The impacts of wind power on power systems operation

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Abstract: The wind power sector is growing rapidly in Portugal and the National objectives for energy include a significant increase of wind power during the next years. The large penetration of wind power in Portugal will influence significantly the energy system cost, but it seems also essential to materialize the international energetic and environmental commitments. This paper focuses on the impact of large scale wind scenarios on the power system operation. CO_2 abatement potential is estimated along with the effects on the operating costs of thermal power plants. Simulations for different wind scenarios were run for 2016, assuming the possibility of exports. According to the results, it seems that about 20% of wind power penetration may be achieved in Portugal with minor losses of efficiency of the global system.

Key-Words: Wind power, value of wind, CO_2 abatement, electricity system operation, simulation.

1. Introduction

The Portuguese electricity generating system is a mixed hydrothermal system. The total installed power reached in 2006 about 13700 MW, distributed between thermal power plants (coal, fuel oil, natural gas and gas oil), hydro power plants and Special Regime Producers (SRP-renewable plants and cogeneration).

The wind sector is growing rapidly in Portugal. The National objectives for energy include a significant increase of wind power during the next years. If the drawn objectives are accomplished, by 2010 the wind power share may reach values comparable to the present Danish situation and higher than in Germany or Spain. Table 1 resumes the main characteristics of the portuguese electricity system at present and the expected characteristics in 2016.

Table 1- Distribution of installed power in mainland Portugal, 2006.

	Installed power (MW)	
	Beginning 2006	**2016**[(1)]
Coal	1820	4520
Natural gas	2404	4516
Oil*	1672	0
Large hydro	4582	5805
SRP		
Wind	1496	4750
Other	1795	3245

* fueloil and gasoil. [(1)] Source: [9]

REN forecasts for 2005 [9] predict a 41% increase of the total installed power between 2006 and 2011, and an additional 24% increase until 2016. According to these forecasts there will be a reduction of the thermal and large hydro quote and a large increase of the SRP quote. The growth of the SRP will be mostly due to the increase of the renewable energy sector, in particular wind. According to these scenarios, in 2011, the wind sector will achieve about 25% of the total installed power.

A full description of the Portuguese electricity market and an overview of the wind power sector may be found in Refs. [5] and [4].

Adding new wind power to the system will result in a reduction of the electricity production from other power plants. Depending on the characteristics of the electricity system this may lead to great or moderate reduction of the CO_2 emissions and of fuel consumption. The calculation of fuel savings may look straightforward, but it depends, among other factors, on the operating characteristics of the fossil fuel plants [8].

Works like Refs. [1], [6] and [10], already called attention to this issue, when analysing the effect of wind power production on the emissions from generation plants. Another work for UK [11] also reports that coal and gas units operate less efficiently when partially loaded, with an efficiency loss of about 20%, although with a lower effect on the coal plant. ESB National Grid [2] study on the impact of wind power generation in the operation of the Irish conventional plants concludes that the fuel costs of the thermal power plants do not decrease in proportion to their decrease in output, due to the increase start-ups and lower load factor.

The aim of this paper is also to address the effects of large scale wind power but for the particular case of the Portuguese electricity system. For this, simulations with increasing amounts of wind were conducted. Next section describes the simulation process and the assumed wind scenarios. In the third section the results are presented, detailing expected changes in both CO_2 emissions and operating costs. Fourth section contains the discussion of the results. The main conclusions are summarised at the end.

2. Simulation process.

For the simulation process the Portuguese company holding the concession of the National Electricity Transmission Grid in mainland Portugal and also in charge of the overall management of the Public Electricity Supply Service, was contacted. The simulation run was executed on their exploration planning software for the Portuguese power market[1]. The simulation was made for 1 year and the running/dispatch of the production units was simulated for different values of installed wind power. For simplicity reasons, the installed power of the other plants was set equal to the one expected under REN [9] scenarios for 2016. The pattern of expected demand was based also on REN growth forecasts [9] and on the historical pattern of the demand during the year.

