Including start-up and shut down constraints into generation capacity expansion models for liberalized electricity markets

A. Nogales, E. Centeno, S. Wogrin

I. Abstract:

Generation capacity expansion has evolved considering that nowadays renewable generation technologies are expected to reach large penetration levels. These technologies are changing the plants scheduling, and thus the unit-commitment costs, of the rest of the generating facilities and as a result, the operation-related issues become more and more important for the capacity expansion problem. The models historically used for generation capacity expansion analysis rely on highly simplified approximations for operating costs that ignore details such as plant startups. Due to highly predictable and fairly slow time dynamics of historic load patterns these details have successfully been largely ignored. In this paper we study how including some unit-commitment details, such as start-up and shut down costs, can affect expansion planning and to this end we use an equivalent optimization problem of an open loop capacity expansion equilibrium model. A case study were we applied the proposed formulation is also presented to analyze the effect of effect of start-up costs in capacity expansion planning.

II. Overview

A large penetration in renewable technologies will change the capacity mix and also the short-term scheduling operation regime of the conventional thermal plants, increasing the need of cycling them. These changes will impact capacity generation expansion problems since flexibility, and its implications of detailed short-term operational costs, will have to be valued along other operational costs and capital investments as pointed out by Batlle and Rodilla in [1].

In [2] Palmintier and Webster introduce a method for combining unit commitment and the generation expansion planning into a single mixed-integer optimization model in a centralized market. This formulation groups generators into categories allowing integer commitment states from zero to the installed capacity. A development of the traditional screening curves technique in order to incorporate a representation of the cycling operation of thermal units is also presented in [1]. Nevertheless, the aforementioned methods use a chronological time frame (and evolution of the system), instead of a monotonic load curve in order to represent demand, which generally lead to a larger-size problem than the load curve approach, which can complicate the resolution of the problem. For this reason in our models we have adopted a load curve approach in order to be able to model the long term.

The model we present is an equivalent optimization problem of an open loop capacity expansion equilibrium model with a conjectured price response market representation which includes unit-commitment constraints (start-ups and shut downs) as an extension of the models presented by Barquín, Centeno and Reneses in [3] and by Wogrin, Centeno and Barquín in [4]. We also use a monotonic load curve by introducing the concept of *state* of the system which will be further developed in Section III.

In this paper we will first describe the model, in Section III. In Section IV we present a study case to show the usefulness of the model and finally we draw some conclusions in Section V.

III. Methods

In this section we first present the concept of state of the system, secondly we introduce the conjectured-price response market representation of the market equilibrium that has been used in the generation expansion model and finally we describe the model in which we have included start-up and shut down decisions.

A. State of the system

In every hour the system can be characterized by different variables such as demand, production of non dispatchable technologies, amount of inflexible generation capacity, hydro generation, etc. Depending on the variables chosen to represent the system and the chosen range of values for these variables, we can define different states of the system. A system state can therefore be defined as a vector of variables that describe the power system in a particular moment or over a particular period of time. In the model described in this paper, the state of the system is going to be defined by one only variable, i.e., net demand, which is defined as system demand minus the wind energy production.

Each considered period of time in which we have divided the time frame to be studied (usually years), can be also divided into as many states as wanted, and the more states we have, the closer we get to a chronological representation (the most detailed one being a representation considering 8760 states if our time frame is divided into years) but the larger the problem size. Due to these reasons it is not trivial to choose the right number of states that will define the system to be studied.

Once we have defined the states of the system, we can calculate the probability of shifting from one state to another in a period and by this means we can introduce short term operating details such as plant start-ups and shut downs.

B. Conjectured-price response market representation

The model we present in this paper, represents the market equilibrium by means of a conjectured-price response market approach such as the one presented in [5], [3] and [7]. This subsection summarises the main features of this model by presenting a simplified version of the open loop capacity expansion equilibrium model.

