LINEAR PROGRAMMING APPROACH FOR THE TRANSITION FROM MARKET-GENERATED HOURLY ENERGY PROGRAMS TO FEASIBLE POWER GENERATION SCHEDULES

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Abstract – The paper aims at providing linear optimization models useful for a generating company for the solution of the transition problem from hourly energy programs – provided by day-ahead market auctions – to feasible power generation dispatches and to refined energy programs, as may be requested by the system operator. The feasible power generation dispatches and the refined scheduling should comply with both the energy constraint, i.e. they should provide the same hourly-energy productions defined by the day-ahead electricity market, and with all the power plant operating constraints. As some important power plant characteristics, such as ramp constraints, are not usually taken into account by the market auction mechanism, a feasible solution of the problem requires some additional efforts to be achieved. The paper describes a two-steps linear programming approach, based on constraint relaxation and coordination, conceived with the aim of solving the above problem and with the goal to achieve a minimization of the production costs. The features and qualities of the implemented models are shown by case studies that refer to the present rules of the Italian electricity market.

Keywords: Energy markets, Generation scheduling, linear programming.

1 INTRODUCTION

Several day-ahead electricity auctions clear the hourly market without consideration of inter-temporal constraints, i.e. they do not allow bidders to specify some technical constraints on the dispatch, such as ramp rate ones [1]. In the literature (e.g. [2]) the advantages and drawbacks of this scheme with respect to more centralized systems, which involve auctions allowing bidders to specify more technical constraints on the dispatch, have been investigated.

This paper proposes a the solution for the problem faced by generating companies when they have to adjust the market-generated hourly energy program in feasible power generation schedules to be implemented by power plant operators. The problem has also an impact on the use of generation reserves and on the performance of automatic generation control schemes [3].

Not every energy delivery that complies with the maximum and minimum generation limits can be realized by a power unit, if ramp-constraints are enforced [4]. Particularly in the case of day-ahead market auctions where a specific hourly energy program is settled for each generating plant – such as the Italian one – it often happens that a power generation schedule satisfying both the energy program and the capabilities of the units is not achievable. Therefore, the mismatches between hourly energy programs and feasible generation schedules must be compensated in following balancing market sessions.

The proposed linear programming approach aims at providing a tool for the definition of a feasible generation schedule that satisfies the given hourly energy program as much as possible, and, at the same time, allows the minimization of the operating production costs.

As the Italian market rules require also that generating companies provide a refined energy scheduling with shorter time steps (15 minutes) – used by the independent system operator performing usual security assessments – the proposed approach is structured in two coordinated linear programming optimization problems.

The objective function of the first problem contains the relaxed energy constraint and a function that takes into account other objectives, such as the minimization the production costs. It provides the power generation schedule, which is forced to meet all the operating constraints of the generating unit.

The output of the second problem is the refined energy program; it is forced to respect the hourly-energy productions defined by the electricity market. Its objective function provides the coordination between the two problems, by requiring the minimization of the energy mismatches between the output and the feasible production schedule, obtained as a solution of the first problem.

The paper has three additional sections.

Section 2 describes the model relevant to the first problem as a multiobjective optimization problem. Both a linear weighted sum strategy and the ε-constraint method are used to solve the problem. The ε-constraint method allows to easily assess if the hourly energy program can be satisfied without violating the ramp constraints, or to identify the minimum amount of energy that cannot be satisfied and a number of noninferior solutions. Section 3 presents the second problem linear formulation. Section 4 presents a sensitivity analysis of the results, obtained by considering typical cases of thermoelectrical power plants in different conditions – although also hydro power plants may be characterized by complex constraints, such as restricted operating zones and discharge ramping constraints [5].

The concluding section reviews the main points of the paper and the aspects that require an additional research effort.

2 TRANSITION FROM MARKET-GENERATED HOURLY ENERGY PROGRAMS TO FEASIBLE POWER GENERATION SCHEDULES

With reference to a single power unit scheduled for the entire next day, the problem of the transition from the market-generated hourly energy programs to a feasible power generation schedule can be formulated as a multiobjective optimization problem. In particular, three objectives can be recognized: 1) the minimum production cost, 2) the smoothest output power plant profile for the minimization of the stress on the plant components, and 3) the minimum unbalance between the hourly energy program and the energy produced with the feasible schedules.