The results were described by the power output of each power station for four previously defined "hourly steps"[2] of each week.

The average load factor (LF) of each power plant was computed during one year according to equations 1 and 2.

$$\overline{P}^{x} = \frac{\left[\sum_{j=1}^{4}\sum_{n=1}^{52} HS_j P_{nj}^{x}\right]_{\notin P_{nj}^{x} \neq 0}}{52 \times \sum_{j=1}^{4} HS_j} \qquad (1)$$

$$\overline{LF}^{x} = \frac{\overline{P}^{x}}{IP^{x}} \qquad (2)$$

where $\overline{P}^{x}$ is the average power output of plant x during the analysed year; HS_j is the number of hours of hourly step j; P_{nj}^{x} is the average power output of plant x during the hourly step j of week n; $\overline{LF}^{x}$ is the average load factor of power plant x during the analysed year and IP^{x} is the installed power of plant x.

The simulation was conducted assuming four different wind power scenarios in 2016:

- Low growth (W1): installed wind power equal to 2000 MW.
- Moderate growth (W2): installed wind power equal to 3500 MW.
- Reference scenario (W3): installed wind power equal to 4750 MW.
- High growth (W4): installed wind power equal to 7700 MW (includes 1000 MW offshore).

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[1] The authors want to express their gratitude for REN for their interest and essential collaboration on this work.

[2] Hourly steps of the week represent the average power output of each power plant for the: 8 hours of greater electricity consumption in the week (HS1), following 72 hours (HS2), following 26 hours (HS) and 62 hours of lesser electricity consumption in the week (HS3).

3. Simulation results.

The simulation scheduling was based on the cost variable cost of the system, taking into consideration operational constraints and assuming the possibility of transmission between Portugal and Spain. Figure 2 presents the simulation results for the transmission balance (exports-imports) and production in Portugal, for the four wind power scenarios in 2016. The results indicate that wind power will not replace hydro power, since the hydro production levels will remain more or less the same, regardless of the available wind power in the system. This way, a clean energy form will not replace another renewable and emissions free electricity production.

Wind production added to the system will decrease mostly thermal power production. Although being expected a reduction of the coal power electricity generation, these plants will still be base load and will be operating near full load. However, for large wind power scenarios a reduction on the number of operating hours may be observed for older coal power plants. Natural gas power plants will be the most affected from large wind power scenarios. Having more wind in the system means increased part load operation and also reduction on the numbers of operating hours. Also, adding wind to the system will increase the exports to Spain.

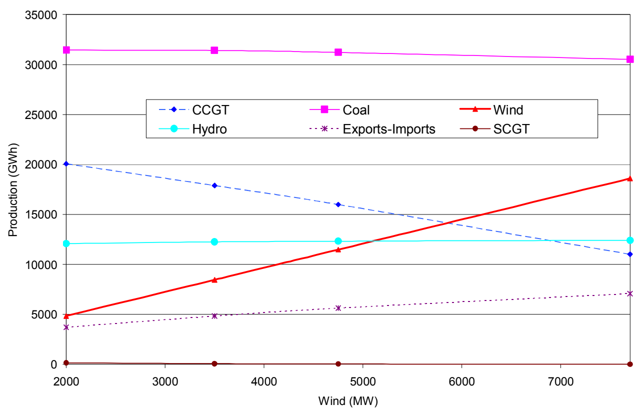

Figure 1- Simulation results for the electricity production and exports, when adding wind power to the Portuguese system.

Table 2 resumes the results of the simulation process for coal and CCGT. The expected average load factor is presented along with the specific CO_2 emission values (COEF) and specific fuel consumption values (SFC), for average CCGT and coal power plants presently in operation.

For the CCGT, the values of the specific CO_2 emission and specific fuel consumption were obtained from the characteristic curve of the gas power plants presently operating in the Iberian market. The average values for CCGT and coal power plants were drawn from 2005 consolidated data published by the operators of the existing plants in Portugal.

Table 2- Results of the simulation for CCGT and coal power operation.

