INFLUENCE OF PRICE FORECASTING ON SHORT-TERM THERMAL SCHEDULING WITH ENVIRONMENTAL CONCERNS

J.P.S. Catalão, S.J.P.S. Mariano
UBI
Covilha, Portugal
{catalao, sm}@ubi.pt

V.M.F. Mendes
ISEL
Lisbon, Portugal
vfmendes@isel.pt

L.A.F.M. Ferreira
IST
Lisbon, Portugal
lmf@ist.utl.pt

Abstract – This paper proposes a practical approach to solve the short-term thermal scheduling (STTS) problem with environmental concerns. Under deregulation, minor changes in the energy price may give a significant change in the power generation of thermal units. Hence, the influence of price forecasting on STTS with environmental concerns is an important research issue, which is analysed in this paper considering different price profiles. This analysis is made in connection with a case study based on the standard IEEE 30-bus system.

Keywords: Thermal scheduling, Emission limitations, Multiobjective optimisation

1 INTRODUCTION

In a competitive environment, a generating company (GENCO) has a goal to produce electricity and sell it with maximum profit. The traditional short-term thermal scheduling (STTS) problem is defined as the task of establishing the minimum total fuel cost for the hourly generation schedule of the thermal units during a time horizon of one day up to one week, satisfying the demand of electrical energy and all physical and operational constraints. Redefining the STTS problem for the competitive environment involves changing the demand constraint from an equality to less than or equal constraint, and changing the objective function from cost minimisation to profit maximisation.

The STTS problem is usually treated as a deterministic one due to the short-term time horizon. Where stochastic quantities are included, the corresponding forecasts are used [1,2].

Energy conversion from fossil fuels into electric energy provides the backbone of the electricity supply industry worldwide [3]. Fossil fuels provide a reliable and affordable source of energy. However, one of the main contributions to the emission of greenhouse gases into the atmosphere, which is thought to be responsible for climate change on our environment, is through the use of fossil-fuelled power plants.

It is now recognised that the greenhouse effect can be slowed down only if the emission of carbon dioxide and other greenhouse gases is reduced drastically. A major step in this direction is the Kyoto Protocol, an international treaty under which industrialized countries will reduce their collective emissions of greenhouse gases by 5% over the five-year period of 2008–2012 compared to the year 1990. For the European Union (EU) the Kyoto target is an 8% reduction.

In December 2002, the EU created an emissions trading scheme (ETS) in an effort to meet the Kyoto targets. Quotas were introduced in six key industries: energy, steel, cement, glass, brick making, and paper/cardboard. There are also fines for member nations that fail to meet their obligations.

An unprecedented change is bound to occur in the new competitive and environmentally constrained electricity supply industry, where the role of the traditional coal-fired power plant is likely to change. Coal is by far the most abundant and cheapest fossil fuel with sufficient resources to sustain our long run needs for energy during centuries, but the combustion of coal in power plants discharges significant quantities of ash, nitrogen, sulphur oxides, mercury and greenhouse gases into the atmosphere.

In the old carbon unconstrained electricity supply industry, coal-fired power plants achieved a superior merit order, due to lower fuel costs, although posing a higher impact on the environment. In the presence of emission allowances, coal-fired power plants may move down in the merit order, due to higher carbon emission intensity. Hence, natural gas-fired power plants in combined cycle configuration, or even the new promising technology for coal power plants with zero emissions, will go up in the merit order. Gas-fired power plants will need less emission allowances than coal-fired power plants, resulting in a tendency for a shift in the merit order of the power plants [4].

Environmental concerns have become more and more important for fossil-fuelled power plants and they have to be considered in their management, giving rise to emission limitations. Fossil-fuelled power plants posing different emission levels should not be considered in the same way in what regards the generation decision. Some research work concerning emission limitations has already been done, but mainly for the economic dispatch (ED) problem [5,6], deciding only the power contribution of each unit but not its commitment status and availability for generation at each hour.

The account of emission limitations in the STTS problem, as in [7,8], did not receive lately as much attention as in the ED problem. Moreover, the environmental concerns have been included only in the minimum-cost optimisation problem, but not in the maximum-profit optimisation problem with different energy price profiles, which represents the new contribution of this paper.