As already mentioned, it is convenient, and often required by the market rules, to define the feasible generation schedules at time intervals shorter than an hour: typically each 15 minutes.

Moreover, for the calculation of the energy produced in each 15-minutes interval, one must also set the power profile within each period. In order to take into account realistic profiles other than the linear one (e.g. profile b) of Figure 1), while preserving the linearity of the model, a one-minute time-step discretization has been chosen. Note that, such a thin discretization is adopted only to let the optimization model deal with typical power plant non-linear behaviors between consecutive load-reference changes, which, it is worth reminding, are set by plant operators at intervals of 15 minutes.

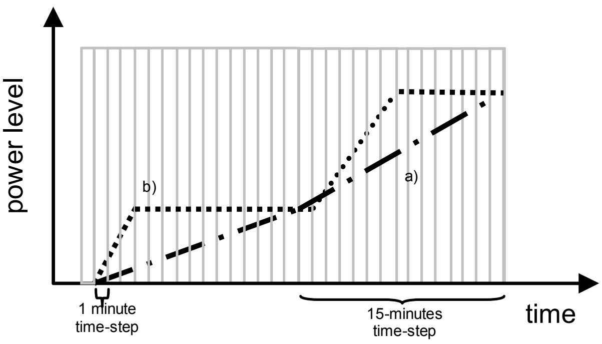


Figure 1 Examples of power profiles within 15-minutes periods: a) linear profile, b) maximum allowed ramp followed by constant level.

We here therefore consider the minimization problem of the following vector of three objective functions $\mathbf{F}(\mathbf{p})=\{F_1(\mathbf{p}), F_2(\mathbf{p}), F_3(\mathbf{p})\}$, where $\mathbf{p}$ is the vector of active output levels p_k at the end of each 1-minute time step k (k=1,…, 60·24), p_0 being the known value of the initial power level.

1. Minimization of the absolute values of the differences between consecutive power levels within each hour i

$$F_1(\mathbf{p}) = \sum_{h=1}^{24} \sum_{k=60(h-1)+2}^{60\cdot h} \left| p_k - p_{k-1} \right| \tag{1}$$

Note that, for the case of a single unit and for a given hourly energy program, this requirement means, in turn, the minimization of production costs. Indeed, whatever concave cost function is adopted, the cost minimization of hourly production is reached when the unit works at the same marginal cost and therefore, as far as possible depending on schedule and unit constraints, at constant output level in every sub-periods of each one-hour interval.

The occurrence in the objective of the absolute value of function a (i.e. $|a|$) can be replaced with a nonnegative slack variable s, subject to inequality constraints:

$$a+s \geq 0 \qquad \text{and} \qquad a-s \leq 0 \tag{2}$$

As in our case a is linear, this transformation allows to handle (1), and similar cases that will be shortly introduced, as linear models.

2. Minimization of the slope variations inside each 15-minutes interval j (j=1,…, 4·24):

$$F_2(\mathbf{p}) = \sum_{j=1}^{24\cdot 4} \sum_{k=15(j-1)+1}^{15\cdot j-1} \left| p_{k-1} - 2p_k + p_{k+1} \right| \tag{3}$$

To a certain extent, this minimization completes objective function 1 as it forces to distribute the differences between power levels among the various 1-minute intervals, throughout the 15-minutes interval.

3. Minimization of the unbalance between the hourly energy program $\mathbf{E}=\{E_1,\ldots, E_{24}\}$ and the energy produced with the feasible schedules inside each hour h

$$F_3(\mathbf{p}) = \sum_{h=1}^{24} \left| \left(\frac{1}{60} \sum_{k=60(h-1)+1}^{60\cdot h} \frac{p_k + p_{k-1}}{2} \right) - E_h \right| \tag{4}$$

The power generation schedules must be feasible, i.e. must respect the operating requirements of the generating unit. The problem formulation is thus completed by the following hard constraints:

— power level p_k can never be lower than a given value P_{min}, nor higher than a given value P_{max}:

$$P_{\min} \leq p_k \leq P_{\max} \qquad \forall k \tag{5}$$

— the absolute value of the difference between two consecutive power levels cannot exceed a given maximum ramp-up value Δ_u (if the power is increased), or a given maximum ramp-down value Δ_d (if the power is decreased):

$$-\Delta_d \leq p_k - p_{k-1} \leq \Delta_u \qquad \forall k \tag{6}$$

A weighted sum strategy converts the multiobjective problem of minimizing the vector into a scalar problem by constructing a weighted sum of all the objective components F_i. In our case, we can write:

$$\min_{\mathbf{p}\in\Omega} \sum_i w_i \cdot F_i(\mathbf{p}) \tag{7}$$

where Ω is the feasible region that satisfies constraints (5)-(6), and w_i denotes the weight assigned to component F_i.

In general, hourly energy programs have not flat profiles. Therefore, in particular when the energy unbalances (4) cannot be cancelled out due to the ramp constraints, F_1 and F_2 components of the objective are competing with F_3. Thus, the solution of the multiobjective problem is not unique, but significantly depends on the choice of the various weighting coefficient values, which is not straightforward.

Instead to try to define an optimal solution, for this first problem of the proposed two-steps linear programming approach we are looking to non inferior solutions [6], i.e., in our case, solutions in which an improvement in objectives F_1 and F_2 requires a degradation of objective F_3.

In order to simply identify a number of noninferior solutions, the so-called ε-constraint method is applied, minimizing objective components F_1 and F_2, and expressing the other objective, F_3, in the form of inequality constraints.

$$\min_{\mathbf{p}\in\Omega}\left\{w_1 \cdot F_1(\mathbf{p}) + w_2 \cdot F_2(\mathbf{p})\right\} \tag{8}$$

subject to

$$F_3(\mathbf{p}) \le \varepsilon \tag{9}$$

First of all, we find the minimum value ε* of the nonnegative variable ε that allows a feasible solution of problem (8)-(9). If such a value is ε*=0, it means that at least one feasible power generation schedule can be obtained from the market-generated hourly energy program. If ε*>0, ε* is the minimum level of energy unbalance that cannot be avoided due to the operating constraints of the power plant.

As already mentioned, the problem can be formulated as a linear program:

$$\begin{aligned} &\min \mathbf{c}^T \cdot \mathbf{x} \\ &\text{s.t.} \qquad \mathbf{A}\cdot\mathbf{x} = \mathbf{b} \\ &\qquad\quad \mathbf{l_{bounds}} \le \mathbf{x} \le \mathbf{u_{bounds}} \end{aligned} \tag{10}$$

where **x** is the column vector of n variables, **c** is a column vector of n constants, **b** is column vector of the known quantities of m equality constraints ($m<n$), **A** is the $m{\cdot}n$ matrix of the coefficient relevant to the equality constraints, $\mathbf{l_{bounds}}$ and $\mathbf{u_{bounds}}$ are the column vector of n lower and upper bounds, respectively. Superscript T indicates a transposed vector.

As inequality constraints can be transformed in equality constraints by the addition of slack variables, for the considered problem (8)-(9), the n components of vector **x** are:

- 60·24 variables, bounded between P_{min} and P_{max}, as required by (5), corresponding to the elements of vector **p**;
- 60·24 nonnegative slack variables relevant to the absolute values present in (1) (objective F_1);
- 60·24-1 nonnegative slack variables relevant to the absolute values present in (3) (objective F_2);
- 24 nonnegative slack variables relevant to the absolute values present in (4) (objective F_3);
- 2·60·24 nonnegative slack variables needed to transform inequality constraints of type (2) in equality constraints, for the case of the absolute values present in (1);
- 2·(60·24-1) nonnegative slack variables needed to transform inequality constraints of type (2) in equality constraints, for the case of the absolute values present in (3);
- 2·24 nonnegative slack variables needed to transform inequality constraints of type (2) in equality constraints, for the case of the absolute values present in (4);
- 60·24 variables, bounded between $-\Delta_d$ and Δ_u, as required by (6), corresponding to the differences between two consecutive power levels;
- 1 nonnegative slack variable needed to transform inequality constraint (9) in an equality constraint.

