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# Load-Following Reserves Procurement Considering Flexible Demand-Side Resources Under High Wind Power Penetration

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***Abstract*—The variable and uncertain nature of the leading renewable energy resources, such as wind power generation, imposes the development of a sophisticated balance mechanism between supply and demand to maintain the consistency of a power system. In this study, a two stage stochastic programming model is proposed to procure the required load-following reserves from both generation and demand side resources under high wind power penetration. Besides, a novel load model is introduced to procure flexible reserves from industrial clients. Load following reserves from load serving entities (LSE) are also taken into account as well as network constraints, load shedding and wind spillage. The proposed methodology is applied to an illustrative test system, as well as to a 24-node system.**

***Index Terms*—Demand response, flexible load, load-following reserves, stochastic programming, wind power.**

## NOMENCLATURE

The main nomenclature used throughout the paper is stated below in alphabetical order. Other abbreviations and symbols are defined as required.

*Indices (Sets):*

| | |
|---|---|
| $d(D)$ | Index (set) of industrial loads. |
| $f(F^i)$ | Index (set) of steps of the marginal cost function of unit $i$. |
| $g(G^d)$ | Index (set) of groups of processes. |
| $i(I)$ | Index (set) of conventional generating units. |
| $j(J)$ | Index (set) of LSEs. |
| $l(L)$ | Index (set) of transmission lines. |
| $n(N)$ | Index (set) of nodes. |
| $p^h_{type}$ | Set of process types: $h = 1$ for continuous, $h = 2$ for interruptible. |
| $p(P^d)$ | Index (ordered set) of processes. |
| $r(R)$ | Index (set) of inelastic loads. |
| $s(S^w)$ | Index (set) of wind power scenarios of wind farm $w$. |
| $t(T)$ | Index (set) of time periods. |
| $w(W)$ | Index (set) of wind farms. |

*Parameters:*

| | |
|---|---|
| $a^{\max}_{p,g,d}$ | Positive integer- maximum number of available production lines for process $p$ of group $g$ of industry $d$. |
| $a^{\max}_{p,g,d}$ | Positive integer- maximum number of production lines per hour for process $p$ of group $g$ of industry $d$. |
| $\mathrm{B_{i,t,f}}$ | Size of step $f$ of unit $i$ marginal cost function in period $t$ [MW]. |
| $B_{l,n}$ | Susceptance of line $l$ [per unit]. |
| $C^{\mathrm{R^{x,y}}}_{\mathrm{x',t}}$ | Offer cost of down/non-spinning/up reserve ($x = \{D, NS, U\}$) by resource $x'$ of type $y$ that may be industrial load, unit or LSE ($y = \{In, \varnothing, LSE\}$) in period $t$ [€ /MWh]. |
| $\mathrm{C_{i,f,t}}$ | Marginal cost of step $f$ of unit $i$ marginal cost function in period $t$ [€ /MWh]. |
| $D^{\min}_{d,t}$ | Minimum power for industry $d$ in period $t$ [MW]. |
| $\mathrm{DT_i}$ | Minimum down-time of unit $i$ [h]. |
| $f^{\max}_l$ | Maximum capacity of line $l$ [MW]. |
| $L_{r,t}$ | Demand of inelastic load $r$ in period $t$ [MW]. |

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| | |
|---|---|
| $\mathrm{P_i^{max}}$ | Maximum power output of unit $i$ [MW]. |
| $\mathrm{P_i^{min}}$ | Minimum power output of unit $i$ [MW]. |
| $P_{p,g,d}^{line}$ | Power of production line of process $p$ of group $g$ of industry $d$ [MW]. |
| $\mathrm{P_{t,w}^{WP,max}}$ | Maximum wind power that can be scheduled from wind farm $w$ in period $t$ [MW]. |
| $P_{t,w,s}^{WP}$ | Power output of wind farm $w$ in scenario $s$ in period $t$ [MW]. |
| $\mathrm{RD_i}$ | Ramp-down rate of unit $i$ [MW/min]. |
| $\mathrm{RU_i}$ | Ramp-up rate of unit $i$ [MW/min]. |
| $SDC_i$ | Shut-down cost of unit $i$ [€]. |
| $SUC_i$ | Start-up cost of unit $i$ [€]. |
| $T_{p,g,d}^{c,\max}$ | Maximum completion time of process $p$ of group $g$ of industry $d$ [h]. |
| $T_{p,g,d}^{g,\max}$ | Maximum time interval between processes $p$ and $p+1$ of group $g$ of industry $d$ [h]. |
| $T_{p,g,d}^{g,\min}$ | Minimum time interval between processes $p$ and $p+1$ of group $g$ of industry $d$ [h]. |
| $\mathrm{UT_i}$ | Minimum up-time of unit $i$ [h]. |
| $V^{LOL}$ | Cost of involuntary load shedding for inelastic loads [€ /MWh]. |
| $V^S$ | Cost of wind energy spillage [€ /MWh]. |
| $\Delta T$ | Length of a period [min]. |
| $\lambda_{\mathrm{j,t}}^{\mathrm{D}}$ | Utility of industrial $d$ load in period $t$ [€ /MWh]. |
| $\lambda_{\mathrm{j,t}}^{\mathrm{LSE}}$ | Utility of LSE $j$ load in period $t$ [€ /MWh]. |
| $\pi_s$ | Probability of wind power scenario $s$. |

*Variables:*

| | |
|---|---|
| $a_{p,g,d,t}$ | Positive integer variable- number of production lines scheduled in period $t$ for process $p$ of group $g$ of industry $d$. |
| $a_{a,g,d,t}^{x}$ | Positive integer variable- number of production lines that contribute in scheduled down/non-spinning/up reserve $(x=\{down,ns,up\})$ in period $t$ from process $p$ of group $g$ of industry $d$. |
| $a_{p,g,d,t,s}^{x,rt}$ | Positive integer variable- actual number of production lines actually contributing in down/non-spinning/up reserve $(x=\{down,ns,up\})$ in period $t$ of scenario $s$ for process $p$ of group $g$ of industry $d$. |
| $a_{a,g,d,t,s}^{2}$ | Positive integer variable- actual number of production lines in period $t$ of scenario $s$ for process $p$ of group $g$ of industry $d$. |
| $b_{i,t,f}$ | Power output scheduled from the $f$th block by unit $i$ in period $t$ [MW]. |
| $f_{l,t,s}$ | Power flow through line $l$ in period $t$ of scenario $t$ [MW]. |
| $L_{r,t,s}^{shed}$ | Load shed in scenario $s$ from inelastic load $r$ in period $t$ [MW]. |
| $\mathrm{LSE_{j,t}^{S}}$ | Scheduled demand from LSE $j$ in period $t$ that is limited by $\mathrm{LSE_{j,t}^{S,min}}$ and $\mathrm{LSE_{j,t}^{S,max}}$ [MW]. |
| $LSE_{j,t,s}^{C}$ | Actual power consumed by LSE $j$ in scenario $s$ in period $t$ [MW]. |
| $P_{d,t}^{ind,S}$ | Scheduled consumption in period t for industry $d$ [MW]. |
| $P_{d,t,s}^{ind,C}$ | Actual power consumption in period $t$ of scenario $s$ for industry $d$ [MW]. |
| $P_{i,t}^{S}$ | Power output scheduled for unit $i$ in period $t$ [MW]. |
| $P_{i,t,s}^{G}$ | Actual power output of unit $i$ in scenario $s$ in period $t$ [MW]. |
| $P_{p,g,d,t}^{pro,S}$ | Scheduled consumption in period t for process $s$ of group $g$ of industry $d$ [MW]. |
| $P_{p,g,d,t,s}^{pro,C}$ | Actual power consumption in period $t$ of scenario $s$ for process $p$ of group $g$ of industry $d$ [MW]. |
| $P_{t,w}^{WP,S}$ | Scheduled wind power in period $t$ by wind farm $w$ [MW]. |
| $R_{x',t}^{x,y}$ | Down/non-spinning/up reserve $(x=\{D,NS,U\})$ scheduled in period $t$ from resource $x'$ of type $y$ that may be industrial load, unit or LSE $(y=\{In,\varnothing,LSE\})$ in period $t$ [MW]. |
| $R_{p,g,d,t}^{x,pro}$ | Down/non-spinning/up reserve$(x=\{D,NS,U\})$ scheduled in period $t$ from process $p$ of group $g$ of industry $d$ [MW]. |
| $r_{x',t,s}^{x,y}$ | Down/non-spinning/up reserve $(x=\{D,NS,U\})$ deployed by resource $x'$ of type $y$ that may be unit or LSE $(y=\{\varnothing,LSE\})$ in scenario $s$ in period $t$ [MW]. |
| $r_{i,t,s,f}^{G}$ | Reserve deployed from the $f$th block of unit $i$ in scenario $s$ in period $t$ [MW]. |
| $r_{p,g,d,t,s}^{x,pro}$ | Down/non-spinning/up reserve $(x=\{D,NS,U\})$ deployed in period $t$ of scenario $s$ from process $p$ of group $g$ of industry $d$ [MW]. |
| $S_{t,w,s}$ | Wind spilled in scenario $s$ from wind farm $w$ in period $t$ [MW]. |
| $u_{i,t,s}^{1}$ | Binary variable-1 if unit $i$ is committed during period $t$, else 0. |

$u^2_{i,t,s}$ Binary variable-1 if unit $i$ is committed during period $t$ in scenario $s$, else 0.

