Models for the generation expansion problem in the Italian electricity market

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Abstract. We present deterministic and stochastic models for determining the optimal mix of different technologies for electricity generation, ranging from carbon, nuclear and combined cycle gas turbine to hydroelectric, wind and photovoltaic, taking into account the actual sites and the cost of investment in new sites, the cost of of mantainance, the use of emission quotas and the relative constraints as well as the green certificates one may use. The stochasticity is related to the future price of energy and to the future price of emissions, in this paper we limit our study to the variaility of fuels. The stochasticity appears in the expected costs and the probability that the total cost do not overcome a specific threshold is taken into account by considering CVaR risk measure. A comparison between the deterministic solution and the stochastic solution shows the role of using the risk the importance to use risk measure in the stochastic long run approach.

1 Introduction

The incremental selection of energy generation capacity is of great importance for energy planners; one can split the problem in two main stream-lines:

1. the single power producer's generator (GENCO) point of view,
2. the system operator's perspective.

For case (1) we need a mathematical model to determine the optimal expansion plan subject to all the relevant factors (regulations and prices) with the aim of finding an optimal trade-off between profit and risk. For case (2) we need a zonal representation of production and transmission system, to determine GenCo's expansion plans (where and when) taking into account the impact on the transmission network with the goal of minimizing system cost of satisfying load. There are various references in literature referring to case (1) or (2). We mention papers [1] and [3] for case (1). Paper [3] is the base of our model. We differ from it both for dealing differently the fixed and variable costs and for using a stochastic programming

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based model. More details about our model can be found in report [9]. Reference [2] is particularly useful in evaluating the use of different risk measures. For case (2) we mention the relevant contributions by [4], [5], [8].

In this paper we deal with case (1), i.e. we want to determine the optimal generation expansion plan of a single generation company (GenCo) over a long term planning horizon consisting in I years (generally, 20 or more years). Section 2 describes the model, Section 3 discusses the numerical results, the conclusions follow.

2 The stochastic model

The main factors affecting power producers decision can be summarized in the following:

- regulatory constraints
- uncertainty of prices (fuels, electricity CO2 emission and green certificates)
- characteristics of available technologies
- sites where plants can be located
- budget.

In the model we suppose that sites for locating new plants of each technology are already available, thus we want to determine the number of sites for each technology.

Let J^{ET} denote the set of existing thermal plants and J^{ER} denote the set of existing renewable plants, J^{NT} denote the set of candidate thermal plants and J^{NR} denote the set of candidate renewable plants. Let $J = J^{ET} \cup J^{ER} \cup J^{NT} \cup J^{NR}$. The model decision variables are the following:

- Real variables: let $E_{j,i}$ be the electricity produced by a plant of technology j in year i; the types of available tachnologies and their characteristics are illustrated in Table 1 and 2.
- Integer variables: let $w_{j,i}$ be the number of plants of technology j whose construction has to be started in year i.

In our model the capacity expansion is not a continuous variable but takes into account the size of each candidate plant.

The main goal of the model is to determine the evolution of the optimal investment along the planning horizon.

The total number of new plants for technology j, that can be built in the planning horizon, is bounded above by the number of available sites:

$$\sum_{i=1}^{I} w_{j,i} \leq \bar{M}_j. \tag{1}$$

Table 1: Technologies available for new plants and their characteristics

	installed capacity (MW)	construction time (years)	industrial life (years)
Coal	600	4	25
CCGT	800	2	25
Nuclear	1200	7	50
Biomass	20	1	15
Wind (non progr)	100	1	20
Geothermal	40	3	15
Mini hydro (partly progr.)	1	1	40

Table 2: Technologies available for new plants and their characteristics (cont.)

