A stochastic model for capacity planning in the electricity production sector in the long run

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Abstract. We present a single stage stochastic mixed integer linear model for determining the optimal mix of different technologies for electricity generation, ranging from coal, nuclear and combined cycle gas turbine to hydroelectric, wind and photovoltaic, taking into account the existing plants, the cost of investment in new plants, maintenance costs, purchase and sale of CO_2 emission trading certificates and green certificates, in order to satisfy regulatory requirements. The power producer is assumed to be a *price-taker*. Stochasticity of future fuel prices, which affect the generation variable costs, is included in the model by means of a set of scenarios. The main contribution of the paper, beyond considering stochasticity in the future fuel prices, is the introduction of CVaR risk measure in the objective function in order to limit the possibility of low profits in bad scenarios with a fixed confidence level.

1 Introduction

The incremental selection of energy generation capacity is of great importance for energy planners. The problem can be considered from either the single power producer's (GenCo) point of view or the system operator's perspective. For the power producer's capacity expansion problem a mathematical model is needed for determining the optimal expansion plan, subject to all the relevant factors (regulatory constraints, fuel prices, electricity prices,...) that affect the power producer's decision, with the aim of finding an optimal trade-off between profit and risk. This problem has been studied in [Bjorkvoll *et al.*(2001)] and [Genesi *et al.*(2009)] and for a discussion of different risk measures see [Conejo *et al.*(2010)]. For the capacity expansion problem from the system operator's perspective a mathematical model is needed that includes a zonal representation of the production network and of the transmission system, in order to determine the GenCo's expansion plans while taking into account the impact on the transmission network and aiming at minimizing the system cost of satisfying load. See the relevant contributions in [Han *et al.*(2009)], [Moghdass-Tafreshi *et al.*(2011)], [Botterud *et al.*(2007)], [Hariyanto *et al.*(2009)], [Roh *et al.*(2007)], [Roh *et al.*(2009)] and [Sauma & Oren(2006)].

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In this paper we deal with the problem of determining the optimal generation expansion plan of a single generation company over a long term planning horizon, choosing among different production technologies, i.e. thermal power plants using fossil fuels, thermonuclear power plants and power plants using Renewable Energy Sources (RES). The model used for our analysis (see the technical reports [Vespucci *et al.*(2011a)], [Vespucci *et al.*(2011b)] for further details) is based on the one introduced in [Genesi *et al.*(2009)], but it differs from it both in the way the stochasticity of prices is taken into account, i.e. by means of a Stochastic Programming model instead of a Montecarlo approach, and in the introduction of a risk measure in the objective function.

The influence of several factors on the power producer's decisions is taken into account, namely regulatory constraints, characteristics of generation technologies, market constraints, uncertainty of prices and power producer's attitude toward risk. Indeed, rules are issued by the Regulatory Authority with the aim of containing CO_2 emissions and of promoting and supporting the development of power generation from RES. In particular, the Regulatory Authority imposes the following restrictions to the power producer: a payment is due proportional to the amount of CO_2 released into the atmosphere and a prescribed ratio between the electricity generated using RES and the total electricity generated in a year must be attained. To this aim Green Certificates have been introduced, which are tradable commodities giving evidence of power generation from RES: they provide a benefit to their holders, who may use them to comply with their obligation to inject into the power grid a certain quota of electricity generated using RES.

Both the candidate power plants and the existing power plants, i.e. those owned by the producer at the time (called *year 0*) when the generation expansion decisions are taken (called *year 0*), differ in terms of CO_2 emission rate, operating hours per year, investment cost, construction time, industrial life and fuel cost. The power producer's decision is also subject to the number of potential sites available in the planning horizon for constructing new power plants of every candidate generation technology.

The influence of the market on the power producer's decision is taken into account by imposing an upper bound to the increase of his own market share in every year of the planning horizon. Forecast of prices along the planning period for electricity, CO_2 emission permits, green certificates and fuels are a major factor affecting generation expansion decisions, which highly depends on the expectations about price volatility along the planning horizon as well as on the degree of risk aversion characterizing the power producer. Finally, the power producer's decision is subject to the budget available in the planning horizon for investment in new power plants.

