Gao	TILGAZ	Signé		Contrepartie en cours de mobilisation
17.	Fanidiama	Sikasso	COGEACOM		Signée	Exploitation assurée par l’Opérateur. Plan d’Affaires et étude d’exécution déposés.
18.	N'Goko 2	Sikasso	COGEACOM		Signée	Exploitation assurée par l’Opérateur. Plan d’Affaires et étude d’exécution déposés.
19.	Samogossoni	Sikasso	Sahel Energie	Signé		
20.	Simidji	Koulikoro	Collectivité			Population opte pour une gestion communautaire
21.	Touna	Ségou	Et Jean DAKOUO		Signée	Contrepartie en cours de mobilisation
22.	Boni	Mopti	EGI SARL		Signée	Exploitation assurée par l’Opérateur.PCASER en attente de signature
23.	Douékiré	Tombouctou	EMC SARL		Signée	Exploitation assurée par l’Opérateur. Plan d’Affaires et étude d’exécution déposés.PCASER en attente de signature
24.	Meykoré	Tombouctou	EMC SARL		Signée	Exploitation assurée par l’Opérateur. Plan d’Affaires et étude d’exécution déposés. PCASER en attente de signature

1.4 Liste des localités précédemment sous gestion Protocole ayant fait l'objet de signature de convention de financement pour passer en PCASER.

N°	Localités	Région	Opérateur	Source d'énergie	Observations
1.	Mouliné	Kayes	GIE Kalaou	Diesel	Contrepartie notifiée à l'Operateur. Travaux ont démarré.
2.	Kalaou	Kayes	GIE Kalaou	Diesel	Contrepartie notifiée à l'Operateur. Travaux ont démarré.
3.	Lobougoula	Sikasso	Ets AT	Diesel	L'Operateur a satisfait les conditions de mise en place de sa contrepartie. Notification en cours par l'AMADER.
4.	Diafarabé	Mopti	Kama sarl	Diesel	Contrepartie notifiée à l'Operateur. Travaux ont démarré mais interrompus par la crue des eaux.
5.	Korientzé	Mopti	GIE Haoukouna	Diesel	Contrepartie notifiée à l'Operateur. Travaux en cours de démarrage.
6.	Diboli	Kayes	SEF	Diesel	Contrepartie mobilisée par l'Opérateur. Programmation d'une mission de réception en cours par l'AMADER
7.	Ouré zantiebg	Sikasso	ACCESS	Diesel/Huile de Pourghère	Contrepartie non encore mobilisée par l'Opérateur.
8.	Sébékoro	Kayes	ESE 2	Diesel	Une partie de contrepartie mobilisée par l'Opérateur
9.	Diangounté C	Kayes	Entrep.KANGNELA	Diesel	Une partie de contrepartie mobilisée par l'Opérateur
10	Troungoumbé	Kayes	Boulonnerie Bouné Industrie,	Diesel	Contrepartie mobilisée par l'Opérateur. Programmation d'une mission de réception en cours par l'AMADER

1.5 Liste des localités avec PCASED

	Opérateurs privés	Villages	Communes Rurales	Cercles	Surface (ha)
1.	Action Couverture et Développement (Kita Ouest) ; (ACD) Tél : 220 30 76, cell 6676 72 50 BP 1122 Bamako Mali	Thien Bamanan; Tien Marka; Markala	Markala	Ségou	20
2.	ONG Koungo Lakana So ; Région de Sikasso Tél : 66 76 35 94, 76 19 09 72	Wayèrè, Kandiandougou, Kalifabougou, Nontanso et M'Bedougou	Commune rurale de Farakala	Sikasso	20
3.	Association SIGIDA KANU ; Porte 560- rue 660 N'Tomikorobougou Tél 75 31 46 59	Boumbala	Commune rurale de Sido	Bougouni	20
4.	Association CIWARA VACANCES, Porte 397, rue 260- Lafiabougou Tél 66 72 50 00	Forêt classée de Missira	Bancoumana	Kati	9
5.	GIE Au Service de l'Environnement (ASE)Tél. 66 68 76 73	Djélibani, Sélofara et Komana-Kouta	Sido	Bougouni	20
6.	Association pour le Développement Au Sahel Tél. 66 79 72 49	Délibani, Sélofara et Komana-Kounta	Karan et Balan-Bacama	Kangaba	20
	TOTAL				**109**