	CO2 emission rate (t/GWh	operating hours per year(hours)	Current fuel cost (euro/MWh)	Investment cost (Meuro/MW)
Coal	338	7884	30	1
CCGT	200	7884	50	0.47
Nuclear	–	7884	5	2.1
Biomass	–	6000	30	2.2
Wind	–	2215	–	1.75
Geothermal	–	7500	–	3.5
Mini hydro	–	3500	–	3

The maximum production of new plants in year i depends on the installed capacity P_j, the maximum number H_j of operating hours of plant j in year i and on the total number $W_{j,i}$ of operative plants j available for production in year i

$$E_{j,i} \leq P_j \cdot H_j \cdot W_{j,i} \tag{2}$$

where

$$W_{j,i} = \sum_{i-(S_j+L_j-1)\leq k\leq i-S_j} w_{j,k} \tag{3}$$

that is the sum of plants j, whose construction started in year k, provided in year i construction (S_j describes the length in years for construction)is completed and industrial life L_j is not ended.

The maximum production of existing plants in year i depends on installed capacity P_j, the maximum number H_j of operating hours of plant j in year i and on the residual life $\hat{L}_j$.

$$E_{j,i} = \bar{E}_{j,i} = \begin{cases} P_j \cdot H_j & \text{if} \quad i \leq \hat{L}_j \\ 0 & \text{if} \quad i > \hat{L}_j \end{cases} \tag{4}$$

The green certificates (GC) to be bought or sold are given by

$$G_i = \eta_i \cdot \left(\sum_{j \in J} E_{j,i}) \right) - \left(\sum_{j \in J^{ER} \cup J^{NR}} E_{j,i}) \right) \tag{5}$$

where the first term is total production using non-renewable in year i (η_i represents the ratio between renewable energy and total energy) and the second term is total production using renewable in year i.

The CO_2 emission permits to be bought or sold are given by

$$Q_i = \sum_{j \in J^{ET} \cup J^{NT}} \theta_j \cdot E_{j,i} - A_i^{CO_2} \tag{6}$$

where the first term represents the total emission in year i (existing and new thermal plants) and the last term represents the CO_2 emission allowance.

The budget constraint is given by

$$\sum_{i=1}^{I} \frac{1}{(1+r)^{i-1}} \cdot \left(\sum_{j \in J^{NT} \cup J^{NR}} I_j^a \cdot W_{j,i} \right) \leq B \tag{7}$$

where r is the discount rate, the quantity in parenthesis represents the annual investment cost (I_j^a represents the annual investment cost for technology j and B the available budget.

In this paper we consider scenarios for fuel prices (coal, gas, nuclear fuel). Scenarios are built on the ratios "estimated price over current price" of fuels for thermal plants combining in all possible ways the quantities in Tables 3, 4 and 5.

Table 3: COAL (30 Euro/MWh)

ratio	0.85	0.90	1.00	1.30	1.80	2.30	2.70	3.00
prob	0.010	0.050	0.560	0.220	0.109	0.035	0.014	0.002

Table 4: GAS (50 Euro/MWh)

ratio	0.90	0.98	1.00	1.20	1.60	2.20	2.60	3.00
prob	0.005	0.030	0.500	0.300	0.116	0.030	0.014	0.005

Table 5: NUCLEAR FUEL (5 Euro/MWh)

ratio	0.80	0.90	1.00	1.40	1.80	2.00	2.50	3.00
prob	0.020	0.090	0.752	0.120	0.010	0.005	0.002	0.001

The supply of gas may in some period be more critical than coal, while the supply of nuclear fuel is always available. These considerations are reflected in prices, leading to more stable prices for nuclear fuel with respect to coal and more volatile price for gas with respect to coal.

The expected profit term in the objective function takes the following form:

$$\sum_{i=1}^{I} \frac{1}{(1+r)^{i-1}} \Bigg(\pi_i^E \cdot \sum_{j \in J} E_{j,i} - \pi_i^{GC} \cdot G_i - \pi_i^{CO_2} \cdot Q_i + \\ - \sum_{j \in J^{ER}, i \leq \hat{L}_j} (f_j + v_j \cdot E_{j,i}) - \sum_{j \in J^{NR}} \left[(I_j^a + f_j) \cdot W_{j,i} + v_j \cdot E_{j,i} \right] + \\ - \sum_{s \in S} p_s \cdot \left\{ \sum_{j \in J^{ET}, i \leq \hat{L}_j} (f_j + v_{j,s} \cdot E_{j,i}) + \sum_{j \in J^{NT}} \left[(I_j^a + f_j) \cdot W_{j,i} + v_{j,s} \cdot E_{j,i} \right] \right\} \Bigg) \tag{8}$$

where $\pi_i^E, \pi_i^{GC}, \pi_i^{CO_2}$ are respectively the prices for electricity, green certificates and CO_2, f_j are fixed costs, v_j are variable costs for renewable, $v_{i,s}$ are variable costs for thermal plants and p_s is the probability of scenario s.

