# Risk analysis of fuel and $CO_2$ prices volatility in electricity generation expansion planning

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## Abstract

In the present days of continuing electrical power sector liberalization, generation companies must face difficult challenges, including new investment decisions, with very little knowledge of the future environment. Regulatory changes as well as fuel and $CO_2$ prices evolution may change dramatically the situation for plants of specific technologies.

This paper analyses the risk involved in different electricity generation expansion plans due to changes in long-term prices. A general methodology that allows making numerical comparisons between different mixes of generation technologies is introduced. Guidelines to solve each detail of the methodology and a study following them are presented.

In the study, several expansion plans based on different technologies are considered facing different fuel and $CO_2$ price scenarios. A model based in an equilibrium approach is used to determine the market clearing. The average and the standard deviation of the total generation costs, computed as net present cost and considering the probabilities of each price scenario, are the proposed indicators to compare the behaviour of the different expansion plans.

## Keywords

Electricity generation expansion, risk analysis, power generation investments, fuel prices, carbon prices.

## 1. Introduction

Deregulation and privatisation of the power generation sector has been accomplished throughout the world during last years. In this context, strategic decisions like building new power plants are not taken in a centralised way any longer. The companies must take their own decisions considering a large number of involved risks [1].

New investments are particularly exposed to high levels of uncertainty, because in the long-term, regulatory changes as well as different fuel and $CO_2$ prices evolutions can take place. The regulator should build a suitable framework to ensure energy supply at the lowest cost for the society, encouraging companies in order to achieve objectives like reasonable reliability levels, adequate use of clean generation and a solid technologies portfolio against prices uncertainty. The present study is focused on this last point, selecting a portfolio with reasonable average and low volatility costs.

Generation companies usually have a high level of risk aversion and their most common behaviour is to chose technologies with short building periods and fast investment recovery. For this reason, the combined cycle (CCGT) is the most popular technology right now, as it seems to comply with both requirements. However, if gas prices keep their present escalating trend, a generation mix dominated by CCGT power plants may give rise to high generation costs and therefore high electricity prices. Besides, some of the main natural gas deposits and the pipelines required for transportation are located in countries without a high level of political stability, what implies uncertainty in the supply. Moreover, difficulties in the storage of this fuel at large scale, makes hedging against price fluctuations not an easy task. For all these reasons a generation park very dependant on gas prices could be a risky election.

Other technologies could be considered for expansion as coal, wind or even nuclear. Being conservative, a coal option can be taken, considering that it is a more stable price fuel, but again price risk must be considered. In this case, the risk of high $CO_2$ emission right prices, which affects directly to the coal generation costs, may compromise this choice. Although wind technologies still have a high degree of dependence from subsidies, premiums or other kind of helps to compensate their higher costs, their independence of fuel and $CO_2$ prices should be taken into account in the design of a solid expansion plan. Finally, at first sight, a very controversial technology as nuclear power also has a good behaviour against fuel and $CO_2$ price changes, as it is stated in [2]. Nuclear plants have no $CO_2$ emissions because no combustion process is required for their operation. Besides, nuclear fuel seems to be less exposed to remarkable price changes. However, nuclear power prices should include the costs of externalities not considered now, like nuclear waste management or plant dismantling. Adding this as extra fixed costs, the cost advantage of nuclear power plants would not be so evident. In short, it seems undoubtedly that fossil fuel and emission right prices can have a relevant influence in the total generation costs, and so they should be considered when building expansion plans.

This paper proposes an analysis based on the study of the average and variance of the net present total generation costs (NPC), as a tool for the regulator to select the most appropriate expansion plan to achieve a solid generation portfolio against fuel and $CO_2$ price fluctuations. Finding the correct incentives to encourage companies to follow this investment plan is a different issue that would not be treated in this paper. The companies can also obtain some helpful information from this study about the risk of expansion plans based on certain technologies and consider the most suitable investment plan for them, according to its risk aversion level.

