Optimization models to support sustainable electricity planning decisions

Sérgio Pereira

Paula Ferreira

A. Ismael Vaz

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Sérgio Pereira[†]   Paula Ferreira[‡]   A. I. F. Vaz[§]

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Abstract

Over the last decades, models and concepts related to sustainable electricity planning decisions have been changed according to the society, energy policy objectives and concerns. New and clean energy technologies are emerging as major contributors for the achievement of a set of imposed goals, being the energy efficiency combined with renewable energy sources (RES) a key strategy for a sustainable future. Power planning based on optimization models plays an important role for, not only electricity industry decision making process, but also for all processes where complex decision must be made. Following the idea of sustainability combined with the emergence of RES, this study aims to present an on-going research project that involves the development of a set of mathematical models to be used on the electricity planning. Assuming a time period of 10 years and through scenario analysis, the expected impacts in terms of costs and CO_2 emissions were evaluated. The behavior of system when coal and gas fuel price varies is observed. The results put evidence the significant wind power and hydro power impacts on the electricity sector performance and demonstrate importance of these technologies to achieve the European Union goals for the sector.

Keywords: Energy decision making, electricity generation

1 Introduction

The 20-20-20 targets are an example of how objectives changed envisaging now to combat climate changes and to increase the European Union energy security and competitiveness. These targets also contribute to reach a high energy-efficient and a low carbon economy at the European level. Because of that, new and clean energy technologies are emerging as major contributors for the achievement of these set of goals. Energy efficiency combined with RES is then a key strategy for a sustainable future.

Power planning based on optimization models plays an important role for, not only electricity industry decision making process, but also for all processes where complex decision must be made. The paradigm of power planning where only economic interests were taken in consideration, is now overcame. The diversity of available technologies to produce electricity along with the social and environmental arguments turn the task of decision makers more difficult turning the planning based on optimization models an essential tool. Moreover, the importance of these models for generation expansion planning is well addressed in literature. To Pereira and Saraiva (2010), generation expansion planning allows to identify the most adequate technology and expansion size taking into account economic criteria, ensuring at same time that the installed capacity follows the expected technical, sustainable and policy concerns. Also Meza et al. (2009), consider that generation expansion planning aims to determine the best solution for future generation utilities taking into consideration that minimum mistake will result in a loss of a large amount of money and that society welfare concerns must be taken into account in the way that demand must be met to avoid social costs. To Tekiner et al. (2009), the main concern of generation expansion planning is to find the least cost expansion plan according to the characteristics of each electricity system.

Although a great importance is given to the economic aspect of generation expansion planning, it is interesting to observe an increase of environmental concerns over the last years. To Li et al. (2010), beside the economical aspect, optimization tool can be extremely useful to solve decision maker's problems where environmental issues are considered. Also Figueira et al. (2005) encompass on their study both the importance of the economic dimension of the energy decisions and the minimization of environmental impacts. Cai et al. (2009) enhance the environmental aspects latent on the electricity decision making. On the authors study, these concerns and others like fossil fuel increasing prices, reliability and security of supply are seen as on-going challenges faced by decision makers around the entire world.

However, nowadays power planning models start to be more complexes than in past decades. This is largely due to the diversity and increasing of power RES generation technologies, especially those with variable output. Also, the liberalization trend of electricity markets and the increasing decentralization of electricity production systems create additional needs to traditional planning models. Given this, the analyses of the effects of RES in traditional electricity power plants operating performance, is frequently addressed or included as an important factor to be considered in generation expansion planning optimization models. Works like Holttinen and Pedersen (2003), Kamalinia and Shahidehpour

(2010), Rosen et al. (2007) or Isaac et al. (2010) among many others addressed the impact of large-scale wind power on thermal power system operation, on additional reserve needs and on the importations-exportations balance. These works demonstrate the need to properly take into account these expected impacts of the increasing installed wind power during the formulation of the electricity generation planning models.

Following literature concerns described above, this paper aims to study the impacts that large hydropower plants and wind power plants have on electricity sector, considering fluctuations of coal and gas fuel prices.

The remaining sections of this paper are structured as follows: section 2 presents the dataset and the proposed electricity planning model, section 3 describes and analysis the cost and emissions results of the proposed model and section 4 presents the conclusions.