Energy prices are important input data to achieve a successful generation schedule based on profit maximisation. This data has uncertainty due to the deregulation of the electricity markets. Hence, an accurate forecast of energy prices is a very valuable tool for a GENCO to optimally schedule its thermal units [9,10].

Under deregulation, minor changes in the energy price may give a significant change in the power generation of thermal units. Hence, the influence of price forecasting on STTS with environmental concerns is an important research issue, which is analysed in this paper considering different price profiles. This analysis is made in connection with a case study based on the standard IEEE 30-bus system.

2 PROBLEM FORMULATION

In the new competitive and environmentally constrained electricity supply industry, a GENCO with thermoelectric facilities faces the optimal trade-off problem of how to achieve maximum-profit by the management of the energy available in fossil fuels for power generation minimising the environmental impact. Hence, a maximum-profit optimisation problem with different energy price profiles is considered in this paper, instead of the minimum-cost optimisation problem considered in [5,6,7,8].

In the STTS problem under consideration, the objective function is a measure of the profit attained by the conversion of the energy available in fossil fuels into electric energy. Thus, the objective function to be maximised can be expressed as:

$$f(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})=\sum_{i=1}^{I}\sum_{k=1}^{K}\pi_k\,p_{ik}-C_{ik}\,(x_{i,k-1},u_{ik},p_{ik}) \quad (1)$$

subject to global and local constraints, where I is the total number of thermal units, K is the total number of periods in the scheduling time horizon, π_k is the forecasted energy price during period k, C_{ik} is the total fuel cost incurred by thermal unit i during period k, and x_{ik}, u_{ik}, p_{ik} are respectively the state, commitment decision and power generation of thermal unit i during period k. The commitment decision identifies if the unit is on-line or shutdown. The unit's state depends not only on the commitment decision, but also on the start-up and shutdown constraints. Once started or shutdown, a unit must remain committed or uncommitted for minimum durations: minimum up and down times. In addition to constraints on start-up and shutdown, a unit may have ramp-rate constraints: some generation levels cannot be reached from one period to the next [1,2].

Global constraints may further be divided into: hourly generation constraints, the power generated by the thermal units is less than or equal to the demand of electrical energy D_k during period k:

$$\sum_{i=1}^{I}p_{ik}\le D_k \quad k\in K \quad (2)$$

and cumulative constraints:

$$\sum_{i=1}^{B_n}\sum_{k=1}^{K}H_{ni}\,(x_{i,k-1},u_{ik},p_{ik})\le H_n^{\mathrm{req}} \quad n\in N \quad (3)$$

where B_n is the set of thermal units on nth cumulative constraint, H_{ni} is the function which describes contribution of thermal unit i to nth cumulative constraint, H_n^{req} is the upper bound on nth cumulative constraint and N is the number of cumulative constraints [1,2]. An example of these constraints would be the limitation on emission by a group of units over the scheduling time horizon [7,8].

The local constraints are the state equations for the thermal units:

$$(x_{ik},p_{ik})=A_{ik}\,(x_{i,k-1},u_{ik}) \quad i\in I,\ k\in K \quad (4)$$

where A_{ik} is the thermal unit i state function during period k, providing the state and power generation of thermal unit i during period k for the state during period $k-1$ and the commitment decision during period k. The time dependence of the state function A_{ik} is needed to account for the user-specified time-varying state constraints [1,2]. A dispatch function P_{ik} maps the decision u_{ik} and the resulting state x_{ik} into the power generation admissible range:

$$p_{ik}=P_{ik}(x_{ik},u_{ik}) \quad i\in I,\ k\in K \quad (5)$$

where the decision u_{ik} belongs to the set of admissible decisions U_{ik}, which is state dependent; and the initial state x_{i0} and final state $x_{i\mathrm{f}}$ belong to the initial state set X_i^0 and the final state set X_i^{f}, respectively:

$$u_{ik}\in U_{ik} \quad x_{i0}\in X_i^0 \quad x_{i\mathrm{f}}\in X_i^{\mathrm{f}} \quad i\in I,\ k\in K \quad (6)$$

The set of feasible variables is defined by (2) to (6):

$$F=\left\{(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}):\ \text{constraints (2) to (6) are satisfied}\right\}$$

The STTS problem may be reformulated into a minimisation problem. Thus, the objective function to be minimised can be expressed as:

$$g(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})=\sum_{i=1}^{I}\sum_{k=1}^{K}C_{ik}\,(x_{i,k-1},u_{ik},p_{ik})-\pi_k\,p_{ik} \quad (7)$$

The total fuel cost incurred by thermal unit i during period k is given by the sum of the start-up cost with the operation cost. We consider the start-up cost given as a constant, and the operation cost mathematically modelled as a convex function.

