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Electricity Power Planning: the Role of Wind Energy

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Abstract**—**Combining energy efficiency with renewable energy sources constitutes a key strategy for a sustainable future. The wind power sector stands out as a fundamental element for the achievement of the European renewable objectives and Portugal is no exception to the increase of the wind energy for the electricity generation. This work proposes an optimization model for the long range electricity power planning in a system similar to the Portuguese one, where the expected impacts of the increasing installed wind power on the operating performance of thermal power plants are taken into account. The main results indicate that the increasing penetration of wind power in the electricity system will have significant effects on the combined cycle gas power plants operation and on the theoretically expected cost reduction and environmental gains. This research demonstrated the need to address the impact that energy sources with variable output may have, not only on the short-term operational planning, but especially on the medium to long range planning activities, in order to meet the strategic objectives for the energy sector.

Keywords**—**Wind power, electricity planning model, cost, emissions.

I. Introduction

THE wind electricity generation sector is essential for the attainment of the European renewable objectives. According to the European Union (EU) forecasts, the large hydropower will maintain its dominant position in renewable energy sources (RES) for electricity generation for the near future. However, the use of wind energy will continue expanding and, in 2020 the wind electricity generation capacity will overcome the hydro sector in the EU-27 [1]. During the period 1993 to 2009, the world wind power installed capacity increased from 2900 MW to 157932 MW. In the EU-25, the total installed capacity reached 76185 MW, mostly concentrated in Germany, Spain and Denmark [2]. At the European Union level, the contribution of wind energy in electricity power generation is expected to grow over time, reaching 8.2% of total electricity production in 2030 [1].

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Portugal is no exception to the increase of wind energy for electricity generation, and the wind sector is growing rapidly. [3] even classified the 2006 growth of the Portuguese wind market as "spectacular", with more than 600 MW installed during the year corresponding to a 61% increase over the installed capacity at the beginning of the year. In 2009 the wind power share reached 21% of the total installed power, a value comparable to the ones obtained for leading countries like Denmark or Spain.

The main objective of this paper is to analyse the impact that increasing wind power scenarios may have on an electricity system like the Portuguese one, characterised by a mix of hydro, thermal and wind generation technologies. Based on an optimization model, feasible electricity generation plans are described and the cost and emission saving potential of wind power is evaluated.

II. The Integration of Wind Power on Power Systems

Renewable energies have in general much lower emissions than conventional thermal power plants, thus making them strongly favored by the environmental regulation for the energy sector. However, using technologies of variable output such as wind energy to produce electricity differs from generating electricity by conventional power plants. The fluctuations on wind power output occur in a random pattern and have to be compensated for by the production of schedulable, conventional capacities in the power system [4]. Because of this, wind power does not work as a simple fuel saver, since it cannot easily be controlled and accurately predicted [5]. Both the CO_2 abatement value and additional cost assigned to the system are highly dependent on the characteristics of the electricity system under analysis. As the [6] report underlines, the size and the inherent flexibility of the power system are crucial aspects determining the system's capability of accommodating a high amount of wind power.

Reference [7] concluded that wind power contributes to a reduction of final fuel usage and emissions but, at high penetration levels, an optimal system may require changes in the conventional capacity mix. Also [4] underline that an increasing scale of the fluctuations is a challenging phenomenon and the resulting effects cannot be ignored, neither in power system operation, nor in long-term energy expansion planning. Wind power variations will affect the scheduling of conventional power plants to an extent that depends on forecast as well as on the flexibility of the conventional power producers in the system area [6]. More recently, [8] research indicated that the wind potential in

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Germany will not allow a significant reduction of fossil capacities but the cost-saving potential for electricity production is quite significant. Reference [9] analyzed the impact of large amounts of wind power on the operation of the Belgian electricity generation system, concluding that significant amounts of emissions can be avoided. However, the possibility of forecast errors can lead to a reduction of the potential decrease of the operational costs.

In general, it seems that wind power can make an important contribution to the reduction of fuel consumption and to complying with environmental international commitments. However, the interconnection capacity, the existing generation capacity mix and the characteristics of the wind power system itself have a significant effect on how the variable production is assimilated into the system and on the extent of this contribution.

A.The Portuguese electricity generation system

At present, the Portuguese electricity generating system is basically a mixed hydrothermal system. The total installed power reached in 2009 about 16738 MW, distributed between thermal power plants (coal, fuel oil, natural gas and gas oil), hydro power plants and Special Regime Producers (SRP-renewable energy power plants and cogeneration). In addition, the Portuguese system is interconnected with Spain. In 2009, the total electricity consumption reached 52808 GWh [9]. Fig. 1 presents the general characteristics of the Portuguese electricity system in 2009 and the expected ones for 2019.