$y^1_{i,t}$ Binary variable-1 if unit $i$ is starting up in period $t$, else 0.

$y^2_{i,t,s}$ Binary variable-1 if unit $i$ is starting up during period $t$ in scenario $s$, else 0.

$z^1_{i,t}$ Binary variable-1 if unit $i$ is shut down in period $t$, else 0.

$z^2_{i,t,s}$ Binary variable-1 if unit $i$ is shut down during period $t$ in scenario $s$, else 0.

$v^1_{p,g,d,t}$ Binary variable-1 if process $p$ of group $g$ of industry $d$ is in progress in period $t$, else 0.

$v^2_{p,g,d,t,s}$ Binary variable-1 if process $p$ of group $g$ of industry $d$ is in progress in period $t$ of scenario $s$, else 0.

$\zeta^1_{p,g,d,t}$ Binary variable-1 if process $p$ of group $g$ of industry $d$ is terminated in period $t$, else 0.

$\zeta^2_{p,g,d,t,s}$ Binary variable-1 if process $p$ of group $g$ of industry $d$ is terminated in period $t$ of scenario $s$, else 0.

$\psi^1_{p,g,d,t}$ Binary variable-1 if process $p$ of group $g$ of industry $d$ is beginning in period $t$, else 0.

$\psi^2_{p,g,d,t,s}$ Binary variable-1 if process $p$ of group $g$ of industry $d$ is beginning in period $t$ of scenario $s$, else 0.

$\partial_{n,t,s}$ Voltage angle of node $n$ in period $t$ of scenario $s$ [rad].

## I. Introduction

### A. Motivation

It is widely accepted that renewable energy sources (RES) are likely to represent a significant portion of the production mix in many power systems around the world, a trend expected to be increasingly followed in the next years. Programs like the European Union (EU) Climate and Energy Package [1], mostly known as the "20–20–20" targets, which stand for the raise of the share of EU energy consumption produced from renewable resources to 20% among others, confirm this trend.

However, the economic and environmental benefits that arise from the integration of these resources into the power system lead to additional problems due to the fact that their production is highly variable and unpredictable.

Thus, their implementation into the grid requires the balancing authorities of the respective power systems to procure more ancillary services (AS) in order to ensure that power quality, reliability and security of the system operation are maintained [2].

In the restructured environment, AS are treated as a commodity that has significant economic value. Traditionally, these services are procured only from the generation side.

Nevertheless, the increased needs introduced by the large-scale penetration of RES and the growth of the electricity demand, in combination with the scarcity and the increased cost of conventional fuels and the limited new investments in new units, bring upon a peculiar situation.

Various studies including [3] argue that resources located in the demand side can also provide some types of AS and even with the significant advantages of fast, statistically reliable response and distributed nature.

In practice, although the importance of having an active demand side contributing in system reliability efforts is recognized, only a few leading independent system operators (ISO) and transmission system operators (TSO), especially in North America, have established recently demand response (DR) programs that allow the participation of consumers in the provision of critical AS. A notable example is the Demand Side AS Program (DSASP), initiated in 2009 by the New York ISO, which exploits the ability of DR to provide regulation, synchronous reserve and non-synchronous reserve [4]. In Europe, DR activities are generally in an initial status [5] despite the fact that the provision of AS by DR has been recognized as mandatory [6] to support greater future integration of RES, mainly due to regulatory barriers.

### B. Literature Survey

There are several works dealing with reserve allocation from both production and demand side sources to cope with uncertainties in system operation.

A comprehensive description of AS needed for the reliable operation of a power system can be found in [7]. In [8] and [9], existing ancillary mechanisms for eleven power systems have been summarized and their economic features underlined. A detailed evaluation of DR activities for AS can be found in [10]. Apart from the commonly met AS types, a new type was recently proposed from Midwest ISO [11] and California ISO [12] as flexible ramping products to increase the robustness of the load following reserves under uncertainty, such as high wind power fluctuation.

Jafari *et al.* [13] proposed a stochastic programming based multi-agent market model incorporating day-ahead and several intra-day markets, as well as a spot real-time energy-operating reserve market in order to adjust wind fluctuations based system uncertainties. In [13], no other demand-side resource apart from load-shedding was considered. In [14], a contingency analysis based stochastic security constrained system operation under significant wind power condition was analyzed, while demand-side resources were not considered. In [15], a switching operation between two separate energy markets named "conventional energy market" and "green energy market" was proposed where profit maximization of green energy systems was formulated in a stochastic programming framework without considering demand side facilities. Similar studies neglecting demand side resources for reserve procurement to overcome system uncertainties were also presented in [16]–[18]. It is also worthy to note that studies in [16]–[18] considered the combination of different approaches in order to mainly provide a computationally efficient way to solve unit commitment under uncertainties. The computational efficiency of unit commitment under uncertainty was also addressed in [19]. On the other hand, there are some studies providing implicit evaluation of reserves under wind penetration. Among them, required levels or spinning and non-spinning reserves under high levels of wind penetration was the scope of the study realized by Morales *et al.* [20]. In [20], uncertainty induced by modeling some portion of load demand as elastic that contributes to reserve procurement by load shedding was also taken into account.

Wind and load uncertainties were covered by scheduling optimal hourly reserves using security-constrained unit commitment (SCUC) approach in [21]. A two-stage stochastic programming framework with a set of appropriate scenarios solved using dual decomposition algorithm was provided in [22]. The dual decomposition algorithm was employed in [22] in order to address the computational issues emerging from the use of stochastic programming incorporated in unit commitment policies. Some further studies focusing mainly on demand and stochastic programming also take place in the literature. Parvania and Firuzabad [23] proposed a short-term stochastic SCUC that jointly schedules energy and spinning reserve from units and DR resources where the main contribution to the literature was the reserve modeling of DR that actually are aggregated retail customer responses submitted as bids to the market. Also, in [24] a day-ahead market structure was presented where demand side can participate in order to provide contingency reserves by bidding an offer curve representing the cost of making their loads available for curtailment. Shan *et al.* [25] also considered a DR based load side contribution to reserves under high levels of wind penetration where demand was a linear price-responsive function. As a different study with also reliability consideration, load uncertainty and generation unavailability were covered in [26] without additional wind power based uncertainty in a two-stage stochastic programming framework. Apart from the stochastic programming based literature papers referred above, many studies considering different modeling frameworks such as probabilistic, rolling stochastic and Monte Carlo criteria can also be found in [27]–[30]. There are also more studies not referred here contributing to the literature from reserve procurement perspective considering different aspects of uncertainties in the system operation. However, there is a lack of studies dealing with more detailed evaluation of responsive loads in the concept of DR based reserve allocation under both demand and production side uncertainties in a stochastic programming framework.

### C. Contributions

The contribution of the presented study is to provide a joint energy and reserve scheduling and dispatching tool, taking into account demand side resources for the procurement of flexible load-following reserves in a system with significant penetration of wind power. Demand side resources in the current study include load serving entities (LSE) and industrial loads that can in real-time reschedule their production to meet the wind power changes. To the best knowledge of the authors, a novel linear generalized load model for industrial consumers is also developed in this study.

### D. Organization

The rest of this paper is organized as follows: Section II provides an overview of the presented model and the assumptions adopted. The mathematical formulation is developed in Section III. In Section IV, the proposed model is applied first to a small illustrative test case, and then a 24-node system is analyzed. Finally, in Section V, conclusions are duly drawn.

## II. Model Description

### A. Model Overview

To accommodate the uncertain nature of wind power production, a network-constrained day-ahead market clearing model is proposed under a two-stage stochastic programming framework.

The first stage of the model represents the day-ahead market where energy and reserves are jointly scheduled to balance wind volatility. The variables of this stage do not depend on any specific scenario realization and constitute *here-and-now* decisions.

The second stage of the model stands for several actual system operation possibilities. The variables of this stage are scenario-dependent and have different values for every single wind scenario. The second stage variables constitute *wait-and-see* decisions.

Reserves can be procured by several resources located both in the generation and the demand side:

1) *Generating Units:* They can provide up spinning, down spinning and non-spinning reserves.
2) *LSE:* These market participants can provide some flexibility in altering their consumption. In this paper, they are not thoroughly modeled, because their behavior can significantly vary depending on the type of loads they represent. Since industrial loads are separately modeled in this work, they generally represent commercial and residential consumers that participate in the market through an aggregator. They can offer up and down spinning reserves.
3) *Industrial Customers:* These market participants can increase (down spinning reserve) or decrease (up spinning reserve) in a discrete amount their power consumption or even reschedule (non-spinning reserve) their production processes.

It should be noted that the spinning and non-spinning reserves terminology in the case of demand-side reserves is adopted in accordance with the unit procured reserves. Spinning tends to mean "alteration of an existing consumption", while non-spinning in the case of the industrial consumers stands for a time-shift of a process. For instance, in [20], where a simplified responsive load was modeled, the terms spinning and non-spinning were omitted since they are not needed to distinguish the reserve mechanisms.

