European Journal of Operational Research 240 (2015) 457–475

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Decision Support

# Weekly self-scheduling, forward contracting, and pool involvement for an electricity producer. An adaptive robust optimization approach

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ARTICLE INFO

*Article history:*
Received 9 January 2014
Accepted 4 July 2014
Available online 18 July 2014

*Keywords:*
OR in energy
Robust optimization
Electricity market
Renewable energy

ABSTRACT

This paper addresses the optimization under uncertainty of the self-scheduling, forward contracting, and pool involvement of an electricity producer operating a mixed power generation station, which combines thermal, hydro and wind sources, and uses a two stage adaptive robust optimization approach. In this problem the wind power production and the electricity pool price are considered to be uncertain, and are described by uncertainty convex sets. To solve this problem, two variants of a constraint generation algorithm are proposed, and their application and characteristics discussed. Both algorithms are used to solve two case studies based on two producers, each operating equivalent generation units, differing only in the thermal units' characteristics. Their market strategies are investigated for three different scenarios, corresponding to as many instances of electricity price forecasts. The effect of the producers' approach, whether conservative or more risk prone, is also investigated by solving each instance for multiple values of the so-called budget parameter. It was possible to conclude that this parameter influences markedly the producers' strategy, in terms of scheduling, profit, forward contracting, and pool involvement. These findings are presented and analyzed in detail, and an attempted rationale is proposed to explain the less intuitive outcomes. Regarding the computational results, these show that for some instances, the two variants of the algorithms have a similar performance, while for a particular subset of them one variant has a clear superiority.

## 1. Introduction

In general, electricity producers operating in electricity markets sell their energy through bilateral contracts or in the pool. The details of these operations depend on the specific market design where the producer is integrated. For a review on market structure and designs see Conejo, Carrion, and Morales (2010) and Oliveira, Ruiz, and Conejo (2013).

From the point of view of the electricity producer, the selling strategy for each time period should take in consideration the power generation capacity of the producer, and to some extent also to the option to buy electricity from the market to meet the committed sales. Therefore, in this decision making problem the producer faces two integrated challenges: (1) the self-scheduling of the generation units and (2) the optimal forward contract selection and pool involvement.

The basic problem involving unit self-scheduling determines the optimal power outputs of the producer's generation units subject to feasible operation, which provides a basis to define the market involvement. In general, self-scheduling problems are related to Unit Commitment (UC) problems of thermal and/or hydro units. These are classical scheduling problems that have been addressed by a number of authors using decomposition strategies such as Lagrangian Relaxation, and in the last decade with Mixed Integer Linear (MILP) models, see for example Arroyo and Conejo (2000) and Li and Shahidehpour (2005). Several authors have proposed UC MILP models for systems with thermal units, aiming at developing: (a) tight linear relaxations, by generating facets of the ramping up and down constraints of the units (Ostrowski, Anjos, & Vannelli, 2012), convex hull formulations for the minimum up and down time constraints (Lee, Leung, & Margot, 2004; Rajan & Takriti, 2005), and tight approximate formulations for the linearization of the quadratic objective function (Frangioni, Gentile, & Lacalandra, 2009); (b) compact formulations (Hedman, Ferris, O'Neill, Fisher, & Oren, 2010; Morales-Espana, Latorre, & Ramos, 2013a); and (c) accurate representations of the operations and

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http://dx.doi.org/10.1016/j.ejor.2014.07.013

## Nomenclature

*Sets*

| | |
|---|---|
| $F$ | forward contracts |
| $HY$ | hydro pump-storage generation units |
| $J$ | blocks of the forward contracts |
| $I$ | generating units |
| $O$ | optimality cuts in the Master problem |
| $S$ | feasibility cuts in the Master problem |
| $T$ | time periods |
| $TH$ | thermal generation units |

*Parameters*

| | |
|---|---|
| $A_i,\ B_i$ | production cost function coefficients for unit $i$ (€/hour) |
| $CS_i$ | cold start-up cost of unit $i$ (€/hour) |
| $DM_i$ | number of periods unit $i$ must be off at the beginning of the time horizon |
| $D_f$ | time periods spanned by contract $f$ |
| $DC_i$ | shut-down cost (€) |
| $DT_i$ | minimum down time of unit $i$ (hour) |
| $FM_i$ | minimum number of periods a unit $i$ must be off at the beginning of the time horizon |
| $HS_i$ | hot start cost of unit $i$ (€/hour) |
| $LM_i$ | minimum number of periods a unit $i$ must be on at the beginning of the time horizon |
| $P_i^l$ | minimum power output of unit $i$ (megawatt) |
| $P_i^u$ | maximum power output of unit $i$ (megawatt) |
| $P0_i$ | power produced at $t = 0$ by unit $i$ (megawatt) |
| $RD_i$ | maximum ramp-down rate of unit $i$ (megawatt) |
| $RU_i$ | maximum ramp-up rate of unit $i$ (megawatt) |
| $SD_i$ | maximum shutdown rate of unit $i$ (megawatt) |
| $SR_t$ | spinning reserve for period $t$ (megawatt) |
| $SU_i$ | maximum start-up rate of unit $i$ (megawatt) |
| $U_i$ | number of periods unit $i$ must be on at the beginning of the time horizon |
| $U0_i$ | initial state of unit $i$ {on, off} = {1, 0} |
| $UT_i$ | minimum up time of unit $i$ (hour) |
| $T_i^c$ | cold start hours of unit $i$ (hour) |
| $T_i^I$ | initial status of unit $i$ (hour) |
| $G$ | conversion factor between cubic hectometers$^3$ and meter$^3$/seconds in one hour |
| $H_i$ | water head in plant $i$ (meter) |
| $K_i^p$ | power consumption factor |
| $K_i^t$ | power generation factor |
| $Q_i^{in}$ | natural inflow of water for plant $i$ (meter$^3$/seconds) |
| $Q_i^u$ | maximum turbined and pumped flow of water for plant $i$ (meter$^3$/seconds) |
| $V_i^u$ | maximum volume of water in the reservoir of plant $i$ (cubic hectometers$^3$) |
| $V_i^l$ | minimum volume of water in the reservoir of plant $i$ (cubic hectometers$^3$) |
| $V_i^E$ | minimum volume of water in the reservoir of plant $i$ at the of the horizon (cubic hectometers$^3$) |
| $\lambda_{f,j}^{buy}$ | energy price of buying block $j$ of forward contract $f$ (€/megawatt hour) |
| $\lambda_{f,j}^{sell}$ | energy price of selling block $j$ of forward contract $f$ (€/megawatt hour) |