Consider a set of i companies, playing a game consisting of deciding at the same time yearly investment and production for a set of load levels in the market for each technology t, year y and load level l. Each company tries to maximize its overall profit B, that includes market revenues (price π times production q), minus investment cost (unitary investment cost per year β, times yearly capacity investment x), minus production cost (unitary production cost δ, times production q). In this expression D is the duration of each load level and R is a yearly actualization factor.

$$B_i = \sum_{t,y,l} D_{y,l} \cdot R_y \cdot \left(p_{y,l} \cdot q_{i,t,y,l} - \delta_{i,t} \cdot q_{i,t,y,l} \right) - \sum_{t,y} R_y \cdot \beta_{i,t} \cdot x_{i,t,y} \qquad (0)$$

Demand is considered to be affine (parameter α and S are known) with respect to price, and must be supplied by the joint productions of all generation companies. Price will be established as a result of the overall production of all the generation companies.

$$\sum_{i,t} q_{i,t,y,l} = d_{y,l} = S_{y,l} - \alpha_{y,l} \cdot \pi_{y,l} \qquad (1)$$

As an additional hypothesis the effect of each company over the price when modifying production is considered to be known. It is represented by the so-called conjectured-price variation. It is an exogenous parameter that represents the capacity of each agent of affecting the price. The minus sign is included in order to make the parameter positive.

$$\theta_{i,y,l} = -\frac{\partial \pi_{y,l}}{\partial q_{i,y,l}} \qquad (2)$$

Considering the previous profit expression (0) and zeroing the derivative in order to find the maximum:

$$\frac{\partial B_i}{\partial q_{i,t,y,l}} = 0 = \pi_{y,l} - \theta_{i,y,l} \cdot q_{i,t,y,l} - \delta_{i,t} \qquad (3)$$

The equilibrium problem that results from the simultaneous maximization of the companies profit functions can be stated using an equivalent optimization problem as shown in [3].

This formulation provides a tool to determine Nash equilibrium for the “investment plus market” problem, that is easy to compute and, under reasonable hypothesis, easy to solve. In short, the previous formulation of the Nash equilibrium corresponds to the solution of this set of equations:

$$\forall_i$$

$$\begin{aligned}
\max_{q,x,\pi,d} \quad & \sum_{i,t,y,l} D_{y,l} \cdot R_y \cdot \left(p_{y,l} \cdot q_{i,t,y,l} - \delta_{i,t} \cdot q_{i,t,y,l} \right) - \sum_{t,y} R_y \cdot \beta_{i,t} \cdot x_{i,t,y} \\
s.t. \quad & 0 \le x_{i,t,y} \le x_{i,t,y+1} \\
& q_{i,t,y,l} \le x_{i,t,y} \\
& \sum_{i,t} q_{i,t,y,l} = d_{y,l} \\
& d_{y,l} = S_{y,l} - \alpha_{y,l} \cdot \pi_{y,l}
\end{aligned} \tag{4}$$

C. Model description

The model we present in this section is the equivalent optimization problem of an open loop capacity expansion equilibrium problem with a conjectured-price response market representation. This is an extension of the model presented in [3], and the investment model presented in Wogrin et al. [4], to incorporate unit-commitment decisions as well.

The indices used in the formulation are: i, for generation companies, t for thermal generation technologies, $to(t)$ for pre-existent thermal technologies, $tn(t)$ for new thermal technologies, y for periods and s for the states of the system.

In the objective function, given by equation (5), the first three terms represent the equivalent optimization problem of the market equilibrium. The fourth term represents total investment costs and the last term includes the costs of the start-ups and shut downs. The problem has as decision variables the thermal power production $q_{i,t,y,s}$, the new capacity investments $x_{i,tn,y}$, the commitment decision $u_{i,t,y,s}$, and the start-up and shut down decisions $a_{i,t,y,s,s*}$, $z_{i,t,y,s,s*}$, from state s to state s*.

$$\begin{aligned}
\underset{q,x,u,a,z,d}{Min} \quad & \sum_{i,t,y,s} D_{y,s} \cdot R_y \cdot \delta_{i,t} \cdot q_{i,t,y,s} + \frac{1}{2} \sum_{i,y,s} D_{y,s} \cdot R_y \cdot \theta_{i,y,s} \cdot \left(\sum_t q_{i,t,y,s} \right)^2 \\
& - \sum_{y,s} D_{y,s} \cdot R_y \cdot \alpha_{y,s} \left(S_{y,s} \cdot d_{y,s} - \frac{d_{y,s}{}^2}{2} \right) \\
& + \sum_{i,tn,y} R_y \cdot \beta_{i,tn} \cdot x_{i,tn,y} \\
& + \sum_{i,y,s,s*} R_y \cdot N_{s,s*} \cdot \left(\sum_t CA_{i,t} \cdot a_{i,t,y,s,s*} + CZ_{i,t} \cdot z_{i,t,y,s,s*} \right)
\end{aligned} \tag{5}$$