### B. Assumptions

The most important assumptions that are made by the authors, in order to render the rigorous mathematical formulation of the problem practical, are:

1) The only source of uncertainty is deemed the wind production. Thus, no contingencies are taken into account, while the load forecasting as well as the response of the demand side resources are considered perfectly reliable.
2) The response of the demand side resources (LSE and industrial consumers) is considered instant (in practice several minutes [7]) and thus, no ramping constraints are enforced concerning these types of resources.
3) Wind power producers are not considered competitive participants. For the market clearing procedure wind energy is considered free of cost. Practically, it could be paid a regulated tariff [20] out of the day-ahead market scope.
4) The cost of deploying reserves by the units is considered equal to their energy costs. The cost of deploying reserves by the demand side is considered equal to their utilities. However, any pricing scheme can be implemented within the proposed formulation.
5) A linear representation of the network is considered, neglecting active power losses. One could include a linear approximation of the losses as explained in [20].
6) Load shedding is only possible for totally inelastic loads that are not subject to any resource offering scheme. Furthermore, energy constraints are not enforced for LSE, thus no phenomena that occur due to the response of the load (e.g., load recovery effect) are taken into consideration. The extension of the model to accommodate these effects is conceivable.
7) Scheduling horizon is one day with hourly granularity.

## III. Formulation

### *A. Objective Function*

$$
\begin{aligned}
\mathrm{EC}=&\sum_{\mathrm{t}\in\mathrm{T}}\Bigg[\sum_{\mathrm{i}\in\mathrm{I}}\Big[\sum_{\mathrm{f}\in\mathrm{F^i}}(\mathrm{C_{i,f,t}}\cdot\mathrm{b_{i,t,f}})+\mathrm{SUC_i}\cdot\mathrm{y^1_{i,t}}+\mathrm{SDC_i}\cdot\mathrm{z^1_{i,t}}\\
&\quad+\mathrm{C^{R^D}_{i,t}}\cdot\mathrm{R^D_{i,t}}+\mathrm{C^{R^U}_{i,t}}\cdot\mathrm{R^U_{i,t}}+\mathrm{C^{R^{NS}}_{i,t}}\cdot\mathrm{R^{NS}_{i,t}}\Big]\\
&-\sum_{\mathrm{j}\in\mathrm{J}}\lambda^{\mathrm{LSE}}_{\mathrm{j,t}}\cdot\mathrm{LSE^S_{j,t}}\\
&+\sum_{\mathrm{j}\in\mathrm{J}}\left(\mathrm{C^{D,LSE}_{j,t}}\cdot\mathrm{R^{D,LSE}_{j,t}}+\mathrm{C^{R^{U,LSE}}_{j,t}}\cdot\mathrm{R^{U,LSE}_{j,t}}\right)\\
&-\sum_{\mathrm{d}\in\mathrm{D}}\lambda^{\mathrm{D}}_{\mathrm{d,t}}\cdot\mathrm{P^{ind,S}_{d,t}}\\
&+\sum_{\mathrm{d}\in\mathrm{D}}\left(\mathrm{C^{R^{D,In}}_{d,t}}\cdot\mathrm{R^{D,In}_{d,t}}+\mathrm{C^{R^{U,In}}_{d,t}}\cdot\mathrm{R^{U,ind}_{d,t}}+\mathrm{C^{R^{NS,In}}_{d,t}}\cdot\mathrm{R^{NS,ind}_{d,t}}\right)\Bigg]\\
&\sum_{s\in S}\pi_s\\
&\cdot\sum_{t\in T}\Bigg\{\sum_{i\in I}\left[\mathrm{SUC_i}\cdot(y^2_{i,t,s}-\mathrm{y^1_{i,t}})+\mathrm{SDC_i}\cdot(z^2_{i,t,s}-\mathrm{z^1_{i,t}})\right]\\
&+\sum_{i\in I}\sum_{f\in F^i}(\mathrm{C_{i,f,t}}\cdot r^G_{i,t,s,f})\\
&+\sum_{j\in J}\lambda^{\mathrm{LSE}}_{\mathrm{j,t}}\cdot\left(r^{U,LSE}_{j,t,s}-r^{D.LSE}_{j,t,s}\right)\\
&+\sum_{d\in D}\lambda^{\mathrm{D}}_{\mathrm{d,t}}\cdot\sum_{g\in G}\sum_{p\in P}(r^{U,pro}_{d,g,p,t,s}-r^{D,pro}_{d,g,p,t,s}r^{NS,pro}_{d,g,p,t,s})\\
&+\sum_{w\in W}V^S\cdot S_{t,w,s}+\sum_{r\in R}V^{LOL}\cdot L_{r,t,s}\Bigg\}.
\end{aligned}
\tag{1}
$$

The objective function (1) stands for the minimization of the total expected cost (EC) emerging from the system operation. The first two lines of the objective function express the costs associated with energy provided from the generating units, the start-up and shut-down costs and the commitment of the units to provide reserves. The third line expresses the utility of the LSE load and the fourth line expresses the cost associated with the commitment to provide up and down reserves. The fifth and the sixth lines consider the utility of the industrial load and the cost of committing reserves from this resource.

The rest of the objective function is scenario dependent, as indicated by the summation over the scenario index. The eighth line considers the cost of changing the status of the generating units, while the ninth line stands for the cost of deploying reserves from the generating units. The tenth and the eleventh lines consider the costs of deploying reserves from LSE and industrial consumers, respectively. Finally, the last line considers the wind spillage cost and the expected cost of the energy not served for the inelastic loads. Since wind power production is assumed to be free, the algorithm would avoid integrating high amounts because of the costs that emerge due to the reserves that should be scheduled and deployed. The minimization of wind spillage cost indicates that it is required to integrate as much wind into the power system as possible (e.g., to achieve $CO_2$ emission reductions).

### *B. First Stage Constraints*

*1) Generation Limits:*

$$P^S_{i,t}=\sum_{f\in F^i}b_{i,t,f}\ \forall i,t \tag{2}$$

$$0\le b_{i,t,f}\le B_{i,t,f}\ \forall f,i,t \tag{3}$$

$$P^S_{i,t}-R^D_{i,t}\ge P^{\min}_i\cdot u^1_{i,t}\ \forall t,i \tag{4}$$

$$P^S_{i,t}+R^U_{i,t}\ge P^{\max}_i\cdot u^1_{i,t}\ \forall t,i. \tag{5}$$

The generator cost function is considered convex and it is approximated using a step-wise linear marginal cost function as in [31]. This is enforced by (2) and (3). Constraints (4) and (5) limit the output of a generating unit considering also the scheduled down and up reserves, respectively.

*2) Generator Minimum up and Down Time Constraints:*

$$\sum_{\tau=t-UT_i+1}^{1}y^1_{i,t}\le u^1_{i,t}\ \forall i,t \tag{6}$$

$$\sum_{\tau=t-DT_i+1}^{1}z^1_{i,t}\le 1-u^1_{i,t}\ \forall i,t. \tag{7}$$

Constraint (6) forces a unit to remain committed for at least $UT_i$ periods once it starts up, while (7) forces a unit to remain off-line for at least $DT_i$ periods once it is shut-down.

*3) Unit Commitment Logic Constraints:*

$$y_{i,t}^1 - z_{i,t}^1 = u_{i,t}^1 - u_{i,(t-1)}^1 \ \forall i, t \quad (8)$$
$$y_{i,t}^1 + z_{i,t}^1 \leq 1 \ \forall i, t. \quad (9)$$

Equation (8) enforces the start-up and shut-down status change logic, while (9) states that a unit cannot start-up and shut-down during the same period.

*4) Ramp-Up and Down Limits:*

$$P_{i,t}^S - P_{i,(t-1)}^S \leq \Delta T \cdot RU_i \ \forall t, i \quad (10)$$
$$P_{i,(t-1)}^S - P_{i,t}^S \leq \Delta T \cdot RU_i \ \forall t, i. \quad (11)$$

Constraints (10) and (11) consider the effect of the ramp rates that limit the changes of the unit's output. $\Delta T$ is the length of a period in minutes.

*5) Generator Side Reserve Limits:*

$$0 \leq R_{i,t}^D \leq T^S \cdot RD_i \cdot u_{i,t}^1 \ \forall t, i \quad (12)$$
$$0 \leq R_{i,t}^U \leq T^S \cdot RU_i \cdot u_{i,t}^1 \ \forall t, i \quad (13)$$
$$0 \leq R_{i,t}^{NS} \leq T^{NS} \cdot RU_i \cdot (1 - u_{i,t}^1) \ \forall t, i. \quad (14)$$

Constraints (12)–(14) impose a limit in the procurement of spinning up and down reserves, as well as non-spinning reserve from the generating units. $T^S$ and $T^{NS}$ is the time in minutes the reserves should respond.

*6) Wind Generation Limits:*

$$0 \leq P_{t,w}^{WP,S} \leq P_{t,w}^{WP,\max} \ \forall t, w. \quad (15)$$

Constraint (15) limits the scheduled wind power production. In [20], the minimum and maximum limits are considered as parameters that are submitted by the wind power producer together with its bidding and the maximum limit is considered infinite. Other limits that could be imposed are the maximum wind scenario values, the wind power forecast and the installed capacity of the wind farm. In this paper, it is considered that the $P_{t,w}^{WP,\max}$ coincides with the installed capacity of a wind farm and thus the parameter is practically time-independent.