*Continuous variables*

| | |
|---|---|
| $cd_{i,t}$ | shut-down cost of unit $i$ in period $t$ (€) |
| $cop$ | total startup, shutdown, production, and online cost of unit $i$ (€) |
| $cp$ | total startup, shutdown and online cost of unit $i$ (€) |
| $cu_{i,t}$ | startup cost of unit $i$ in period $t$ (€) |
| $f_{f,j}^{buy}$ | power bought through block $j$ of forward contract $f$ (megawatt) |
| $f_{f,j}^{sell}$ | power sold through block $j$ of forward contract $f$ (megawatt) |
| $P$ | operational profit of the producer per week (€) |
| $p_{i,t}$ | power output of unit $i$ in period $t$ (megawatt) |
| $p_{i,t}^{buy}$ | power bought in the pool in period $t$ (megawatt) |
| $p_t^{sell}$ | power sold in the pool in period $t$ (megawatt) |
| $ptb_{i,t}$ | power output of the pumped-storage hydro unit $i$ in period $t$ (megawatt) |
| $pp_{i,t}$ | power consumption of the pumped-storage hydro unit $i$ in period $t$ (megawatt) |
| $q_{i,t}$ | turbined flow of water in plant $i$ in period $t$ (meter$^3$/seconds) |
| $qp_{i,t}$ | pumped flow of water in plant $i$ in period $t$ (meter$^3$/seconds) |
| $v_{i,t}$ | volume of water stored in the reservoir of plant $i$ (cubic hectometers$^3$) |
| $\alpha_t, \xi_{i,t}, \pi_{i,t}$ | dual variables of the inner problem of the recourse problem |
| $\beta_{i,t},\ \gamma_{i,t},\ \zeta_{i,t}$ | dual variables of the inner problem of the recourse problem |
| $\eta_{i,t},\ \vartheta_{i,t},\ \mu_{i,t}$ | dual variables of the inner problem of the recourse problem |
| $\nu_{i,t},\ \varpi_{i,t},\ \rho_{i,t}$ | dual variables of the inner problem of the recourse problem |
| $\tau_{i,t},\ \upsilon_{i,t},\ \varphi_{i,t}$ | dual variables of the inner problem of the recourse problem |
| $\Theta$ | variable that approximates the recourse problem optimal value |

*Binary variables*

| | |
|---|---|
| $u_{i,t}$ | on/off status of unit $i$ in period $t$ |
| $u_{i,t}^{up}$ | startup status of unit $i$ in period $t$ |
| $u_{i,t}^{dn}$ | shutdown status of unit $i$ in period $t$ |
| $y_f^{buy}$ | selection of forward contract $f$ to buy energy |
| $y_f^{sell}$ | selection of forward contract $f$ to sell energy |

*Uncertain related parameters*

| | |
|---|---|
| $\bar{w}_t$ | nominal wind power output in period $t$ (megawatt) |
| $w_t^l$ | down deviation from the nominal wind power output in period $t$ (megawatt) |
| $w_t^u$ | up deviation from the nominal wind power output in period $t$ (megawatt) |
| $\bar{\lambda}_t$ | nominal pool price in period $t$ (€/megawatt hour) |
| $\lambda_t^l$ | down deviation from the nominal pool price in period $t$ (€/megawatt hour) |
| $\lambda_t^u$ | up deviation from the nominal pool price in period $t$ (€/megawatt hour) |
| $\Gamma$ | budget of uncertainty parameter for the pool prices and wind power output |

*Uncertain related continuous variables*

| | |
|---|---|
| $w_t$ | wind power output in period $t$ (megawatt) |
| $v_t^+$ | dummy variable to replace the bilinear term $z_t^+\alpha_t$ |
| $v_t^-$ | dummy variable to replace the bilinear term $z_t^-\alpha_t$ |
| $\lambda_t$ | pool price in period $t$ (Dollar/megawatt hour) |

*Uncertain related binary variables*

| | |
|---|---|
| $y_t^+$ | =1 if the pool price is at the upper bound of the set |
| $y_t^-$ | =1 if the pool price is at the lower bound of the set |
| $z_t^+$ | =1 if the wind power output is at the upper bound of the set |
| $z_t^-$ | =1 if the wind power output is at the lower bound of the set |