In this paper we investigate how the stochasticity of fuel prices impacts on power producer's decisions. This is done by means of a Stochastic Programming model, whose objective function is a linear combination of the expected profit and of a risk term, by which fuel prices uncertainty along the planning period is taken into account. The risk term is represented by CVaR risk measure in the formulation introduced by [Rockafellar & Uryasev(2000)], [Rockafellar & Uryasev(2002)]. The proposed model, which is described in Section 2, allows several parameters to be treated as stochastic ones, namely market electricity prices, Green

Certificate prices, CO_2 emission permit prices and thermal plants variable production costs, the main component of which are the fuel costs. In the case study presented in Section 3, however, we restrict ourselves to considering one forecast for market electricity prices, Green Certificate prices and CO_2 emission permit prices, while uncertainty of variable production costs is represented by means of scenarios. Random outages of generators and volatility and uncertainty of RES are taken into account in a simplified way, namely by considering average operating hours for each technology on the Italian territory. This choice is a semplification with respect to the work presented in [Roh *et al.*(2009)]. Conclusions follow in section 4.

2 The mixed-integer linear stochastic model

In order to introduce the model, we define the following sets, parameters and variables.

Sets

J^T	set of candidate technologies for thermal power production;
J^R	set of candidate technologies for power production from RES;
K^T	set of thermal power plants owned by the power producer in year 0;
K^R	set of power plants using RES owned by the power producer in year 0;
I	set of years in the planning horizon;
S	set of scenarios.

Parameters

$\overline{Z}_j$	$[-]$	number of sites ready for constructing a power plant of candidate technology $j \in J^T \cup J^R$;
S_j	$[years]$	construction time of a power plant of candidate technology $j \in J^T \cup J^R$;
I_j	$[M\text{Euro}/MW]$	investment cost of a power plant of candidate technology $j \in J^T \cup J^R$;
R_j	$[k\text{Euro}]$	annualized investment cost of a power plant of candidate technology $j \in J^T \cup J^R$;
L_j^J	$[years]$	industrial life of a power plant of candidate technology $j \in J^T \cup J^R$;
P_j^J	$[MW]$	rated power of a power plant of candidate technology $j \in J^T \cup J^R$;
H_j^J	$[h]$	operating hours per year of a power plant of candidate technology $j \in J^T \cup J^R$;
ν_j^J	$[-]$	percentage of loss of a power plant of technology $j \in J^T \cup J^R$;
$\overline{E}_{j,i}^J$	$[GWh]$	maximum energy produced by a power plant of technology $j \in J^T \cup J^R$ in year $i \in I$;
θ_j^J	$[t/GWh]$	CO_2 emission rate of a thermal power plant of candidate technology $j \in J^T$;
f_j^J	$[k\text{Euro}]$	fixed production cost of a power plant of technology $j \in J^T \cup J^R$;

v_j^J	[kEuro]	variable production cost of a RES power plant of candidate technology $j \in J^R$;
$v_{j,s}^J$	[kEuro]	variable production cost of a thermal power plant of candidate technology $j \in J^T$ in scenario $s \in S$;
L_k^K	[$years$]	residual life of power plant $k \in K^T \cup K^R$ owned by the power producer in year 0;
P_k^K	[MW]	rated power of power plant $k \in K^T \cup K^R$;
H_k^K	[h]	operating hours per year of power plant $k \in K^T \cup K^R$;
ν_k^K	[$-$]	percentage of loss of power plant $k \in K^T \cup K^R$;
$\overline{E}_{k,i}^K$	[GWh]	maximum energy produced by power plant $j \in J^T \cup J^R$ in year $i \in I$;
θ_k^K	[t/GWh]	CO_2 emission rate of thermal power plant $k \in K^T$;
f_k^K	[kEuro]	fixed production cost of power plant $k \in K^T \cup K^R$;
v_k^K	[kEuro]	variable production cost of RES power plant $k \in K^R$;
$v_{k,s}^K$	[kEuro]	variable production cost of thermal power plant $k \in K^T$ in scenario $s \in S$;
$\pi_{i,s}^E$	[kEuro$/GWh$]	market electricity price in year $i \in I$ in scenario $s \in S$;
$\pi_{i,s}^{GC}$	[kEuro$/GWh$]	Green Certificate price in year $i \in I$ in scenario $s \in S$;
$\pi_{i,s}^{CO_2}$	[kEuro$/t$]	CO_2 emission permit price in year $i \in I$ in scenario $s \in S$;
β_i	[$-$]	ratio "electricity from RES / total electricity produced" to be attained in year $i \in I$;
$\overline{M}_i$	[GWh]	market share in year $i \in I$;
p_s	[$-$]	probability of scenario $s \in S$;
B	[MEuro]	budget available;
r	[$-$]	interest rate;
ρ	[$-$]	risk-aversion parameter ($0 \leq \rho \leq 1$);
α	[$-$]	confidence level.

