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# Impact of Renewable Energy Quotas and Emission Trade on Generation Planning

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***Abstract*—Growing environmental concern and compelling regulatory directives have forced Generation Companies (GENCOs) to revise criteria previously used for long term generation expansion planning. Constraints on renewable energy production and on $CO_2$ emission affect the economy of generation acting as a powerful drift towards the adoption of novel generation technologies. In the present work, the mathematical model of generation planning is presented aiming at the maximization of the net present value of the investment made in generation expansion, taking all the above limitations into account. A model is developed with reference to the present and the future generation mix of a given GENCO. The Lagrangian Relaxation method is used to solve the generation planning model requiring the solution of many sub-problems each relative to one generation plant a time. The solution of these sub-problems, obtained by dynamic programming, is interesting in its own right since it allows the decision maker to gauge the economic impact of the different generation technologies now available.**

***Index Terms* — Generation expansion planning; green certificates; emission trade; Lagrangian Relaxation; dynamic programming.**

## I. Nomenclature

$r$ discount rate (%) used to find the present value of future cash flows

$N_y$ number of years of the optimization horizon considered

$N_s$ number of sub-intervals in one year

$\rho_{ik}^{e}$ expected energy market price (€/MWh) for the *k*-th sub-interval of the *i*-th year of the optimization horizon

$\rho_{ik}^{gc}$ expected price of the "green certificates" (€/MWh)

$\rho_{ik}^{CO_2}$ expected cost of $CO_2$ emission (€/ton)

$\eta_i$ percentage of non-renewable generation to be covered yearly by renewable sources or by acquisition of green certificates

$N_{tot}^{ex}$ set of all the existing generation plants

$N_{tot}^{new}$ set of all the candidate new generation plants

$I_{jik}$ investment cost of the *j*-th new power plant incurred in the specified sub-interval $i,k$

$E_{ik}^{sold}$ total amount of energy sold at the market in the specified sub-interval

$G_{ik}^{sold}$ $\left(G_{ik}^{bou}\right)$ green certificate sold (bought) at the market

$Q_{ik}^{sold}$ $\left(Q_{ik}^{bou}\right)$ $CO_2$ emission right sold (bought) at the market

$\varepsilon_{j}^{CO_2}$ coefficient relating the $CO_2$ emission of plant *j* to the corresponding energy generation

$E_{jik}$ $\left(E_{jik}^{new}\right)$ electric energy produced by existing (new) plant *j* during sub-interval $i,k$

$\overline{E}_{jik}$ $\left(\overline{E}_{jik}^{new}\right)$ upper bound on the electric energy produced by existing (new) plant *j* during sub-interval $i,k$

$C_j\left(E_{jik}\right)$ cost incurred in the generation of energy $E_{jik}$

$w_{jik}$ binary variable associated with candidate new power plant *j*: $w_{jik}=1$ if plant *j* is installed and operating in subinterval $i,k$ ; $w_{jik}=0$ if plant *j* is not installed in the specified subinterval.

## II. Introduction

THE selection of generation capacity for addition to the generation park belonging to a given GENCO is of great concern to planners and decision makers. The dynamic interactions in time among the possible investment decisions have to be considered in view of the relevant long-term implications.

Two types of generation planning problems may be considered: the definition of the target generation mix representing the long-term solution [1–3] and the dynamic optimization of year-by-year generation additions [4–8].

The approach described in [1–3], consists in allocating blocks of load (obtained by means of the estimated load duration curve) to the available, or planned, generations ranked in order of increasing incremental cost.

The generation expansion planning problem is solved in [4] by employing optimal control techniques. More recent works exploit a variety of numerical optimization methods; namely linear programming [5–7], Lagrangian Relaxation [7] or Benders decomposition [8].

In the present paper, the dynamic optimization of year-by-year generation expansion planning is considered.

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A model is developed for the analysis and evaluation of the net present value corresponding to a given set of generation units; the adopted model consists of a large scale optimization problem in which the total expected gain of a GENCO is maximized. Constraints on energy balance, renewable energy quotas and $CO_2$ emissions are accounted for; variables include the amount of produced and sold energy and the status of each generation unit (this last modeled as a binary 0–1 variable). Scenario variables such as energy market prices and fuel costs will be assumed known on the basis of data available and reasonable extrapolation to the future. Also the regulatory policies internationally agreed upon have to be carefully modeled to obtain a realistic and viable generation expansion tool.