	Wind (MW)	LF (%)	COEF* (t/MWh)	SFC*
CCGT	2000	72-77	0.359-0.360	164.6-165.1[1]
CCGT	3500	68-69	0.372-0.376	170.6-172.3[1]
CCGT	4750	63-65	0.390-0.397	178.6-181.9[1]
CCGT	7700	45-48	0.455-0.475	208.4-217.5[1]
CCGT	Average (2005)		0.375	174
Coal	2000	90-98	0.844	0.223[2]
Coal	3500	90-98	0.844	0.223[2]
Coal	4750	89-98	0.844	0.223[2]
Coal	7700	84-98	0.844	0.223[2]

* For a power plant presently operating.
[1] m^3N/MWh . [2] t/MWh.

As said, CCGT is the most affected thermal power plants by the increase of wind power in the system. The minimal load factor of the coal power plants is expected to be around 84% (and for most coal power plants this value will be higher than 90%) regardless of the installed wind power.

3.1 Impact of wind power on CO_2 emissions.

The efficiency and consequently the emissions from fossil fuel fired generators are strongly affected by the operation regime of the plants. The quantification of the emissions savings from an increasing share of wind power, must take into consideration that large variations in wind power output can result in operating conventional power plants less efficiently

Figure 2 presents the expected reduction of the average CO_2 emitted over the low growth wind scenario for each one of the remaining three scenarios. Two models were tested: the linear model assumes given average CO_2 emission factors for SCGT, cogeneration plants, CCGT and coal power plants; the interdependent model assumes average CO_2 emission factors for SCGT, cogeneration plants and coal power plants. For the CCGT emission factor the values presented in Table 2 were used for the existing CCGT and a reduction of 6% was assumed for new CCGT. For existing coal power plants also Table 2 values were used. For new coal power plants 13% reduction was assumed.

The results for the Portuguese market indicate that only 70-73% of the theoretically possible cost savings (defined by the linear model) may be realised.

The CO_2 abatement of wind power may be computed from the reduction of CO_2 emissions per unit of electricity produced from wind. The CO_2 savings result from the reduction of fuel that would be consumed in thermal power plants under less wind power alternatives. According to the interdependent model, the moderate growth scenario will reduce 0.168 t CO_2 per each MWh produced over the low growth scenario. This value increases for large wind power scenarios, achieving 0.211 tCO_2/MWh for W4.

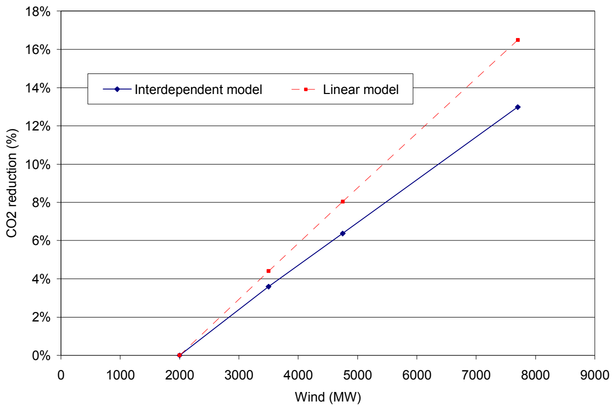

Figure 2-Reduction of CO_2 emissions over the low growth wind scenario.

For the Portuguese simulation, additional wind power will mostly replace CCGT. Only for large wind power scenarios there would be a reduction of coal power production, increasing the CO_2 abatement. It seems that for the Portuguese system, the environmental gains of the increasing wind power overcome the possible loss of efficiency of thermal power plants even for large wind power scenarios. On the other hand, results for West Denmark [7] or for Germany [10], indicated that this CO_2 abatement would be reduced as wind power penetration gets higher.