Decision variables

$w_{j,i}$	[$-$]	number of power plants of candidate technology $j \in J^T \cup J^R$ whose construction is to start in year $i \in I$;
$W_{j,i}$	[$-$]	number of power plants of candidate technology $j \in J^T \cup J^R$ available for production in year $i \in I$;
$E_{j,i}^J$	[GWh]	energy produced by a power plant of technology $j \in J^T \cup J^R$ in year $i \in I$;
$E_{k,i}^K$	[GWh]	energy produced by power plant $k \in K^T \cup K^R$ in year $i \in I$;
G_i	[GWh]	green certificates sold ($G_i \geq 0$) or bought ($G_i \leq 0$) in year $i \in I$;
Q_i	[t]	CO_2 produced in year $i \in I$;
d_s	[kEuro]	auxiliary variable for scenario $s \in S$ used for computing the Conditional Value at Risk;
V	[kEuro]	auxiliary variable whose optimal value corresponds to the Value at Risk (VaR).

The decision variables have to be determined so as to maximize the objective function

$$F = (1-\rho) \cdot \sum_{s \in S} (p_s \cdot F_s) + \rho \cdot \left[V - \frac{1}{\alpha} \cdot \sum_{s \in S} (p_s \cdot d_s) \right] \tag{1}$$

where

$$\begin{aligned} F_s = \sum_{i \in I} \frac{1}{(1+r)^i} \Bigg\{ \pi^E_{i,s} \cdot \Bigg(\sum_{j \in J^T \cup J^R} E^J_{j,i} + \sum_{k \in K^T \cup K^R} E^K_{k,i} \Bigg) + \pi^{GC}_{i,s} \cdot G_i \ - \pi^{CO_2}_{i,s} \cdot Q_i \ + \\ - \sum_{j \in J^T} (v_{j,s} \cdot E^J_{j,i}) - \sum_{j \in J^R} (v_j \cdot E^J_{j,i}) - \sum_{j \in J^T \cup J^R} [(R_j + f_j) \cdot W_{j,i}] \ + \\ - \sum_{k \in K^T} (v_{k,s} \cdot E^K_{k,i}) - \sum_{k \in K^R} (v_k \cdot E^K_{k,i}) - \sum_{k \in K^T \cup K^R} f_k \Bigg\} , \end{aligned} \tag{2}$$

subject to the following constraints:

$$\sum_{i \in I} \frac{1}{(1+r)^i} \cdot \left[\sum_{j \in J} (R_j \cdot W_{j,i}) \right] \leq B \ ; \tag{3}$$

- for $j \in J^T \cup J^R$

$$\sum_{i \in I} w_{j,i} \leq \overline{Z}_j \ ; \tag{4}$$

- for $j \in J^T \cup J^R$ and $i \in I$

$$w_{j,i} \quad \text{non negative integers} \ , \tag{5}$$

$$W_{j,i} = \sum_{i-(S_j+L^J_j-1) \leq l \leq i-S_j} w_{j,l} \tag{6}$$

and

$$0 \leq E^J_{j,i} \leq \overline{E}^J_{j,i} \cdot W_{j,i} \ ; \tag{7}$$

- for $k \in K^T \cup K^R$ and $i \in I$

$$0 \leq E^K_{k,i} \leq \overline{E}^K_{k,i} \ ; \tag{8}$$

- for $i \in I$

$$\sum_{j \in J^T \cup J^R} E^J_{j,i} + \sum_{k \in K^T \cup K^R} E^K_{k,i} \leq \overline{M}_i \ , \tag{9}$$

$$G_i = \beta_i \cdot \left(\sum_{j \in J^T \cup J^R} E^J_{j,i} + \sum_{k \in K^T \cup K^R} E^K_{k,i} \right) - \left(\sum_{j \in J^R} E^J_{j,i} + \sum_{k \in K^R} E^K_{k,i} \right) \tag{10}$$

and

$$Q_i = \sum_{j \in J^T} \left(\theta^J_j \cdot E^J_{j,i} \right) + \sum_{k \in K^T} \left(\theta^K_k \cdot E^K_{k,i} \right) \ ; \tag{11}$$

- for $s \in S$

$$d_s \geq V - F_s \tag{12}$$

and

$$d_s \geq 0 \ . \tag{13}$$

The model determines the optimal generation expansion plan, which is represented by the values of the integer variables $w_{j,i}$, i.e. by the number of new power plants of technology j whose construction is to start in each year i of the planning horizon. The optimal annual productions $E^K_{k,i}$ and $E^J_{j,i}$, of existing and new power plants respectively, are also determined. Constraints (10) define the amount of electricity for which in year i the corresponding Green Certificates are bought, if $G_i \leq 0$, or sold, if $G_i \geq 0$. Constraints (11) define the amount Q_i of CO_2 emissions the power producer must pay for in year i. We notice that a stochastic model with complete recourse is obtained by defining decision variables $E^K_{k,i,s}$, $E^J_{j,i,s}$, $G_{i,s}$ and $Q_{i,s}$ to substitute variables $E^K_{k,i}$, $E^J_{j,i}$, G_i and Q_i respectively.