Results obtained consist in the most profitable generation expansion plan, i.e. the decision whether installing a particular generation unit during the optimization horizon. The aim is that of maximizing the net present value achievable by the GENCO considered, in correspondence to a given choice of scenario variables and expected regulatory policies. Cash flow behaviour and the evolution of the investment net present value over time can be readily evaluated as a by-product.

In this work, the Lagrangian Relaxation (LR) algorithm was adopted for the solution of the large-scale optimization problem deriving from the proposed generation expansion planning model. The LR algorithm allows the decomposition of the model into smaller sub-problems (involving one generation unit at a time) to be solved by dynamic programming. In this stage of the computation, the logical constraints on construction time and plant life-cycle duration are accounted for.

The solution procedure was implemented in the Matlab programming language and applied to carry out the generation expansion planning with reference to different price and regulatory policy scenarios.

## III. Formulation of the Single GENCO Model

### A. Model Structure

The objective function $F$, to be maximized, consists of the present value of the gains obtained by the GENCO over a time horizon of $N_y$ years into the future.

$$F = \sum_{i=1}^{N_y} (1+r)^{-(i-1)} \sum_{k=1}^{N_s} \Big[ \rho_{ik}^{e} E_{ik}^{sold} + \rho_{ik}^{gc} \left( G_{ik}^{sold} - G_{ik}^{bou} \right) + \rho_{ik}^{CO_2} \left( Q_{ik}^{sold} - Q_{ik}^{bou} \right) - \sum_{j \in N_{tot}^{new}} w_{jik} \left\{ C_j \left( E_{jik}^{new} \right) + I_{jik} \right\} - \sum_{j \in N_{tot}^{ex}} C_j \left( E_{jik} \right) \Big] \tag{1}$$

The incomes of the GENCO derive from the sale of energy $E_{ik}^{sold}$, green certificates $G_{ik}^{sold}$ and emission rights $Q_{ik}^{sold}$; the expenses derive from the purchase of green certificates $G_{ik}^{bou}$ and emission rights $Q_{ik}^{bou}$ as well as from the costs of generating energy by the power plants already in operation and by the new ones. With reference to the power units planned for installation, the investment cost $I_{jik}$ is to be taken into account.

The maximization of the objective function $F$ must comply with a number of limitations depending on both physical and regulatory constraints. In particular constraint:

$$\sum_{j \in N_{tot}^{ex}} E_{jik} + \sum_{j \in N_{tot}^{new}} w_{jik} E_{jik}^{new} = E_{ik}^{sold} \tag{2}$$

relates the amount of energy sold at the market to the production of existing and new power units. Constraint (2) must be enforced for each sub-interval of the whole optimization horizon.

The fulfillment of renewable energy quotas results in the following constraint to be satisfied for every year of the optimization horizon:

$$\sum_{k=1}^{N_s} \left[ G_{ik}^{bou} + \sum_{j \in N_{ren}} \left( E_{jik} + w_{jik} E_{jik}^{new} \right) \right] - \sum_{k=1}^{N_s} \left[ G_{ik}^{sold} + \eta_i \sum_{j \in N_{th}} \left( E_{jik} + w_{jik} E_{jik}^{new} \right) \right] = 0 \tag{3}$$

In (3), $N_{ren}$ and $N_{th}$ are the sets of renewable energy plants and of fossil-fueled units. Constraint (3) is supplemented by the following non-negativity condition on the amount of traded green certificates:

$$G_{ik}^{bou} \ge 0; \quad G_{ik}^{sold} \ge 0 \tag{4}$$

The combined effect of constraints (3) and (4) implies that, for each sub-interval, the considered GENCO will be either selling or buying green certificates, but not both.

$CO_2$ emission limitations are taken into account by the following two constraints:

$$\sum_{k=1}^{N_s} \left[ Q_{ik}^{sold} - Q_{ik}^{bou} + \sum_{j \in N_{th}} \varepsilon_j^{CO_2} \left( E_{jik} + w_{jik} E_{jik}^{new} \right) \right] = A_i^{CO_2} \tag{5}$$

$$Q_{ik}^{bou} \ge 0; \quad Q_{ik}^{sold} \ge 0 \tag{6}$$

which are analogous to (3) and (4) respectively; in (5), $A_i^{CO_2}$ is the yearly $CO_2$ allowance.

