Ultra high wind penetration in simple wind-diesel power systems in Cape Verde

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Abstract

The Cape Verde islands are situated west of Africa in the northern trade wind belt with excellent wind conditions for wind power. The islands are presently powered almost solely by diesel power, and it is obvious to integrate wind power. In order to design a wind power project sufficient attractive for the potential bidders in terms of scale and simplicity, the operation of the combined wind & diesel generation resulting in the maximum technical and economic amount of wind power has been studied. The power systems at three of the Cape Verdean islands with varying expected demand developments and varying wind power capacities have been simulated, using the IPSYS time series simulation tool. The results of the simulations indicate that it may be economically justified to invest in more wind power capacities that actually expected can be fully utilised the first years of operation. However, with the expected demand development, the wind power could be fully utilised after few years. The amount of potential wind power generation that cannot be utilised the first year of operation varies from 0% to 10% for the three power systems. All the wind power expects to be fully utilised after few years.

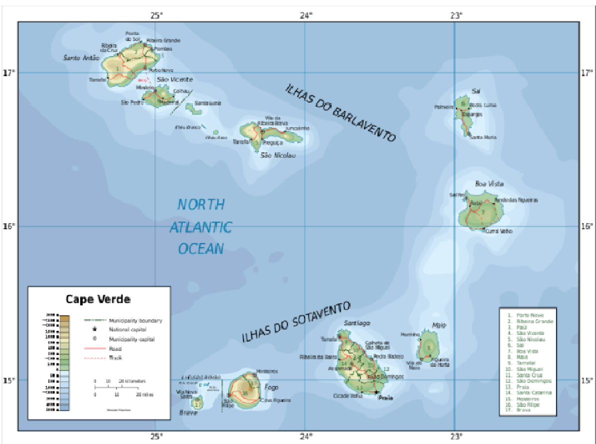

Figure 1: Map of Cape Verde. (Source: Wikipedia, 2008)

Keywords: Cape Verde; wind power; wind-diesel; high penetration.

1. Introduction

In Cape Verde, a group of islands in the North Atlantic Ocean, 500 km west of the African continent, the power supply is almost solely based on diesel generation and imported diesel fuel. However, the islands are located in the trade wind belt with exceptional good and reliable wind resources, and wind power is an obvious option for power generation.

As consultants to InfraCo[1], Risø DTU has investigated the technical and economic conditions by introducing high amount of wind power in the existing diesel based power supply systems in four islands in Cape Verde.

The population in Cape Verde is around 500 000, spread at 10 populated islands. The islands are not electrically interconnected and have their individual power supply systems, operated by Electra, the national power utility company. The electricity demands at each of the larger islands are typically 10-20 MW. The demand have been constantly growing during the last years, and a dramatic growths in the electricity demand are expected in the coming years due to planed

[1] **InfraCo,** a donor-funded infrastructure development company, aims to stimulate greater private investment in African and Asian infrastructure development.

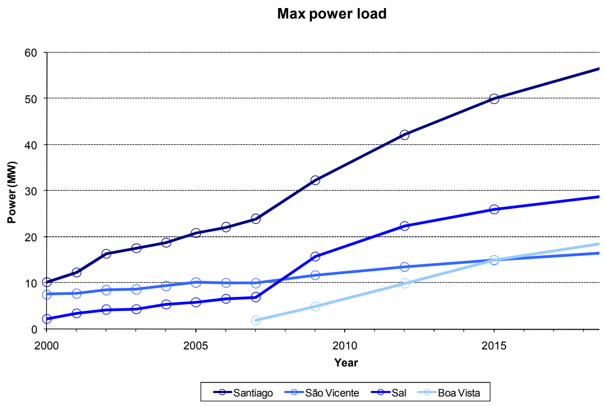

Figure 2: Indication of the historical and the expected development in the power demand in the four islands in question. (Data source: Electra, 2007)

development of the tourism business at at least four of the island – Santiago, São Vicente, Sal and Boa Vista (see Figure 1).

With the present international market situation for wind turbines, small wind power projects in remote areas with limited additional market potentials are not the most attractive for the wind turbine suppliers, and it is difficult to create economic feasible projects. A challenge for the technical design of the project was therefore to make the project as attractive for the potential suppliers as possible to get acceptable offers. This has been interpreted as as large wind power projects as possible and at the same time as simple projects as possible.