The operation cost is assumed to be computed by a quadratic function of power generation as [6]:

$$C_{ik}^{\mathrm{op}}\,(u_{ik},p_{ik})=u_{ik}\,(a_i+b_i\,p_{ik}+c_i\,p_{ik}^2) \quad (8)$$

where a_i, b_i and c_i are the cost coefficients for thermal unit i.

Alternatively, the objective function to be minimised can be the total emission, expressed as:

$$h(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) = \sum_{i=1}^{I}\sum_{k=1}^{K} E_{ik}\,(x_{i,k-1}, u_{ik}, p_{ik}) \tag{9}$$

The emission is assumed to be computed by the sum of quadratic and exponential functions of power generation as [5]:

$$E_{ik}^{\text{em}}\,(u_{ik}, p_{ik}) = u_{ik}\,\big[\,10^{-2}(\alpha_i + \beta_i\, p_{ik} + \gamma_i\, p_{ik}^2) + \zeta_i \exp(\lambda_i\, p_{ik})\,\big] \tag{10}$$

where α_i, β_i, γ_i, ζ_i and λ_i are the emission coefficients for thermal unit *i*. The emission coefficients in (10) are computed by the given data for the type of pollutant.

3 PRACTICAL APPROACH

The STTS problem with environmental concerns is formulated in this paper as the following multiobjective optimisation (MO) problem:

$$\mathit{Min}\ \{\, g(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}), h(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})\,\} \tag{11}$$

subject to:

$$(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) \in F \tag{12}$$

In our generation schedule problem with two individualized objective functions, an efficient solution to the MO problem, also known as non-dominated or Pareto-optimal solution, corresponds to a compromise where attempts to improve the value of one objective function lead to a degradation in the value of the other objective function. The collection of non-dominated solutions is called the Pareto-optimal set. The trade-off curve represents the image of the Pareto-optimal set into the space of objectives.

If the problem had been reduced to a single objective problem by treating the emission as a constraint, it would be difficult to obtain the trade-off relations [5]. This is an advantage of using the multiobjective criteria instead of a single objective regarding the profit maximization. The availability of the Pareto-optimal set and trade-off curve between profit and emission will give a quantitative base to decision-makers for readjusting the scheduling according to emission allowance trading.

The most widely used method for generating non-dominated solutions and trade-off curve is the weighted sum method, especially when the MO problem has only two objectives. Adopting the weighted sum method, a non-dominated solution to the MO problem can be determined by a convex combination of the objective functions:

$$o(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) = w\, g(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) + (1-w)\,\xi\, h(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) \tag{13}$$

where w is the weighting factor and ξ is the scaling factor, given for instance by a carbon market price, price, which is assumed constant over the scheduling time horizon.

The trade-off curve can be found by parametrically varying the weighting factor w between 0 and 1, thus solving single objective optimisation problems. The best emission commitment (BEC) corresponds to $w = 0$, while the best profit commitment (BPC) corresponds to $w = 1$.

Our practical approach may merge the weighted sum method with the $\varepsilon-$constraining method into a hybrid method, which constraints the objective functions by some allowable levels ε:

$$\sum_{i=1}^{I}\sum_{k=1}^{K} C_{ik} - \pi_k\, p_{ik} \le \varepsilon_C^{\text{req}} \tag{14}$$

or

$$\sum_{i=1}^{I}\sum_{k=1}^{K} E_{ik} \le \varepsilon_E^{\text{req}} \tag{15}$$

in order to overcome the difficulty on finding the non-convex Pareto-optimal set for the MO problem.

Hence, a non-dominated solution m in the Pareto-optimal set, representing a 168 hours generation schedule, is characterized by a total profit and a total emission in the space of objectives.

4 CASE STUDY

The proposed practical approach has been applied on a case study based on the standard IEEE 30-bus system.