Constraints (4) guarantee that for every candidate technology j the total number of new power plants constructed along the planning horizon is not greater than the number $\overline{Z}_j$ of sites ready for construction of a new power plant, i.e. sites for which all administrative permits have been released. These upper bounds could also be considered as varying from year to year. Constraints (6) determine for every year i the number of new power plants of technology j available for production, i.e. those plants for which both construction is completed and industrial life is not ended.

The annual debt repayment R_j is given by

$$R_j = \frac{I_j \cdot P^J_j \cdot r \cdot 1000}{1 - (\frac{1}{1+r})^{L^J_j}}. \tag{14}$$

The sum of the actualized annual debt repayments, which depends on the number of new power plants of each technology j available for production in every year i, is required by constraint (3) not to exceed the available budget.

Constraints (9) guarantee that the electricity generated in year i does not exceed the market share. Constraints (7) take into account that the annual electricity production obtained by new power plants of technology $j \in J^T \cup J^R$ is bounded above by the number of new plants available for production in year i times the maximum annual production $\overline{E}^J_{j,i}$ of every plant, which is defined as

$$\overline{E}^J_{j,i} = \frac{1}{1000} \cdot P^J_j \cdot H^J_j \cdot (1 - \nu^J_j) \ , \tag{15}$$

where the value H^J_j already accounts for possible plant breakdown and maintenance. Moreover, for some technology a lower bound to the annual electricity production could be imposed, in order to take into account technical limitations. Analogously, constraints (8) take into account that the annual electricity production of power plant $k \in K^T \cup K^R$ is bounded above by the maximum annual production $\overline{E}^K_{k,i}$, given by

$$\overline{E}^K_{k,i} = \begin{cases} \frac{1}{1000} \cdot P^K_k \cdot H^K_k \cdot (1 - \nu^K_k) & \text{if} \quad i \leq L^K_k \\ 0 & \text{if} \quad i > L^K_k \ . \end{cases} \tag{16}$$

The model are of help for the decision maker but then, for production purposes, one needs to use short and medium term models. Constraints (12) and (13) define the auxiliary variable associated to scenario $s \in S$ in the computation of the Conditional Value at Risk of profit, where the profit F_s in scenario s is defined by (2).

Among all sets of decision variable values that satisfy constraints (3) - (13), one must be found that maximizes the objective function (1), i.e. the convex linear combination of the expected profit and of the Conditional Value at Risk (CVaR) of profit, see [Rockafellar & Uryasev(2000)], [Rockafellar & Uryasev(2002)]. The CVaR of profit is a risk measure by which the fuel prices uncertainty along the planning period is taken into account. The expected profit is the sum, over the years of the planning horizon, of the actualized annual profits. The profit in year i in scenario s, represented by the expression in curl brackets in equation (2), consists of the following terms:

1. revenues from sale of electricity;
2. revenues from sale, or cost for purchase, of Green Certificates;
3. costs for purchase of CO_2 emission permits;
4. variable production costs of new thermal power plants;
5. variable production costs of new power plants using RES;
6. fixed production costs and annual debt repayment of all new power plants;
7. variable production costs of thermal power plants owned by the producer in year 0;

8. variable production costs of power plants using RES owned by the producer in year 0;

9. fixed production costs of all power plants owned by the producer in year 0.

The combination coefficient of the CVaR-of-profit term is the risk-aversion parameter ρ, with $0 \leq \rho \leq 1$.

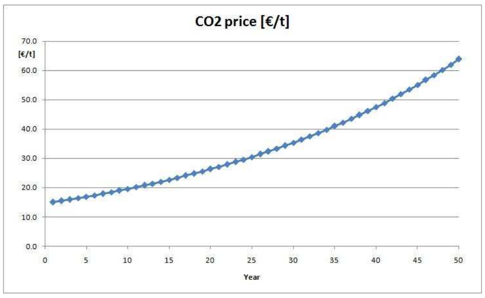

Figure 1: Scenario for CO_2 price (EUA).

3 Case study

The stochastic model introduced in Section 2 has been implemented in GAMS v.23.2.1 and the CPLEX solver v. 12.1.0 has been used for computing the optimal solutions. In order to validate the model a set of test examples has been used. The data shown in Tables 1, 2, 3 are stylized views of various information related to generation plants, characteristic of technologies and fuels found in italian industry at the time of this writing. They do not correspond to particular projects but they are realistic.