Additional constraints are those pertaining to the different generation technologies available to the GENCO as either existing or candidate generation units. In the simplest case generation plants are characterized by upper/lower bound constraints of the following type:

$$0 \le E_{jik} \le \bar{E}_{jik} \tag{7}$$

$$0 \le w_{jik} E_{jik}^{new} \le w_{jik} \bar{E}_{jik}^{new} \tag{8}$$

Constraints (7) and (8) refer to existing or to candidate new plants respectively.

The value of the upper bound $\bar{E}_{jik}$ or $\bar{E}_{jik}^{new}$ must be evaluated according to amount of producible energy computed with reasonable accuracy on the basis of historical data analysis, for existing units, or predicted for new plants by comparison with similar projects.

In addition to (7) and (8), all plants must satisfy logical constraints regarding the duration of each unit life-cycle (of the order of some tens of years in general). Moreover, a new plant cannot become operative (i.e. $w_{jik} = 1$) unless the corresponding construction time has elapsed. These logical constraints have the effect of coupling the integer variables $w_{jik}$ corresponding to several subsequent sub-intervals of the optimization horizon.

### B. Cost Components

Beside the investment cost, explicitly accounted for in (1), all remaining cost components are gathered in the expression $C_j\left(E_{jik}^{new}\right)$ and $C_j\left(E_{jik}\right)$. Cost is given as the sum of a constant term, corresponding to expenditures to be made independently of the actual energy generation, and of a variable term that can be expressed as a function of energy generation. The constant term takes into account amortization and decommissioning costs as well as a part of the operation and maintenance cost. The variable term mainly depends from fuel cost, but it also includes the remaining part of the operation and maintenance cost, expressed as a linear function of energy generation.

In the present work, the following linear expression was adopted for the fuel cost $C_j^{fuel}$ of the *j*-th generation unit:

$$C_j^{fuel}\left(E_j\right) = \frac{860\, c_{fuel}}{\eta_T LHV_{fuel}} E_j$$

In the above formula $c_{fuel}$ is the fuel unit price, $\eta_T$ is the thermodynamic efficiency of the plant and $LHV_{fuel}$ is the fuel lower heating value (expressed in Mcal/kg or Mcal/m$^3$ as the case may be).

According to these assumptions, the single GENCO model (SGM) becomes a large-scale linear programming problem with mixed (real and integer) variables. However, the logical constraints on construction time and plant life-cycle make the choice of existing mixed integer LP solvers impractical.

## IV. Lagrangian Relaxation

### A. Outline of the method

The majority of the constraints of SGM, namely those labeled (7)–(8), involve only one generation plant at a time. Constraints (2)–(6) involve the energy generation of many power plants considered at the same sub-interval of the optimization horizon. Constraints involving a single generation plant as (7), (8) are defined "*decoupled* " while those labeled (2)–(6), are called "*coupling*" constraints.

To tackle the mathematical complexity of SGM, it would be desirable to relax the coupling constraints in such a way that the resulting relaxed problem could be more easily solved for one generation unit a time. In the case of SGM, constraints (2) can be eliminated from the model by simply substituting the amount of energy sold $E_{ik}^{sold}$ into the objective function. Constraints (3)–(6) cannot be eliminated by substitution, since they involve all the energy generation of a whole year.

To relax the coupling constraints, the LR technique was used. The objective function $F$ is linearly penalized by adding the expressions of constraints (3) and (5) multiplied by a suitable estimate of the corresponding Lagrange multipliers $\lambda_i$ and $\mu_i$.