The single-line diagram of the IEEE 30-bus system is shown in Figure 1.

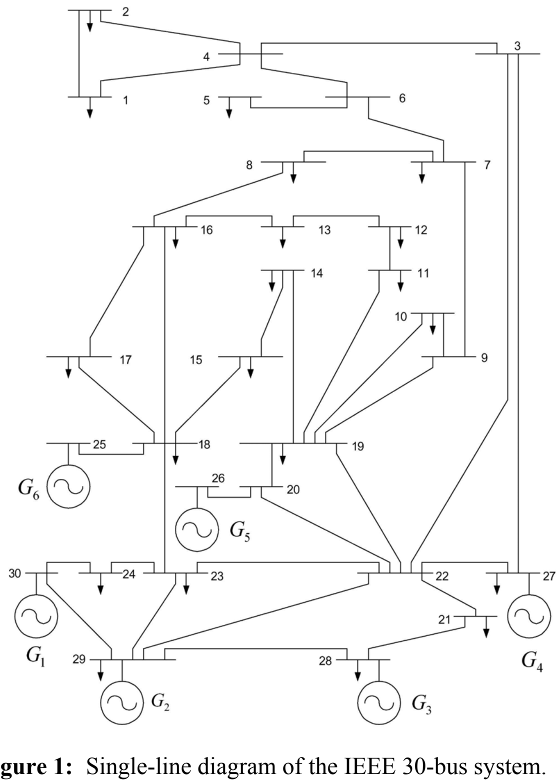

Figure 1: Single-line diagram of the IEEE 30-bus system.

Table 1 shows the units coefficients for fuel cost and emission [5].

unit	*1*	*2*	*3*	*4*	*5*	*6*
a	10	10	20	10	20	10
b	200	150	180	100	180	150
c	100	120	40	60	40	100
α	4.091	2.543	4.258	5.426	4.258	6.131
β	-5.554	-6.047	-5.094	-3.550	-5.094	-5.555
γ	6.490	5.638	4.586	3.380	4.586	5.151
ζ	2.0e-4	5.0e-4	1.0e-6	2.0e-3	1.0e-6	1.0e-5
λ	2.857	3.333	8.000	2.000	8.000	6.667

Table 1: Fuel cost and emission coefficients.

Table 2 shows the unit's characteristics and constraints on start-up and shutdown. Ramp-rate constraints have not been considered in this case study.

unit	*1*	*2*	*3*	*4*	*5*	*6*
$p_i^{\max}$ *(MW)*	50	60	100	120	100	60
$p_i^{\min}$ *(MW)*	5	5	5	5	5	5
Start-up ($)	20	20	40	20	40	20
Min up (h)	2	2	2	2	2	2
Min down (h)	2	2	2	2	2	2

Table 2: Unit's characteristics and constraints on start-up and shutdown.

Our practical approach was developed and implemented on a 2.8-GHz-based processor with 512 MB of RAM using FORTRAN language. The scheduling time horizon chosen is one week divided into 168 hourly periods.

The three energy price profiles considered over the time horizon are shown in Figure 2 (where $ is a symbolic economic quantity).

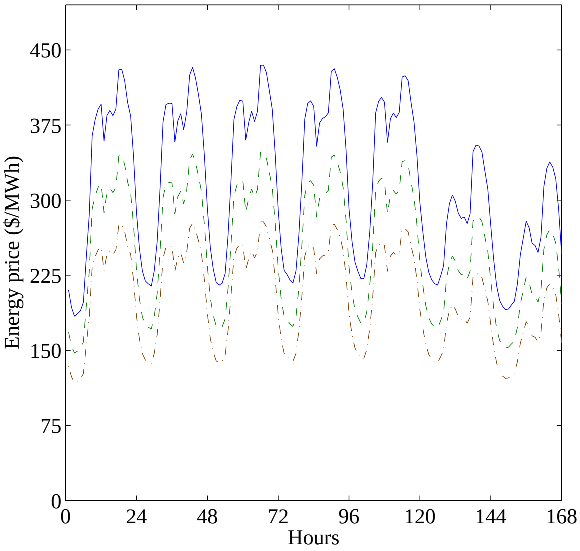

Figure 2: Energy price profiles considered. The solid line denotes profile 1, the dashed line denotes profile 2 and the dash-dot line denotes profile 3.