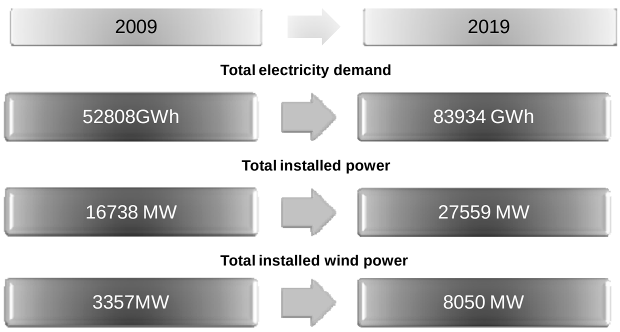

Fig. 1 The Portuguese electricity system in 2009 and 2019. Sources: Own elaboration from [10], [11] and [12].

The move towards renewable energy technologies is strongly stressed in the government policy for the sector and the response of the industry has been positive, in particular in regard to wind power. During the next decade, the structure of power generation is expected to change significantly in favor of renewable. Large hydro is still the dominant renewable energy resource in Portugal but wind power is closely following it and the RES development is mainly driven by the high growth rates of wind energy. At the end of 2009, the total wind power capacity reached a value close to 3357 MW, placing Portugal amongst the top European wind power producers. Forecasts for the sector clearly indicate that this trend will continue, with the installed wind power in Portugal expected to reach more than 8000 MW in less than a decade.

The specific characteristics of the Portuguese electricity system give rise to considerable challenges to the planner. Aspects such as a high dependency of the system on rainfall, the management of a diversified mix of technologies presently operating in the system, the expected impacts of the RES development, the increase in energy demand, and the regulatory environmental policies must be taken into consideration.

References [13] and [14] study on the quantification of the impacts that large wind power scenarios may have on the Portuguese thermal power system efficiency, concluded that, adding wind to the system may result in an increase of the electricity exports to Spain. The results also indicate that wind electricity generation is not expected to replace hydro power. This way, a clean energy form will not replace another RES and emissions free electricity production technology. The increase of the installed wind power would mainly affect combined cycle gas turbine (CCGT) operation. With the exception of the high growth wind scenarios, where a reduction on the number of operating hours for older coal groups could be expected, coal power production would remain stable with these plants operating near full load. In general, these results are consistent with the European Wind Integration Study [15]. According to this study a large increase in installed wind power in Portugal would result mainly in the reduction of gas power production but the coal power plants would remain almost unaffected.

Based on these results, an electricity power planning model was developed and tested in order to obtain optimal cost scenarios for the future, constrained by CO2 limits and taking into account the influence that increasing amounts of wind power may have on the operating conditions of CCGT, and consequentially on their efficiency.

III. The Electricity Planning Model

The aim of the electricity planning model is to determine the type of electricity generation technologies and their utilisation ratios that will best meet the goals of society. The model that will be described deals with the economic and environmental dimensions of the electricity planning problem.

The developed model was applied to the Portuguese electricity sector for a ten years planning period. A system close to the Portuguese one was modeled, taking into account the technologies currently being used, including: special regime producers, coal, natural gas, fuel oil and large hydro power plants. According to the expected future characteristics of the Portuguese system, the new technologies considered for addition included wind, coal and natural gas. A mixed integer non linear model was obtained, incorporating the impact of the

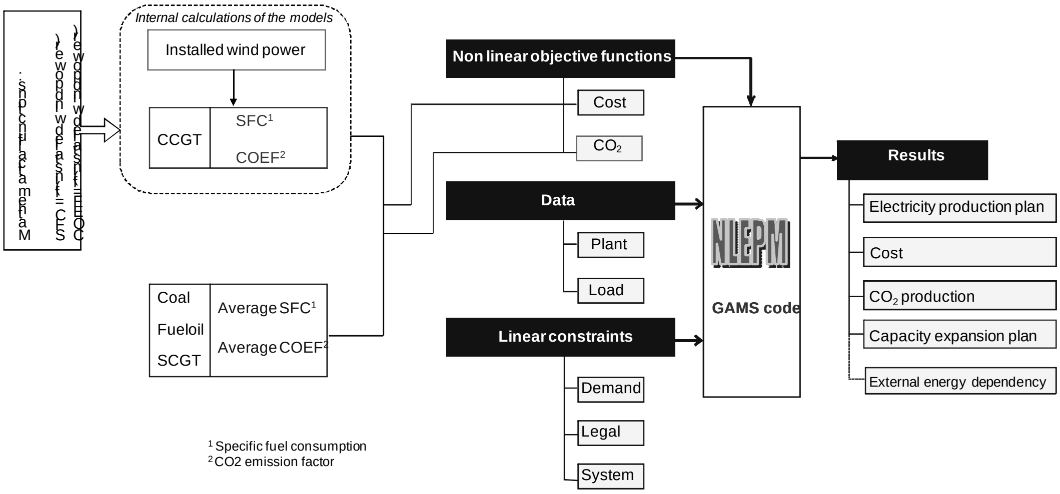

Fig. 2 Non linear electricity planning model (NLEPM)

increasing wind power on the performance of the thermal power plants (see Fig. 2).