The modified objective function $D$ takes the following form:

$$\begin{aligned} D = F &+ \sum_{i=1}^{N_y} \lambda_i \sum_{k=1}^{N_s} \left[ G_{ik}^{bou} - G_{ik}^{sold} + \sum_{j\in N_{ren}} \left( E_{jik} + w_{jik} E_{jik}^{new} \right) \right. \\ &\left. - \sum_{j\in N_{th}} \eta_i \left( E_{jik} + w_{jik} E_{jik}^{new} \right) \right] \\ &+ \sum_{i=1}^{N_y} \mu_i \left\{ A_i^{CO_2} - \sum_{k=1}^{N_s} \left[ Q_{ik}^{sold} - Q_{ik}^{bou} + \sum_{j\in N_{th}} \varepsilon_j^{CO_2} \left( E_{jik} + w_{jik} E_{jik}^{new} \right) \right] \right\} \end{aligned} \tag{9}$$

The new objective function is maximized taking into account the decoupled (7), (8) and logical constraints only, in the course of a so-called "dual iteration"; in this computation, the multipliers $\lambda_i$ and $\mu_i$ are assumed known either by an initial estimation or as the result of the current iteration. The solution of the dual problem is particularly simple since the behaviour of each generation unit can be considered independently of the behaviour of all the remaining generators.

The dual iteration is followed by a "*primal iteration*" in which constraints (3)–(6) are enforced while keeping the integer variables $w_{jik}$ fixed at the values obtained during the dual iteration. With the $w_{jik}$ held fixed, the primal problem can be solved by standard linear programming techniques.

By comparing the values of the primal $F$ and dual $D$ objective functions, it is possible to check the convergence of the LR algorithm. The procedure is stopped after a sequence of alternate primal and dual iterations when the difference between the primal and dual objective functions (the so called *"duality gap"*) falls under a pre-specified tolerance; in general the convergence of the LR method becomes quite fast after the values of the integer variables $w_{jik}$ stabilize to their optimal values.

### B. Implementation issues

As previously mentioned, the dual iteration of the LR algorithm consists in the solution of many optimization subproblems, one for each generation unit.

For a new generation unit exploiting renewable energy, the resulting single plant model (SPM) can be formulated as that of maximizing the following objective function:

$$\sum_{i=1}^{N_y}\sum_{k=1}^{N_s} w_{jik}\left[\frac{\rho_{ik}^{e} E_{jik}^{new} - C_j\left(E_{jik}^{new}\right) - I_{jik}}{\left(1+r\right)^{(i-1)}} + \lambda_i E_{jik}^{new}\right] \tag{10}$$

subject to constraints (8) and to the logical constraints regarding construction time and life-cycle duration.

In the case of a fossil-fueled units to be considered for planning, the objective function would take the following form:

$$\sum_{i=1}^{N_y}\sum_{k=1}^{N_s} w_{jik}\left[\frac{\rho_{ik}^{e} E_{jik}^{new} - C_j\left(E_{jik}^{new}\right) - I_{jik}}{\left(1+r\right)^{(i-1)}} - \left(\eta_i \lambda_i + \varepsilon_j^{CO_2} \mu_i\right) E_{jik}^{new}\right] \tag{11}$$

The solution of SPM relative to any planned new plant, is obtained by two state ( $w_{jik} = 1$ and $w_{jik} = 0$ ) forward dynamic programming.

For an existing plant, the objective function would take the form (10) or (11), with the assumption that $I_{jik} = 0$ and the integer variable $w_{jik}$ is implicitly equal to 1 for the remaining life time of the generation unit.

After SPM has been solved for each unit of the generation park, the variables $G_{ik}^{sold}$, $G_{ik}^{bou}$ and $Q_{ik}^{sold}$, $Q_{ik}^{bou}$ are evaluated so as to enforce the equality constraints (3) and (5) and the value of the dual objective function $D$ is computed.

With the just computed values of the integer values $w_{jik}$ held fixed, the primal iteration would require the solution of a large-scale linear programming problem. Also the primal problem exhibits a structure that can exploited to gain computational efficiency. Indeed, since the logical constraints on the $w_{jik}$ values were taken into account in the preceding dual iteration, the primal problem consists of $N_y$ separate linear programming sub-problems which are solved, one at a time, for each year of the optimization horizon.

The overall scheme of the LR procedure is shown in Fig. 1.