For the risk term we consider two alternatives:

- the variance of thermal generation fuel cost
- the conditional value at risk of thermal generation fuel cost.

The variance is expressed in the usual way, while CVaR is given (see [6] and [7]) by

$$CVaR = \theta + \frac{1}{\alpha} \cdot \sum_{s \in S} (p_s \cdot d_s) \tag{9}$$

with d_s subject to the following constraints:

$$d_s \geq \sum_{j \in J^{NT} \cup J^{NT}} v_{j,s} \cdot E_{j,i} - \theta, \qquad d_s \geq 0. \tag{10}$$

3 Computational results

The stochastic model uses 512 different scenarios, the decision variables are only first stage decision variables and the model maximizes a linear combination of function 8 with the risk measure 9, opportunely weighted by a risk-aversion parameter, subject to constraints (1) to (7) plus constraint (10).

To make a comparison among the two risk measures, we have produced Table 6, where we report the different risk-aversion coefficient that produce aprroximately the same expected profit with the two different measures. We analyze the decision variables for the two risk measures in 4 cases corresponding to different level of risk.aversion parameters.

Table 6: Comparison of results for Variance and CVaR measures

		A	B	C	D
risk-aversion parameter	variance	0.0	$0.2 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
	CVaR		1.16	1.52	1.76
Expected Profit	variance	$2.3 \cdot 10^{8}$	$1.3 \cdot 10^{8}$	$9.1 \cdot 10^{7}$	$8.2 \cdot 10^{7}$
	CVaR		$1.3 \cdot 10^{8}$	$9.0 \cdot 10^{7}$	$8.2 \cdot 10^{7}$
Standard Deviation	variance	$4.0 \cdot 10^{8}$	$1.0 \cdot 10^{6}$	$2.4 \cdot 10^{5}$	$1.0 \cdot 10^{5}$
	CVaR		$1.2 \cdot 10^{6}$	$2.5 \cdot 10^{5}$	$1.1 \cdot 10^{5}$

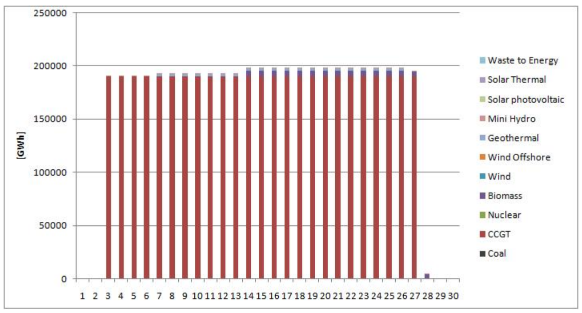

Figure 1: Case A: production of new plants along the planning horizon.

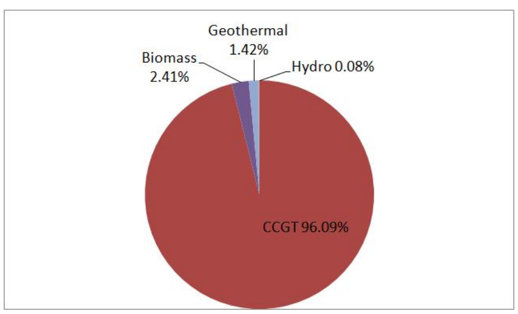

Figure 2: Case A: production of new plants in year $15th$.

From Figures 1 and 2 which correspond to case with risk aversion parameter equal to zero, we notice that almost all production (97%) involves CCGT plants since they have the lowest variable cost. Since variables $w_{j,i}$ are integer, there is a budget residual which is used for biomass, geothermal and mini hydro plants (small size and the cheapest after CCGT technology). The expected profit, as reported in Table 6, corresponds to $2.3 \cdot 10^{8}$ Euros.

