Unit Commitment With Ideal and Generic Energy Storage Units

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***Abstract*—Intermittence and variability of renewable resources is often a barrier to their large scale integration into power systems. We propose a stochastic real-time unit commitment to deal with the stochasticity and intermittence of non-dispatchable renewable resources including ideal and generic energy storage devices. Firstly, we present a mathematical definition of an ideal and generic storage device. This storage device definition has some mathematical advantages: 1) it can be easily integrated within complex optimization problems, 2) it can be modeled using linear programming, suitable for practical large-scale cases. Secondly, a stochastic unit commitment with ideal and generic storage devices and intermittent generation is proposed to solve the joint energy-and-reserves scheduling and real-time power balance problem, reflecting the minute-by-minute intermittent changes and the stochasticity of renewable resources. We also compare our results with those obtained using a deterministic unit commitment with perfect information. The proposed model is illustrated with a 24-bus system.**

***Index Terms*—Mixed-integer linear programming (MILP), real-time unit commitment, storage devices, two-stage optimization model.**

NOTATION

The mathematical symbols used throughout this paper are described below. We have used the operator $\mathbb{E}$ as the expectation of a random function.

Indexes:

i	Conventional generating unit index.
j	Storage unit index.
h	Time period scheduling index, generally on an hourly basis.
t	Real-time period index.
n	Node index.
l	Line index.
ω	Scenario realization index.

Sets:

Ω_{in}	Set containing every conventional generating unit i connected to node n.
Ω_{jn}	Set containing every energy storage unit j connected to node n.

Parameters:

c^g_{ih}	Generation cost for conventional unit i and hour h [$/MWh].
c^{su}_i/c^{sd}_i	Start-up/shut-down cost for conventional unit i [$/h].
c^u_i	Fixed running cost for conventional unit i [$/h].
c^s_{jh}	Storage cost for storage unit j and hour h [$/MWh].
c^p_{jh}	Production cost for storage unit j and hour h [$/MWh].
$c^{r,up}_{ih}/c^{r,dw}_{ih}$	Up/down scheduled reserves cost for unit i and hour h [$/MWh].
$c^{r,s}_{jh}/c^{r,p}_{jh}$	Storage/production scheduled reserves cost for unit j and hour h [$/MWh].
$\hat{c}^{r,up}_{ih}/\hat{c}^{r,dw}_{ih}$	Real-time up/down deployed reserves cost for unit i and hour h [$/MWh].
$\hat{c}^{r,s}_{jh}/\hat{c}^{r,p}_{jh}$	Real-time storage/production deployed reserves cost for unit j and hour h [$/MWh].
$c^{fast\text{-}r}_n$	Fast response generation cost at node n [$/MWh].
c^{ls}	Cost of load shedding [$/MWh].
c^{ws}	Cost of wind spillage [$/MWh].
$c^{p\text{-}spill}_n$	Cost of power spillage at node n [$/MWh].
RD_i/RU_i	Ramp-down/ramp-up limit for generating unit i [MW/h].
SD_i/SU_i	Shutdown/start-up ramp limit for generating unit i [MW/h].

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$\underline{p}_i/\overline{p}_i$	Minimum/maximum power output for generating unit i [MW].
$\overline{r}_i^{dw}/\overline{r}_i^{up}$	Scheduled down/up reserve upper bound for unit i [MW].
$\underline{r}_i^{dw}/\underline{r}_i^{up}$	Scheduled down/up reserve lower bound for unit i [MW].
$\underline{s}_j^s/\overline{s}_j^s$	Minimum/maximum power storage for storage unit j [MW].
$\underline{s}_j^p/\overline{s}_j^p$	Minimum/maximum power production for storage unit j [MW].
$\underline{x}_j/\overline{x}_j$	Minimum/maximum storage capacity for unit j [MWh].
$\underline{x}_j^{end}/\overline{x}_j^{end}$	Minimum/maximum storage capacity for unit j at the end of the study horizon [MWh].
$\overline{f}_l$	Maximum flow capacity for the line l [MW].
φ_{ln}	Element of the power transfer distribution factor matrix associated with line l and node n.
x_j^0	Initial energy level of storage unit j at the beginning of the study horizon [MWh].
d_{nh}	Hourly power demand scheduled in node n [MW].
w_{nh}	Hourly non-dispatchable energy generation scheduled in node n [MW].
$\hat{d}_{nht}(\omega)$	Real-time power demand in node n, hour h, subperiod t and scenario ω [MW].
$\hat{w}_{nht}(\omega)$	Real-time non-dispatchable renewable generation in node n, hour h, subperiod t and scenario ω [MW].
η_j^s/η_j^p	Efficiency rate to store/produce energy in storage unit j.
γ_j	Unitary future value of energy for storage unit j [$/MWh].
$\pi(\omega)$	Probability of scenario ω.
Δ	Real-time slot [h].