In the first part of section 2 the main characteristics of the methodology proposed are presented. Some details on how each step of the study can be carried out and the chosen solutions, hypothesis and simplifications considered for the case study, are described later. In sections 3 and 4 more details about the most singular steps of the methodology are given. The case study is presented in detail in section 5. Finally, some conclusions are stated in section 6.

## 2. Methodology description

The proposed methodology and the guidelines presented allow the regulator to study different expansion plans in order to select a group of them with reasonable reserve margins, and a solid behaviour against fuel and $CO_2$ prices volatility.

The methodology consists of the following steps:

1) Identify a number of possible scenarios with different fuel and $CO_2$ price evolutions, determining the probability of each one.
2) According to the desired reserve margin, the forecast demand, the existing capacity at the beginning of the study, the power plant closures and the hydro and wind plants contribution, determine the new capacity to be added each year.
3) With the information of the previous point, select a number of expansion plans to be studied, characterised by the number and technology of the plants to be added each year.
4) Simulate the clearing market process for the whole temporal horizon to determine the production of each plant and therefore the total generation costs and electricity prices.
5) Analyse the obtained results in terms of average and variance of the net present cost, considering the probabilities of each price scenario.
6) Select a group of expansion plans with better results against fuel and $CO_2$ price volatility.

Identifying a certain group of price scenarios (step 1) can be carried out in several ways. The method proposed in this paper can be divided in three phases. First, generate a large number of possible scenarios, based on historic prices and all other information that could be considered relevant. Then, determine a finite number of scenarios that represent the different cases to be studied. This task can be carried out by selecting some of the generated scenarios or even creating the representatives from the generated ones, as in the present study. See section 3 for a detailed explanation of a proposed solution to solve these two phases. Finally the probability of each selected prices scenario must be calculated, considering the possible correlation between certain fuels and/or $CO_2$ emission right prices (see section 4 for more details). Months are assumed to be a reasonable time period for describing the price scenarios.

While deciding suitable expansion plans for the study (steps 2 and 3), the regulator should take into account the technologies available considering its possible development, fuel availability and all the particular circumstances of its particular case. Geographical characteristics, native fuels and other local aspects can influence the possible plans. Mainly, the decision to be made is the development desired for each technology, what can be expressed in terms of percentage of the new annual capacity corresponding to each technology. A possible solution to select the expansion plans for the analysis may be the one used in the study case, which consists of taking one expansion plan per technology considered. Each plan would be based on that technology although, taking into account its possible restrictions, it could be necessary to include other kind of plants to draw up a feasible plan. Whatever solution is adopted, yearly detailed data seems to be appropriated. Both time periods, years for expansion plans and months for price variations, are not a restriction of the methodology. Different periods can be adopted; however, these ones have been selected, instead of generic ones, in order to simplify the notation in the explanation.

Having the percentages of the different technologies considered, the capacity to be installed each year (or the period considered) is the data required to complete the expansion plans. The first action is to decide the reserve margin ($RM^y$) desired for each year. The available capacity, considering load factors ($lf$) of each plant, divided by the peak demand of the year ($Dmax^y$) must be equal to this reserve margin. The new capacity to be added each year can be obtain from the next equation.

$$RM^y = \frac{\sum_{g=1}^{G(y-1)} P_g \cdot lf_g + NNP^y}{Dmax^y} \tag{1}$$

In (1) $g$ is the index of the generators, $G(y-1)$ represents the total number of existing generators in the year before ($y-1$) and $NNP^y$ the net new power to be installed in this year ($y$). The installed capacity and load factor of the existing plants is assumed to be known. For the new ones, a standard capacity per plant ($P^{std}$) and load factor ($lf^{std}$) can be assumed for each technology (*tec*). Taking into account these standard capacities and also, that only an integer number of plants ($n$) can be built (only wind technology is considered to grow up in any number of MW per year, $P^y_{wind}$), the expansion plan must follow expression (2), where $T$ represents the total number of technologies considered for the expansion plan except for the wind.