The m constraints, which define the m rows of matrix **A** and the m elements of vector **b**, are:

- 2·60·24 constraints of type (2) , for the case of the absolute values present in (1) (objective F_1);
- 2·(60·24-1) constraints of type (2) , for the case of the absolute values present in (3) (objective F_2);
- 2·24 constraints of type (2) , for the case of the absolute values present in (4) (objective F_3);
- 60·24 constraints, given by (6);
- 1 constraint, given by (9).

The non-zero elements of vector **c** are equal to w_1 or w_2: in particular, those multiplying, in (10), the slack variables associated to F_1 are equal to w_1; those elements multiplying the slack variables associated to F_2 are equal to w_2.

2.1 *Example of computational results*

The proposed approach has been implemented in two computer codes, for comparison purposes: one implemented in the model development environment MPL [7], using the CPLEX solver [8], and the second implemented in Matlab, using the LIPSOL solver [9]. The two codes give equivalent results.

Figure 2 shows the results obtained for the thermoelectric power unit whose data are summarized in Table 1. The figure shows the given market-generated hourly energy program, the calculated feasible power schedule and the relevant hourly energy production. The results have been obtained for ε*= 30 MWh, and the energy unbalances relevant to such a value of ε can be observed in the 4th (excess of 4.2 MWh) and 5th hours (lack of 25.8 MWh), due to the ramp-up constraint.

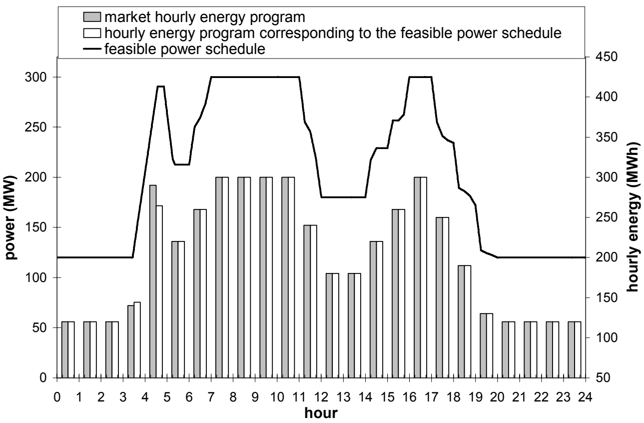


Figure 2 Example of a feasible power level profile of a thermoelectric unit (whose data are shown in Table 1) and the hourly energies corresponding to the power schedules, obtained from a given market hourly energy program (for w_1=1 and w_2=1).

Table 1 Data of the considered generating unit.

P_0 (MW)	P_{max} (MW)	P_{min} (MW)	Δ_u (MW/min)	Δ_d (MW/min)
120	300	120	2.5	3

By gradually increasing the value of parameter ε, we obtain different feasible power schedules corresponding to higher energy mismatches with respect the original market-generated hourly energy program. Figure 3 shows the hourly energy schedule obtained for ε^*=30 MWh, for ε=45 MWh and for ε=80 MWh. Figure 3 also shows the market clearing prices, in a generic monetary unit (m.u.), for each hour. Such a clearing price profile and the unit operating costs[1] have been used to calculate the costs and revenues, for different ε values, shown in Figure 4 as a percentage to the values obtained for ε^* (i.e. $175.1 \cdot 10^3$ m.u. for the costs and $225.2 \cdot 10^3$ m.u. for the revenues). The revenue associated to the original, market-generated, hourly energy program is $225.8 \cdot 10^3$ m.u.. Figure 4 also shows the values of objective function (8) obtained for different ε values, as a percentage of the value obtained for ε^* (740.3).

In the cases in which there is not a feasible power generation schedule that complies with the market-generated hourly energy program, the results shown in Figure 3 and Figure 4 provide an indication on the choice of the most convenient level of energy unbalance that should be compensated in following balancing market sessions.