This optimization model followed a structure close to the one described by [16] for resource planning models, adapted to the Portuguese case:

An economic objective: to minimize the capital costs and variable costs.

An environmental objective: to minimize emissions, measured by total CO_2 emissions.

A set of decision variables: loads carried by each electricity generation unit and installed power of each new power plant.

A set of constraints: capacity limitations, legal requirements and electricity supply needs.

A set of data: expected electricity demand for the planning period and technical and economic characteristics of the power plants in the system selected.

The bi-objective model was treated as a constrained single objective model. The cost function was the primary objective and the CO_2 function was treated as a constraint. Varying the CO_2 allowable levels turned possible obtaining a set of solutions representing trade-offs between cost and emissions. The obtained non linear electricity planning model (NLEPM) was written in a GAMS code and the Branch and Bound algorithm was used, calling BARON solver. A detailed description of the mathematical model formulation may be found in [14]

A. Results of the NLEPM

Fig. 3 graphically represents the set of optimal solutions, corresponding to cost vs. CO_2 trade-offs and close to optimum solutions that, although representing trade-offs between the two objectives, do not belong to the Pareto front of the original NLEPM. The two extreme points of the line obtained correspond to the extreme solutions, obtained with single objective optimization (minimum cost solution and minimum CO_2 solution). Table I summarizes the obtained results, describing the final configuration of the electricity system in 2017 along with the expected average cost and CO_2 emissions for some of the obtained points of the graph.

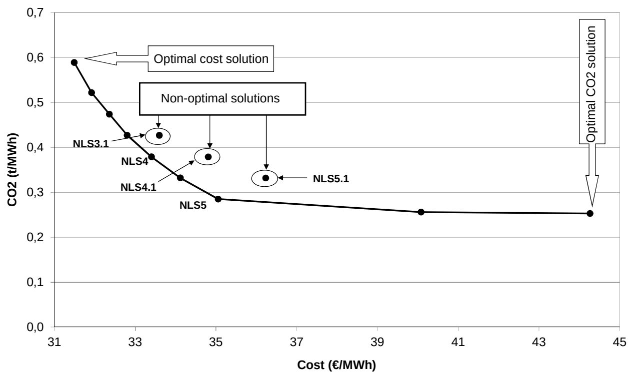

Fig. 3 Original Pareto solutions and additionally constrained solutions

The results obtained, indicate that the drop of CO_2 emissions per unit of cost falls deeply for highly environmentally constrained solutions. Between the optimal cost solution and the dashed line the cost per ton of CO_2 reduction is 12.6 €, a value obtained mainly due to the high environmental gains achieved with the substitution of coal power electricity generation by wind and CCGT production. After that, the ratio increases to 307.4 €/ton CO_2. For this range of the curve, the more pollutant plants are not producing any electricity anymore and the environmental gains may only be achieved by the installation of new CCGT and new wind power plants.

The initial effect of imposing increasing CO_2 constraints on the model is a reduction of the investment in new coal power plants, combined with the increase of investment in new onshore wind power plants and a small increase of investment in new CCGT. The following solutions present both a reduction on installed coal and wind power, and the integration of new CCGT into the system compensates this reduction and ensures the imposed CO_2 limits. The installed wind power will only present a more significant increase when very low CO_2 limits are imposed to the model, as in solution S4.

Imposing values for installed wind power beyond the original optimal solutions would affect the operating conditions of the system and the share of electricity supplied by each technology. In general, the electricity production from CCGT would be reduced but the share of electricity produced from both coal and wind power would increase. This new impositions lead to higher costs but, at the same time, contribute to the reduction of the external dependency and to the increase of the share of electricity produced from RES.