$s.t.$

$$0 \le x_{i,tn,y} \le x_{i,tn,y+1} \qquad \perp \mu^{\underline{IC}}_{i,tn,y}; \mu^{\overline{IC}}_{i,tn,y} \qquad \forall i, tn, y \tag{6}$$

$$\underline{Q_{to}} \cdot u_{i,to,y,s} \leq q_{i,to,y,s} \leq K_{i,to} \cdot u_{i,to,y,s} \quad \perp \mu_{i,to,y,s}^{\underline{Qto}}; \mu_{i,to,y,s}^{\overline{Qto}} \quad \forall i,to,y,s \tag{7}$$

$$\underline{Q_{tn}} \cdot u_{i,tn,y,s} \leq q_{i,tn,y,s} \leq S_{y,s} \cdot u_{i,tn,y,s} \quad \perp \mu_{i,tn,y,s}^{\underline{Qtn}}; \mu_{i,tn,y,s}^{\overline{Qtn}} \quad \forall i,tn,y,s \tag{8}$$

$$q_{i,tn,y,s} \leq x_{i,tn,y} \quad \perp \mu_{i,tn,y,s}^{x} \quad \forall i,tn,y,s \tag{9}$$

$$0 \leq u_{i,t,y,s} \leq 1 \quad \perp \mu_{i,t,y,s}^{\underline{u}}; \mu_{i,t,y,s}^{\overline{u}} \quad \forall i,t,y,s \tag{10}$$

$$0 \leq a_{i,t,y,s,s*} \leq 1 \quad \perp \mu_{i,t,y,s,s*}^{\underline{a}}; \mu_{i,t,y,s,s*}^{\overline{a}} \quad \forall i,t,y,s,s* \tag{11}$$

$$0 \leq z_{i,t,y,s,s*} \leq 1 \quad \perp \mu_{i,t,y,s,s*}^{\underline{z}}; \mu_{i,t,y,s,s*}^{\overline{z}} \quad \forall i,t,y,s,s* \tag{12}$$

$$a_{i,t,y,s,s*} - z_{i,t,y,s,s*} = u_{i,t,y,s} - u_{i,t,y,s*} \quad \perp \lambda_{i,t,y,s,s*}^{Acop} \quad \forall i,t,y,s,s* \tag{13}$$

$$T_{y,s} \cdot R_y \cdot (d_{y,s} - \sum_{i,t} q_{i,t,y,s}) = 0 \quad \perp \pi_{y,s} \quad \forall y,s \tag{14}$$

In these expressions $D_{y,s}$ is the duration of each state, $R_y = 1/(1+F)^y$, where F *is* the discount rate, $\delta_{i,t}$ is the unitary production cost, $\beta_{i,tn}$ is the unitary investment cost per year, $\theta_{i,y,s}$ represents the conjectured price response of each company, $\alpha_{y,s}$ and $S_{y,s}$ are the demand slope and intercept in each state and $CA_{i,t}$ and $CZ_{i,t}$ are the costs of an start-up and a shut down respectively. $N_{s,s*}$ is the number of state changes from *s* to *s** which is obtained by the probability of state change in a period $P_{y,s,s*}$ as in (15).

$$N_{y,s,s*} = P_{y,s,s*} * Hours_y \tag{15}$$

A monotonicity constraint for investment variables has to be fulfilled (6). Constraints (7) and (8) are upper and lower production bounds for old technologies ($\underline{Q_{to}}$, $\overline{Q_{to}}$) and new technologies ($\underline{Q_{tn}}$, $\overline{Q_{tn}}$) respectively. Power production for new technologies must also be lower than the new capacity investment (9). The decision variables $u_{i,t,y,s}$, $a_{i,t,y,s,s*}$ and $z_{i,t,y,s,s*}$ can only have values in the interval [0,1], (10), (11) and (12). We have included a logical consistency constraint relating to start-ups, connections and shut downs (13). Finally (14) is a demand balance constraint whose dual variable $\pi_{y,s}$ is the price in each state.

IV. Results

In this section we present the case study where we have applied the proposed formulation to a numerical example. We first describe the electric power system that serves as our case study and then we present and analyze the results.

A. System Description

We consider a system with two different generation companies (i1 and i2) in the market, and three different technologies, that is, nuclear, coal and combined cycle gas turbine (CCGT). The pre existent generation capacity $K_{i,to}$ $[GW]$ is given in TABLE I. The variable costs of each technology, as well as its investment costs, are given in

TABLE II, based on [8]. The lower production bounds for old and new technologies are equal, and are 0.8 GW for nuclear, 0.2 GW for coal and 0.12 GW for CCGT. The upper production bounds are considered to be equal to $K_{i,to}$ $[GW]$ for the old technologies and equal to $S_{y,s}$ for the new ones.