2   DATASET AND MODEL

2.1   Electricity Sector in Portugal

Considering the growth of human lifestyle that is seen nowadays, an increased in power demand is being expected. Portugal is no exception and according REN 2008 report, until 2019 is expected an increasing of the power demand and peak load at a medium rate of 4.4%. However, a more recent REN report (REN (2011)) shows that from 2009 to 2010, the Portuguese electricity consumption have suffer an increasing of 4.7% from 49873 to 52205 GWh.

Portuguese Decree-Law n° 29/2006 of March 15 established the organization and operation of the Portuguese electricity sector. The electricity production activities may be classified in two different regimes: The ordinary regime production (OPR) and the special regime production (SRP) The special regime corresponds to the production of electricity based on cogeneration and endogenous and renewable energy sources supported mainly by feed in tariffs. On the other hand, the ordinary regime corresponds to the traditional centralized power plants such as the large thermal and hydropower groups. In 2010, with a total production of 32169 GWh, ordinary regime production contributed to about 62% of total production. From ordinary regime almost half of it, 46%, was provided from hydro power and the remaining come from traditional large thermal power plants, 54% (REN (2011)). Special regime production, which encompasses essentially the wind power, is coming to increasing. This can be proven with the increase of 24% from 2009 to 2010, which comprise a share of 34% of total production in 2010.

It is notorious that Portuguese power generation electricity system comprises mainly a mix of hydrothermal system complemented by an increasing share of wind power. With a total installed power of 7407 MW, thermal power units are still the largest source of electricity generation. This thermal power generation is provided essentially by coal, gas and fuel oil power units, each one with specific operation characteristics. Thermal power units like coal power stations, because of its lower flexibility as well as its lower operation price, tend to be the major source of electricity production operating several times as base

load security. One the other hand combined cycle gas turbines despite its higher fuel prices are characterized by its lower emissions and its higher flexibility, and so usually used to cover peak load situations (Frayer and Uludere (2001)). Despite of this, power production originated from large thermal power plants have been decreasing. A reduction of 27% was seen from 2009 to 2010 where fuel oil and coal were the most affected with a reduction of 88% and 45% respectively, while gas presented only a reduction of 7%. In on one hand this may be explained by the need to mitigate Greenhouse gas (GHG), leading to strong investment in new and clean energy sources and the decommissioning of the oldest and more pollutant units, on the other hand 2010 was a wet year favoring the hydropower production rather the thermal power. The privileged geographical position of Portugal is essential for the new investments in what concerns RES. Hydropower production provided from large dams and run-of-river units is a perfect example of that. With a total installed power of 4578 MW, hydro power production increased 88% comparatively to 2009, contributing to 28% of total consumption in 2010. This significant production increase was related to an high Hydraulic Productivity Index (HPI), about 1.3, that was verified during 2010. This was a rainy year and HPI reached a value unseen since 2003 (REN (2011)). To take advantage of this potential, in 2007 the national dams plan with high hydraulic potential (PNBEPH) was published (INAG (2007)). Among others measures, reinforcement of existing hydropower units as well as the investment in new ones is considered. Until 2020, a total installed power of 7000 MW is expected to be operational. This value corresponds to 70% of Portuguese potential and an increase of approximately 53% from the current values.

Besides the Portuguese geographical characteristics and the mitigation of GHG emissions objective, the large dependency from other countries to as well as the economic boost for the country is seen by the Portuguese government as important reasons to invest in new and clean technologies. In 2007, energy importations reached 82,9% of the total energy consumption and only the production of renewable energy sources contributed to the reduction of external dependency (DGEG website). However, in 2010 the energy importations reduced by 23% comparatively to 2009. On the other hand, exportations have increase 108%. This can be seen as a reflection of the effort of Portugal to meet European Commission directives and Kyoto protocol in an attempt to mitigate the environmental issues and also due to the fact of 2010 has been a rainy year which contributed to a higher hydropower production. A necessary increase in the investment on new power sources, especially wind power, is so being noted. Only in 2010, about half of total SRP production was provided from wind power sources which represent an increase of 20% in relation to 2009. This production corresponds to a total installed power of 3702 MW (INAG (2007)) that is been increasing during the last years as shown in the plot of Figure 1.