One of the main problems in the implementation of the LR method is the choice of the initial values of the multipliers $\lambda_i$, $\mu_i$ and of their update at the end of each iteration of the whole procedure. By the sensitivity properties of the Lagrange multipliers, $\lambda_i$ and $\mu_i$ can be estimated as the change in the objective function $F$ for a 1 MWh, or respectively 1 ton of $CO_2$, change in the right-hand-side of (3) or (5). Therefore a good choice for the initial estimate of the multipliers is given by the following expressions:

$$\lambda_i = \frac{\bar{\rho}_{ik}^{gc}}{\left(1+r\right)^{(i-1)}}; \quad \mu_i = \frac{\bar{\rho}_{ik}^{CO_2}}{\left(1+r\right)^{(i-1)}} \tag{12}$$

in which $\bar{\rho}_{ik}^{gc}$ and $\bar{\rho}_{ik}^{CO_2}$ are the yearly average values of the green certificates and of the $CO_2$ emission rights.

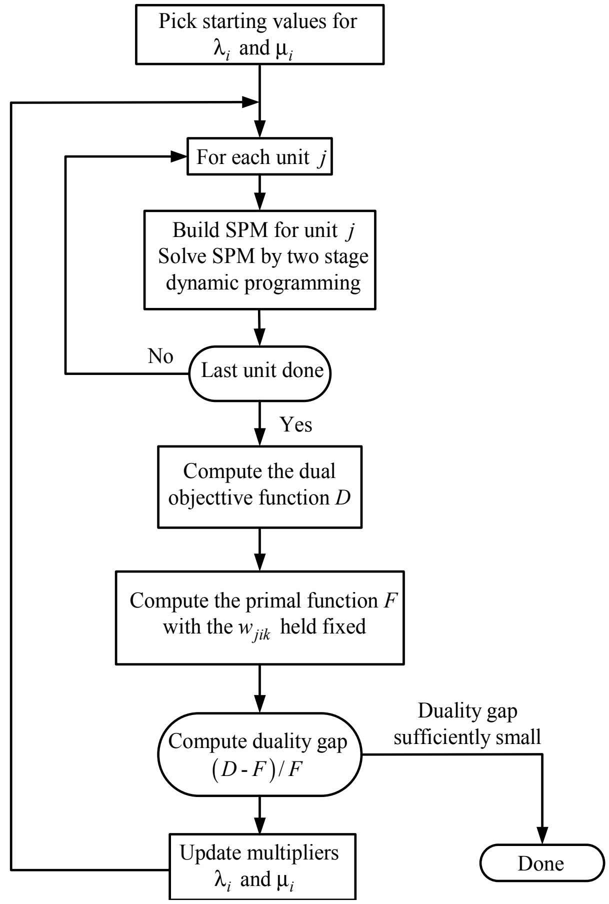


Fig. 1. Flow chart of the Lagrangian Relaxation procedure for SGM

The proposed implementation of the LR algorithm exhibits a fast convergence thanks to the adoption of the following multiplier update strategy:

$$\begin{aligned} \lambda_i &= w_d \lambda_i^d + w_p \lambda_i^p \\ \mu_i &= w_d \mu_i^d + w_p \mu_i^p \end{aligned} \tag{13}$$

In (13), $\lambda_i^d$, $\mu_i^d$ ( $\lambda_i^p$, $\mu_i^p$ ) are the multiplier values employed in the preceding dual (primal) iteration; $w_d$ and $w_p$ are non-negative coefficients satisfying the condition $w_d + w_p = 1$.

## V. Tests and Results

The proposed generation expansion planning procedure was implemented in the Matlab programming language exploiting the vectorization capabilities of this computation environment wherever possible. The two state dynamic programming algorithm employed to perform the SPM optimization was implemented autonomously; the linear programming solution required by the primal iteration was entrusted to the Matlab function "linprog" implementing a variant of Mehrotra's interior point method.

The procedure was tested on a 2.66 GHz personal computer based on the Intel Core 2 Duo processor on which Matlab 7.5 was installed.

### A. Test System and Scenario Variables Definition

The generation expansion planning of an hypothetical GENCO was considered with reference to a time horizon of 20 years subdivided into one week sub-intervals. Inside each sub-interval, the difference between peak and off-peak load hours is accounted for, by employing different energy price levels.

The composition of the existing generation park available is shown in Fig. 2. In Fig. 3, the prospective behaviour of the yearly renewable energy quota $\eta_i$ is illustrated.