Here we report the results obtained for a power producer who owns in year 0 the medium-size generation system described in Table 1.

In Table 2 for each technology available for new power plants the following data are reported: investment cost, rated power, operating hours per year, construction time, industrial life and efficiency.

For each fuel measure unit, lower heating value, CO_2 emission rate and cost are reported in Table 3.

For both coal and gas, nine alternative values of the ratio "estimated price over price in year 0" are considered, together with the associated probabilities (see Tables 4 and 5); analogously, for the nuclear fuel seven alternative values and associated probabilities are considered (see Table 6). By combining the considered alternatives in all possible ways, 567 independent scenarios of fuel prices are obtained, which represent the stochasticity of future fuel prices.

The CO_2 emission permit price $\pi_i^{CO_2}$ is assumed to increase along the years of the planning horizon, as shown in Fig. 1.

Table 1: Generation plants owned by the power producer in year 0.

power plant	rated power P_j $[MW]$	residual life $\hat{L}_j$ $[years]$	efficiency η_j $[-]$
$CCGT_1$	860	29	0.53
$CCGT_2$	840	26	0.52
$CCGT_3$	2978	24	0.54
$CCGT_4$	425	22	0.52
$CCGT_5$	1090	20	0.50
$CCGT_6$	532	17	0.51
$CCGT_7$	402	14	0.51
$CCGT_8$	75	13	0.52
$CCGT_9$	227	9	0.50
$COAL_1$	600	6	0.39
$COAL_2$	600	3	0.40
Total	8629	–	–

Table 2: Characteristics of technologies available for new plants.

Technology	investment cost I_j $[M\text{Euro}/MW]$	rated power P_j $[MW]$	operating hours per year H_j $[h]$	construction time S_j $[years]$	industrial life L_j $[years]$	efficiency η_j $[-]$
Coal	1	600	7446	4	25	0.44
CCGT	0.47	800	7446	2	25	0.56
Nuclear	3.2	1200	7884	7	40	0.34
Biomass	3	20	6000	1	15	0.35
Wind	1.65	100	2215	1	20	–
Geothermal	3.5	40	7500	3	20	–
Mini hydro	3	1	3500	1	40	–

Table 3: Characteristics of fuels.

Fuel	Measure Unit $[m.u.]$	Fuel cost in year 0 [Euro$/m.u.$]	Lower heating value $[kWh/m.u.]$	Fuel cost in year 0 [Euro$/MWh$]	CO_2 emission rate $[t/GWh]$
Coal	$[t]$	100	8141	12.3	338
Gas	$[Nm^3]$	0.3	9.58	31.3	200
Nuclear	$[kg]$	2100	950171	2.21	0
Biomass	$[kg]$	0.81	10138	8.98	0

Fig. 2 shows the GenCo annual market share $\overline{M}_i$, for which a 2% increase per year is assumed. The ratio β_i "electricity from RES / total electricity produced" is set according to the 20-20-20 European target from year 2011 to year 2020 (i.e. from year 1 to year 10 of the

Table 4: Coal price in year 0: 100 Euro/t (12.3 Euro/MWh).

ratio	0.7	0.8	0.9	1.00	1.2	1.4	1.6	1.8	2.0
probability	0.005	0.03	0.1	0.565	0.20	0.06	0.025	0.01	0.005

Table 5: Gas price in year 0: 0.3 Euro/Nm^3 (31.3 Euro/MWh).

ratio	0.7	0.8	0.9	1.00	1.2	1.4	1.6	1.8	2.0
probability	0.005	0.03	0.1	0.565	0.20	0.06	0.025	0.01	0.005

Table 6: Nuclear fuel price in year 0: 2100 Euro/kg (2.21 Euro/MWh).

ratio	0.70	0.85	1.00	1.20	1.40	1.70	2.00
probability	0.01	0.07	0.72	0.15	0.035	0.01	0.005

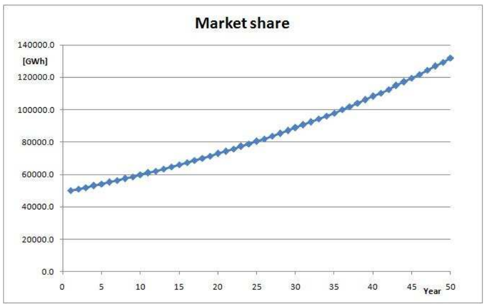

Figure 2: Scenario for the market share $\overline{M}_i$.

planning period); after 2020 a further increase is assumed as shown in Fig. 3.

