Applied Energy 225 (2018) 622–636

Contents lists available at ScienceDirect

Applied Energy

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

Demand-side management via optimal production scheduling in power-intensive industries: The case of metal casting process

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HIGHLIGHTS

- Unified framework for participation of production plants in energy and reserve market.
- MILP model integrating production and electricity market aspects.
- Optimal scheduling for cost minimization in day-ahead energy market.
- Exploitation of residual flexibility in capacity market.

ARTICLE INFO

Keywords:
Scheduling
Demand response
Industrial demand-side management
Metal casting foundry
Spot market
Ancillary market

ABSTRACT

The increasing challenges to the grid stability posed by the penetration of renewable energy resources urge a more active role for demand response programs as viable alternatives to a further expansion of peak power generators. This work presents a methodology to exploit the demand flexibility of energy-intensive industries under Demand-Side Management programs in the energy and reserve markets. To this end, we propose a novel scheduling model for a multi-stage multi-line process, which incorporates both the critical manufacturing constraints and the technical requirements imposed by the market. Using mixed integer programming approach, two optimization problems are formulated to sequentially minimize the cost in a day-ahead energy market and maximize the reserve provision when participating in the ancillary market. The effectiveness of day-ahead scheduling model has been verified for the case of a real metal casting plant in the Nordic market, where a significant reduction of energy cost is obtained. Furthermore, the reserve provision is shown to be a potential tool for capitalizing on the reserve market as a secondary revenue stream.

1. Introduction

The last decade has witnessed a major paradigm shift in EU energy market and policies. In 2014 European leaders adopted a climate and energy framework to ensure a 40% cut in greenhouse emissions from 1990 level by 2030. In addition, the framework sets a binding target to increase the share of renewables to 27% of the final energy consumption at EU level. One of the main barriers to the integration of renewable energy sources (RES) is their intermittency and unpredictability. Their non-responsive nature makes the already challenging task of maintaining supply-demand balance even more difficult and, if not properly managed, could jeopardize the grid reliability.

In Europe, Transmission System Operators (TSOs) are in charge of ensuring the physical balance of power in the grid. Lacking cheap and efficient storage systems, TSO traditionally relies on dispatchable fossil fuel generation sources to bring production and demand into balance and stabilize the grid frequency. In the event of an imbalance, grid operator sequentially calls upon three types of generation reserves – categorized based on their response time [1] – to bring the grid frequency back to its nominal value of 50 Hz. In order to provide up/downward regulating reserve, involved power plants need to run slightly under/over their max/minimum generation capacity. Consequently, growing imbalance caused by widespread integration of RES requires new solutions beyond traditional dispatchable resources. A viable alternative to peak generation capacity is engaging consumers in power balancing and using their flexibility to avoid the peaks. Techniques involving such practices are referred to as Demand-Response (DR) or Demand-Side Management (DSM) solutions.

Electricity market liberalization can be regarded as the most important enabler for DR initiatives. In Europe DR access to the deregulated markets is granted through balance responsible parties (BRP) and aggregators. BRPs are financially responsible to balance the expected

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https://doi.org/10.1016/j.apenergy.2018.03.084
Received 22 December 2017; Received in revised form 24 February 2018; Accepted 25 March 2018

Nomenclature

Continuous variables

$p^{k}_{f,m,j}$	power [kW]
$p^{\mathrm{bl+/bl-}}_{q,c}$	positive/negative imbalance power [kW]
$t_{f,m,j}$	stage starting time [s]
$R_{q,c}$	power reserve [kW]

Discrete variables

$x^{k}_{f,m,j}$	stage activation
$y^{k}_{f,m,j}$	supplementary features (semi-continuity, pre-emption, power rate)
$\zeta_{f,m,j}$	Day-After Flexibility (DAF) for reserve
$\nu_{q,c}$	positive imbalance direction
$\beta_{d,c},\mu_{d,c}$	multiple reserve activation