$$\sum_{tec=1}^{T} n^y_{tec} \cdot P^{std}_{tec} \cdot lf^{std}_{tec} + P^y_{wind} \cdot lf_{wind} \approx NNP^y \qquad (2)$$

The next step is to simulate the wholesale electricity market (step 4) to evaluate the prices and, what is more important for this study, the production of each plant in order to calculate the total generation costs. A market equilibrium approach like the one presented in [3] may be used to carry out this step. The scenarios selected in step 1 are used here to determine the variable cost of the thermal plants according to its fuel and its $CO_2$ emissions rate. Therefore, thermal plant bids would change month by month (if that was the period time selected for step 1) and from one scenario to another. In other words, the merit order of the different thermal technologies could change along the study temporary horizon or from one scenario to another because of the different evolution in their variable costs. Calculating the total generation costs, which is the objective of this step, fixed and investment costs must be added to the variable costs obtained from the clearing market process. Finally, a discount rate must be chosen to compute the NPC in each case.

The proposed indexes to evaluate a good technology expansion plan (step 5) are the average and variance of the net present total generation cost, although a glance at the market prices is also interesting. Calculating NPC or electricity price average and standard deviation, the probability of each scenario price must be included and therefore, the NPC and electricity prices of the most probable scenarios will have larger weight than the less probable ones.

Finally a group of expansion plans with low total costs (low average) and a good behaviour against fuel and $CO_2$ price volatility (low variance) must be selected (step 6). Obviously there are other aspects to be considered by the regulator for choosing the most appropriate expansion plan. Regarding this subject, the group of plans selected with this methodology could be a good starting point for further analysis of those other aspects.

## 3. Price scenario building

As it has been said, many ways of building the study price scenarios can be considered. A relatively simple method is proposed in this paper, taking into account the difficulty of finding very precise ones for long temporary horizons. Following the guidelines given in the previous section, the first thing to do is generating a large number of possible scenarios and then, selecting representatives.

There are generally two strategies to generate prices forecasts. The first one relies on the analysis of the fundamentals, that is, the variables that drive the price evolution. In this particular case, that would be tantamount to simulate the future evolution of world energy economy. This is a very ambitious task that, nevertheless, is pursued by some entities as the IEA. The second one is based on the statistical analysis of historical price series. A serious limitation is that the history of gas market prices is not very long when considering a 20 or 30 years timeframe for the study. Therefore, it is not expected to be very representative of the long-term future. Difficulties with CO2 time series are, of course, much more serious.

Given this difficulties, a quite simple statistical price model have been chosen. Probably, a simple model with few parameters with clear meaning can provide a more robust representation of the involved uncertainties that a more sophisticated one [4]. There is a possible miss of reliable in a price forecast made with this kind of model and with short series of data. However, as the intention of this study is to look for robust expansion plans, this miss may be addressed by considering different scenarios generated with the proposed model.

So, a huge number of fuel and $CO_2$ prices scenarios (“random scenarios”) are generated. Then, as a high time-consuming system simulation is performed for each case, a representative selection of scenarios must be chosen. With the proposed methodology, the “global price scenarios” are given by combining all the fuel and $CO_2$ representatives. To reduce the number of cases, an acceptable hypothesis consist of taking into account only the fuels with the most unpredictable long-term price behaviour. Regarding this, nuclear fuel can be considered fairly constant. Higher variations can be observed in coal prices but still small comparing with oil or natural gas. The decision of not considering variations in coal prices is also supported by the possibility of keeping large storages of this fuel relatively easily, as no special container or location is needed. Considering a low percentage of biomass or other less common fuels in the generation mix, there are only two fuels that can’t be ignored for this topic: natural gas and fuel-oil or other oil derivatives. Considering the existing correlation between oil and natural gas prices, one fuel can be taken as reference for all of them. The frequent delay of the natural gas following oil evolution can be introduced when translating fuel prices to variable costs of the plants in each period of time. Notice that from this point, “fuel price” would be used to refer to the reference price, oil or gas. Finally, considering just two elements in the design of the global scenarios, the selected fuel price and the $CO_2$ price, the probabilities of these scenarios can be evaluated as it is explained in the next section.