*7) LSE Limits and Reserves Scheduling:*

$$\mathrm{LSE_{j,t}^{S,min}} \leq \mathrm{LSE_{j,t}^{S}} \leq \mathrm{LSE_{j,t}^{S,max}} \ \forall j, t \quad (16)$$
$$0 \leq \mathrm{R_{j,t}^{U,LSE}} \leq \mathrm{LSE_{j,t}^{S}} - \mathrm{LSE_{j,t}^{S,min}} \ \forall j, t \quad (17)$$
$$0 \leq \mathrm{R_{j,t}^{D,LSE}} \leq \mathrm{LSE_{j,t}^{S,max}} - \mathrm{LSE_{j,t}^{S}} \ \forall j, t. \quad (18)$$

In Fig. 1, (16)–(18) are visually explained. By providing up reserve the LSE is committed to decrease its consumption. This does not necessarily mean that this extra energy is used by end-users, but it can be for instance stored or can be made available for out-of-the-market energy trading.

*8) Industrial Customer Constraints:* In this study the industrial load is considered to comprise of different groups that can work in parallel and include several individual processes, similar to real-life industrial examples. Generally, we can refer to three categories of processes: totally flexible, flexible and inflexible. Totally flexible processes can be considered the ones that are not physically constrained to maintain power for a continuous interval (e.g., a set of production facilities that work as long as there is input material). Flexible processes are the ones that should be completed at most within a certain time interval, but with the flexibility of allocating energy consumption. Within their completion time, they can be continuous (type 1) or interruptible (type 2). The most rigid processes are the inflexible ones that have to be completed in a strictly specified time and energy allocation (e.g., a metallurgy process). For the sake of simplicity, in the proposed formulation we considered that the hourly limit of energy is uniform for each process. There are specific cases that this assumption does not cover, but this restriction is easy to overcome by defining a time varying hourly energy limit.

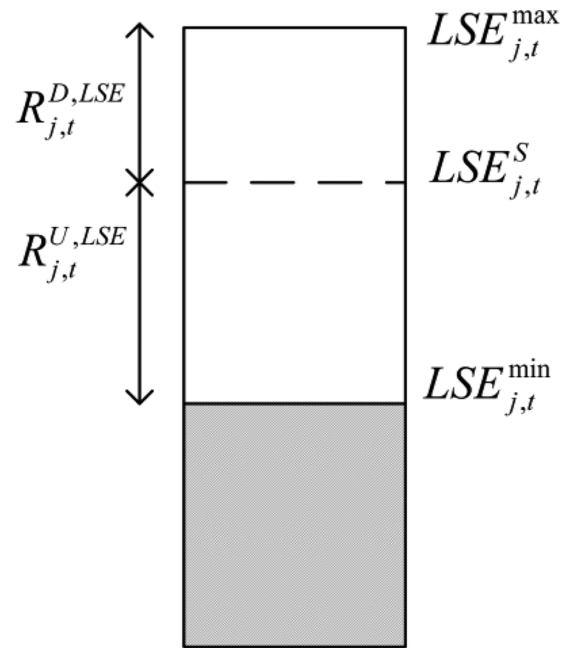


Fig. 1. LSE reserve scheduling.

A process is characterized by several parameters that define the different types of flexibility in terms of energy treatment, as seen in Fig. 2. The totally flexible process consumes energy that can be allocated in four discrete blocks during the day. The only restriction is that no more than two blocks of energy may be allocated in a single period. The flexible process has to consume energy that can be allocated in four discrete blocks. The restrictions are that the process has to be completed in maximum three hours after it starts (no restriction in which period to start) and that no more than two energy blocks can be allocated in a single period. Also, there has to be at least one power block allocated per period (type 1). This type of process offers two degrees of freedom. First, the optimal starting period is selected, and then some parts of the consumption may be shifted in adjacent time periods.

Finally, the inflexible process has to be completed in exactly two periods after it begins (no restriction in which period to start), allocating energy blocks in a predefined manner. The only flexibility of this type of process is that the starting time can be optimally selected.

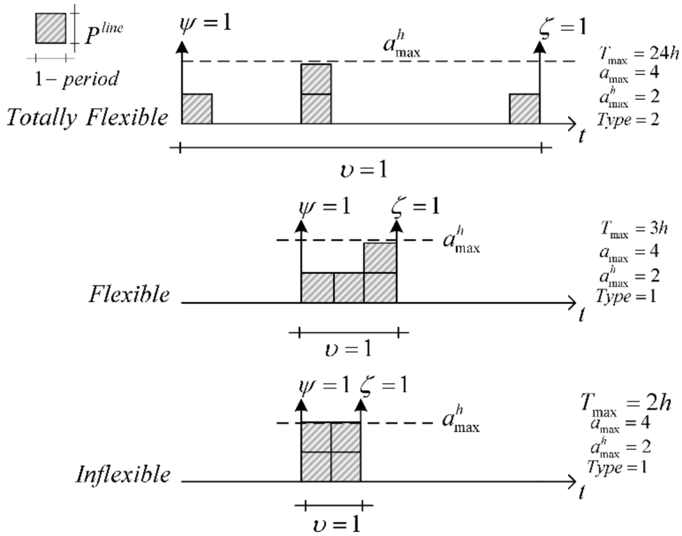


Fig. 2. Types of industrial processes.

*Model of the Operation of the Industry:*

$$\sum_{t\in T} a_{p,g,d,t} = a_{p,g,d}^{\max} \forall p,g,d,t \tag{19}$$

$$P_{p,g,d,t}^{pro,S} = a_{p,g,d,t}\cdot P_{p,g,d}^{line} \forall p,g,d,t \tag{20}$$

$$P_{d,t}^{ind,S} = D_{d,t}^{\min} + \sum_{g\in G}\sum_{p\in P} P_{p,g,d,t}^{pro,S} \forall d,t. \tag{21}$$

Equation (19) is an energy requirement constraint. It states that all the processes should be completed throughout the scheduling horizon. Equation (20) and (21) define the power a process and the industry consumes during a given period. Especially, (21) states that the total power consumed by the industry consists of the time-flexible controllable process load and an inelastic part that is characterized as minimum or mandatory for a period (e.g., stands for must-run or uncontrollable processes of the industry):

$$v_{p,g,d,t}^{1} \le a_{p,g,d,t} \le a_{p,g,d}^{\max,h}\cdot v_{p,g,d,t}^{1} \forall p \in P_{type}^{1}, g,d,t \tag{22}$$

$$0 \le a_{p,g,d,t} \le a_{p,g,d}^{\max,h}\cdot v_{p,g,d,t}^{1} \forall p \in P_{type}^{2}, g,d,t. \tag{23}$$

Constraints (22) and (23) impose limits on the number of processes that could be scheduled for every hour by the industry. They cover both interruptible and continuous processes and they can be used in order to guarantee that limitations such as the installed power of the industry are not violated. It should be noted that the term "production line" is a general term adopted here by the authors in order to express discrete amounts of power that can be treated by processes, not necessarily referring to physical production lines. Constraints (24)–(28) describe the logic of the commitment of a process. Especially, (24) guarantees that a process is finished within the required completion time. Constraints (25)–(28) define the logic of operating, starting and ending a process. Constraints (29)–(30) stipulate that a process can be run only once in the scheduling horizon:

$$\sum_{\tau=t-T_{p,g,d}^{c,\max}+1}^{t} a_{p,g,d,\tau} \ge a_{p,g,d}^{\max}\cdot \zeta_{p,g,d,(t+1)}^{1} \forall p,g,d,t \tag{24}$$

$$a_{p,g,d,t} \ge \zeta_{p,g,d,(t+1)}^{1} \forall p,g,d,t \tag{25}$$

$$\psi_{p,g,d,t}^{1} \le a_{p,g,d,t} \forall p,g,d,t \tag{26}$$

$$\psi_{p,g,d,t}^{1} + \zeta_{p,g,d,t}^{1} \le 1 \forall p,g,d,t \tag{27}$$

$$\psi_{p,g,d,t}^{1} - \zeta_{p,g,d,t}^{1} = v_{p,g,d,t}^{1} - v_{p,g,d,(t-1)}^{1} \forall p,g,d,t \tag{28}$$

$$\sum_{t\in T} \zeta_{p,g,d,t}^{1} = 1 \forall p,g,d \tag{29}$$

$$\sum_{t\in T} \psi_{p,g,d,t}^{1} = 1 \forall p,g,d. \tag{30}$$

Omitting constraints (29) and (30) will cause a violation of constraint (24). Thus, special care should be taken when dealing with multiple operations of a specific process:

$$\psi_{p,g,d,t}^{1} \le \sum_{\tau=t-T_{(p-1),g,d}^{g,\max}}^{t-T_{(p-1),g,d}^{g,\min}} \zeta_{(p-1),g,d,\tau}^{1} \forall p \in \{P \mid p>1\}, g,d,t. \tag{31}$$

In case of several processes that should be executed in a predefined order, (31) guarantees that the next process will begin after a number of periods that can be within a minimum and a maximum limit. Naturally, this is a generic formulation and the appropriate values can cover any possible sequencing preferences.