Profile 1 is a high-price profile and has a peak value of 434.8 $/MWh. Profile 2 has a peak value of 347.9 $/MWh. Profile 3 is a low-price profile and has a peak value of 278.3 $/MWh.

We carried out the following computation strategy: at first, profit and emission are independently optimised to determine the anchor points of the trade-off curves: BPC and BEC; then, profit and emission are merged according to the weighted sum method mentioned in our practical approach.

The computed hourly total generation for profile 1, 2 and 3 are shown respectively in Figures 3, 4 and 5.

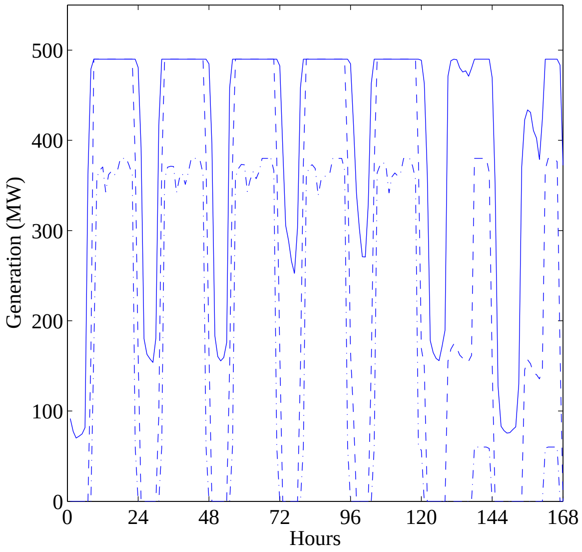

Figure 3: Hourly total generation for profile 1. The solid line denotes BPC results, $w = 1$, while the dashed and dash-dot lines denote compromise commitment results for $w = 0.6$ and $w = 0.4$, respectively.

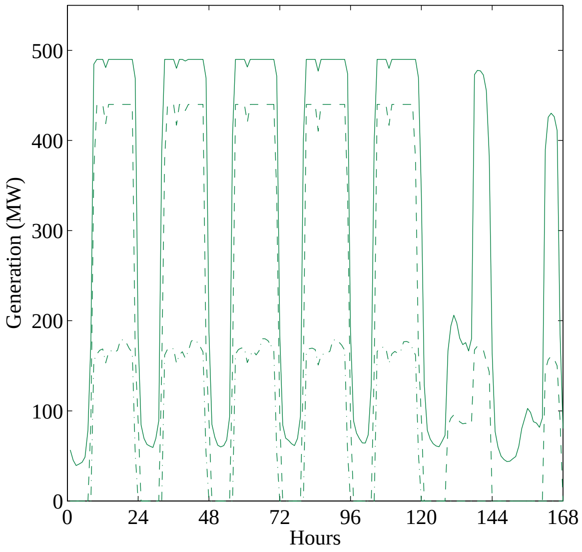

Figure 4: Hourly total generation for profile 2. The solid line denotes BPC results, $w = 1$, while the dashed and dash-dot lines denote compromise commitment results for $w = 0.6$ and $w = 0.4$, respectively.

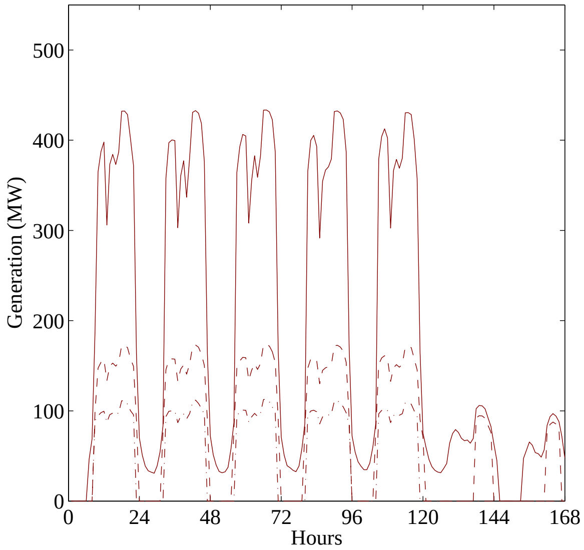

Figure 5: Hourly total generation for profile 3. The solid line denotes BPC results, $w = 1$, while the dashed and dash-dot lines denote compromise commitment results for $w = 0.6$ and $w = 0.4$, respectively.