To generate the random scenarios for the fuel and the $CO_2$, a simple but widely accepted model is assumed where prices of each month ($p_i$) – remember other time periods can be valid too – only depends on the price in the month before ($p_{i-1}$) and a noise factor. The particularization of this sort of models used in this case is the normal model, represented by (3), where the price in one month is evaluated as the price in the month before plus a noise ($u_i$). The noise is supposed to be Gaussian what means that it follows a normal distribution. Historic prices can be used to determine the average ($\mu$) and standard deviation ($\sigma$) of that normal distribution.

$$\begin{aligned} p_i &= p_{i-1} + u_i \\ u &\to N\left(\mu_{hist}, \sigma_{hist}\right) \end{aligned} \tag{3}$$

After generating a large number of random scenarios following the model introduced, the selection of representatives is the next phase. Although sophisticated methods as clustering techniques can be used to carry out the selection, again a simple method is proposed. It consists of generating the representative scenarios by taking for each month the price of the random scenario which exceeds a certain number of other random prices for the same month. In other words, the key is to sort out the prices given by the random scenarios month by month (therefore the original random scenario of each price would be never known again) and take for the representatives the prices located in certain positions. To give an example, a possible choice could be considering the prices in the 20th, 50th and 80th position as representatives of low, medium and high prices. Of course, any other reasonable choice could be valid too. Obviously those representatives have lower variance than any of the original ones, but this misrepresentation can be assumed as long as the objective of the study is to compare total cost variance against different prices scenarios, but not variance along the time.

## 4. Probability of price scenarios

No matter what method has been used for selecting the price scenarios, clustering techniques, the proposed one or any other, if global scenarios come from combining fuel representatives with CO2 representatives, the probability of each global scenario can not be evaluated as the product of both representatives probability. The correlation factor between both price series, which seems to be not null, must be considered. When aggregating the results of the study a probability that depends on this correlation must be given to each global scenario.

The probability of each scenario is based on the normal distribution expression. If $X$ is a random variable that follows a normal distribution of average $\mu$ and standard deviation $\sigma$, (4) is the density function.

$$X \sim \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}} \tag{4}$$

Considering this expression, the probability ($\omega_i$) of any pair of fuel and $CO_2$ price increments ($u$) for a certain moment ($\overline{u}_i$ represents the pair of $u^{FUEL}$ and $u^{CO2}$ in the moment $i$), taking into account their correlation, can be expressed as (5) where $t$ means transposed matrix. The correlation factor between fuel and $CO_2$ price increments month to month, is represented by $\rho$. The average growing (month to month) of each price is represented by $\mu^{FUEL}$ and $\mu^{CO2}$ and finally $\sigma_{FUEL}$ and $\sigma_{CO2}$ represent the standard deviation of the increments of fuel and $CO_2$ prices. $\Sigma$ is the covariance matrix considering the correlation and $\Sigma^*$ is the covariance matrix without considering the correlation.

$$\begin{aligned} \omega(\overline{u}_i) &= \frac{1}{\sqrt{1-\rho^2}} \cdot e^{-\frac{1}{2}(Q-Q^*)} \\ Q &= (\overline{u}_i - \overline{\mu})^t \, \Sigma^{-1} \, (\overline{u}_i - \overline{\mu}) \\ Q^* &= (\overline{u}_i - \overline{\mu})^t \, \Sigma^{*-1} \, (\overline{u}_i - \overline{\mu}) \\ \overline{u}_i &= \begin{bmatrix} u^{FUEL} \\ u^{CO_2} \end{bmatrix}_i \\ \overline{\mu} &= \begin{bmatrix} \mu^{FUEL} \\ \mu^{CO_2} \end{bmatrix} \\ \Sigma &= \begin{bmatrix} \sigma_{FUEL}^2 & \rho\sigma_{FUEL}\sigma_{CO_2} \\ \rho\sigma_{FUEL}\sigma_{CO_2} & \sigma_{CO_2}^2 \end{bmatrix} \\ \Sigma^* &= \begin{bmatrix} \sigma_{FUEL}^2 & 0 \\ 0 & \sigma_{CO_2}^2 \end{bmatrix} \end{aligned} \tag{5}$$