TABLE I
RESULTS FOR THE ORIGINAL PARETO AND CLOSE TO OPTIMUM SOLUTIONS IN 2017

		S1	S1a	S2	S2a	S3	S3a	S4
Observations		Pareto	$IP_{wind} \geq 6500$	Pareto	$IP_{wind} \geq 6500$	Pareto	$IP_{wind} \geq 6500$	Pareto
Total installed power (MW)	Coal (new)	900	2700		2400		600	
	Coal (existing)	1820	1820	1820	1820	1820	1820	1820
	Natural gas (new)	4030	1650	5040	1860	5110	3720	6830
	Natural gas (existing)	2916*	2916*	2916	2916*	2916*	2916*	2916*
	Wind (new)	3583	6500	3225	6514	3225	6500	4569
	Wind (existing)	1515	1515	1515	1515	1515	1515	1515
	Large hydro	5805	5805	5805	5805	5805	5805	5805
	NWSRP[a]	3245	3245	3245	3245	3245	3245	3245
	Total	23814	26151	23566	26075	23636	26121	26700
Contribution to electricity supply (%)	Coal (new)	8	26	0	23	0	5	0
	Coal (existing)	18	5	10	11	0	7	0
	Natural gas (new)	33	16	49	18	49	36	59
	Natural gas (existing)	1	6	1	2	11	4	0
	Wind	14	22	13	22	13	22	16
	Large hydro	15	14	16	13	16	15	14
	NWSRP	11	11	11	11	11	11	11
	Total	100	100	100	100	100	100	100
Share of RES (%)[b]		39	46	39	45	39	46	40
External dependency (%)[c]		65	57	65	58	65	57	53
Cost (€/MWh)		33.001	33.864	33.627	34.961	34.365	36.950	38.554
CO_2 (ton/MWh)		0.427	0.427	0.379	0.379	0.332	0.332	0.262
2017 electricity demand		85951						

*Includes 750 MW SCGT.
[a] NWSRP- Non wind special regime producers. Includes the production from cogeneration and renewable sources except wind and large hydro.
[b] Share of electricity consumption from RES. Large and small hydro power share corrected by the HPI (equal to 1.22) of the base year of Directive 2001/77/EC (1997).
[c] Proportion of energy used in meeting the demand for electricity that comes from imports.

IV. CONCLUSIONS

The expectations and incentives around the wind energy are comprehensible. Besides, being a renewable energy source, the expected development and the consequent reduction of the costs will turn this technology even economically attractive to the investors. Wind power presents the obvious advantage of having operational costs invulnerable to fuel and emissions markets volatility. This represents a clear advantage in an electricity system highly dependent on external energy sources as it is the case of Portugal. However, this research demonstrated that expansion of the wind technology in Portugal will influence significantly the energy system costs and emissions.

According to the results, the increasing penetration of wind power in the Portuguese electricity system will have significant effects on the CCGT operation and on the theoretically expected cost reduction and environmental gains. Not taking into account these effects will result in overestimation of the economic and environmental value of wind power.

As wind power capacity increases, the extra cost of part load operation of CCGT leads to an increase of their global operating costs. Due to this, the NLEPM penalizes the combination of wind and CCGT, favoring the coal-wind power mix in order to minimize costs. Nevertheless, the model results indicate that under the assumed conditions, the least expensive way to achieve the Kyoto protocol reference solution (S2) is the strong investment in new CCGT and the continuous investment in new wind power plants during the planning period.

The results indicate that for low CO_2 levels, the cost minimization should involve large CCGT investments and not necessarily maximize wind power in the system. However, solutions with higher wind penetration, although not optimal from the cost minimization point of view, might reduce external energy dependency with the country's security of supply, compensating for the cost increase. It seems, then, that exclusively relying on the cost aspect for decision making may be a too simplistic view for such a complex problem.

A previous study [17] analyzed the cost of the electricity generation options, based on private and external costs of generation in Portugal. However, these techniques used to study the generation alternatives, even when considering the externalities and avoided costs and emissions, tend to ignore the interaction between all the elements in the electricity system, which are fundamental for long range planning. The present study intends to go beyond the economic evaluation of the individual electricity generation options. The presented models allow dealing with a complex and dynamic model, recognizing that planning and operating decisions regarding one generation option should not be taken individually, because this will strongly affect the entire system.

The research project is now proceeding with the development of optimization models able to integrate the short term operational planning with the long range planning model. This is expected to make a contribution on properly dealing with the impact of renewable energy sources of variable output have on the electricity system management. This new approach creates additional complexity and must be supported by the development of robust optimization procedures that may deal not only with non linear mixed integer models fully characterizing mixed hydro-thermal-wind systems but also able to combine optimal decisions in different time frames plants. The analysis and quantification of the social acceptance of different electricity plans is also part of this ongoing research project (see [14]), as it is a fundamental aspect of the electricity planning process, with strong implications for the policy decision making and for the effective realization of the drawn plans.

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