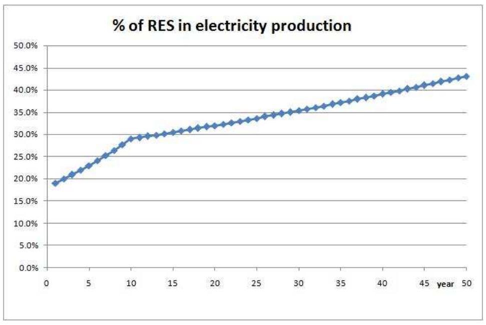

Figure 3: Scenario for ratio β_i "electricity from RES / total electricity produced".

The GenCo can satisfy the imposed β_i ratio either by producing from RES or by buying Green Certificates, see constraint (10). However, according to Decree 3 March 2011, this incentive is going to be substituted in Italy by a *feed-in tariff* (or a *feed-in premium*), to be applied to renewable energy sold in the Italian electricity market. Fig. 4 shows the maximum generation capacity, along the years in the planning horizon, of the power plants owned by the producer in year 0. The GenCo's maximum generation capacity is biased towards the CCGT technology and is consequently highly dependent on the gas price.

The available initial budget of the GenCo is equal to 7.68 GEuro.

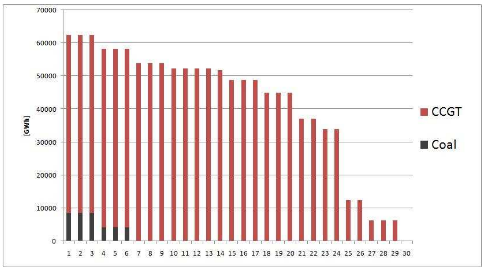

Figure 4: Generation capacity, along the years of the planning horizon, of power plants owned by the producer in year 0.

Numerical tests have been performed in order to assess how the optimal investment decisions are affected by the values of the model parameters. In the following, two sets of numerical results are presented:

1. the first set is obtained with the Green Certificate price $\pi_i^{GC} = 80$ Euro$/MWh$ and three alternative values of the risk-aversion parameter ρ, namely 0.167, 0.762 and 0.846;

2. the second set is obtained with the risk-aversion parameter $\rho = 0.762$ and two alternative values of the Green Certificate price, namely 80 Euro$/MWh$ and 85 Euro$/MWh$.

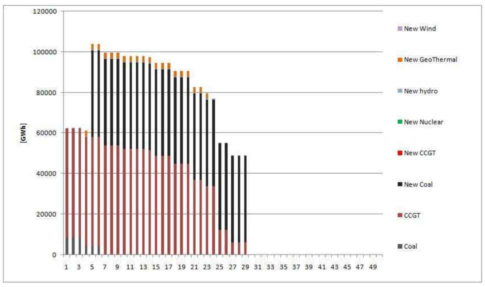

Figure 5: Optimal generation mix for risk-aversion parameter $\rho = 0.167$.

For Green Certificate price $\pi_i^{GC} = 80$ Euro$/MWh$ and risk-aversion parameter value $\rho = 0.167$ the new investments are essentially in coal plants, with the geothermal and mini-hydro technologies having only a residual role. The resulting optimal generation mix along the planning horizon is shown in Fig. 5, while in Fig. 6 the composition of the new generation capacity is shown for year 12, in which the construction of the new power plants is completed.

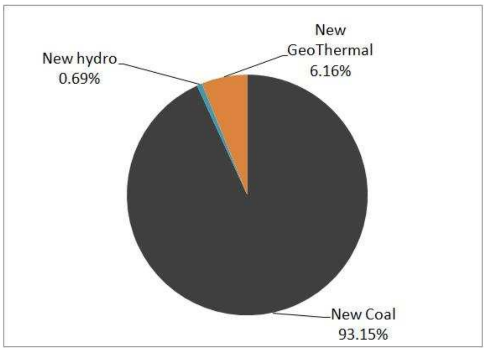

Figure 6: Production of new generation technologies in year 12 for $\rho = 0.167$.

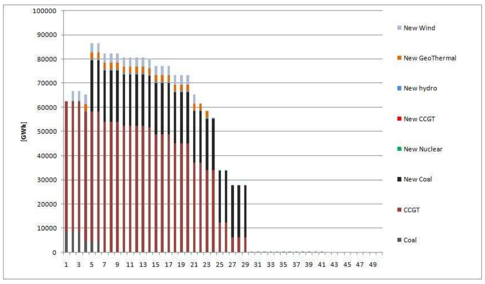

Figure 7: Yearly total production with risk-aversion parameter $\rho = 0.762$.