However, wind installed power is still far away from the potential offered by Portuguese wind potential. According to Ministry of Economy, Innovation and Development (MEID), until 2020 a total installed power of 8500 MW is expected. This value takes already into account a set of factors such as power demand evolution and technical and economic viability of offshore technology. According to Portuguese government targets for 2020, 60% of total electricity production will come from RES, instead of the 45% projected to 2010.
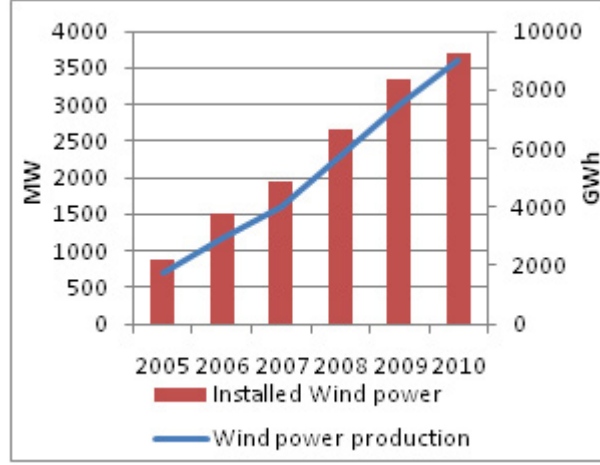
Figure 1: Wind power evolution in Portugal (source: own elaboration from REN data)

The evolution of electricity sector in Portugal during the last years, as well as the existing future investments projects, reflects the government policy aiming to reach European Union target on emissions reductions, contributing also to the reduction of external energy dependency and to the growth of Portuguese economy.

2.2 Generation Expansion Planning Model

The non-renewable characteristic of fossil fuels and the continuous exploitation of this kind of resources by human kind, together with the policy instability noted worldwide during the past years, caused essentially due to oil interests, are related with the continuous upswing of fuel prices. Besides of that, the increase of environmental concerns is nowadays in focus. The presented model aims to minimize the total costs and emissions of future power generation units.

$$\sum_{t \in T} \sum_{n \in N} \left[\left(Ic_n \frac{j(1+j)^{lt_n}}{(1+j)^{lt_n} - 1} + CFOM_n \right) Ip_{n,t}(1+j)^{-t} \right] +$$

$$\sum_{t \in T} \sum_{m \in M} \sum_{i \in I} \left[(CVOM_i + F_i + Cp_i + EC \times CO_{2_i}) P_{i,m,t} \Delta_m (1+j)^{-t} \right], \quad (1)$$

$$\sum_{t \in T} \sum_{m \in M} \sum_{i \in I} CO_{2_i} P_{i,m,t} \Delta_m. \quad (2)$$

Equations 1 and 2 presented above are the objective functions of the proposed model, aiming to minimize both values. Equation 1 represents the total costs of generation expansion planning while equation 2 represents the total emissions amount, measured by the CO_2 value. A set of equations referred to model constraints are also used, taking into

account, important assumptions on demand requirements, technical characteristics and political concerns. A full description of the model may be found in Pereira et al. (2011).

The dataset for plants description and demand growth forecast was obtained on the literature, essential from REN (data), and Ferreira (2008)

The model was calculated for a scenario considering coal and gas prices evolution during the forecast period in order to allow the comparison with the same case study of Pereira et al. (2011) where no evolution on fuel prices was considered. International Energy Agency (OECD/IEA (2010)), forecast until 2020 an annual growth rate of 1,33% and -1,21% for gas and coal respectively. According to IEA (OECD/IEA (2010), the decline seen on coal prices rate is due to the competition between coal supplies that may lead to a significant increase on productivity in coal mining, resulting also in cost reduction. On the other hand IEA also believes that given world hard coal reserves, 729 billion tonnes, very high prices will not last (OECD/IEA (2010)).

The next section presents the results and discussion of model solution taking into consideration Portuguese electricity sector characteristics and IEA (2010) perspectives for gas and coal prices evolution.

3   RESULTS AND DISCUSSION

The plot shown in Figure 2 represents the Pareto curve results for the specific study considering the case of coal and gas variable fuel prices, obtained after all model simulation ($R0$ to $R9$). Simulation $R0$ refers to the optimal cost solution while simulation $R9$ to optimal emission solution. The other simulations are related with intermediate values of CO_2 between optimal cost and optimal emission solutions. For this particular case of study, Pareto curve represents the trade-off between costs in €/MWh and the CO_2 (t/MWh) originated from power production.
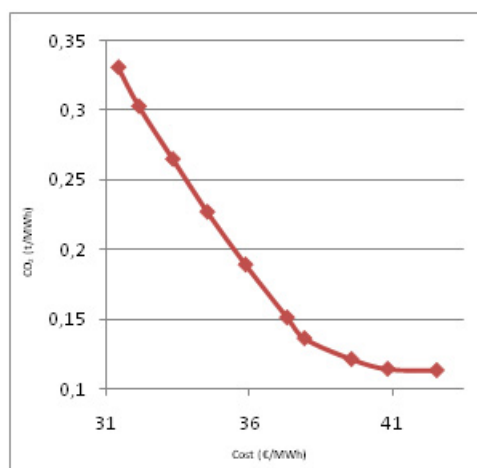