In the BPC results, $w = 1$, the units are committed in order to achieve maximum profit, regardless of emission. The generation profile tends to follow the shape of the energy price profile. In the compromise commitment results, the maximum power generation is reduced as the weighting factor w decreases, in order to attain an adequate emission level, thus implying a lower total profit. In the BEC results, $w = 0$, all units are uncommitted in order to achieve minimum emission, since no must-run units were considered in this case study. Also, if necessary a non-null profit or emission can be considered as a minimum value to avoid total shutdown.

The computed trade-off curves for profile 1, 2 and 3 are shown respectively in Figures 6, 7 and 8.

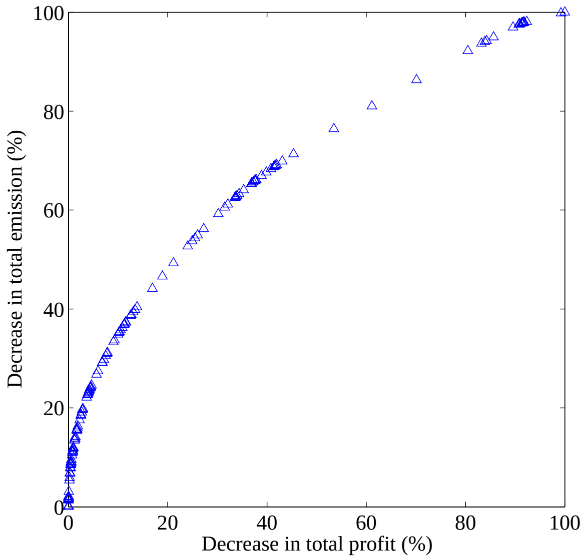

Figure 6: Trade-off curve with 201 non-dominated solutions, giving the percentage decrease in total emission against percentage decrease in total profit for profile 1.

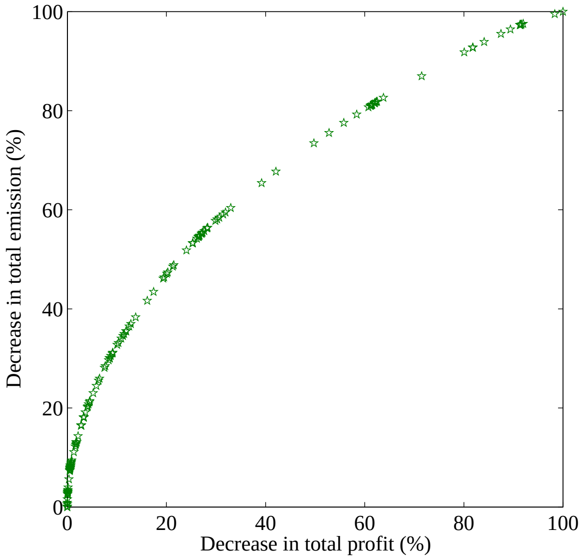

Figure 7: Trade-off curve with 201 non-dominated solutions, giving the percentage decrease in total emission against percentage decrease in total profit for profile 2.

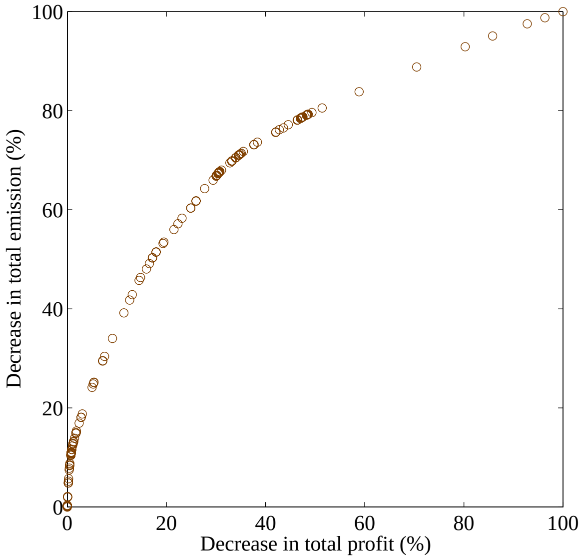

Figure 8: Trade-off curve with 201 non-dominated solutions, giving the percentage decrease in total emission against percentage decrease in total profit for profile 3.