As a finite number of random scenarios have been generated, the weight ($w_i$) to consider for any pair should be calculated as in (6), dividing the probability of the pair by the sum of the probabilities of all pairs for that time period, in order to achieve that the sum of weights be one.

$$w(\overline{u}_i) = \frac{\omega(\overline{u}_i)}{\sum_{\overline{u}_i} \omega(\overline{u}_i)} \tag{6}$$

With the methodology proposed, each value of any global scenario represents to all the pairs coming from combining a certain part of the random scenarios of fuel prices with a certain part of the random scenarios of $CO_2$ prices. The sum of all those pair weights gives the one ($W_i^k$) to consider for the global scenario $k$, for a single moment $i$.

$$W_i^k = \sum_{\overline{u}_i \in k} w(\overline{u}_i) \tag{7}$$

Finally, extending this to the whole temporary horizon, the weight of a global price representative scenario is given by the productory of the weights calculated with (7) extended to all the months of the study. As mixed scenarios are ignored (that means for example if low fuel and $CO_2$ prices are considered for a month, the next month is considered to have again low fuel and $CO_2$ prices), to obtain weights which sum is one, it is required to divide by the sumatory of productories.

$$W^k = \frac{\prod_i W_i^k}{\sum_k \left( \prod_i W_i^k \right)} \tag{8}$$

## 5. Case study

### A. Case description

Following the proposed methodology, building the price scenarios (step 1) is based on historical data of fuel and $CO_2$ prices. In this case, the fuel considered as indicator of fuel prices is the natural gas. The U.S. Gas Wellhead Prices has been taken as reference for them. The Energy Information Administration provides information about this index and its relationship with the Henry Hub spot prices in [5]. It also presents monthly data of gas Wellhead prices in [6]. Historic gas prices from January 1976 to January 2005 have been used to determine the average and standard deviation of the monthly price increment. The $CO_2$ prices have a much shorter history, at least in the UE. December 2003 to April 2005 prices, obtained from $CO_2$ Solutions official web page [7], have been considered to evaluate average and standard deviation in the monthly increment of $CO_2$ price.

TABLE I. – Gas and CO2 increment price statistics measured in \$/1000ft$^3$ gas and €/t $CO_2$ respectively

| | | |
|---|---|---|
| Gas prices increment | Avg. ($\mu^{GAS}$) | 0.0143 |
| | Std. Dev. ($\sigma_{GAS}$) | 0.3009 |
| $CO_2$ prices increment | Avg. ($\mu^{CO2}$) | 0.0895 |
| | Std. Dev. ($\sigma_{CO2}$) | 2.0585 |
| Gas and $CO_2$ price increments correlation factor ($\rho$) | | 0.1500 |

One hundred random scenarios for both gas and $CO_2$ have been generated using the presented normal model. Therefore, the price in each moment of a scenario has been calculated by summing to the price in the previous time step, a random noise which follows a normal distribution with the parameters shown in TABLE I. Thirty years are considered in this study case from 2005 to 2034.

Following the idea of selecting representatives for gas and $CO_2$, three scenarios have been considered in both cases, which represent low, medium and high prices scenarios. To determine them, the method explained have been employed, which, in this case, consist of taking as representative scenario price for each month the 20$^{th}$, 50$^{th}$ and 80$^{th}$ price, sorting all random scenario prices of that month. Fig. 1 and Fig. 2 show the resulting scenarios for gas and $CO_2$ respectively.