With reference to the costs and prices behaviour, three different scenarios were considered. Scenario S1 roughly corresponds to the present day price situation regarding green certificates, $CO_2$ emission rights and fuels. This scenario is used here since it gives the feeling of what is presently perceived as convenient on a purely economical basis.

Scenario S2 simulates a fuel shortage situation in which fuel costs have increased to a larger extent with respect to energy prices.

Scenario S3 assumes that energy prices and fuel costs are increased as in S2, but a marked increase in the prices of green certificates and $CO_2$ emission rights forces the GENCO to invest in the field of renewable energy sources.

Base case and modified data relative to the different scenarios are summarized in Table I.

The generation technologies tested with reference to the three mentioned scenarios are those shown in the first column of Table II.

Coal, combined cycle and nuclear plants are intended to carry out base load service; mini hydro, with a rated power of up to 1 MW, is included on the assumption that larger and more economically convenient plants were already exploited in the past and are possibly included in the existing generation park. The data pertaining these and the remaining renewable source generation units (such as investment and all operation related costs) are consistent with those that can be found in the technical literature [9]. Table II shows the rated power of planned generation units and the maximum limits, pertinent to each technology, of the power to be installed according to the proposed generation planning procedure. In addition to the constraints of Table II, a limit of 8000 M€ was set on the amount of total investment cost relative to the entire 20 year optimization period.

The results corresponding to the three scenarios S1, S2 and S3 are shown in Fig. 4.

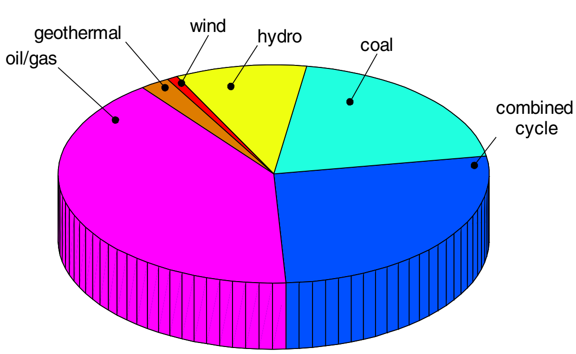


Fig. 2. Existing generation park composition

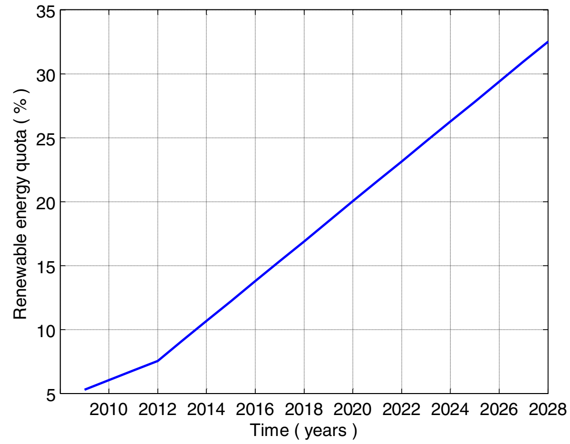


Fig. 3. Renewable energy quota behaviour

The results obtained from S1 and S2 are similar, the only difference being the allocation of 200 MW installed biomass generation with scenario S2 and a modest change in hydro power generation (961 MW for S1 and 815 MW for S2). The reasons for this behaviour have to be found in the philosophy of the model adopted for the present work. It is recalled that the aim of SGM is that of maximizing the total net present

TABLE I
COST-PRICE SCENARIOS USED IN THE TESTS

| | Scenarios | | |
|---|---|---|---|
| | S1 | S2 | S3 |
| $\rho_{ik}^{e}$ (1) (€/MWh) | 80 | 160 | 160 |
| $\rho_{ik}^{e}$ (2) (€/MWh) | 120 | 240 | 240 |
| $\rho_{ik}^{gc}$ (€/MWh) | 80 | 80 | 160 |
| $\rho_{ik}^{CO_2}$ (€/ton) | 11 | 11 | 200 |
| gas price (€/$m^3$) | 0.21 | 0.70 | 0.70 |
| coal price (€/kg) | 0.07 | 0.40 | 0.40 |
| nuclear fuel (€/kg) | 1280 | 3600 | 3600 |