For Green Certificate price $\pi_i^{GC} = 80$ Euro$/MWh$ and risk-aversion parameter value $\rho = 0.762$ the investment in coal plants is reduced with respect to the case with $\rho = 0.167$ and substituted by investment in wind power plants; the investment in geothermal and mini-hydro technologies is also slightly increased. The resulting optimal generation mix along the planning horizon is shown in Fig. 7 and in Fig. 8 the composition of the new generation capacity in year 12 is shown.

Notice that the model never suggests to invest in new CCGT plants, as the GenCo is already oriented toward this technology and a further dependence from gas fuel would not be safe. This forces the generation portfolio diversification toward other technologies, depending on the risk level the GenCo is prepared to face.

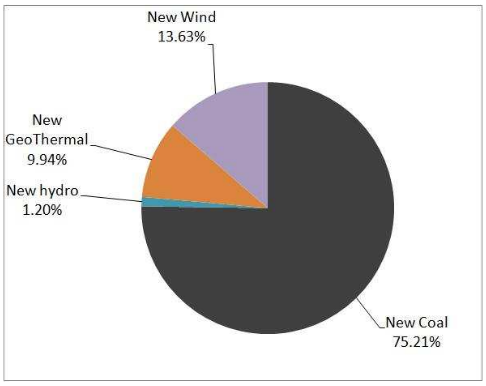

Figure 8: Production of new generation technologies in year 12 for $\rho = 0.762$.

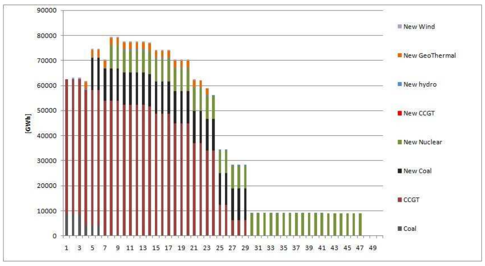

Figure 9: Yearly total production with risk-aversion parameter $\rho = 0.846$.

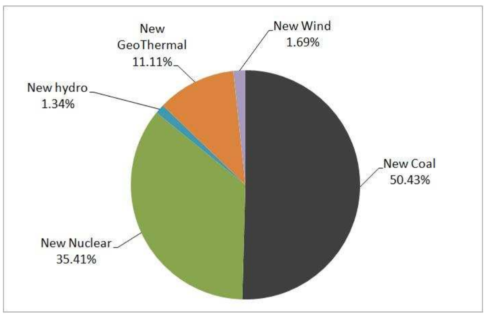

Figure 10: Production of new generation technologies in year 12 for $\rho = 0.846$.

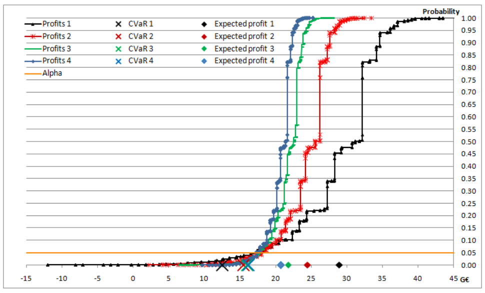

Figure 11: Profit distributions for different risk-aversion parameters and different GC prices.

For Green Certificate price $\pi_i^{GC} = 80$ Euro$/MWh$ and risk-aversion parameter value $\rho = 0.846$ the investment in coal plants is further reduced with respect to the previous cases; the nuclear and geothermal technologies play an essential role, while the investment in wind power and mini-hydro plants is only residual. The resulting optimal generation mix along the planning horizon is shown in Fig. 9 and in Fig. 10 the composition of the new generation capacity in year 12 is shown.

Fig. 11 shows the profit distributions (Profits 1,2,3) for the above considered values of the risk-aversion parameter. They include the values of profit in the 567 scenarios with their respective cumulated probabilities. For increasing values of ρ the optimal investment decisions suggested by the model correspond to decreasing expected value of profit, increasing Conditional Value at Risk of profits and increasing risk premium, i.e. expected profit per unit of standard deviation. These results are summarized in Table 7 (cases 1,2,3).