The idea (in economically terms) of combining diesel generation with wind power is to substitute part of the diesel fuel consumption, the fossil fuel dependency and the running costs with upfront wind turbine investment costs and local renewable energy sources. The avoided fuel consumption and the additional investment are therefore the main economic parameters for the feasibility analysis. The wind power investment costs relative to the wind power generation (determined by the actual offers) expect to depend on the scale of the project (in terms of MW), on the complexity of the combined system, on the the risk and the responsibilities. The larger, the simpler, the less risky and the less responsibility, the better relative prices are expected.

However, the higher wind power capacity in the system, the more advanced system control is required, ending in the need for additional components and control options like stability units, storage units and load management. The aim of the study was *to study the impact of high penetration integration of wind power into the existing diesel power system without introducing additional control components* or load management, even there is a large potential in Cape Verde for load management (e.g. related to water desalination and the hotels air conditioning).

2. Power system simulations

The operation of the proposed combined wind-diesel power systems have been simulated and analysed for three of the islands: Santiago, São Vicente and Sal. The power supply in Boa Vista was not included in the project from the beginning, and the Boa Vista power system has not been analysed the same way.

Aggregated models of the three power systems, with the diesel power station, the wind farm, the main load centres and the critical power lines, were developed (see Figure 3) and implemented into the numerical power system time series analysis tool IPSYS - see Box 1.

Box 1

IPSYS is a flexible simulation framework, developed by Risø DTU, for integrated energy systems with multiple forms of energy and complex control structures. It has been developed with system performance simulations in mind, particularly involving large amounts of renewable energy.
IPSYS calculates an energy balance for each form of energy, taking their interdependencies into account. The simulation is quasi-static, with calculation time steps typically in the range of a few seconds to some minutes. The internal structure of each energy subsystem can be explicitly modelled as a network of components. All components can be connected to simulated controllers which are themselves able to exchange information, in order to implement system-wide control. This feature can be used to build control hierarchies as well as distributed control configurations. The components and controllers in the library are easy to customize, and new types can be added.
The simulation accepts various forms of time series input, either provided by one of the built-in generators or read from an external source, such as measured data. IPSYS is written entirely in C++ and runs on multiple operating systems, including Windows and Linux.
http://www.risoe.dtu.dk/vea-ves/projects/ipsys/