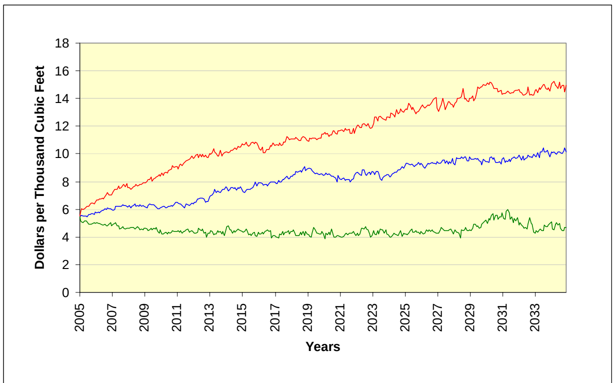


Fig. 1. Gas prices scenarios

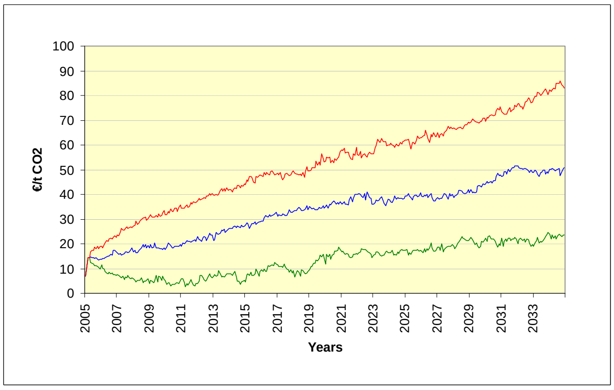


Fig. 2. CO2 prices scenarios

The final nine global scenarios considered are formed by combining gas and $CO_2$ price scenarios. The weights of each global scenario have been evaluated by following the method given in section 4. From the small series of simultaneous gas and $CO_2$ prices, a correlation factor of 0.3607 can be obtained. This value addresses to a 93% of probability for the "medium-medium" scenario and very low probabilities for the rest of them. As this situation does not seem to reflect well the reality, a value of 0.15 (see TABLE I) which addresses to more reasonable probabilities, has been considered as correlation factor. The resulting weights are presented in TABLE II.

TABLE II. – Price scenario weights

| SCENARIO | GAS PRICE | $CO_2$ PRICE | WEIGHT |
|---|---|---|---|
| #1 | Low | Low | 17.07% |
| #2 | Low | Medium | 2.12% |
| #3 | Low | High | 1.31% |
| #4 | Medium | Low | 7.97% |
| #5 | Medium | Medium | 26.48% |
| #6 | Medium | High | 12.14% |
| #7 | High | Low | 4.73% |
| #8 | High | Medium | 21.82% |
| #9 | High | High | 6.36% |

Next thing to do is fixing the expansion plans (steps 2 and 3). In this case study, four plans have been evaluated. Each one of them is focused on one technology: nuclear, coal, CCGT and wind. Other technologies as gas turbines, CHP or biomass power plants may be considered in further analysis. In each case, a reasonable amount of the characteristic technology is included in the expansion plan while the rest of the required capacity is filled with CCGT and a certain amount of wind (250 MW per year). Besides the wind power, the rest of the required capacity is shared in the next way for each plan: in the "Nuclear Plan", 50% of nuclear power (1000 MW per plant) and the rest, cycles; in the "Coal Plan" 65% of coal (500 MW per plant) and the rest cycles; in the "CCGT Plan", 100% combined cycles (400 MW per cycle); finally, for the "Wind Plan", 1750 extra wind MW per year (2000 in total) and the rest cycles.

The starting generation system considered is based on the Spanish case, with 53150 MW of installed capacity. Data of the initial mix and the new investments are shown in TABLE III and TABLE IV respectively. A 3% has been taken as yearly demand growing and a 10% as reserve margin. The load factor considered for the wind is 0.26 and 1 for the rest of technologies. With all these information the four plans can be developed.