Figure 2: Pareto curve of model

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The non-linearity of the system trade-off is visible in the Pareto curve. As the CO_2 get more restrictive values, the cost of operation and investment in power system will be higher. Note that for values up to 37.425 €/MWh the curve slope is much higher which means that the cost is increasing in an acceptable way since the amount of CO_2 reduction is significant. On the other hand, for values higher than 37.425 €/MWh, a substantial increase of cost is observed for an insignificant decrease of CO_2 emissions. Comparing with Pareto curve of Pereira et al, 2011, where coal and gas fuel prices were assumed as constants, differences in new power plants assigned to each solution, although slightly, were obtained. For the optimal cost solution simulation ($R0$), lower cost where obtained, for the variable coal and gas price scenario under analysis. If no emissions limits are imposed or any environmental concerns are taken into account, the model converges mainly to the investment in new and less expensive coal power plants. This is even more evident when the coal price is assumed has being decreasing during the analyzed period. On the other hand, for the optimal emission solution simulation ($R9$), higher costs were obtained compared with Pereira et al. (2011). The decommissioning of old coal power plants assumed by model, based on REN (2008)), the non-investment in new coal power plants and the investment in CCGT units considered to be less pollutant but more expensive, were the reason for this increase. Besides that, the investment in new and cleaner power units such as wind power plants, characterized by its higher investment costs, contributed to the increasing of costs. Table 1shows all the results addressed above.

Table 2 at appendix presents the production of all considered power units for the year 2020 for the variable fuel prices scenario. Comparing both scenarios, the increase of coal power units' production when fuel prices were considered variable is evident. This is essentially because of the negative rate growth of coal price considered for this study. It is also important to refer that coal power unit's production is verified only for solution cases $R0$ to $R3$, mainly because of the low emissions targets imposed. Comparing the existent coal and gas power units' production the significant amount of coal unit's production over CCGT units when no emission limits was considered is also noticeable. Besides that, is possible to observe the decrease of coal production and the increasing of CCGT production as more environmental ambitious measures are imposed to the model.

The achievement of environmental targets is only possible with the investment in new clean technologies. However this investment has higher cost. The plot shown in Figure 3in appendix represents the wind power cost influence when different values of installed power were considered. In the specific $R2$ simulation case, values of 1300 MW, 1500 MW, 2000 MW, 3600 MW and 4000 MW were imposed to new onshore wind installed power. For the first three cases higher investment cost were obtained due to the need to resource to the much more expensive offshore wind power plants.

In addition to the targets achievement, the investments in renewable technologies also allow to reduce the external energy dependency of the electricity system. From the results, comparing with the results presented in Pereira et al. (2011), small changes were obtained. These results were basically caused by the considerations used on fuel prices and consisted on an increase of coal power production in detriment of gas production. An increase on new coal power units' production was seen and consequently the production of old gas

power units has decrease once no new gas power plants were installed. The others power units' production variations were obtained mostly because of modeling considerations.

4 CONCLUSIONS AND FURTHER RESEARCH

This paper follows the same model addressed in Pereira et al. (2011) for the optimization of electricity planning and in particular for the generation expansion planning. A deterministic programming model is presented aiming to support the long term strategic decision and taking into account the need to reconcile economic and environmental objectives. A case study close to the Portuguese electricity system was addressed, characterized mainly by a mixed hydro-thermal-wind power system where coal and gas fuel prices are assumed as variable during the entire planning period. The results indicate that as the CO_2 objectives become more restrictive, in general the least expensive way to comply with this restriction is the replacement of coal by CCGT and wind power production. On the other hand, considering no CO_2 restrictions coal power units will be the main power sources, with an increase on installed power and a significant increase in the production. Wind power contribution only increases significantly for highly environmentally constrained solutions. In what concerns hydropower, the influence of this energy source on the RES share is evident and noted for all scenario simulation results

Imposing to the models fixed values of new installed wind power lead to different scenarios that, although not being optimal Pareto solutions, may be interesting from the strategic decision makers' perspective. These solutions ensure the required CO_2 levels at a higher cost but contribute to the reduction of the external energy dependency of the country and the increase of RES share in the electricity balance. For this particular case study, comparing with the one seen in Pereira et al. (2011), slight changes in RES share and consequently energy dependency were noted. However, even with slight changes on results, these were seen principally on gas and coal production and installed power. The increase of coal installed power replacing gas may be easily explained by the coal reduction price and the assumed increase of gas price verified. It is also important to refer that the consideration of a possible increase on coal fuel price was not forgotten and it is seen as a consideration to be taken into account for future work analysis.