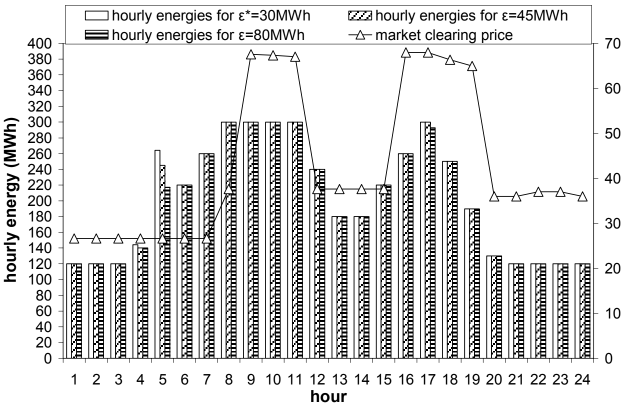


Figure 3 Assumed market clearing price and hourly energy programs associated to feasible schedules obtained for different values of parameter ε, for the same case of Figure 2.

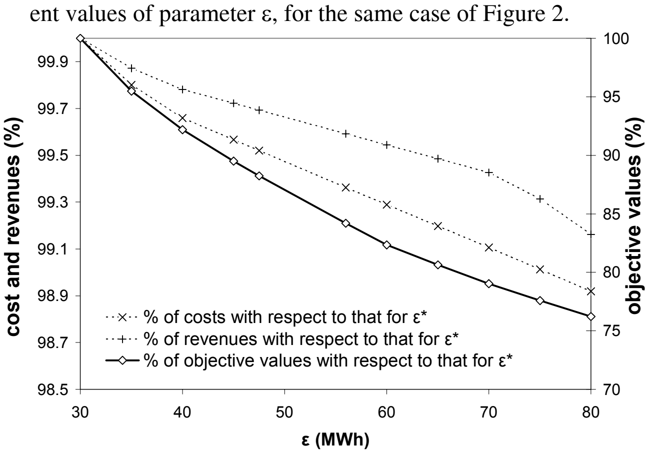


Figure 4 Percentages of costs, revenues and values of the objective function for different ε values with respect to the values for ε*, for the same case of Figure 2 and Figure 3.

[1] The operating costs are represented by a quadratic function of the power level, with coefficients c_0 = 1023 m.u./h, c_1 = 29,63 m.u./MWh and $c_2 = 5{,}39 \cdot 10^{-3}$ m.u./MW^{2}h.

3 REFINED 15-MINUTES ENERGY PROGRAM

The Italian market rules also require that the generating companies provide a refined energy for each power unit that complies exactly with the market hourly energy program. The duration of the time steps of the refined energy program is 15 minutes. Such a program is used by the system operator in order to carry out the preventive security assessments.

It is therefore convenient to build this refined energy program with 15-minutes time steps so that the operating constraints of the power unit are taken into account, as much as possible. It is moreover convenient that the 15-minutes energy program conforms to the feasible power schedule obtained with the procedure described in section 2.

The problem can be seen as the second part of a coordinated two step problem. Also this second part can be formulated as a multiobjective problem, set out by the following vector of two objectives **F'**(**p'**)={F_1'(**p'**), F_2'(**p'**), F_3'(**p'**)}, where **p'** is the vector of active output levels p'_k at the end of each 1-minute time step k (k=1,…, 60·24) corresponding to the 15-minutes energy program.

The objectives in this case are:

1. Minimization of the absolute values of the differences between the feasible power schedule **p** obtained as a solution of the first problem and the power schedule relevant to the refined energy program:

$$F_1'(\mathbf{p}') = \sum_{k=1}^{60\cdot 24} \left| p'_k - p_k \right| \tag{11}$$

This objective provides the coordination between the solution of this second problem and the feasible schedule **p**.

2. Minimization of the slope variations inside each 15-minutes interval j (j=1,…, 4·24), as in the first problem:

$$F_2'(\mathbf{p}') = \sum_{j=1}^{24\cdot 4} \sum_{k=15(j-1)+1}^{15\cdot j-1} \left| p'_{k-1} - 2p'_k + p'_{k+1} \right| \tag{12}$$

3. Minimization of the violations of the maximum up and down ramp constraints, that can be formulated as a linear model:

$$F_3' = \sum_{k=1}^{60\cdot 24} s'_k$$

$$\text{s.t. } (\forall k) \quad p'_k - p'_{k-1} + s'_k \geq -\Delta_d \tag{13}$$

$$p'_k - p'_{k-1} - s'_k \leq \Delta_u$$

The new power generation schedule **p**' corresponds to a 15-minutes energy program that must comply with the P_{min} and P_{max} constraints and with the market generated hourly energy program:

$$\left(\frac{1}{60} \sum_{k=60(h-1)+1}^{60\cdot h} \frac{p'_k + p'_{k-1}}{2} \right) = E_h \qquad \forall h \in \{1,\ldots,24\} \tag{14}$$