The Pareto-optimal set has 201 non-dominated solutions. Trade-off characteristics give the percentage decrease in total emission against percentage decrease in total profit.

The trade-off curves have a sharp slope at the BPC neighbourhood. At the beginning of the curves, a significant percentage decrease in total emission is obtained with a small percentage decrease in total profit. For instance, a 16.3% reduction in total emission can be achieved by only a 1.9% decrease in total profit for profile 1. It should be noted that at the end of the curves the opposite occurs.

Table 3 shows the computational results for the proposed practical approach.

		Total profit *($)*	*Total generation* *(MWh)*	*Total emission* *(Mg)*
Profile 1	$w = 1$	77926	67668	3199
	$w = 0.6$	69206	46409	2022
	$w = 0.4$	45400	26747	992
	$w = 0$	0	0	0
Profile 2	$w = 1$	36203	50564	2451
	$w = 0.6$	31561	35412	1545
	$w = 0.4$	13965	12004	461
	$w = 0$	0	0	0
Profile 3	$w = 1$	10780	32451	1707
	$w = 0.6$	7544	12619	567
	$w = 0.4$	5772	7038	373
	$w = 0$	0	0	0

Table 3: Computational results for the proposed practical approach.

The total CPU-time for a trade-off curve was about 10.98 s, with an average 0.05 s for each non-dominated solution representing a 168 hours generation schedule. Hence, the proposed practical approach is computationally acceptable.

5 CONCLUSION

The new competitive and environmentally constrained electricity supply industry requires new computing tools to ensure both competitiveness to generating companies in the electricity market and environmental protection by limiting the emission of greenhouse gases into the atmosphere. This paper proposes a practical approach to solve the short-term thermal scheduling problem with environmental concerns. The proposed practical approach has been successfully tested on a case study based on the standard IEEE 30-bus system, considering different price profiles. The results show that the proposed practical approach is efficient for obtaining the schedule and the trade-off curves with a small CPU-time requirement.

REFERENCES

[1] L. A. F. M. Ferreira et al, “Short-Term Resource Scheduling in Multi-Area Hydrothermal Power Systems”, International Journal of Electrical Power & Energy Systems, Vol. 11, No. 3, pp 200-212, July 1989

[2] V. M. F. Mendes et al, “Optimal Short-Term Scheduling in Large Hydrothermal Power Systems”, 11th PSCC Proceedings, pp 1297-1303, September 1993

[3] J. Catalão et al, “Unit Commitment with Environmental Considerations: A Practical Approach”, 15th PSCC Proceedings, August 2005

[4] J. P. S. Catalão et al, “Short-Term Scheduling of Thermal Units: Emission Constraints and Trade-Off Curves”, European Transactions on Electrical Power, Vol. 18, No. 1, pp 1-14, January 2008

[5] M. A. Abido, “Environmental/Economic Power Dispatch using Multiobjective Evolutionary Algorithms”, IEEE Transactions on Power Systems, Vol. 18, No. 4, pp 1529-1537, November 2003

[6] M. Muslu, “Economic Dispatch with Environmental Considerations: Tradeoff Curves and Emission Reduction Rates”, Electric Power Systems Research, Vol. 71, No. 2, pp 153-158, October 2004

[7] S. Kuloor, G. S. Hope and O. P. Malik, “Environmentally Constrained Unit Commitment”, IEE Proceedings-Generation, Transmission and Distribution, Vol. 139, No. 2, pp 122-128, March 1992

[8] T. Gjengedal, “Emission Constrained Unit-Commitment (ECUC)”, IEEE Transactions on Energy Conversion, Vol. 11, No. 1, pp 132-138, March 1996

[9] A. T. Lora et al, “Electricity Market Price Forecasting Based on Weighted Nearest Neighbors Techniques”, IEEE Transactions on Power Systems, Vol. 22, No. 3, pp 1294-1301, August 2007

[10] J. P. S. Catalão et al, “Short-Term Electricity Prices Forecasting in a Competitive Market: A Neural Network Approach”, Electric Power Systems Research, Vol. 77, No. 10, pp 1297-1304, August 2007