Table 7: Expected profit, $CVaR$, VaR and Risk premium for the considered risk-aversion and GC parameter values.

case	risk-aversion parameter	GC price (Euro / MWh)	Expected profit [G Euro]	$CVaR$ [G Euro]	VaR [G Euro]	Risk premium [$-$]
1	0.167	80	28.88	12.48	17.41	15.89
2	0.762	80	24.44	15.47	17.99	20.73
3	0.846	80	21.78	16.00	17.68	25.53
4	0.762	85	20.70	16.20	17.30	29.01

The second set of numerical tests aims at evaluating the role of incentives to power generation using RES. For the risk-aversion parameter $\rho = 0.762$ the impact on the optimal investment plans suggested by the model is shown for two alternative values of the Green Certificate price, namely 80 Euro/MWh and 85 Euro/MWh. The results for the case with $\pi_i^{GC} = 85$ Euro/MWh are reported in Fig. 12, 13: it can be noticed that the optimal solution is significantly affected by the Green Certificate price, resulting in higher investment in wind power technology. In Fig. 11, it is shown that the corresponding cumulated profit distribution (Profits 4) is the one with the lowest variability among the considered cases, but with the lowest expected profit.

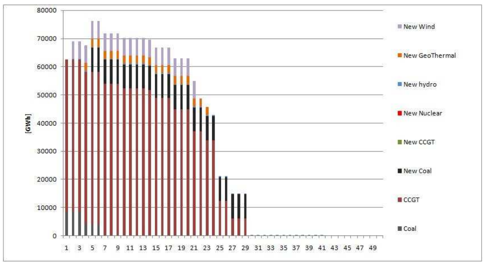

Figure 12: Yearly total production with $\rho = 0.762$ and $\pi_i^{GC} = 85$ Euro/MWh.

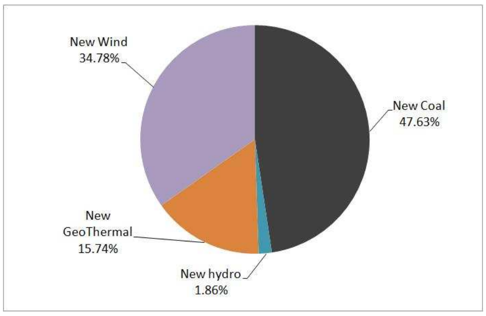

Figure 13: Production of new generation technologies in year 12 for $\rho = 0.762$ and $\pi_i^{GC} = 85$ Euro/MWh.

Looking at Table 7 we can compare case 2, $\pi_i^{GC} = 80$ Euro/MWh, with case 4, $\pi_i^{GC} = 85$ Euro/MWh : when the Green Certificate price is high, the expected profit decreases, because of the high costs of the Green Certificates to be bought in some scenarios, and the CVaR increases, because in scenarios with high fuel costs the GenCo has a high wind power production, which allows to reduce the power generated by thermal plants and therefore the amount of Green Certificates to be bought.

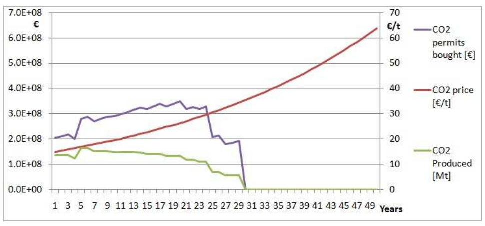

Figure 14: CO_2 price, CO_2 produced, CO_2 permits bought.

We have also considered the dependence of investment and production decisions on the CO_2 price. In scenarios with high CO_2 prices there are no investments in coal plants. With the current CO_2 price in year 0 and the forecast shown in Fig. 1, in all four cases discussed above, thermal power plants are constructed at the beginning of the planning horizon, when the CO_2 price is low, and no more generation technologies that produce CO_2 are active after year 30 of the planning horizon. However, the CO_2 price considered in this scenario does not impact on production decisions along the planning horizon, since capacity of available plants is fully used along the plant industrial life. In Fig. 14 the amount of CO_2 produced along the planning horizon and the value of the corresponding CO_2 emission permits bought is shown for the CO_2 price scenario shown in Fig. 1 and for Green Certificate price $\pi_i^{GC} = 80$ Euro/MWh with risk-aversion parameter value $\rho = 0.167$. Similar graphs are obtained in the other cases, namely for $\rho = 0.846$, $\rho = 0.762$ and in the case with $\pi_i^{GC} = 85\ /MWh$ and $\rho = 0.762$.

4 Conclusion

A multiperiod stochastic model is proposed for determining the optimal investment plans of power producer. The results show that the optimal solution is highly dependent on the power producer's attitude towards risk, represented by the risk-aversion model parameter. The model allows also to assess the impact of incentives to power generation from RES, as it has been shown by the sensitivity analysis performed on the Green Certificate price. The model can therefore be an useful tool to support power producers' investment decisions as well as Regulatory Authorities' analysis. Further work is under going for developing a multistage stochastic model with budget split along different times (stages) and future branching scenarios depending on new available information.

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