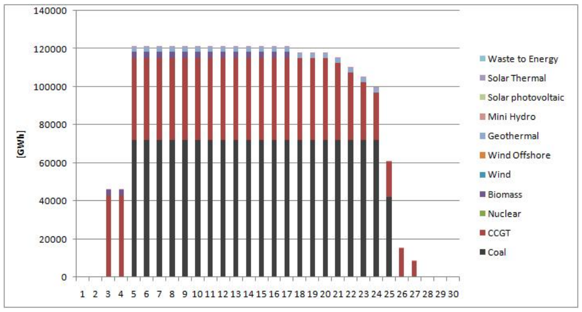

Figure 3: Case B with variance: production of new plants along the planning horizon.

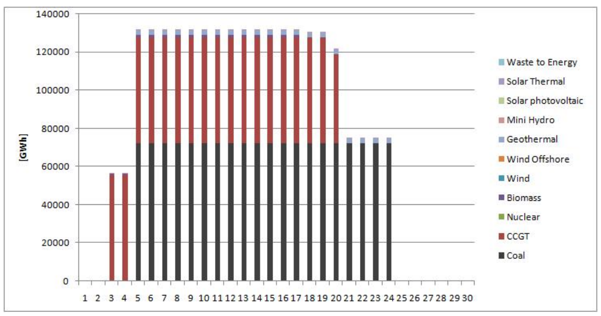

Figure 4: Case B with CVaR: production of new plants along the planning horizon.

Figures 3 and 4 correspond to risk aversion parameters (different values for the variance or CVaR cases) that give profit around $1.3 \cdot 10^8$ Euros. In year $15th$ both with variance and CVaR, only coal and CCGT plants are used for the thermal technology and no nuclear is used. With variance approach renewables plants are used for 5.1%, while with CVaR approach they are used for 3.2%.

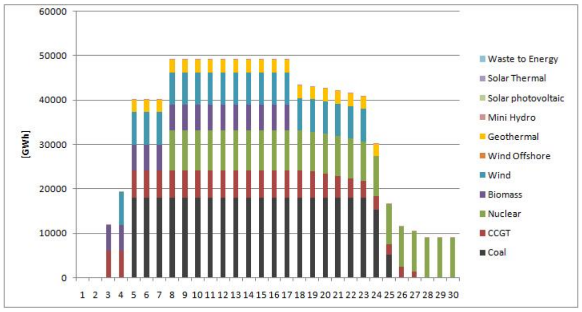

Figure 5: Case C with variance: production of new plants along the planning horizon.

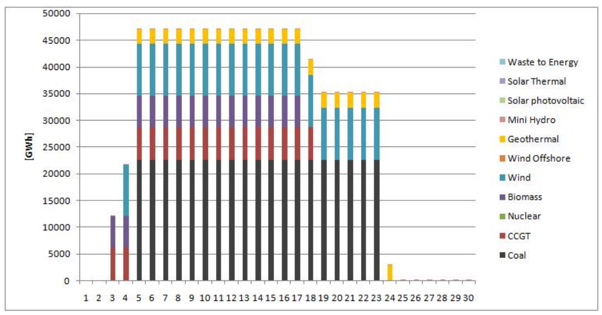

Figure 6: Case C with CVaR: production of new plants along the planning horizon.

With an expected profit of $9.1 \cdot 10^7$, see Table 6, which correpond to Figures 5 and 6, we notice that in year $15th$ with variance approach, coal and CCGT plants are used for the 49%, nuclear for 18% and renewables for 33%. With CVaR approach, coal and CCGT plants are used for the 61% and renewables for 39%.

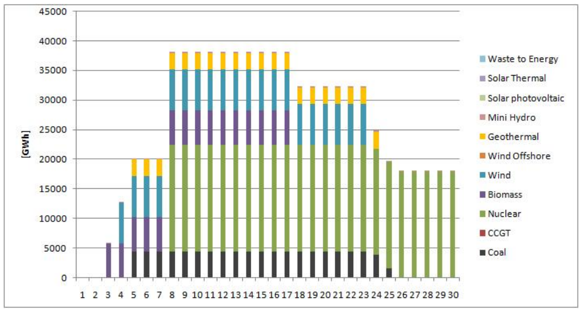

Figure 7: Case D with variance: production of new plants along the planning horizon.