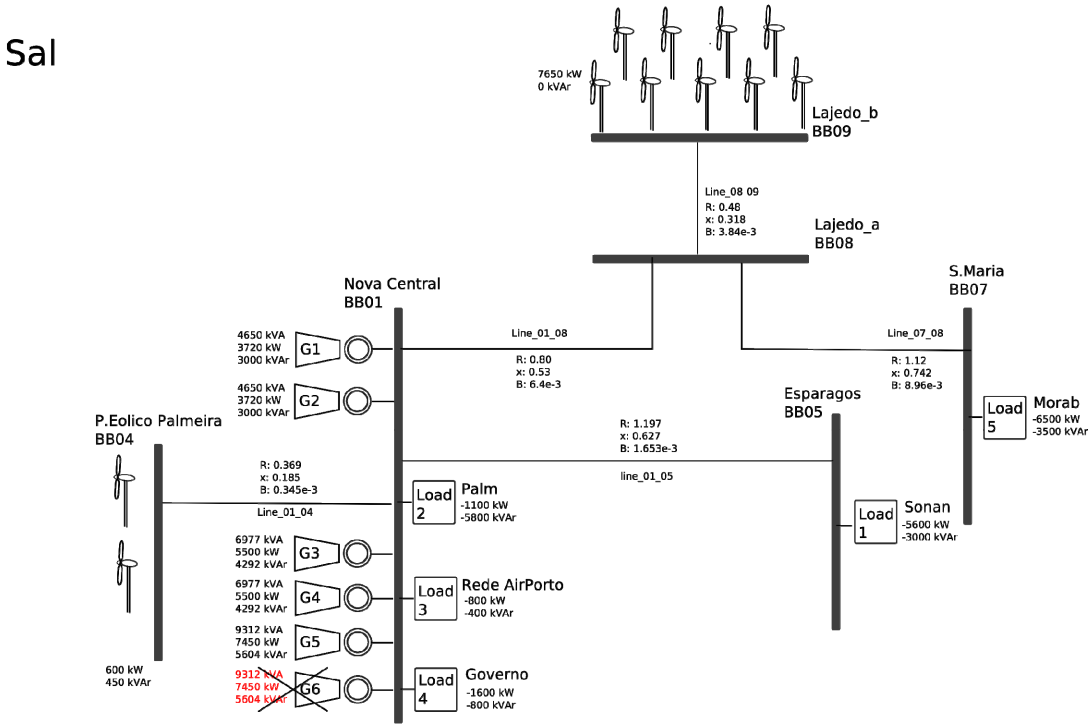

Figure 3: The aggregated single line diagram of the power system in Sal used in the IPSYS simulation. (Source: Risø, 2007)

The following have been assumed in the simulations:

- A central power system controller determines dynamically the set of diesel generators connected to the grid (the dispatching of the diesel generator units), the maximum number of wind turbines connected to the grid and the maximum wind power generation.
- The diesel generator units have the (main) responsibility for the power system stability and the power quality (the voltage and the frequency control).

The following control strategy was used in the simulations:

1) Minimum continuous load of the diesel engines: 30% (optional 50%).
2) Minimum instantaneous load of the diesel engines: 10%.
3) Minimum spinning reserve diesel capacity connected to the grid: 200% of the observed fluctuation of the diesel load within the last hour and minimum 50% of the actual diesel load (if possible).
4) Minimum diesel capacity connected to the grid: 2 times the wind capacity connected to the grid.
5) Minimum number of diesel generator units connected to the grid: 2.
6) Minimum operation time of a diesel engine: 4 hours.

Condition 1 is to prevent the diesel engines from sooting up at low load. The wind power generation may be limited to fulfil this condition.

Condition 2 is to prevent for negative load of the diesel generators.

Condition 3 is to be prepared for the fluctuations in the wind power and in the load.

Condition 4 is to ensure dynamic stability of the system. In situations with low consumer load and high wind, some of the wind turbines may be shut down and disconnected from the grid to enable more diesel generators to be shut down and disconnected and still fulfilling the control condition.

Condition 5 is not to relay on a single diesel generator unit.

Condition 6 is to minimise the number of start / stop of the diesel engines.

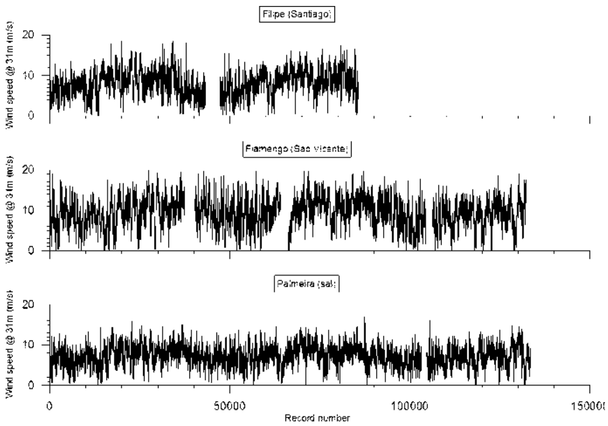

Figure 4: The project has access to high quality wind data from Santiago, São Vicente and Sal. (Data source: Risø, 2004)

Load patterns representative for a full year were simulated on hourly basis based on observed historical load data provided by Electra from the three islands – see Figure 5.

The wind patterns in the three islands are well documented by high quality wind measurements during 2-3 years – see Figure 4 and Figure 6.

3. Simulation results

IPSYS time series simulations with 10 minutes time steps were performed for the three power systems with different amounts of wind power integration from year 2009. Generic 1 MW wind turbine units were used in the simulation.