The problem has been implemented as a linear program (10). The n variable components of vector **x** are:

— 60·24 variables, bounded between P_{min} and P_{max}, corresponding to the elements of vector **p'**;

— 60·24 nonnegative slack variables relevant to the absolute values present in (11) (objective F_1');
— 60·24-1 nonnegative slack variables relevant to the absolute values present in (12) (objective F_2');
— 60·24 nonnegative slack variables s_k present in (13) (objective F_3');
— 2·60·24 nonnegative slack variables needed to transform inequality constraints of type (2) in equality constraints, for the case of the absolute values present in (11);
— 2·(60·24-1) nonnegative slack variables needed to transform inequality constraints of type (2) in equality constraints, for the case of the absolute values present in (12);
— 2·60·24 nonnegative slack variables needed to transform inequality constraints (13) in equality constraints.

The m constraints, which define the m rows of matrix **A** and the m elements of vector **b**, are:

— 2·60·24 constraints of type (2) , for the case of the absolute values present in (11) (objective F_1');
— 2·(60·24-1) constraints of type (2) , for the case of the absolute values present in (12) (objective F_2');
— 2·60·24 constraints (13) (objective F_3');
— 24 constraints, given by (14).

The no null elements of vector **c** are equal to w_1' or w_2' or w_3': those multiplying, in (10), the slack variables associated to F_1' are equal to w_1', those elements multiplying the slack variables associated to F_2' are equal to w_2', and those elements multiplying the slack variables associate to F_3'are equal to w_3'.

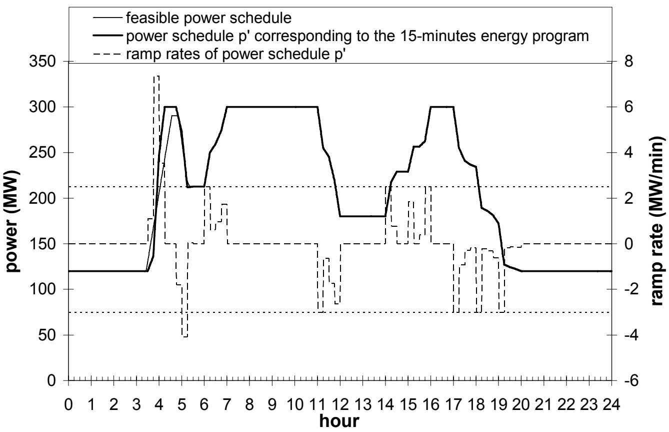


Figure 5 Comparison between the feasible schedule of Figure 2 and the power schedule **p**', solution of the second problem (for w_1'=1, w_2'=10^3, w_3'=1), with its ramp rates.

As done for the first problem of section 2, also this problem has been implemented in a computer code. Figure 5 shows the new power schedule **p**' corresponding to the 15-minutes energy program, solution of this second problem, for the case of the power unit of Figure 2. Figure 5 also show the comparison between **p**' and the feasible schedule **p**, as well as the ramp rates of **p**', which violate limit Δ_u in the last quarter of the 4th hour and the first quarter of the 5th hour, and violate limit Δ_d in the first quarter of the 6th hour.

4 SESTITIVITY ANALYSIS

This section presents some of the results concerning instances of the problem of interest different to those already analyzed, as an example, in the previous sections.

Section 4.1 presents the results obtained considering the same technical characteristics of the power unit of Table 1, with a different profile of the market hourly energy program.

Section 4.2 shows the comparison of the results obtained for various values of the maximum ramp-up and ramp-down limits.