*Reserve Scheduling From the Industrial Client:* Up, down spinning and non-spinning reserves that can be procured by the industrial processes are described by (32)–(40):

$$R_{d,t}^{U,ind} = \sum_{p\in P}\sum_{g\in G} R_{p,g,d,t}^{U,pro} \forall d,t \tag{32}$$

$$R_{p,g,d,t}^{U,pro} = a_{p,g,d,t}^{up}\cdot P_{p,g,d}^{line} \forall p,g,d,t \tag{33}$$

$$0 \le a_{p,g,d,t}^{up} \le a_{p,g,d,t} \forall p,g,d,t. \tag{34}$$

Constraint (32) stands for the total up reserve scheduled by the industrial load during a period, while (33) and (34) stand for the specific process reserve participation. Especially, (34) states that no more than the number of scheduled production lines for a given interval can be scheduled for up reserve. It should be noted that (34) is considered together with (22) and (23) according to the process type:

$$R_{d,t}^{D,ind} = \sum_{p\in P}\sum_{g\in G} R_{p,g,d,t}^{D,pro} \forall d,t \tag{35}$$

$$R_{p,g,d,t}^{D,pro} = a_{p,g,d,t}^{down}\cdot P_{p,g,d}^{line} \forall p,g,d,t \tag{36}$$

$$0 \le a_{p,g,d,t}^{down} \le a_{p,g,d}^{\max,h}\cdot v_{p,g,d,t}^{1} - a_{p,g,d,t} \forall p,g,d,t. \tag{37}$$

Similarly, (35)–(37) stand for the down reserve scheduling. Especially, (37) states that the increase of consumption cannot overcome the hourly limit:

$$R_{d,t}^{NS,ind} = \sum_{p\in P}\sum_{g\in G} R_{p,g,d,t}^{NS,pro} \ \forall d,t \tag{38}$$

$$R_{p,g,d,t}^{NS,pro} = a_{p,g,d,t}^{ns} \cdot P_{p,g,d}^{line} \ \forall p,g,d,t \tag{39}$$

$$0 \leq a_{p,g,d,t}^{ns} \leq a_{p,g,d}^{\max,h} \cdot (1 - v_{p,g,d,t}^{1}) \ \forall p,g,d,t. \tag{40}$$

Non-spinning reserves are defined by (38)–(40). Especially, (40) states that no more than the maximum discrete amounts of energy can be used in a given interval.

The meaning of the reserve services that can be procured from the industrial load and were described in a previous section of the paper is now rendered evident through constraints (34), (37) and (40). Up and down spinning reserves stand for a decrease or an increase of the consumption of a process that is scheduled to operate during an interval, while non-spinning reserve stands for the total shifting of the process in other periods.

*9) Day-Ahead Market Power Balance:*

$$\sum_{i\in I} P_{i,t}^{S} + \sum_{w\in W} P_{t,w}^{WP,S} = \sum_{r\in R} L_{r,t} + \sum_{j\in J} JSE_{j,t}^{S} + \sum_{d\in D} P_{d,t}^{ind,S} \ \forall t. \tag{41}$$

Equation (41) enforces the market power balance. It is common in the literature [20] and also in real systems (e.g., the insular power system of Crete, Greece) not to enforce the network constraints in the day-ahead formulation. Nonetheless, any market scheme can be implemented within the proposed formulation.

### C. Second Stage Constraints

*1) Generation Limits:*

$$P_{i,t,s}^{G} \geq P_{i}^{\min} \cdot u_{i,t,s}^{2} \ \forall i,t,s \tag{42}$$

$$P_{i,t,s}^{G} \leq P_{i}^{\max} \cdot u_{i,t,s}^{2} \ \forall i,t,s. \tag{43}$$

Minimum and maximum unit output constraints are also enforced in the second stage of the problem by (42) and (43).

*2) Generator Minimum up and Down Time Constraints:* By substituting $y_{i,t}^1$, $y_{i,t}^1$, and $u_{i,t}^1$ in (6) and (7) with $y_{i,t,s}^2$, $z_{i,t,s}^2$, and $u_{i,t,s}^2$, respectively, minimum up and down time constraints are enforced for each scenario as well.

*3) Unit Commitment Logic Constraints:* Similarly, to enforce the unit commitment logic constraints in the second stage, (8) and (9) should be reformulated in order to account for the appropriate scenario-dependent variables.

*4) Ramp-Up and Down Limits:* Ramp limits are enforced in the second stage for each scenario by substituting $P_{i,t}^S$ in (10) and (11) with $P_{i,t,s}^S$.

*5) Wind Power Generation Spillage Limits:*

$$0 \leq S_{t,w,s} \leq P_{t,w,s}^{WP} \ \forall t,w,s. \tag{44}$$

A portion of available wind production can be spilled if it is necessary to facilitate the operation of the power system. This is enforced by (44).

*6) Involuntary Inelastic Load Shedding:*

$$0 \leq L_{r,t,s}^{shed} \leq L_{r,t} \ \forall r,t,s. \tag{45}$$

As a last resort the ISO can decide to shed a part of the inelastic demand in order to keep the consistency of the system. This is enforced by (45).

*7) Industrial Load Constraints:* The scenario-dependent analogous of the relevant industrial load constraints presented and explained in the first stage of the problem is enforced by substituting in (19) and (22)–(31) the first stage variables with the appropriate second stage variables.

*8) Network Constraints:*

$$\begin{aligned} &A_{n,w}^{wf} \cdot \sum_{w\in W} (P_{t,w,s}^{WP} - S_{t,w,s}) + A_{n,i}^{unit} \cdot \sum_{i\in I} P_{i,t,s}^{G} \\ &- \sum_{l\in L:n\equiv nn} f_{l,t,s} + \sum_{l\in L:n\equiv n} f_{l,t,s} \\ &= A_{n,r}^{inel} \cdot \sum_{r\in R} (L_{r,t} - L_{r,t,s}^{shed}) + A_{n,j}^{LSE} \cdot \sum_{j\in J} LSE_{j,t,s}^{C} \\ &+ A_{n,d}^{ind} \cdot \sum_{d\in D} P_{d,t}^{ind,C} \\ &\forall n \in N, t \in T, s \in S \end{aligned} \tag{46}$$

$$f_{l,t,s} = B_{l,n} \cdot (\delta_{n,t,s} - \delta_{nn,t,s}) \quad \forall (n,nn) \equiv l \in L, n \in N, t \in T, s \in S \tag{47}$$

$$-\pi \leq \delta_{n,t,s} \leq \pi \ \forall n \in N, t \in T, s \in S \tag{48}$$

$$\begin{aligned} &\delta_{n,t,s} = 0 \ \forall t \in T, s \in S \ if \ n \equiv reference \ bus \\ &-f_l^{\max} \leq f_{l,t,s} \leq f_l^{\max} \ \forall l \in L, t \in T, s \in S. \end{aligned} \tag{49}$$

Constraints (46)–(49) stand for the network representation. Specifically, (46) enforces the power balance for each node. $A_{n,x}$ is the node to resource x incidence matrix, where $x$ can be unit, wind-farm, inelastic load, LSE or industrial consumer. Constraint (47) determines the power flow through the transmission lines. Angles are constrained by (48) while the reference bus angle is fixed to zero. Active power losses are neglected but they could be easily incorporated using the detailed linear approximation described in [20] as mentioned before. Transmission capacity constraints are described in (49).

### D. Linking Constraints

This set of constraints links the market and the actual operation of the power system. It enforces the fact that reserves in the actual operation of the power system are no longer a stand-by capacity, but are materialized as energy.

*1) Decomposition of Generator Power Outputs:*

$$P_{i,t,s}^{G} = P_{i,t}^{S} + r_{i,t,s}^{U} + r_{i,t,s}^{NS} - r_{i,t,s}^{D} \ \forall i,t,s. \tag{50}$$

Constraint (50) involves the scheduled day-ahead unit outputs with the scenario-dependent deployed power. It is clear that up spinning and non-spinning reserves stand for an increase of the output power and down spinning stands for a decrease.

*2) Generation-Side Deployed Reserve Determination:*

$$0 \leq r_{i,t,s}^{U} \leq R_{i,t}^{U} \; \forall i,t,s \tag{51}$$
$$0 \leq r_{i,t,s}^{NS} \leq R_{i,t}^{NS} \; \forall i,t,s \tag{52}$$
$$0 \leq r_{i,t,s}^{D} \leq R_{i,t}^{D} \; \forall i,t,s \tag{53}$$
$$r_{i,t,s}^{U} + r_{i,t,s}^{NS} - r_{i,t,s}^{D} = \sum_{f \in F^i} r_{i,t,s,f}^{G} \; \forall i,t,s \tag{54}$$
$$r_{i,t,s,f}^{G} \leq B_{i,t,f} - b_{i,t,f} \; \forall i,t,s,f \tag{55}$$
$$r_{i,t,s,f}^{G} \geq -\, b_{i,t,f} \; \forall i,t,s,f. \tag{56}$$

Constraints (51)–(56) stipulate that the deployed reserves cannot be greater than their respective scheduled values. Constraints (54)–(56) decompose the deployed reserves into energy blocks.

