Models for the generation expansion problem in the Italian electricity market

Maria Teresa Vespucci*, Marida Bertocchi§, Mario Innorta*, Stefano Zigrino*

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 maintainance, 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 variability 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

§Department of Mathematics, Statistic, Computer Science and Applications, Bergamo University, Via dei Caniana 2, Bergamo 24127, Italy. e-mail: marida.bertocchi@unibg.it

*Department of Information Technology and Mathematical Methods, University of Bergamo, Via Marconi 5a, 24044 Dalmine (BG), Italy. e-mail: mtvespucci@tin.it, mario.innorta@fastwebnet.it, stefano.zigrino@unibg.it
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 technologies 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:

$$ \sum_{i=1}^{I} w_{j,i} \leq M_j. $$ (1)
### Table 1: Technologies available for new plants and their characteristics

<table>
<thead>
<tr>
<th>Technology</th>
<th>Installed Capacity (MW)</th>
<th>Construction Time (years)</th>
<th>Industrial Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>600</td>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>CCGT</td>
<td>800</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1200</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>Biomass</td>
<td>20</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Wind (non progr.)</td>
<td>100</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Geothermal</td>
<td>40</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Mini hydro (partly progr.)</td>
<td>1</td>
<td>1</td>
<td>40</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Technology</th>
<th>CO2 Emission Rate (t/GWh)</th>
<th>Operating Hours per Year (hours)</th>
<th>Current Fuel Cost (euro/MWh)</th>
<th>Investment Cost (Meuro/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>338</td>
<td>7884</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>CCGT</td>
<td>200</td>
<td>7884</td>
<td>50</td>
<td>0.47</td>
</tr>
<tr>
<td>Nuclear</td>
<td>–</td>
<td>7884</td>
<td>5</td>
<td>2.1</td>
</tr>
<tr>
<td>Biomass</td>
<td>–</td>
<td>6000</td>
<td>30</td>
<td>2.2</td>
</tr>
<tr>
<td>Wind</td>
<td>–</td>
<td>2215</td>
<td>–</td>
<td>1.75</td>
</tr>
<tr>
<td>Geothermal</td>
<td>–</td>
<td>7500</td>
<td>–</td>
<td>3.5</td>
</tr>
<tr>
<td>Mini hydro</td>
<td>–</td>
<td>3500</td>
<td>–</td>
<td>3</td>
</tr>
</tbody>
</table>

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 $i$:

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

where

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

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 $\hat{L}_j$:

$$E_{j,i} = E_{j,i} = \begin{cases} P_j \cdot H_j & \text{if } i \leq \hat{L}_j \\ 0 & \text{if } i > \hat{L}_j \end{cases}$$
The green certificates (GC) to be bought or sold are given by

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

(5)

where the first term is total production using non-renewable in year \( i \) (\( \eta_i \) 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

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

(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

\[ \sum_{i=1}^{I} \frac{1}{(1 + r)^{i-1}} \cdot \left( \sum_{j \in J^{NT \cup J^{NR}}} I^a_j \cdot W_{j,i} \right) \leq B \]  

(7)

where \( r \) is the discount rate, the quantity in parenthesis represents the annual investment cost (\( I^a_j \) 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)

<table>
<thead>
<tr>
<th>ratio</th>
<th>0.85</th>
<th>0.90</th>
<th>1.00</th>
<th>1.30</th>
<th>1.80</th>
<th>2.30</th>
<th>2.70</th>
<th>3.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>prob</td>
<td>0.010</td>
<td>0.050</td>
<td>0.560</td>
<td>0.220</td>
<td>0.109</td>
<td>0.035</td>
<td>0.014</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 4: GAS (50 Euro/MWh)

<table>
<thead>
<tr>
<th>ratio</th>
<th>0.90</th>
<th>0.98</th>
<th>1.00</th>
<th>1.20</th>
<th>1.60</th>
<th>2.20</th>
<th>2.60</th>
<th>3.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>prob</td>
<td>0.005</td>
<td>0.030</td>
<td>0.500</td>
<td>0.300</td>
<td>0.116</td>
<td>0.030</td>
<td>0.014</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 5: NUCLEAR FUEL (5 Euro/MWh)

<table>
<thead>
<tr>
<th>ratio</th>
<th>0.80</th>
<th>0.90</th>
<th>1.00</th>
<th>1.40</th>
<th>1.80</th>
<th>2.00</th>
<th>2.50</th>
<th>3.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>prob</td>
<td>0.020</td>
<td>0.090</td>
<td>0.752</td>
<td>0.120</td>
<td>0.010</td>
<td>0.005</td>
<td>0.002</td>
<td>0.001</td>
</tr>
</tbody>
</table>

4
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:

\[
\sum_{i=1}^{I} \frac{1}{(1+r)^{i-1}} \left( \pi_i^E \cdot \sum_{j \in J} E_{j,i} - \pi_i^{GC} \cdot G_i - \pi_i^{CO_2} \cdot Q_i + \right. \\
- \sum_{j \in JER, i \leq L_j} (f_j + v_j \cdot E_{j,i}) - \sum_{j \in JNR} [(I_j^a + f_j) \cdot W_{j,i} + v_j \cdot E_{j,i}] + \\
- \sum_{s \in S} p_s \cdot \left\{ \sum_{j \in JET, i \leq L_j} (f_j + v_{j,s} \cdot E_{j,i}) + \sum_{j \in JNT} [(I_j^a + f_j) \cdot W_{j,i} + v_{j,s} \cdot E_{j,i}] \right\} 
\]

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

\[
CVaR = \theta + \frac{1}{\alpha} \cdot \sum_{s \in S} (p_s \cdot d_s)
\]

with \( d_s \) subject to the following constraints:

\[
d_s \geq \sum_{j \in JNT \cup JNT} v_{j,s} \cdot E_{j,i} - \theta, \quad d_s \geq 0.
\]

### 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 approximately 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

<table>
<thead>
<tr>
<th>risk-aversion parameter</th>
<th>variance CVaR</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.0</td>
<td>0.2 \cdot 10^{-4}</td>
<td>1.2 \cdot 10^{-4}</td>
<td>3.6 \cdot 10^{-4}</td>
</tr>
</tbody>
</table>

| Expected Profit         | variance CVaR | 2.3 \cdot 10^8 | 1.3 \cdot 10^8 | 9.1 \cdot 10^7 | 8.2 \cdot 10^7 |
| Standard Deviation      | variance CVaR | 4.0 \cdot 10^6 | 1.0 \cdot 10^6 | 2.4 \cdot 10^5 | 1.0 \cdot 10^5 |

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.
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%.
With an expected profit of $9.1 \cdot 10^7$, see Table 6, which correspond 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%.
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 total 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 by Regione 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

generation planning and risk management in a liberalized market, IEEE Porto
Power Tech Proceedings, 1, 426-431 (2001)

in electricity market, International Series in Operations Research and Manage-

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

tion expansion planning system using multi-criteria decision making rule The
international Conference on Electrical Engineering (2009)

Aghaei J., Generation expansion planning in Pool market: a hybrid modified
game theory and particle swarm optimization, Energy Conversion and Manage-
ment, 52, 1512-1519 (2011)

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

[7] Rockafellar R.T., Uryasev S., Conditional value-at-risk for general loss distri-

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 stochas-
tic models for investments in different technologies for electicity production in
the long period, Technical Report,Department of Information Technology and
Mathematical Methods, University of Bergamo (2011)