TABLE III. − Starting portfolio

| Technology | Installed Capacity | Variable Costs (€/MWh) | Emission Rate | Yearly Fixed Costs (€/MW) |
|---|---|---|---|---|
| Nuclear | 13% | 1 − 11 | - | 57000 |
| Coal | 23% | 20 − 38 | 0.95 | 30000 |
| CCGT | 16% | 23 − 29 | 0.37 | 33000 |
| Fuel | 12% | 38 − 47 | 0.80 | 13000 |
| Hydro | 21% | - | - | 13000 |
| Wind | 15% | - | - | 22000 |

TABLE IV. − New investment data

| Tech. | Cap. per plant (MW) | Var. Costs* (€/MWh) | Emis. Rate | Yearly Fixed Costs (€/MW) | Invest. (M€ per plant) |
|---|---|---|---|---|---|
| Nuclear | 1000 | 7 | - | 42000 | 1200 |
| Coal | 500 | 25 | 0.90 | 20000 | 600 |
| CCGT | 400 | 20 | 0.37 | 33000 | 240 |
| Wind | - | - | - | 22000 | 1.2** |

* Reference values based on the initial gas price and without considering emission costs.
** M€/MW

Before entering the market clearing process (step 4), it is necessary to take into account the prices of gas and $CO_2$ considered in each scenario to calculate the variable costs of each plant for each month of the study. The nuclear power plants and the wind capacity do not suffer variations in their variable costs along the time or from one scenario to another. The rest of technologies are affected by the price of the $CO_2$ according to their emission rate. This cost is added to the original variable cost where emissions plus is not included. A simplification is made at this point, considering that variations in gas prices only affect CCGT variable costs. According to the IEA report about costs of electricity generation [8], about an 88% of the variable costs of a CCGT correspond to fuel costs. Considering this, the variable costs in each month are evaluated as the 12% of the reference cost, which correspond to operation and management costs, plus 0.88 multiplied by the new gas price and divided by the reference gas price. This is used for both existing and new plants.

Running the market clearing process can be carried out now. In this case, a tool based in a market equilibrium approach like the one presented in [3] is used. Ten hour blocks are considered, which is enough detailed for a long-term study. Medium hydraulic inflows will be assumed, but the profile along the year (wet/dry months) and also the demand profile (peak hours) is considered. Wind generation is taken as constant along the year and it is calculated by multiplying the installed capacity by the given wind load factor. Hydro and wind production is subtracted from the total demand to be covered. This procedure means a simplification because hydro and wind uncertainty is not considered. However, it is a common procedure when dealing with long-term analysis.

The clearing process must be solve once for each price scenario to evaluate each expansion plan, what addresses to 9 x 4 = 36 market clearing processes, each one of them with 30 years. This is obviously the principle time-consuming obstacle to evaluate a large number of scenarios for each plan. The results of the clearing process are the production of each plant and the price. With the production data, the yearly variable costs of the whole system can be evaluated.

Finally, to calculate net present costs (step 5), fixed and investment costs must be added to the obtained variable costs. The fixed cost of each plant will be considered as long as the plant exists, so the closures must be taken into account. For simplicity, the whole investment cost is considered to take place in the first year of the plant life. Additionally, it is necessary to represent the difference between having, by the end of the study horizon, a very new generation portfolio or a very obsolete one. To include this effect, what can be called "depreciation cost" is added to the yearly cost. The hypothesis is that the plants have a linear depreciation according to their span life (the data used are 50 years for nuclear plants, 30 for coal plants and 25 for cycles and wind turbines). The existing capacity depreciation costs are not included as long as they can be considered as stranded costs. Moreover, these costs would affect in the same way to all the expansion plans, thus it is irrelevant to consider them in this comparative study.