*3) Decomposition of LSE Consumption:*

$$LSE_{j,t,s}^{C} = \mathrm{LSE}_{\mathrm{j,t}}^{\mathrm{S}} - r_{j,t,s}^{U,LSE} + r_{j,t,s}^{D,LSE} \; \forall j,t,s. \tag{57}$$

Unlike the reserves deployed by the generating units, the meaning of up reserves by the LSE is a decrease in the consumption while down reserves is an increase. This is enforced by (57).

*4) LSE Deployed Reserve Determination:*

$$0 \leq r_{j,t,s}^{U,LSE} \leq \mathrm{R}_{\mathrm{j,t}}^{\mathrm{U,LSE}} \; \forall j,t,s \tag{58}$$
$$0 \leq r_{j,t,s}^{D,LSE} \leq \mathrm{R}_{\mathrm{j,t}}^{\mathrm{D,LSE}} \; \forall j,t,s. \tag{59}$$

Constraints (58) and (59) restrict the deployed reserves from the LSE to be within the limits of the schedule, at the first stage of the problem.

*5) Decomposition of Industrial Load Consumption:*

$$P_{d,t,s}^{ind,C} = D_{d,t}^{\min} + \sum_{g \in G} \sum_{p \in P} P_{p,g,d,t,s}^{pro,C} \; \forall d,t,s \tag{60}$$
$$P_{p,g,d,t,s}^{pro,C} = P_{p,g,d,t}^{pro,S} + r_{p,g,d,t,s}^{D,pro} - r_{p,g,d,t,s}^{U,pro} + r_{p,g,d,t,s}^{NS,pro} \quad \forall p,g,d,t,s. \tag{61}$$

Constraints (60) and (61) determine the actual consumption of the industrial load. Especially, (60) reallocates the power of every single process (through the determination of reserves), while (61) sums all the consumptions of the single processes up to the actual consumption of the industry.

*6) Industrial Load Reserve Determination:*

$$r_{p,g,d,t,s}^{U,pro} = a_{p,g,d,t,s}^{up,rt} \cdot P_{p,g,d}^{line} \forall p,g,d,t,s \tag{62}$$
$$0 \leq r_{p,g,d,t,s}^{U,pro} \leq R_{p,g,d,t}^{U,pro} \forall p,g,d,t,s \tag{63}$$
$$0 \leq a_{p,g,d,t,s}^{up,rt} \leq a_{p,g,d,t}^{up} \forall p,g,d,t,s \tag{64}$$
$$r_{p,g,d,t,s}^{D,pro} = a_{p,g,d,t,s}^{down,rt} \cdot P_{p,g,d}^{line} \forall p,g,d,t,s \tag{65}$$
$$0 \leq r_{p,g,d,t,s}^{D,pro} \leq R_{p,g,d,t}^{D,pro} \forall p,g,d,t,s \tag{66}$$
$$0 \leq a_{p,g,d,t,s}^{down,rt} \leq a_{p,g,d,t}^{down} \forall p,g,d,t,s \tag{67}$$
$$r_{p,g,d,t,s}^{NS,pro} = a_{p,g,d,t,s}^{ns,rt} \cdot P_{p,g,d}^{line} \forall p,g,d,t,s \tag{68}$$
$$0 \leq r_{p,g,d,t,s}^{NS,pro} \leq R_{p,g,d,t}^{NS,pro} \forall p,g,d,t,s \tag{69}$$
$$0 \leq a_{p,g,d,t,s}^{ns,rt} \leq a_{p,g,d,t}^{ns} \forall p,g,d,t,s. \tag{70}$$

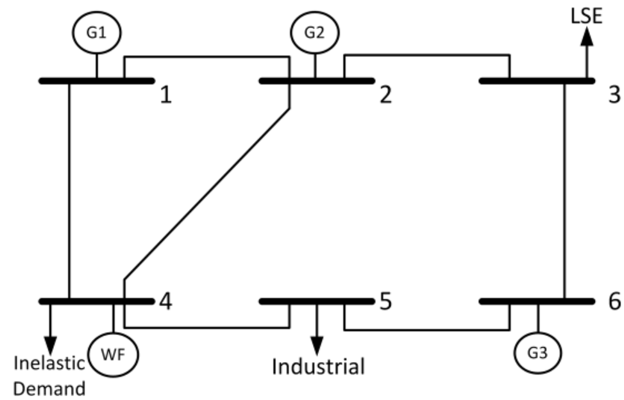


Fig. 3. Network model.

Constraints (62)–(70) determine the reserves provided by the reallocation of the energy needs of the processes. The rationale followed is similar to the reserve determination for generating units and LSE.

## IV. Tests and Results

In this section, the applicability of the proposed formulation is evaluated by extensive simulations. Firstly, a small-test case is thoroughly analyzed in order to render evident the use of the model. Then, the scalability of the model is examined by providing relevant results from simulations conducted on a 24-node system. Finally, computational and modeling issues are also discussed.

### A. Illustrative Example

In the study, a sample three generator test case shown in Fig. 3 is realized to analyze the performance of the proposed methodology. Besides, the technical and economic data for the mentioned generators are presented in Table I. These data are adapted from [31] and are adjusted to the needs of the test case. The network topology and the line data are derived from [32]. For the sake of simplicity, it is assumed that for all the scheduling-periods the generators offer the same prices for energy and reserves. The marginal costs range from 29 € /MWh to 32 € /MWh for Unit 1, from 55 € /MWh to 57.5 € /MWh for Unit 2 and from 85 € /MWh to 95 € /MWh for Unit 3. All three generators are considered to be able to provide up and down spinning reserves at a cost of 8 € /MWh, but only the peak Unit 3 can provide non-spinning reserve at a cost if 5 € /MWh. Spinning reserves have to be provided in 15 min, while non-spinning reserve has to be delivered in 30 min. The initial conditions are treated within the context of the extension of the scheduling horizon as described in [31].

Regarding the LSE, it may provide up and down reserves at a cost of 50 € /MWh. The cost for the provision of reserves by the LSE is equal to its utility cost and the value is derived from [20]. The utility of the industrial load is 160 € /MWh, while it provides all its supported types of reserves at a very low price equal to 0.5 € /MWh. The selection of these prices depicts the fact that the total energy consumed by the industry is enforced over the scheduling horizon, assuming that it makes

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.



TABLE I
TECHNICAL DATA OF GENERATING UNITS

| | $P_{max}$ [MW] | $P_{min}$ [MW] | UT [h] | DT [h] | RU [MW/min] | RD [MW/min] | $P_{ini}$ [MW] | $T_{ini}$ [h] | SUC [€] | SDC [€] |
|---|---|---|---|---|---|---|---|---|---|---|
| **Unit1** | 274 | 100 | 8 | 4 | 2 | 2 | 120 | 20 | 46600 | 20000 |
| **Unit2** | 378 | 200 | 4 | 3 | 24 | 24 | 120 | 20 | 16012 | 10000 |
| **Unit3** | 152 | 63 | 1 | 1 | 8 | 8 | 0 | -6 | 2568 | 1000 |

TABLE II
TECHNICAL DATA OF INDUSTRIAL LOAD

| | | Type | Pline [MW] | amax | amaxh | Tcomp [h] | Tgmin[h] | Tgmax [h] |
|---|---|---|---|---|---|---|---|---|
| **GR.1** | **PRO.1** | 1 | 2 | 4 | 2 | 2 | 0 | 0 |
| | **PRO.2** | 1 | 2 | 6 | 2 | 4 | | |
| **GR.2** | **PRO.1** | 2 | 2 | 10 | 10 | 24 | - | - |
| **GR.3** | **PRO.1** | 1 | 2 | 4 | 2 | 3 | 2 | 5 |
| | **PRO.2** | 1 | 2 | 6 | 6 | 10 | | |

TABLE III
WIND SCENARIOS, INELASTIC, INDUSTRIAL LOAD, AND LSE DEMAND (MW)

| Time | Wind | | | Inelastic | LSE | Min. Ind. Load. | Time | Wind | | | Inelastic | LSE | Min. Ind. Load. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | | | | | S1 | S2 | S3 | | | |
| **1** | 77 | 59 | 43 | 136 | 34 | 30 | **13** | 55 | 45 | 34 | 276 | 69 | 60 |
| **2** | 70 | 60 | 46 | 128 | 32 | 30 | **14** | 49 | 38 | 30 | 284 | 71 | 60 |
| **3** | 71 | 57 | 33 | 120 | 30 | 30 | **15** | 49 | 36 | 24 | 272 | 68 | 50 |
| **4** | 60 | 57 | 40 | 112 | 28 | 30 | **16** | 53 | 42 | 28 | 264 | 66 | 50 |
| **5** | 70 | 50 | 34 | 104 | 26 | 30 | **17** | 74 | 59 | 33 | 248 | 60 | 50 |
| **6** | 75 | 53 | 40 | 112 | 28 | 30 | **18** | 79 | 66 | 25 | 256 | 64 | 40 |
| **7** | 70 | 57 | 39 | 120 | 30 | 30 | **19** | 77 | 63 | 43 | 260 | 65 | 40 |
| **8** | 73 | 57 | 39 | 160 | 40 | 60 | **20** | 77 | 51 | 34 | 280 | 70 | 40 |
| **9** | 47 | 38 | 18 | 188 | 47 | 60 | **21** | 79 | 47 | 34 | 276 | 69 | 30 |
| **10** | 55 | 41 | 22 | 200 | 50 | 60 | **22** | 74 | 54 | 33 | 216 | 54 | 30 |
| **11** | 50 | 41 | 25 | 236 | 59 | 60 | **23** | 80 | 65 | 37 | 156 | 39 | 30 |
| **12** | 53 | 42 | 33 | 244 | 61 | 60 | **24** | 66 | 53 | 45 | 116 | 29 | 30 |