TABLE I
EXISTING GENERATION CAPACITY [GW]

	Nuclear	Coal	CCGT
I1	1.0	2.1	1.2
I2	2.0	3.5	1.0

TABLE II
PRODUCTION AND INVESTMENT COST FOR EACH TECHNOLOGY

	$\delta_{i,t}$ [€/MWh]	$\beta_{i,tn}$ [M€/GW/year]
Nuclear	5.8	271.8
Coal	18.9	186.6
CCGT	39.780	59.676

The start-up and shut down costs $CA_{i,t}$ and $CZ_{i,t}$ [k€] for the three different technologies are given in TABLE III. For coal and CCGT we have consider these costs as the fuel costs when starting-up and shutting down these technologies. However, for nuclear technology we have also added to the start-up costs, the estimated loss of benefits for being three months without generating. This is done to capture the effect that nuclear is a base technology which only stops for major reasons such as outages, faults or maintenance.

TABLE III
START-UP AND SHUT DOWN COSTS FOR EACH TECHNOLOGY [K€]

	$CA_{i,t}$	$CZ_{i,t}$
Nuclear	1e5	0.0
Coal	16	1.6
CCGT	22	2.2

In this numerical example we carry out static investment planning and therefore consider the year 2030, in which we consider 90 states of net demand to characterize this future year. We have obtained the demand data for this year starting with the real data for the Spanish demand in 2011 and considering a sustained annual demand increase of 1.6%. Data for wind energy production has been obtained in the same way but considering an annual increase of 3.5%.

Having calculated the net demand for 2030, we have obtained the 90 states and their duration by means of the k-means clustering method [6]. The demand is considered to be elastic so, with the information about the states, the net demand for 2011 and the energy prices for the same year, we have calculated the demand intercept for every state, $S_{y,s}$, which is between the range 71.0981 to 0.8069 [GW]. In addition the demand slope, $\alpha_{y,s}$ is 0.24 [GW/(€/MWh)] for each state, which was based on [7]. A discount rate of 9% is considered. We also have obtained $N_{s,s*}$, by counting the number of changes from one state to another in the studied period. The conjectured price response, $\theta_{i,y,s}$, is considered to be 1.1 [(€/MWh)/GW].

B. *Effect of start-up costs*

In this section we analyze the effect of start-up costs in capacity expansion planning in the system described above. For doing so, we have run the model with different start-up costs. The model presented is a convex, quadratic, optimization problem with an unique solution and was implemented in GAMS version 23.7.3 and solved with the commercial solver CPLEX.

We have considered that the start-up costs for nuclear technology remain fixed and then have studied the effect of changing the start-up costs in the same way for coal and CCGT with four different situations as shown in TABLE IV, ranging from zero to the double of the base case costs.

TABLE IV
START-UP COSTS FOR EACH CASE AND TECHNOLOGY [M€]

	Case 0 (CA = 0)	Case 1 (CA = CA/2)	Case 2 (CA = CA)	Case 3 (CA = CA*2)
Coal	0.000	0.008	0.016	0.032
CCGT	0.000	0.011	0.022	0.044

First we will compare the investment in new capacity in the four cases. As can be seen in FIGURE I there is no new investment in coal in any case. The overall system capacity decreases, however total CCGT capacity increases. The technology that assumes the reduction in investment is the nuclear. It is interesting how investments remain almost the same for the three first cases but when the start-up costs are doubled is when we can appreciate more changes in the investment strategy.