(1) Peak hour price; (2) Off-peak price

TABLE II
LIMITS ON RATED POWER AVAILABLE FOR INSTALLATION

| Generation technology | Unit rated power (MW) | Maximum power (MW) |
|---|---|---|
| coal | 600 | 2000 |
| combined cycle | 400 | 2000 |
| nuclear | 1200 | 2000 |
| mini hydro | 1 | 1000 |
| terrestrial wind power | 100 | 200 |
| off-shore wind power | 100 | 200 |
| biomass (biogas) | 20 | 200 |
| geothermal | 40 | 200 |
| solar (thermodynamic) | 10 | 200 |
| solar (photovoltaic) | 10 | 200 |

value that can be obtained from a set of different technological choices. The net present value contribution of large fossil fueled or nuclear plants remains dominant even in the case of consistent increases in fuel costs. Among the renewable energy sources, hydro, terrestrial wind-power and geothermal plants are constantly selected for installation, thus confirming the economical convenience of these sources. With regard to these last technologies, the limit appears to be due only to the amount of installable power which depends on the maximum availability of hydro, wind and geothermal sources that can be exploited economically.

In contrast, the results obtained with scenario S3 are consistently different from those of S1 and S2; no additional coal or combined cycle units are installed while the renewable source generation available are exploited up to their maximum limits. The comment here is that the cost of green certificates and of $CO_2$ emission rights in particular, may act as a powerful drift toward the adoption of those renewable energy sources that are only marginally convenient from a purely economical point of view, such as off-shore wind power, biomass and (photovoltaic or thermodynamic) solar energy. With reference to scenario S3, it is worth noting that the nuclear resource is fully exploited also in this case; this result is clearly related to the fact that nuclear generation is not subject to the CO2 emission constraints which affect fossil fueled generation units.

### *B. Results of SPM*

The single plant model, described in Section IV.B, is an essential component of the overall SGM procedure, but it may also be considered as a stand-alone problem of particular interest for the planner. Since SPM is the optimization subproblem regarding the behaviour of a single generation for the whole optimization interval, it can be used to assess the techno-economical profitability of investing in a given generation technology. It is sufficient to replace $\lambda_i$ and $\mu_i$ in the objective functions (10) and (11) with their estimate given by (12) to obtain a significant picture of the economical convenience of a generation unit by means of the solution of SPM.

An example of the results of SPM is presented in Fig. 5 where the behaviour of the net present value of a 600 MW

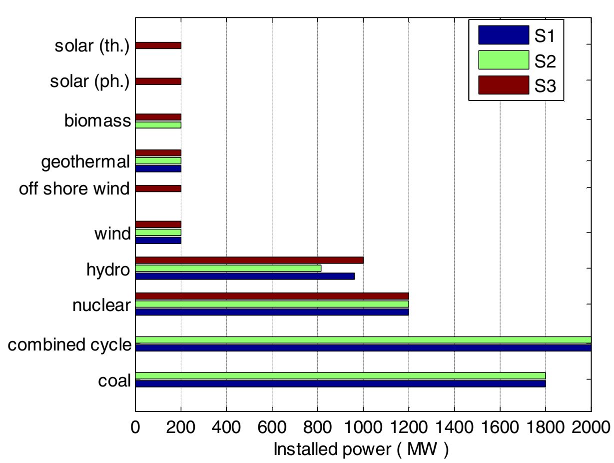


Fig. 4. Installed power according to the three scenarios considered

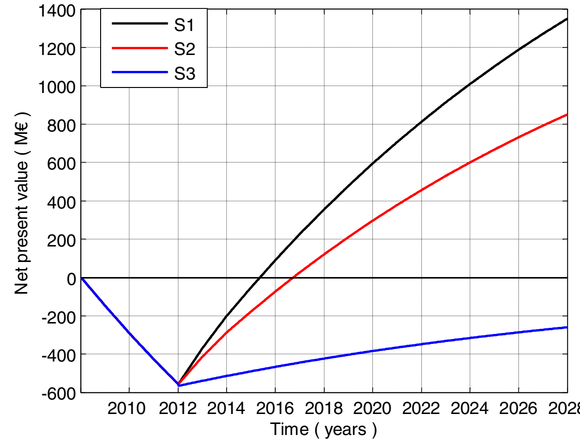


Fig. 5. Behaviour of the net present value of a coal unit

coal unit is shown for a 20 year time interval, with reference to the three previously mentioned scenarios.