The different configuration of the Portuguese system justifies part of these somewhat different values. The Danish and German studies conclude that wind power will mostly replace coal and in a latter stage will replace more efficient CCGT units, in opposition to the Portuguese results. Also, increasing wind power will result in increasing electricity exportations. This way, the total amount of electricity generated in wind plants will not replace the same amount produced by thermal power plants and there will be an increase on the total electricity production. This fact offsets the possible loss of efficiency. Ref. [7] also called attention to this issue and concluded that when transmission possibility was included but the reduction of CO_2 was calculated from only Denmark, values were very modest when compared with the no transmission scenarios or to the effect on full Nordic system.

3.2 Impact of wind power on operating cost of the electricity system.

Once more two models were tested: the linear model assumes given average specific fuel consumption factors for SCGT, cogeneration plants, CCGT and coal power plants; the interdependent model assumes average specific fuel consumption factors for SCGT, cogeneration plants and coal power plants. For the existing CCGT and coal power plants the fuel consumption factors were drawn from Table 2. For new plants a reduction of 5% was assumed for CCGT and 13% for coal plants. The O&M and emission costs were also taken into consideration. However, due to the unavailability of data, for this analysis, the O&M costs were assumed not to be affected by the reduction of the capacity factor of the thermal power plants.

Figure 3 presents the expected reduction of the average operating costs over the low growth wind scenario for each one of the remaining three scenarios. The production cost was corrected for electricity exchange, assuming that the export price is equal to the average production cost.

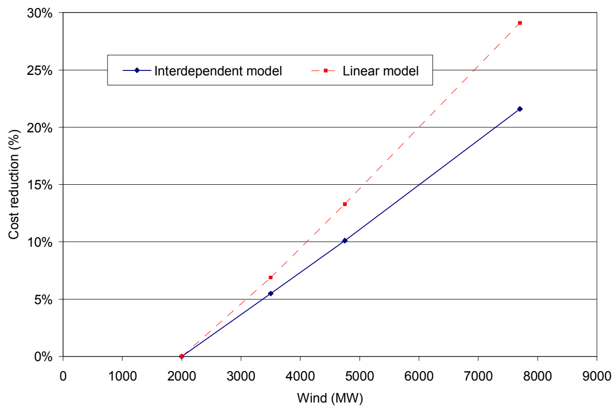

Figure 3-Reduction of the average operating cost over the low growth wind scenario.

The increasing inefficiency of the thermal power plants results in higher specific fuel consumption factors. The fuel and emissions costs reduce at a lesser rate than the rate of reduction of electricity production from thermal power plants, but the increasing wind power production (with null operating costs) seems to compensate part of the lost efficiency of the system.

The results for the Portuguese market indicate that only 65-73% of the theoretically possible cost savings (defined by the linear model) may be realised. A similar effect was already described for the German market [10], although with a much pessimist result (expected real cost savings between 27% and 32% of the theoretically possible). It should, however, be noticed that the authors assumed the theoretical maximum savings coming only from the displacement of hardcoal production. For the Portuguese simulation, the comparison was made against the grid mix production, already optimised according to the wind power production of each scenario. The only difference between the theoretical and interdependent models lays in the computation of the gas consumption of the CCGT.

The value of wind power may be computed from the cost reduction per unit of electricity produced from wind. The avoided costs result from the reduction of fuel that would be consumed by thermal power plant, the consequent reduction of emission costs, and also from the reduction of O&M costs. According to the interdependent model the value of wind power decreases only slightly for large shares of wind power production. The value of wind power over the low growth scenario, ranges from 29.328 €/MWh, for W2 to 28.739 €/MWh, for W4.

Once more these results are different from the ones obtained by Refs. [7] and [9], who observed important reductions on the value of wind power as wind penetration gets higher. However, Ref. [7] results also indicate that for high transmission scenarios the decrease on the value of wind power was much smooth.

4. Discussion of the results.

Large variations in wind power output can result in operating conventional power plants less efficiently [5]. On ESB National Grid study [2], the authors explained the difference between the realisable and the potential CO_2 reduction with the growing inefficiency of the conventional plants portfolio and argue that this represents the growing inefficiency in using wind power to curtail emissions. The simulation of the German electricity system [10] also concluded that emission reductions decrease with a growing share of wind power and the real emission and cost savings were much lower than the theoretically possible values.