FIGURE I
INSTALLED CAPACITY FOR EACH CASE

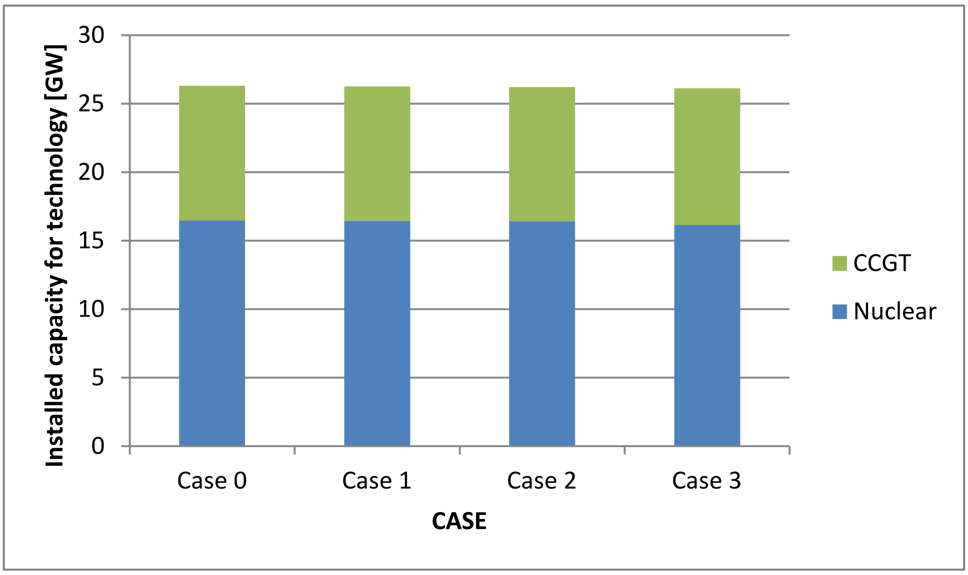
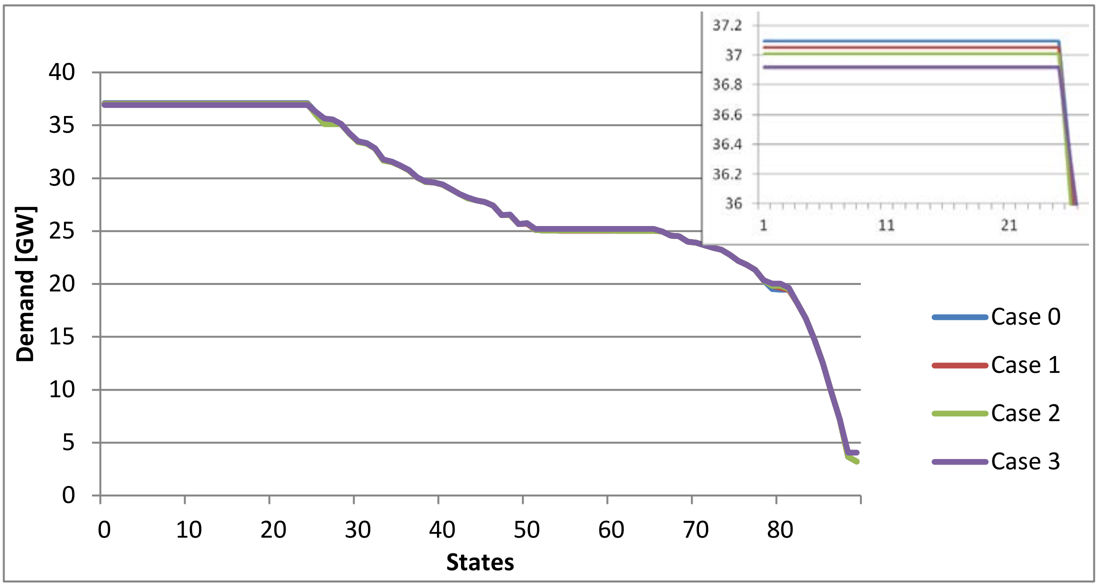