TABLE IV
COMPARISON OF ENERGY AND RESERVE COSTS CONSIDERING AND NEGLECTING RESERVES FROM THE INDUSTRY

| | Energy Cost [€] | Reserve Cost [€] |
|---|---|---|
| **Base Case** | 238280.84 | 6398.4 |
| **No reserves from ind. load** | 243235.02 | 6803.4 |

no difference when the industry receives the energy to accomplish the deferrable processes and also serves the illustrative purposes of this test case. Finally, the wind spillage cost is considered 1000€ /MWh that is also equal to the value of lost load. The industrial load consists of several processes and also a minimum inelastic part. As shown in Table II, processes are categorized in three groups. The first group contains a totally inflexible process $(\mathrm{GR.1}|\mathrm{PRO.1})$ and a flexible process $(\mathrm{GR.1}|\mathrm{PRO.2})$. The second process of this group should start as soon as the first one finishes. The second group comprises a totally flexible process $(\mathrm{GR.2}|\mathrm{PRO.1})$. The third group contains two flexible processes and the time interval between the end of the first and

TABLE V
COMPARISON OF ENERGY AND RESERVE COSTS CONSIDERING AND NEGLECTING RESERVES FROM THE INDUSTRY FOR DIFFERENT LOCATIONS OF THE INDUSTRIAL CONSUMER

| Location of the industry | Reserves from industrial load | | No reserves from industrial load | |
|---|---|---|---|---|
| | Energy[€] | Reserves[€] | Energy[€] | Reserves[€] |
| 2 | 408632 | 799 | 409079 | 1189.5 |
| 3 | 408629 | 804 | 409079 | 1189.5 |
| 10 | 408640 | 804.5 | 409079 | 1189.5 |
| 19 | 408623 | 799.5 | 409079 | 1189.5 |

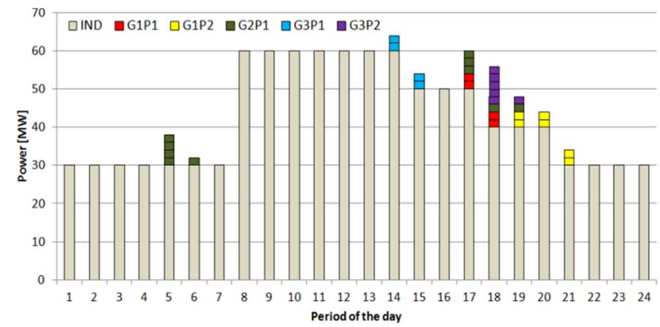


Fig. 4. Scheduled industrial load.

the beginning of the second can vary from two to five hours. Finally, the inelastic consumption of the industry is presented in Table V for each period of the scheduling horizon.

A wind-farm with installed capacity of 100 MW is located at bus 4. Wind uncertainty is considered through three scenarios (High, Moderate, and Low) as also shown in Table V. The occurrence probabilities for each scenario are 0.2 for High (S1), 0.6 for Moderate (S2), and 0.2 for Low (S3). Besides, the data related to other load types considered in this study are presented in Table III. Here, the inelastic load is considered perfectly known in both stages. It should be stated that, as a last resort, the ISO can shed load in the actual operation of the power system at a very high price. The scheduled LSE load can vary 5% from the consumptions presented in Table V and is also able to provide up and down reserves within the same limits. The LSE does not provide any reserve and is scheduled to consume during all the periods 5% more than the values of Table V, because an increase in the load of the LSE would provide an increase of social benefit (reduction in the value of the objective function).

In Figs. 4–7 the process scheduling of the industrial consumer, as well as the re-scheduling in each one of the scenarios, are presented. Through Figs. 4–7 the meaning of the reserve services that can be procured from the industrial consumer is rendered evident. $(\mathrm{GR.1}|\mathrm{PRO.1})$ is an inflexible process that is allocated in periods 17 and 18 and does not provide any reserves (does not shift its operation). The process $(\mathrm{GR.1}|\mathrm{PRO.2})$ starts immediately after the end of $(\mathrm{GR.1}|\mathrm{PRO.1})$ and lasts for a maximum of 4 periods. In the day-ahead market it is scheduled to be completed in 3 periods, which is also the case for S1.

In S2 and S3, one block of energy (2 MWh) is curtailed in periods 20 and 21 (up reserve) and this amount is recovered

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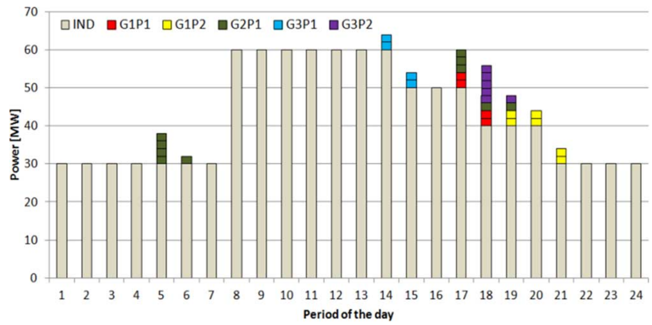


Fig. 5. Industrial load in S1.

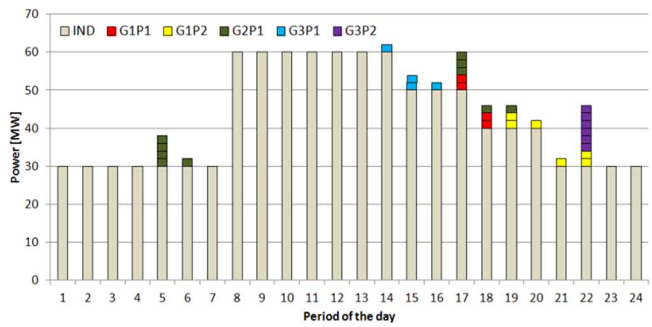


Fig. 6. Industrial load in S2.

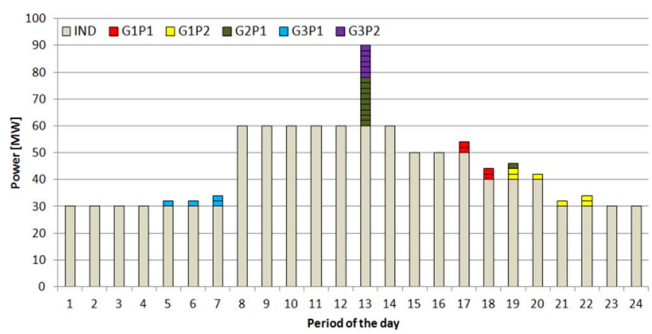


Fig. 7. Industrial load in S3.

during period 22. The process $(\mathrm{GR}.2|\mathrm{PRO}.1)$ is the most flexible one, since it can be allocated accordingly at any period. In the day-ahead market, energy blocks are allocated in periods 5, 6, 17, 18, and 19. Since the duration of this process is considered 24 h, shifting of the process energy needs in S3 during period 13 is considered as down reserve for that period, while for the periods that have energy scheduled in the day-ahead market the shifting is considered up reserve. Finally, process $(\mathrm{GR}.3|\mathrm{PRO}.2)$ has to be started between at least 2 and at most 5 periods after $(\mathrm{GR}.3|\mathrm{PRO}.1)$. In Fig. 7 it can be noticed that $(\mathrm{GR}.3|\mathrm{PRO}.1)$ shifted from periods 14 and 15 to periods 5, 6, and 7. Accordingly, $(\mathrm{GR}.3|\mathrm{PRO}.2)$ shifted from periods 18 and 19 to period 13.

To investigate the impact of the reserve procurement from the industrial consumer, the previous test case (base case) is compared with the case in which the industrial consumer cannot provide reserves, by means of cost of scheduling generation-side energy and reserves. Yet, it is assumed that the system operator can optimally allocate the flexible process operation of the industry. The relevant results are presented in Table IV.

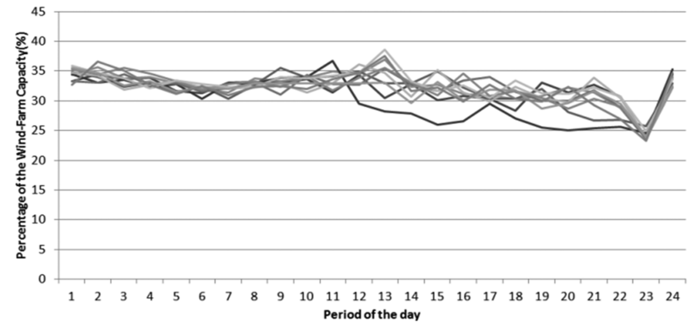


Fig. 8. Wind-power generation scenarios.