Parameters

r^{cast}	casting rate [m^3/s]
r^{of}	overflow rate limit [kW]
r^{pwr}	power rate limit [kW/s]
r^{sp}	splash rate limit [kW]
v	pouring furnace volume [m^3]
$\breve{v}$	tapped volume into pouring furnace [m^3]
$\hat{v}$	cast volume from pouring furnace [m^3]
$\bar{k}_{c,n}$	breakpoint n on casting rate for line c [s]
C	spot market objective function [€]
$E,\hat{E}$	stage energy (actual, min.) [kW h]
$\hat{E}^{\mathrm{sp}}$	minimum $E_{f,m,2}$ causing splash [kW h]
N_q	market discretization to grid step ratio [–]
$L_{\max}$	maximum number of ladles [–]
$P^{\max}$	maximum power [kW]
$P^{\max}_{l}$	maximum power of power pack l [kW]
$P^{\mathrm{min/max}}_{f,m,j}$	min/max stage dependent power [kW]
γ_c	pouring furnace power coefficient [kW/m^3]
$\alpha_{f,j}$	energy correction parameter [–]
λ_t^{m}	price at time t in market m [€/kW h]
λ_t^{re}	reward for reserve availability [€/kW]
$\bar{\tau}$	maximum holding time without reheating [s]
$\hat{\Delta}$	stage time duration (minimal) [s]
$\Delta^{\leftrightarrow}_{f,c}$	ladle travel time [s]
$\hat{\Delta}^{\mathrm{of}}$	min. time with risk of overflow [s]
ΔT_{m}	time discretization step for market m [s]
ΔE_c	energy shifted in DAF mode for line c [s]
δt	time discretization step [s]
Π	maximum likelihood of reserve activation [–]

Indices/sets

$c \in C$	casting furnaces/lines
$d \in \mathcal{D}$	reserve bid slots
$f \in \mathcal{F}$	melting furnaces
$j \in \mathcal{J}$	melting furnace stages
$k \in \mathcal{K}$	global time-grid
$l \in \mathcal{L}$	power units
$m \in \mathcal{M}$	melting jobs
$q \in Q$	baseline/reserve grid

Subsets

$\mathcal{F}_c$	furnaces serving the casting line $c \in C$
$\mathcal{F}_l$	furnaces powered by the power unit $l \in \mathcal{L}$
$\mathcal{J}_{m,f}$	stages in melt cycle m of furnace f
$\mathcal{J}^E$	energy-dependent stages
$\mathcal{J}^T$	time-dependent stages
$\mathcal{K}_q$	grid points in baseline/reserve interval q
Q_d	reserve intervals q in bid slot d

Superscripts

*	optimal
0	initial
bl	baseline
bid	bidding
da	day-ahead market
re	reserve market
tl	tapping ladle
tp	tapping

electricity generation and demand profile for the suppliers and consumers under their jurisdiction. They bid their power profile in the wholesale day-ahead market and subsequently on the real-time market to minimize the deviation of real profile from the contracted one.

While the regulating market is the main platform for restoring grid balance by dispatching reserve capacity, day-ahead market plays a crucial proactive role in the power-balancing decisions taken on a system-wide scale.

The participation of loads in the day-ahead energy and reserve markets – respectively referred to as price-based and incentive-based programmes in DR literature – creates a win–win situation for both the TSO and end user. While it helps TSO in balancing the power via BRPs, consumers can increase their economic welfare by exploiting their consumption flexibility. Furthermore, the consequent growth in the penetration of RES lowers the marginal electricity price by pushing the more expensive fossil fuel power plant out of the market, which is described as “merit-order effect” [2].

Nevertheless, many flexible loads cannot access these markets due to regulatory and technical barriers, the most prohibitive being costly subscription fees for energy and minimum bid size for the regulating power market [3]. This has led to the emergence of aggregators as DR providers for small consumers [4]. Accordingly, in the DR literature, two types of flexible consumers can be identified: small distributed loads such as residential or commercial consumers and single energy-intensive industrial units that are qualified to individually participate in energy or capacity market. In the former group, flexibility is mostly provided by shifting or shedding small non-critical loads such as heating and cooling. Even though such loads are straightforward to manage at the user level, there are still many challenges regarding their aggregation such as complexity of distributed control strategies at the aggregator level and the implementation of advanced metering and communication infrastructure and management systems. This has been extensively addressed in recent years under the ”smart grid” paradigm [5].

Industrial loads, on the other hand, can deliver a much larger flexibility without aggregation, even though industrial clusters may also adopt such a paradigm to exploit their collective flexibility [6].

1.1. Literature review

The potential benefits of industrial Demand-Side Management (iDSM) has been noticed both by academia and industry [7–9]. However, what makes the DSM of industrial consumers challenging is rather the complexity of their underlying processes which demands a deep