The wind power capacity in *Santiago* is limited to 10 MW by the capacity of the wind farm site

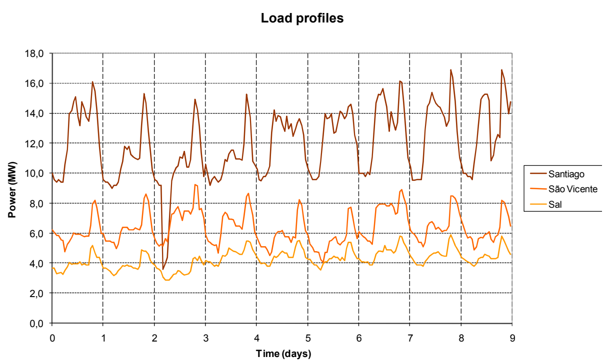

Figure 5: Power load profiles on hourly basis for the three power systems in 2006. (Data source: Electra, 2007)

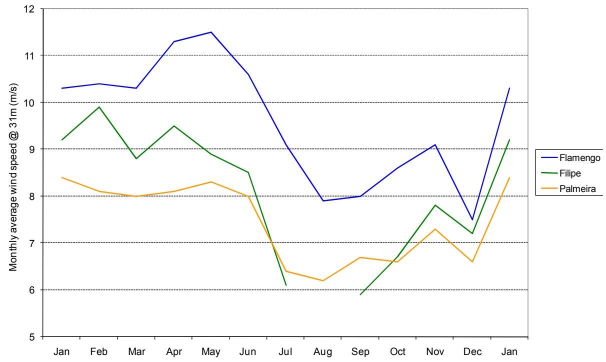

Figure 6: The monthly average wind speeds of the data in Figure 4 are between 6 and 11 m/s.

available for the project. In *São Vicente*, the wind power capacity is limited by the expected moderate demand growth (see Figure 2), and the optimistic, realistic wind power capacity was found to 6 MW. In *Sal*, however, both the capacity of the wind farm site and the expected development growth are huge, and the optimistic and realistic wind power capacity was found to 8 MW.

The results from the simulations of year 2009 with the wind power capacities indicated are summarised in the table below. As seen, the expected amount of available wind energy not utilised in 2009 (the first year of operation of the new proposed wind farms) is 0 % for Santiago, 11 % for São Vicente and 9 % for Sal.

2009	Santiago	Sao Vicente	Sal	
Min load	16	6	7	MW
Max load	32	12	16	MW
Energy consumption	210	70	90	GWh/y
Diesel capacity	44	16	20	MW
Wind capacity	10	6	8	MW
Potential wind energy	35	28	33	GWh/y
Not utilised wind energy	0	3	3	GWh/y
Not utilised wind energy	0%	11%	9%	
Wind power penetration	17%	36%	33%	
Avoided diesel fuel	7	5	6	kt/y

Plots of simulated time series for 9 days in year 2009 of the power balances between the generation (diesel and wind) and the consumption (demand and losses) are shown for the three power systems in Figure 7 (Santiago), Figure 8 (São Vicente) and Figure 9 (Sal). The demand and losses are shown as negative numbers while the wind and diesel generations are shown as positive numbers. Especially in the plot of the simulation of the São Vicente power system (Figure 8) there are clearly periods (during the nights) where not all of the available wind power can be utilised. It is also clear from the plots, that the wind power introduces additional fluctuations of the diesel loads relative to the fluctuations of the demand load.

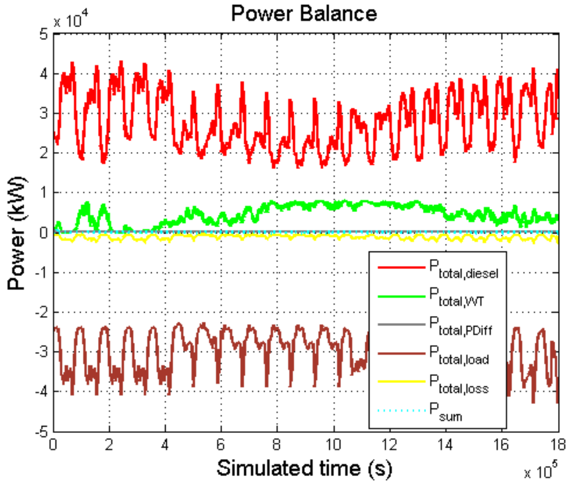

Figure 7: Results from the IPSYS simulation of the Santiago power system year 2009 indicating the power balance. (Source: Risø, 2007)

The relative amounts of the available wind energy that cannot be utilised by the systems as function of the wind power capacities are illustrated in Figure 11. To be able to compare the three systems, the wind power capacities are given in per units (p.u.), where 1 p.u. corresponds to a wind energy penetration of 20 % - see Figure 10. With wind power capacities up till around 1.5 p.u. most of the available wind energy can be utilised by the wind-diesel systems. With more wind power capacity the amount of available wind energy that cannot be utilised increases dramatically.