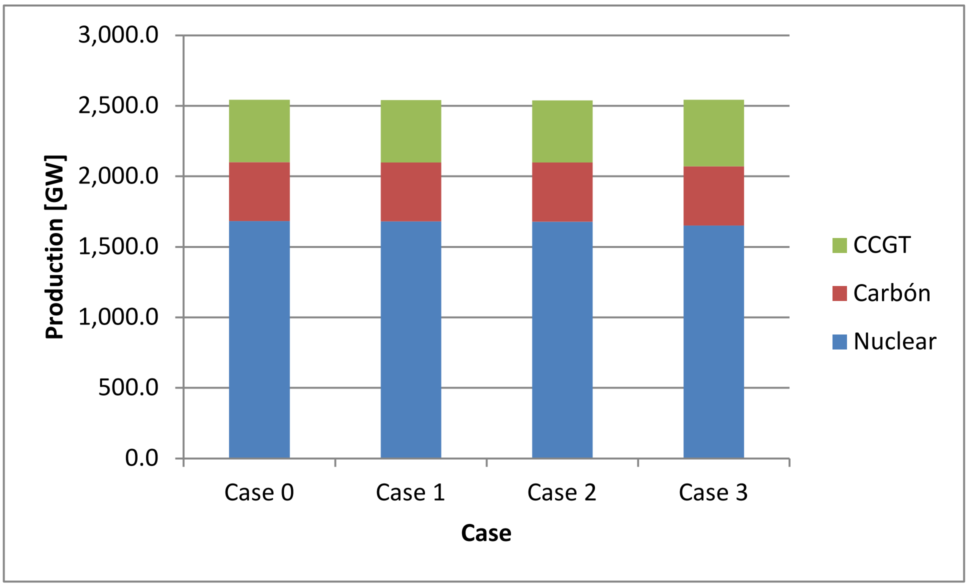
FIGURE II
SYSTEM DEMAND IN EACH STATE



The demand almost remains the same for the different cases of start-up costs considered, as can be seen in FIGURE II. However, if we pay attention to the detail in this figure, it can be seen that in high-demand states the actual demand yielded by the model is slightly different for the different cases of considered start-up costs, in fact the higher the costs the lower the demand in these states. This reduction of the demand in the states with the highest demand, where all the capacity is used, is due to an increase of the total production costs of the system. Nevertheless, in the states that are not capacity limits, the differences between the cases are negligible

As shown in FIGURE III the evolution of total production in the studied year for the four cases is the expected one considering the capacity investment strategies, thus the production diminishes for nuclear, increases for CCGT and stays almost the same for coal.

FIGURE III
THERMAL POWER PRODUCTION IN EACH CASE [GW]



We have also studied the effect of changing the start-up costs for CCGT unilaterally considering the same four cases. The obtained results are almost the same as in the exposed sample case, which are decrease in the overall system capacity but with an increase in total CCGT capacity. The reason behind this is that the variations in the investment and production decisions due to changes in coal and gas start-up costs are very small and in addition there is no new investment in coal so when changing the start-up costs only for CCGT the results are approximately the same.

V. Conclusions

We have introduced an equivalent optimization problem of an open loop capacity expansion equilibrium model with a conjectured-price response market representation in which we have included commitment constraints and start-up and shut down costs. We have presented the concept of state of the system which has allowed us to characterize the system with the net demand and to calculate the probability of changing from one state to another in a period to introduce short-term operating details.

A case study has been presented to analyze the effect of start-up costs in capacity expansion planning. We observe a slightly different investment decisions as the start-up costs change. The greater the start-up costs the lower the investments. Furthermore, there is less investment in base-load technologies but more investment in peak-load technologies. Nevertheless it can be seen that the differences observed for the studied cases are very small so that it can be concluded that the start-up costs in coal and CCGT technologies don't have a significant impact on investment decisions.

This study suggests a number of topics to be addressed in future research. First of all, we want to study the impact of changing the number of the states of the system in a period. It will be very interesting also to study how to define the states of the system with other variables and how to use them to incorporate more short-term operational details into generation capacity expansion models.

VI. Bibliography

[1] Batlle, C., & Rodilla, P. (2012). An enhanced screening curves method for considering thermal cycling operation costs in generation expansion planning. Accepted for publication in IEEE Transactions on Power systems.

[2] Palmintier, B., & Webster, M. (2011). Impact of unit commitment constraints on generation expansion planning with renewables. *2011 IEEE Power and Energy Society General Meeting*.

[3] Barquín, J., Centeno, E., & Reneses, J. (2004). Medium-term generation programming in competitive environments: a new optimisation approach for market equilibrium computing. *IEE Proc. -Gen. Transm. Distrib.*, *151*.

[4] Wogrin, S., Centeno, E., & Barquín, J. (In revision). Generation Capacity Expansion Analysis : Open Loop Approximation of Closed Loop Equilibria. *IEEE Transactions on Power Systems*.

[5] Centeno, E., Reneses, J., & Barquín, J. (2007). Strategic Analysis of Electricity Markets Under Uncertainty: A Conjectured-Price-Response Approach. *IEEE Transactions on Power Systems*, *22*.

[6] MathWorks Documentation Center. www.mathworks.es/es/help/stats/kmeans.html

[7] Centeno, E., Wogrin, S., López-Peña, á., & Vázquez, M. (2011). Analysis of investments in generation capacity: a bilevel approach. *IET Generation, Transmission & Distribution*, *5*.

[8] International Energy Agency, & OECD Nuclear Energy Agency. (2010). Projected Costs of Generating Electricity 2010.