The presented models demonstrated that long term planning decisions regarding one generation option should not be taken individually, because this will affect the entire system equilibrium. Future work will address the need to combine long term energy expansion strategies with the results of short terms operations decisions of the system, recognizing the impact that the hydro-wind power combination strategies may have on the efficiency of thermal power plants. For this, new and complementary optimization models will be developed and presented.

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5   Appendix

Table 1: Comparison of evolution of installed power, cost and CO_2 emissions in year 2020

	R0		R9	
Installed power in 2020 (MW), base scenario (Pereira et al., 2011)				
Coal	4350		–	
Gas	–		6422	
Installed power in 2020 (MW), variable coal and gas fuel prices scenario				
Coal	4659		–	
Gas	–		6441	
	Cost (M€)	CO_2 (Mton)	Cost (€/MWh)	CO_2 (ton/MWh)
	Base scenario (Pereira et al., 2011)			
Optimal cost solution (R0)	20526	218	31.095	0.33
Optimal emission solution (R9)	27307	74	41.367	0.113
	Variable coal and gas fuel prices scenario			
Optimal cost solution (R0)	20402	219	30.907	0.331
Optimal emission solution (R9)	27767	74	42.064	0.113

Table 2: Contribution of electricity generation in 2020, variable Coal and Gas fuel prices scenario

	R0	R1	R2	R3	R4	R5	R6	R7	R8	R9
Coal (n)	44.4	35.5	13.3	0	0	0	0	0	0	0
Coal (e)	4.2	5.2	5.2	5.2	0	0	0	0	0	0
Gas (n)	0	0	23.1	36.7	41	41	41	40.1	40.7	39.4
Gas (e)	0.3	3.9	2.7	2.4	3.5	3.5	3.5	2	0.3	0
Wind (n)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	11.7	14.2	14.5
Wind (e)	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
Hydro (n)	17.4	22.4	18.6	18.9	19.9	21.5	17.4	18.5	18	21
Hydro (e)	8.7	8	12	11.8	10.5	9	13.1	10.1	9.3	7.7
SRP	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
S. RES[1]	47.9	52.3	52.5	52.5	52.4	52.4	52.4	54.7	55.8	57.5
E. dep.[2]	52.1	47.7	47.5	47.5	47.6	47.6	47.6	45.3	44.2	42.5

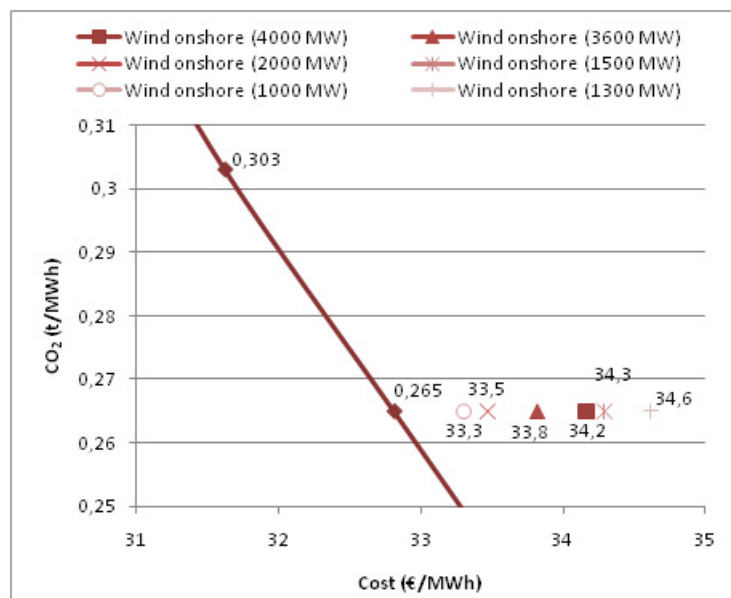[1]Assuming that 3.15% is renewable energy from SRP;

[2]Assuming that 3.15% is non-renewable energy from SRP;

Figure 3: Wind power price influence