It can be noticed that the cost of energy and reserves scheduled by units is higher if no reserves are procured by the industrial client. This is related to the amount of reserves that are scheduled for period 13 and other relatively high-peak periods and especially to the comparatively high value of the minimum power limit of Unit 2. It should be noted that the case in which the system operator has some flexibility in allocating the flexible industrial load is of course favorable, since in another case it could be arbitrarily allocated by the industry itself.

### B. 24-Node Test System

The 24- node system that is analyzed here is based on the single area version of the IEEE Reliability Test System-1996 [33] and all the data are derived from [34]. Given the size of the problem, the binary variables related to the start-up and shutdown of the units are fixed between the stages, thus non-spinning reserves are not provided by the generation side [35]. Also, to further reduce the size of the problem, generators have been grouped by type and bus, so that only one set of binary variables is used to determine the commitment status of one group of units, as in [20]. Furthermore, the wind farm is assumed to be located at node 8. The wind spillage cost is 1000 € /MWh. In this study we focus mainly on the impact of having a flexible industrial consumer that can also provide reserve services to accommodate the wind unpredictability.

For the sake of simplicity, we consider that all the other loads are not flexible and consume their nominal power. The value of lost load is considered to be 1000 € /MWh. Furthermore, an industrial consumer is considered to be available for reserve procurement. The fixed demand of the industry is the same as in Table III.

The cost for the reserves procured by the industrial consumer and its utility are 0.5 € /MWh and 160 € /MWh, respectively. To adequately describe wind uncertainty a sufficient number of scenarios have to be generated. Publicly available data [36] have been used in order to generate ten hourly scenarios with a scenario generation technique based on the Roulette Wheel Mechanism (RWM) [37]. The scenarios normalized with respect to the capacity of the wind farm are presented in Fig. 8 and are equiprobable.

Three different test sets are presented in order to evaluate the impact of the flexible industrial consumers and to evaluate the performance of the proposed methodology.

In the first test set, the impact of the location of the industrial consumer is examined. It is initially considered that the

TABLE VI
COMPARISON OF ENERGY AND RESERVE COSTS CONSIDERING AND NEGLECTING RESERVES FROM THE INDUSTRY FOR DIFFERENT LEVELS OF WIND POWER PRODUCTION PENETRATION

| | Reserve from industrial load | | No reserves from industrial load | |
|---|---|---|---|---|
| WF Cap. [MW] | Energy[€] | Reserves[€] | Energy[€] | Reserves [€] |
| 300 | 395408 | 1273.5 | 395864 | 1785.5 |
| 1000 | 328762 | 5144.5 | 329097 | 5949 |
| 1700 | 295743 | 6980.4 | 295989 | 7739.4 |

industrial consumer is not available for reserve procurement. We distinguish two processes. The first one (PRO1) requires 5 MWh of energy and should be completed at exactly five periods, consuming 1 MWh of energy at each single period. The second process (PRO2) is totally flexible and needs a total of 20 MWh of energy that has to be provided during the day. Firstly, it is assumed that PRO1 spans over periods 8 to 12. Also, 4 MWh are required in periods 13, 15, 16, 17, and 19 for PRO2. Then, these processes are available to be scheduled, such as to provide reserves to balance the wind generation (in blocks of 0.5 MWh and 1 MWh, respectively). It should also be stated that the wind farm is assumed to have 200 MW of installed capacity. The results are presented in Table V for different locations of the industry. It is clear that the procurement of reserves from the flexible industrial customers has a positive contribution in the mitigation of the generation side reserve and energy costs.

In the second test set, the impact of having reserves procured by the industrial consumer, for different wind power production penetration levels, is evaluated. The industry is considered to be located at node 19. The relevant results are presented in Table VI. As concluded in [20], increasing penetration of wind power production decreases the energy production cost of conventional generators, while it increases the security cost (reserves). It is clear from the results that by procuring reserves from the industrial consumer, the system operator profits from the lower energy costs, while mitigating the cost of scheduling reserves from the generation side.

In the third test set, it is considered that the industry has one totally flexible process that can be used in reserve procurement. The impact of the total energy required and the energy block size are examined through these tests. The wind farm has an installed capacity of 1000 MW. Table VII presents the relevant results. For all the tests, the wind-farm is located at node 19. As can be seen, the energy costs for the generators generally tend to increase, as the size of the energy requirement increases. This depends, of course, on the overall system loading condition because of the inelastic loads. Clearly, less generation-side reserves have to be scheduled as the size of the energy block decreases for every case of the flexible process energy requirements. Furthermore, incorporating more flexible capacity to respond to wind power generation fluctuations also reduces the cost of generation-side reserves. It is also to be stated that the energy cost differences for the different energy requirement cases of the flexible processes are not significant.

TABLE VII
COMPARISON OF ENERGY AND RESERVE COSTS FOR VARIOUS FLEXIBLE PROCESS ENERGY REQUIREMENT CHARACTERISTICS

| Total Energy [MWh] | Energy Block Size [MWh] | Energy Cost [€] | Reserves Cost [€] |
|---|---|---|---|
| 30 | 0.5 | 328744 | 4913 |
| 30 | 1 | 328744 | 4914 |
| 30 | 2 | 328744 | 4920.5 |
| 30 | 5 | 328744 | 4960 |
| 50 | 0.5 | 328707 | 4553 |
| 50 | 1 | 328736 | 4568 |
| 50 | 2 | 328744 | 4582.5 |
| 50 | 5 | 328784 | 4638 |
| 100 | 0.5 | 328881 | 4015.5 |
| 100 | 1 | 328898 | 4022 |
| 100 | 2 | 328883 | 4024 |
| 100 | 5 | 328923 | 4081 |

### C. Computational Statistics and Modeling Issues

Because of the size of the proposed formulation and the number of binary variables it is important to discuss here the computational issues related to the solution of the model. The computer used for all the simulations is a windows 64-bit based workstation with two 3.47-GHz 6-core processors and 96 GB of RAM. All the simulations are coded in GAMS v.24.1.3 [38] and the model is solved by CPLEX v.12 [39].The model statistics for the test cases presented are given in Table VIII. It should be noted that for the 24-node based test cases, the time provided is the computational time of the slowest simulation that was performed. The applicability of the proposed reserve scheduling methodology depends on the computational tractability. Several measures to mitigate the computational time include:

1) Define the acceptable trade-off between the quality of the solution and the computational time (relative duality gap greater than 0%).
2) Make use of modern computing options such as grid and cloud computing. This is a logical suggestion since relevant technological upgrades are not mandatory for an ISO, because there exist already companies that rent computational resources at very affordable prices.
3) Make use of decomposition techniques such as Bender's decomposition.
4) Through appropriate scenario reduction techniques, a representing set of them should be used to describe the wind power generation uncertainty.
5) Using the GAMS profiler, it is reported that constraints (31) and (62) contribute significantly in the computational burden. Thus, alternative constraint sets could be developed in order to consider processes with a sequential relationship.

Finally, it is relevant to discuss an ambiguity that can emerge under the proposed formulation. In case that multiple solutions exist, the solver may return one that lacks physical meaning. This is the case for the deployment of reserves from the generating units. For instance, if 10 MW of up spinning reserves are required from a unit, then it is possible to notice a solution of 20

TABLE VIII
COMPUTATIONAL STATISTICS OF THE TEST CASES

| | Equations | Continuous Variables | Discrete Variables | Time [s] | Duality gap [%] |
|---|---|---|---|---|---|
| **6-node (base case)** | 29677 | 45501 | 5225 | 84 | 0 |
| **6-node (no reserves from ind. load)** | 29677 | 45501 | 3929 | 10 | 0 |
| **24-node (considering reserves by ind. consumer)** | 181721 | 325832 | 18015 | 437 | 0.01 |
| **24-node (neglecting reserves by ind. consumer)** | 181721 | 325832 | 17871 | 47 | 0 |
| **24-node (flexible process)** | 174843 | 320145 | 16167 | 227 | 0.005 |

MW of up spinning reserve from the unit plus 10 MW of down spinning reserve from the same unit.

There are some techniques that could be employed to handle this issue. One could include logical constraints that do not allow the same unit to alter its production up and down during the same period. Since this technique would increase the required binary variables, an easier way to overcome this ambiguity is to include the sum of the variables $\mathrm{r}^{\mathrm{U}}_{\mathrm{i,t,s}}$ and $\mathrm{r}^{\mathrm{D}}_{\mathrm{i,t,s}}$ in the objective function and multiply them by a small value (e.g., 10–5) so that the objective value is not affected.

## V. CONCLUSIONS

Higher penetration of renewable resources, especially wind, is a reality that introduces different pros and cons for the power system operation. The volatile nature of wind power is a significant issue that requires use of different strategies to overcome. In this paper, a two-stage stochastic programming based joint energy and reserves day-ahead scheduling model was presented, utilizing load-following reserves procured from both generation and demand sides to overcome the uncertainty of high wind power penetration. Also, a novel linear model of an industrial consumer was provided considering the peculiarities of different types of industrial processes. Simulations allowed demonstrating that through the proposed methodology a power system has the potential to profit from the low-cost wind energy, mitigating the generation side costs of scheduling reserves, under significant wind power penetration. Generalizing the conclusions by analyzing data associated with a long-term period for a real power system is a topic for future research.

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