As 1 p.u. wind power capacity corresponds to 11.8 MW, 3 MW and 6.3 MW for Santiago, São Vicente and Sal respectively, the proposed wind power capacities of 10 MW, 6 MW and 8 MW correspond to 0.85 p.u., 2 p.u. and 1.3 p.u. wind power capacities.

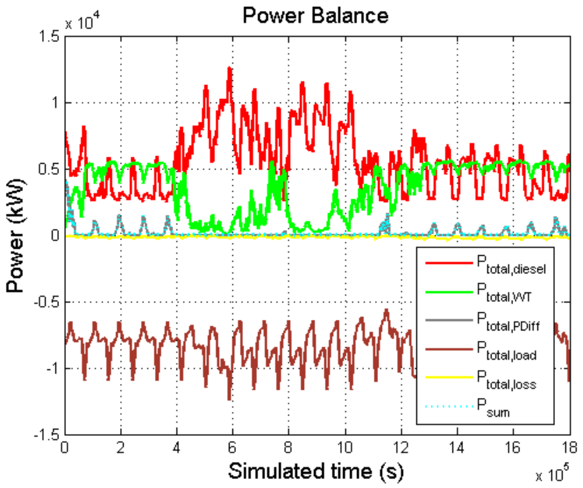

Figure 8: Results from the IPSYS simulation of the São Vicente power system year 2009, indicating the power balance. (Source: Risø, 2007)

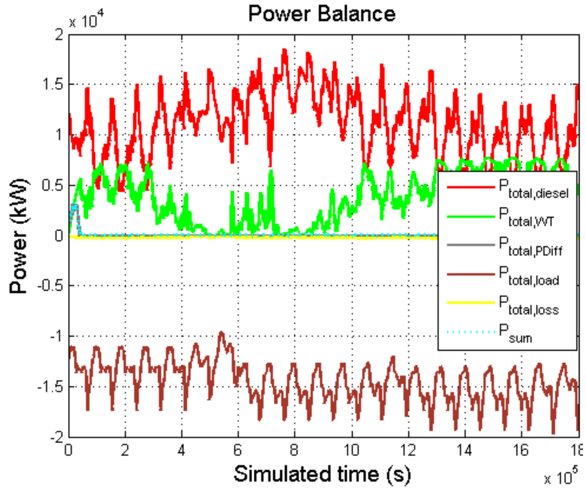

Figure 9: Results from the IPSYS simulation of the Sal power system year 2009, indicating the power balance. (Source: Risø, 2007)

In Figure 13, the amount of not utilised wind energy is illustrated as function of the wind energy penetration level – both as function of the actual obtained wind energy penetration levels (the dashed lines) and as function of the available wind energy penetration levels (the full lines).

The estimated relative amounts of avoided diesel fuel consumption due to the wind power generation as well as the resulting specific fuel consumption are indicated for the three power systems in Figure 12 as function of the wind power capacity (in p.u.).

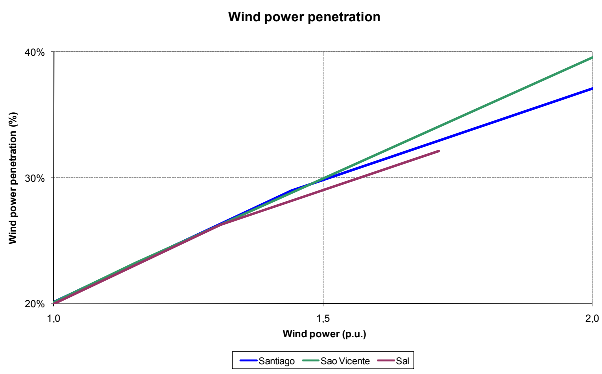

Figure 10: The wind energy penetration as function of the relative installed wind power capacity for the three power systems. 1 p.u. wind power capacity is defined by 20 % wind energy penetration, corresponding to 11.8 MW in Santiago, 3.0 MW in São Vicente and 6.3 MW in Sal.