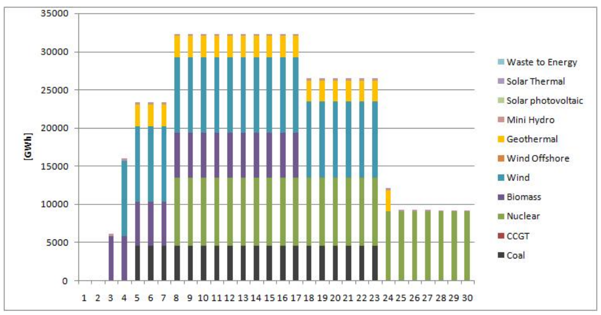

Figure 8: Case D with CVaR: production of new plants along the planning horizon.

Finally, Figures 7 and 8 correspond to an expected profit of $8.2 \cdot 10^7$, see Table 6. In year $15th$ with variance approach, coal plants are used for the 12%, nuclear for 47% and renewables for 41%. With CVaR approach, coal plants are used for the 14%, nuclear for 28% and renewables for 58%.

4 Conclusion

We adopt a simple scenarios generation combining in all possible ways the 8 scenarios for coal, gas and nuclear fuel for a total of $8^3 = 512$ scenarios. The results from the two-stage multiperiod model show that, taking into account risk, the toal expected profit decreases. Moreover, once the new plants come in operation, there is a period of stable energy production that declines towards the end of the planning period. This may be due to the so-called end of effect in stochastic optimization, related to the fact that you may have new plants that still have some residual life beyond the end of the planning horizon.

Acknowledgements The authors acknowledge the support from the grant byReg ione Lombardia "Metodi di integrazione delle fonti energetiche rinnovabili e monitoraggio satellitare dell'impatto ambientale", EN-17,ID 17369.10, and University of Bergamo grants (2010,2011) coordinated by M.Bertocchi and M.T. Vespucci.

References

[1] Bjorkvoll T., Fleten S.E., Nowak M.P., Tomasgard A., Wallace S.W., Power generation planning and risk management in a liberalized market, IEEE Porto Power Tech Proceedings, 1, 426-431 (2001)

[2] Conejo A.J., Carrion M., Morales J.M., Decision making under uncertainty in electricity market, International Series in Operations Research and Management Science. Springer Science+Business Media, New York (2010)

[3] Genesi C., Marannino P., Montagna M., Rossi S., Siviero I., Desiata, L., Gentile G., Risk management in long term generation planning, 6th Int. Conference on the European Energy Market, 1-6 (2009)

[4] Han S., Lee J., Kim T., Park, S., Kim B.H, The development of the generation expansion planning system using multi-criteria decision making rule The international Conference on Electrical Engineering (2009)

[5] Moghdass-Tafreshi S.M., Shayanfar H.A., Saliminia Lahiji A., Rabiee A., Aghaei J., Generation expansion planning in Pool market: a hybrid modified game theory and particle swarm optimization, Energy Conversion and Management, 52, 1512-1519 (2011)

[6] Rockafellar R.T., Uryasev S., Optimization of conditional value-at-risk, Journal of Risk, 2, 21-41 (2000)

[7] Rockafellar R.T., Uryasev S., Conditional value-at-risk for general loss distributions, Journal of Banking and finance, 26, 1443-1471 (2002)

[8] Roh J.H., Shahidehpour M., Fu Y., Market-based coordination of trasmisssion and generation capacity planning, IEEE Transaction on Power Systems, 22(4), 1406-1419 (2007)

[9] Vespucci M.T, Bertocchi M., Innorta I., Zigrino S., Deterministic and stochastic models for investments in different technologies for electricty production in the long period, Technical Report,Department of Information Technology and Mathematical Methods, University of Bergamo (2011)