Using a discount rate of a 5%, the NPC for each plan in each scenario is graphically presented in Fig. 3.


Fig. 3. NPC of each plan in the considered gas and $CO_2$ price scenarios

The weights of TABLE II are used now to calculate the NPC average and standard deviation for each expansion plan. The numerical values and a graphical representation of average against standard deviation are presented in TABLE V and Fig. 4 respectively.

TABLE V. − NPC average and standard deviation of each expansion plan

| Tech. | Nuclear | Coal | CCGT | Wind |
|---|---|---|---|---|
| Average ($\times 10^5$ M€) | 1.89 | 2.83 | 2.64 | 2.78 |
| Std. deviation ($\times 10^4$ M€) | 1.63 | 4.36 | 4.53 | 3.61 |

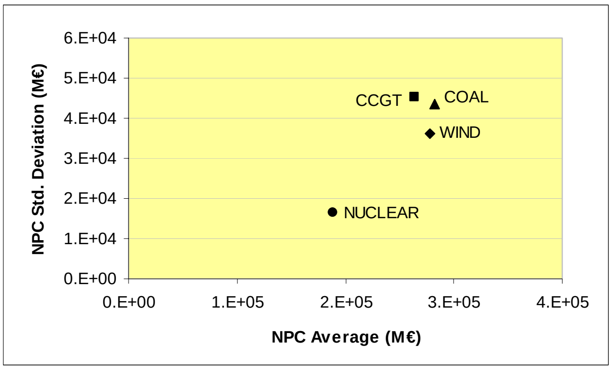


Fig. 4. NPC average and standard deviation of each expansion plan

Considering that all the hypothesis and simplifications do not create significant distortions in the results, some conclusions can be stated. Nuclear power is still a good option taking into account only the normal considered costs. But due to all the problems that the long-term nuclear waste management brings and considering the usual social opposition to this energy, this option may be taken apart. In the present days, the two basic expansion technologies are CCGT and wind turbines which seem to be a good choice according to the results of this analysis. The strong point of combined cycles is their low medium costs, supported mainly by their low fixed and investment costs. As far as the gas prices would move on reasonable prices and the supply would be guarantied, the CCGT seems to be a relevant option. The plan focused on wind generation has higher medium costs although its strong point is its lower dependency on the presumable volatility of $CO_2$, gas or other fuel prices. Obviously the wind technology has limitations because of its dependence on weather conditions and the gradual saturation of adequate locations. The high investment costs and emission rate of coal plants makes that plan getting worse results in both average and variance of its NPC.

Another important thing to be observed is that, except for the nuclear one, any mono-technology plan addresses to high volatility in the total system generation costs. Therefore, it seems unquestionable that it is important to preserve a mixed of several technologies in order to not depend on a specific fuel or any special situation that may affect to a certain group of plants. Moreover, adaptation to the demand curve would be easier with a group of different technologies more suitable to work in base or peak situations.

## 6. Conclusions

A complete methodology to analyse the risk of long-term fuel and $CO_2$ prices when designing expansion plans has been presented. Detailed guidelines have been given to solve every step of the methodology in a relative simple way.

The main steps can be summarized as follows. The first step is to select a number of fuel and $CO_2$ price scenarios, determining their probabilities considering the possible correlations. Steps 2 and 3 involve selecting a number of expansion plans, basing on the desired reserve margin. Step 4 is to simulate a clearing process for the considered time horizon in order to obtain variable costs, taking into account the fuel and $CO_2$ costs and the expansion plan. Step 5 includes adding fixed and investment costs to evaluate the net present cost for each plan in each scenario and finally, comparing the plans according to the average and variance of their net present costs, considering the probabilities of each scenario.

The results of the study allow the regulator to make numerical comparisons of different plans in order to select the best choices (step 6). With this information it may design policies to encourage the companies to follow these plans. The final target is to achieve a generation portfolio with the desired reserve margin and solid against price changes in terms of reasonable and non volatile generation costs.

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