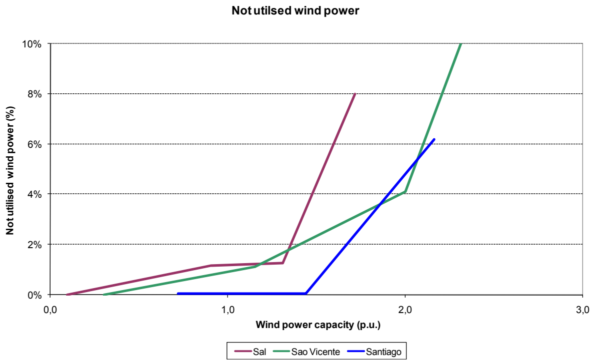

Figure 11: The relative amount of the available wind power generation that is not utilised as a function of the relative wind power capacity installed (1 p.u. corresponds to 20 % wind energy penetration – see Figure 10).

The amount of avoided diesel fuel consumptions are derived by similar power system simulations with and without the wind power. Linear relations are observed as long as most of the available wind energy can be utilised. With higher wind power capacities the not fully utilised wind energy result in less relative value of the wind power capacity in terms of avoided fuel.

However, with the expected growing demand (see Figure 2), more and more of the available wind energy can be utilised with time. The power systems have been simulated with the expected demands in year 2012 and 2015. The development with time of the amounts of wind energy that cannot be utilised are illustrated for the three power systems in Figure 14. In year 2015, most of the available wind energy can be fully utilised.

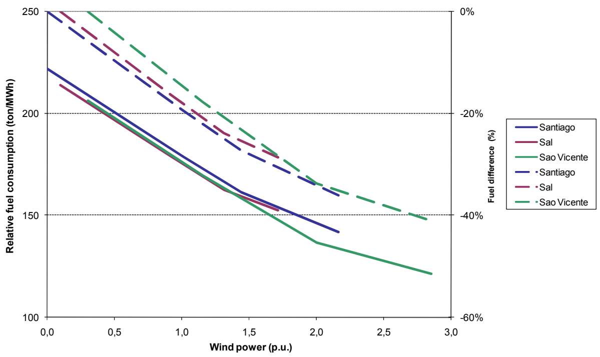

Figure 12: The relative avoided diesel fuel consumption (dashed lines, right axis) and the resulting specific fuel consumption (full lines, left axis) as function of the relative installed wind power capacity (1 p.u. corresponds to 20 % wind energy penetration – see Figure 10).

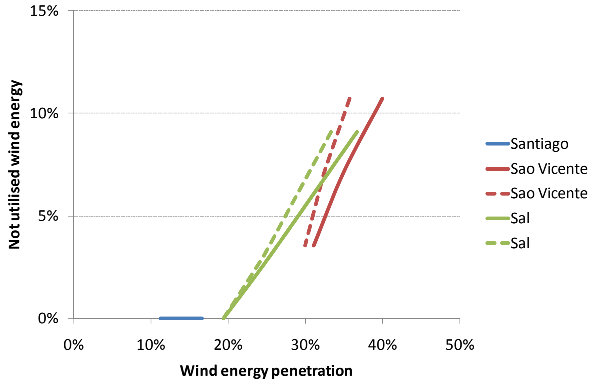

Figure 13: The estimated amount of not utilised wind energy as function of the wind energy penetration level – full line is relative to the potential wind energy penetration and dashed line relative to the actual wind energy penetration.

Finally, comparable simulations have been performed using either 30 % or 50 % minimum continuous diesel load. Main results are presented in Table 1. It is very clear that this parameter is extremely critical for the amount of avoided diesel fuel and thereby for the economy of the project.