4.1 Variation of the market hourly energy program

Figure 6 shows the considered market hourly energy program and the obtained feasible power schedule for the unit whose data are reported in Table 1. The figure shows also the hourly energy program associated to the feasible power schedule. Significant energy unbalancing occurs at 6th, 14th and 22nd hour, corresponding to a total value ε*=22.8 MWh, the minimum value that allows the convergence of the solution of problem (8)-(9). We note that, differently to what examined in the previous sections, the original revenue corresponding to the market hourly energy program is 243.7·10^3 m.u., lower than the revenue associated with the feasible power schedule, equal to 244.5·10^3 m.u.. This is due to the fact that, in this case, the enforcing of the ramp constraints results in an increase of the output energy, with a filling of the profile valleys, rather than a cut of the peaks.

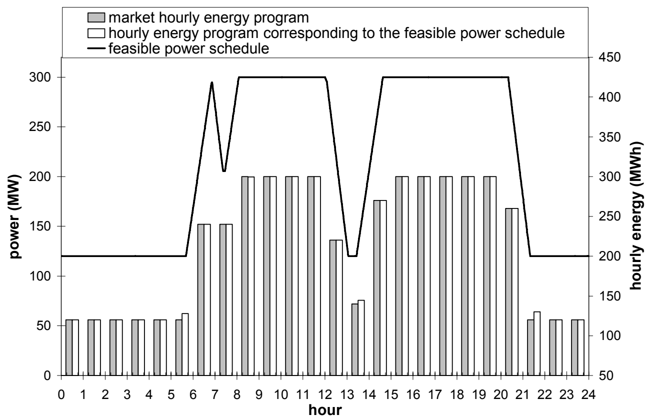


Figure 6 Feasible power level profile of a thermoelectric unit (whose data are shown in Table 1) and the hourly energies corresponding to the power schedules, obtained from a given market hourly energy program (for w_1=1 and w_2=1).

For the same case, Figure 7 shows the results of the second problem, i.e. the development of the refined 15-minutes energy program, described in Section 3. In particular, the figure shows the comparison between the feasible power schedule **p** and the power schedule **p**' corresponding to the refined 15-minutes energy program with the associated ramp rates. The violation of the maximum ramp rate limits occur in the intervals between hours 6-9, 12-15 and in the last quarter of the 21st hour.

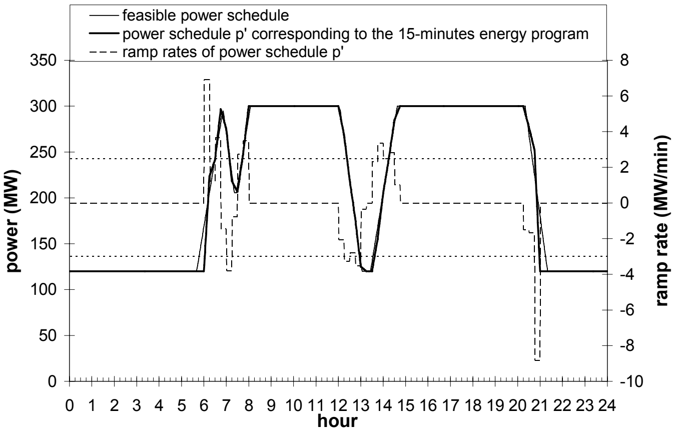
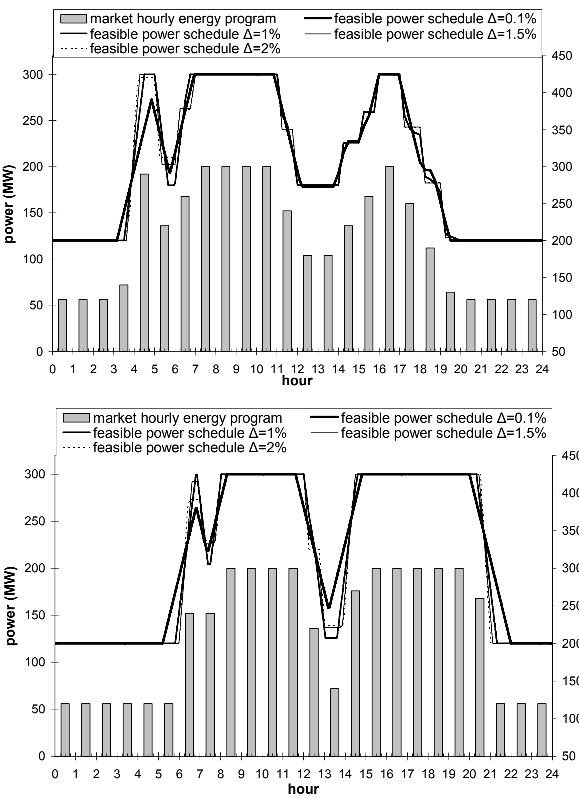


Figure 7 Comparison between the feasible schedule of Figure 6 and the power schedule **p'**, solution of the second problem (for w_1'=1, w_2'=10^3, w_3'=1), with its ramp rates.