From the Portuguese simulation results, it was possible to conclude that an increase of the installed wind power would mostly affect CCGT operation. Coal power plants would remain working in a stable regime near full load, with the exception of the high growth scenario where there would be reduction on the number of operating hours of older coal groups. The SCGT are minimally affected, because they work mostly as operational reserve and their load factor is very low in every wind scenario.

For the CCGT, increasing wind power scenarios reflect on both the number of operating hours and on the average load factor of these thermal power plants. This leads to a growing inefficiency of these plants, consequently increasing specific gas consumption and specific CO_2 emission factor, and may question the value of using wind power to reduce operating costs and control emissions. However, the results indicate that in spite of this efficiency loss, the CO_2 abatement of wind power still increases with increasing wind power in the system and the value of wind power only presents a small decrease for high wind power scenarios.

Simulations in other countries, like Denmark, Ireland and Germany indicate larger CO_2 abatement potential, but lower values for the value of wind. However, most of these simulations assume that large amounts of wind added to the system will mainly replace coal and in a lesser extent gas. Ref. [6] already called attention to this issue, and underlined that if gas price becomes very expensive, the operating cost of gas plants will become higher and this would result in wind power replacing gas instead of coal.

Portugal presents a particular configuration of the electrical system, with a large share of hydro power, no nuclear power plants and the possibility of exchanges with Spain. The simulation assumes a fixed non wind capacity in the system, meaning that increasing wind power will increase the total installed power. Additionally, the evolution installed wind power is Spain is not modelled and the present conditions of the market are assumed. This results in increased capacity of production in Portugal and may explain the large increase in net exports.

The simulation was made for one year, with weekly time steps subdivided in four "hourly steps" and assuming a weekly average load factor of the wind power plants. This allows obtaining the average output of each power plant in each one of these "hourly steps" but the effect of wind power fluctuations during a day is lost. It was however possible to estimate the effect of seasonal changes on both the wind and the hydro sectors. For the Portuguese case, the daily fluctuations of the wind power may be mostly compensated by SCGT and hydro power. As so, it is assumed that the power output of the CCGT and coal power plants will remain close to the average "hourly steps" values obtained.

According to the 2016 simulation, it seemed that about 20% of wind power penetration may be achieved in Portugal with minor losses of efficiency of the global system. The estimated value of wind is about 29 €/MWh and the CO_2 abatement of wind may reach values close to 0.211 tCO_2/MWh. The average variable cost of the system for the high wind growth scenario is about 20% lower than in the low wind growth scenario. As for the CO_2 average emissions, a 13% reduction may be expected for the high growth wind scenario over the low growth wind scenario.

5. Conclusions

The growth of the wind power share will have a strong impact on all the electricity generating system. The large penetration of wind power in Portugal will influence significantly the energy system cost, but it seems also to be essential to materialize the international energetic and environmental commitments.

According to the simulations conducted, the increasing penetration of wind power in the system will affect mostly the CCGT operation with consequences on the theoretically expected cost reduction and environmental gains. However, contrary to other European studies, the results indicate that the value of wind power and its CO_2 abatement potential still present an increasing trend, mostly due to the possibility of exports.

These results are explained partially by the expected particular configuration of the Portuguese electrical system in 2016. According to the simulation, the incremental wind power replaces mainly CCGT power and only for high growth wind scenarios there would be an important effect on the coal power production. However, adding wind power to the system will increase exports, meaning that the expectable reduction of the thermal power production for large wind scenarios may be offset by the possibility of transmission. This way, the exchange smoothes out the variations, and the efficiency of CCGT is not as affected as it would be in the no transmission case.

The research will proceed with the inclusion of the results of the simulation process on an integrated electricity planning model for Portugal. The authors expect to contribute in the future for the drawing of the electricity plan based on realistic assumptions of the role of wind power on the CO_2 abatement and on the reduction of the operating costs.

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