It is apparent from Fig. 5 that the large price of the emission right, according to scenario S3, prevents net present value from reaching a positive value before the end of the optimization interval; so the investment is not economically convenient as previously noticed.

## VI. Conclusions

This work is concerned with the development of a mathematical model for generation expansion planning including not only investment and all different cost components, but also existing regulatory requirements. The resulting single GENCO model is a large-scale mixed integer programming problem including also logical constraints on the construction time and on the duration of generation unit life-cycle. SGM is solved by the Lagrangian Relaxation method which allows exploiting the separable nature of the problem by suitably relaxing the coupling constraints in the so-called dual iteration. Time parallelism is exploited also in the primal iterations of the algorithm, requiring the solution of a standard linear programming problem for each year of the optimization horizon. The generation expansion planning procedure was implemented in the Matlab programming language and tested with reference to different scenarios pertaining cost and regulatory policies.

It is important to point out that the SGM procedure is basically an analytical tool, useful to gauge the merits (and demerits) of a set of different generation technologies on the ground of economics. The results obtained from it, are fully dependent on the particular set of techno-economical data which form the input to the computation code. SGM, by itself, is not suited to serve as a strategic tool, but it should be supplemented with a suitable procedure that properly takes into account all uncertainties in fuel costs, price volatilities and economic risks.

## VII. Acknowledgment

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## IX. Biographies

**Camillo Genesi** received his Dr. Eng. degree in Electrical Engineering from the University of Pavia in 2005. He is presently working towards his Ph.D. in Electrical Engineering. His fields of interest are power system optimization, electricity market restructuring and application of artificial intelligence to power system analysis problems.

**Gian Pietro Granelli** received his Dr. Eng. degree in Electrical Engineering from the Politecnico di Milano, Italy, in 1968. In 1970, he became researcher and later (1973) Assistant Professor and (1985) Associate Professor of Electrical Engineering. He is currently a Full Professor of Electrical Energy Systems at the Department of Electrical Engineering of the University of Pavia, Italy. His main interests are power system optimization, real and reactive scheduling, voltage control and electricity market restructuring.

**Paolo Marannino** (F'01) received his Dr. Eng. degree in Electrical Engineering from the University of Bari, Italy in 1968. He joined the Automation and Computation Research Center of ENEL in Milan, where he was responsible for research activities in the field of power system analysis, optimization and control. Now he is a full professor of Electric Energy Systems at the University of Pavia, Italy. His main interests are power system optimization by deterministic and meta-heuristic methods. state estimation and real and reactive power scheduling.

**Mario Montagna** received his Dr. Eng. degree in Electrical Engineering from the University of Pavia, Italy in 1982. Since 1983 he has been with the University of Pavia as a researcher and later as an associate professor. His interests are in the field power system analysis, parallel computation, state estimation and nondeterministic optimization.

**Stefano Rossi** received his Dr. Eng degree in Electrical Engineering from the University of Pavia in 2007, discussing a thesis on multilateral market trade. He is presently working towards his Ph.D. in Electrical Engineering. His fields of interests are power system optimization and generation planning.

**Ilaria Siviero** received her Dr. Eng. degree in Electrical Engineering from the University of Pavia in 2007. She is currently working toward obtaining her Ph.D. from the same University. Her fields of interests are power system optimization, electricity market restructuring and power system planning.

**Luca Desiata** is a Mechanical Engineer with an MBA at INSEAD. He worked as a strategy consultant with Bain and as an IFC/World Bank advisor for privatization programs in the Balkans. After joining Enel SpA, he was involved, as Head of Strategic Projects, in the fields of nuclear energy, renewables, portfolio strategy, international integration, finance and risk management. He is currently working as Enel CEO assistant for International affairs.

**Giovanna Gentile** has been working at Enel SpA for more than 10 years in the field of energy management, as a controller of the hydroelectric plants and as a trader. She is currently working for the Environmental Policies of Enel, involved in projects and analysis of the main environmental policy themes: Kyoto, Green Package, ETS, NAP. During 2008, she focused on Italy's $CO_2$ Abatement Cost Curve developed with McKinsey. She has been in charge of e8 (Policy Committee) for the Italian chairmanship for the year 2008.