4.2 Sensitivity analysis to ramp constraints

This section presents the results obtained for various values of the ramp limits. Δ_d and Δ_u are taken equal to each other and taken as a fixed percentage of the maximum output of the unit (P_{max}): the values 0.5%, 1%, 1.5%, 2% are investigated.



a)

b)

Figure 8 Comparison between the feasible schedules obtained for different values of the ramp rate limit Δ=Δ_u=Δ_d: 0.5%, 1%, 1.5% and 2% of P_{max}. Results obtained for two market hourly energy programs: a) profile 1, b) Profile 2. (w_1=1, w_2=1)

Figure 8 shows the comparison between the feasible power schedules obtained for various values of maximum ramp limits, both for the hourly energy program examined in sections 2 and 3 (profile 1) and for the hourly energy program taken into consideration in section 4.1 (profile 2).

Assuming, for both profile 1 and profile 2, the same market clearing prices of section 2, Table 2 presents the results of the sensitivity analysis, with the values of minimum energy unbalance ε* for the various values of Δ. Also the operating costs, revenues and objective values (for w_1=1 and w_2=1) are reported, as a percentage of the values obtained for Δ=2%, i.e. for the case in which the ramp constraints are (quite always) not active, namely:

- profile 1
  operating cost = $175.8 \cdot 10^3$ m.u.
  revenue= $225.8 \cdot 10^3$ m.u.
  objective value= 741,1
- profile 2
  operating cost = $184 \cdot 10^3$ m.u.
  revenue= $243.7 \cdot 10^3$ m.u.
  objective value= 766.8

Table 2 Sensitivity analysis results for various values of the maximum ramp limit Δ=Δ_u=Δ_d: 0.5%, 1%, 1.5% and 2% of P_{max}. The values of costs, revenues and objective values are in % of the values obtained for Δ=2%.

Δ (%)	ε* (MWh)	operating cost (%)	revenue (%)	objective value (%)
hourly energy profile 1				
0.5	64.5	99,26	99,51	102,42
1	15	99,82	99,88	110,36
1.5	0.73	99,99	99,99	104,51
2	0	100	100	100
hourly energy profile 2				
0.5	141.5	101,62	101,34	96,07
1	13.6	100,22	100,18	118,20
1.5	2.1	100,03	100,03	107,93
2	0.16	100	100	100

5 CONCLUSIONS

The paper has presented a two-step linear programming model for the transition from hourly energy programs, defined by day-ahead market auctions, to feasible power schedules and refined 15-minutes energy programs.

The first step is conceived to show the most convenient level of energy unbalances with respect the market hourly energy program that should be accepted in order to guarantee the feasibility of the power schedule and would be compensated in following balancing market sessions.

The second step allows obtaining the refined 15-minutes energy program required by the Italian market rules, in order to allow the security assessment procedures.

The results of the sensitivity analysis show the applicability of the proposed linear programming procedure in realistic cases.

At present, the Italian market rules does not allows to consider the various groups of a thermoelectric power plant as a single production unit for maximum output values of the plant exceeding some restricted limits. However, if the market rules would allow this opportunity, the proposed procedure is immediately applicable to the case of a power plant with several identical units and, with some minor modification, to the case of units with different efficiency and production costs. This would be the case, for instance, of power plants originally equipped with several conventional fossil-fired steam units, some of which have been revamped in gas-steam combined-cycle groups. Note that, if the assumed cost-output function is quadratic, the linearity of the model is preserved. Additional modeling effort, involving the adoption of non linear and mixed integer models, is required, however, in order to take into account more complex cost functions and to exploit the possibility to adopt self unit-commitment decisions. Also, more specific models are required for the case of hydroelectric systems with several hydraulically coupled plants and reservoirs.

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