It is the intension that the wind farms will be owned and operated by a private investor (as Independent Power Producer – IPP) with a Power Purchase Agreement (PPA) with the system operator (Electra). The PPA should hold economic incentives both for the IPP to ensure high production availability of the wind turbines and for the system operator to utilise as much of the available wind power as possible. The model for the PPA is therefore to have one take-or-pay feed-in tariff for a specified minimum energy amount (on monthly basis) and a lower tariff (lower than the marginal costs of the diesel power generation) for

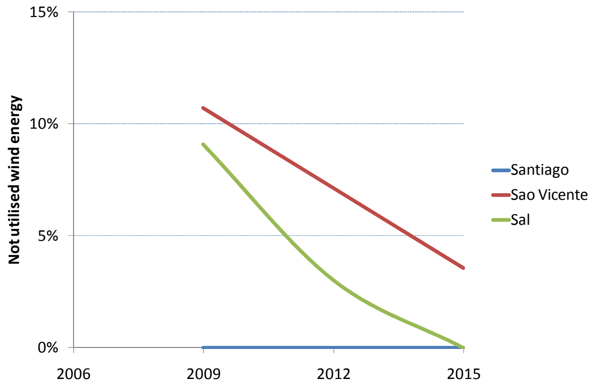

Figure 14: The estimated not utilised wind energy over time as the demand growths.

	Diesel min load	Wind power	Wind penetration	Not utilsed wind	Fuel diff	
	%	MW	%	%	kt/y	
Santiago	30%	8,5	14%	0%	-8,34	-14%
	50%	8,5	14%	0%	-8,34	-14%
Sao Vicente	30%	6,0	40%	4%	-5,32	-34%
	50%	6,0	31%	24%	-4,07	-26%
Sal	30%	8,3	26%	1%	-6,51	-24%
	50%	8,3	25%	4%	-6,29	-23%

Table 1: Results from the IPSYS simulation of the three power systems (Santiago, São Vicente and Sal) indicating the impact of the minimum diesel engine load criteria (30 % and 50 % respectively) on the wind energy penetration, the amount of unutilised wind power generation and the amount of avoided diesel fuel.

the additional utilised wind energy. The IPP will only be paid for the amount he can deliver, and will thereby be motivated to keep the wind turbines in operation. And the system operator will reduce the total production costs the more wind power he can integrate.

A 'worst case' scenario for 2009 (defined by Electra) (with lower diesel-generator capacities, lower annual demands and lower minimum loads assumed in the power system analyses) have been performed to quantify the risks. Main results from these analyses are presented in the table below. The estimated amount of wind energy that cannot be utilised in the Sal power system under the given assumptions (if the expected demand growth will not materialise) will then increase to around 45 % in year 2009.

2009	Santiago	S. Vicente	Sal	
Diesel capacity	26	12	9	MW
Wind capacity	10	6	8	MW
Min load	13	6	5	MW
Demand	170	61	41	GWh/y
Available wind generation	35	28	33	GWh/y
Not utilised wind	0	5	15	GWh/y
Not utilised wind	0	18	45	%
Wind energy penetration	21	38	44	%

4. Conclusion

The single most important and critical parameter for gaining the full benefit of the wind power is the minimum load of the diesel engines. A change of the parameter from 30 % to 50 % results in a shift of the expected amount of wind energy not utilised from 4 % to 24 % for the São Vicente power system. It is therefore important that the system operator has an (economic) incentive to optimise the operation of the combined wind-diesel power system.

The proposed wind power project includes 10 MW, 6 MW and 8 MW wind power plus 4 MW in Boa Vista – in total 28 MW. With this amount of wind power and with the assumed demands it is estimated that around 10 % of the available wind energy cannot be utilised in São Vicente and Sal (and around 15 % in Boa Vista) in year 2009.

If the wind power capacities in São Vicente, Sal and Boa Vista were reduced to 4 MW, 6 MW and 2 MW respectively – in total by 6 MW, corresponding to 20 % of the 28 MW – then almost all of the available wind energy could be utilised from the first year of operation.

If the proposed approach of overinvesting in wind power capacity in the beginning (or investing in the future) should be economic feasible, the offers for the 28 MW project should be 10-20 % lower in price relative to the 22 MW project. This, however, we will never know.

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