Non-Negative Variables:

p_{ih}	Hourly scheduled power generation for generating unit i [MW].
s_{jh}^s/s_{jh}^p	Hourly scheduled power storage/production (withdrawal/injection from/into the network) for storage unit j [MW].
x_{jh}	Energy storage level for unit j at the end of hour h [MWh].
$\hat{x}_{jht}(\omega)$	Real-time energy storage level for unit j and scenario ω [MWh].
r_{ih}^{up}/r_{ih}^{dw}	Hourly scheduled up/down reserve for generating unit i in hour h [MW].
r_{jh}^p/r_{jh}^s	Hourly scheduled production/storage (up/down) reserve for storage unit j in hour h [MW].
$\hat{r}_{iht}^{up}(\omega)/\hat{r}_{iht}^{dw}(\omega)$	Real-time deployed up/down reserve for generating unit i and scenario ω [MW].
$\hat{r}_{jht}^p(\omega)/\hat{r}_{jht}^s(\omega)$	Real-time deployed production/storage (up/down) reserve for storage unit j and scenario ω [MW].
$\hat{p}_{nht}^{fast\text{-}r}(\omega)$	Real-time power generation for a fast response generation unit at node n and scenario ω [MW].
$\hat{ls}_{nht}(\omega)$	Real-time load shedding power at node n and scenario ω [MW].
$\hat{ws}_{nht}(\omega)$	Real-time wind spillage power at node n and scenario ω [MW].
$\hat{p}_{nht}^{spill}(\omega)$	Real-time power spillage at node n and scenario ω [MW].

Binary Variables:

u_{ih}	On/off status of generating unit i in hour h.

Free Variables:

q_{nh}	Hourly scheduled import/export power from/to node n [MW].
$\hat{q}_{nht}(\omega)$	Real-time import/export power from/to node n in the scenario ω [MW].

Functions:

Φ	Scheduled thermal and storage units cost [$].
C_{ih}^{su}/C_{ih}^{sd}	Start-up/shut-down cost function for conventional unit i and hour h [$/MWh].
Υ	Scheduled up/down reserves cost function [$].
$\Theta(\omega)$	Corrective actions cost (only reserves) to accommodate the stochastic real-time net load to the scheduled production [$].
$\Theta'(\omega)$	Corrective actions cost (reserves and emergency actions) to accommodate the stochastic real-time wind and demand to the hourly unit commitment schedule [$].

I. Introduction

A. Background, Motivation, and Approach

STORAGE devices have experienced a very rapid growth in recent years. They are expected to be a good alternative to integrate large amounts of intermittent renewable energy to meet real-time power demand, improving power system reliability and being economically efficient. With this outlook, bulk storage devices are expected to be incorporated into power systems in the near future. Successful cases of incipient bulk energy storage installations are emerging [1], [2]. Reference [3] addresses the importance of including massive storage devices to meet real-time demand with significant integration of intermittent renewable energies.

The evolution of electricity systems indicates an increasing integration of renewable and non-dispatchable energy sources. This means more production volatility, forcing conventional generators to modify their productions according to the intermittence of the renewable energy resources. However, energy storage represents an alternative to cope with future renewable energy penetration.

The potential benefits of bulk storage integration can be summarized as follows:

- no need for network oversizing to deliver energy in peak demand periods;
- substantial renewable energy integration without the need for grid reinforcement;
- power system stability improvement due to the use of energy storage devices to supply ancillary services that help to keep the real-time demand balance;
- providing clean and economic ancillary services;
- implementation of reliable stand-alone systems with large amounts of renewable energies;
- avoiding negative spot prices;
- helping conventional generation to work closely to stationary conditions (reduction of shut-down and start-up events).

In this paper, we propose a centralized energy dispatch based on a unit commitment with real-time power balance, where ideal and generic energy storage devices are included combined with intermittent renewable energy resources. The model is formulated using two-stage stochastic programming. The first stage represents the day-ahead production and reserve scheduling of generating and storage units. The second stage represents real-time power balance. In the second stage reserves are deployed to meet the minute-by-minute demand under the uncertain intermittent renewable production.

In the second stage, realizations are uncertain and production variability is high, since intermittent energy sources are integrated in the system. Several papers have made the assumption that the scheduled variables and the stochastic forecasts are constant throughout each hour. Here, we consider that the second stage representing the real time power balance is defined on a more accurate basis that could range from seconds to a few minutes. Unlike other works, we consider real-time as a small subdivision of an hour (a few minutes), while hourly scheduling variables are simultaneously considered. In this sense, our approach is different from just using a smaller time subdivision, e.g., 15 min, within established unit commitment models.

This paper considers that the power system is mainly composed of conventional thermal generating units, intermittent renewable resources, and several storage devices located in different nodes. The proposed model does not consider investment costs (i.e., storage, generation and transmission investment costs), since our model focuses on optimal operation decisions and not on planning decisions.

B. Literature Review

There is no doubt about the benefits of integrating storage devices in power systems, especially with large amounts of non-dispatchable energy sources [4]. However, their main drawback has been that they were not cost-effective. Recent developments in storage technologies and the increasing use of renewable energy in power systems have made the storage technologies more cost-effective. Several studies have addressed the importance and value of storage devices in power systems [4], [5]. The integration of storage devices can significantly help in load balancing making power systems more reliable and robust even when having large amounts of non-dispatchable energy.

Several references examine the impact of wind variability in energy markets [5]–[10]. They all find out that, as wind power generation increases, the reserves increase. This is translated into a higher reserves cost, but, sometimes, into a lower total operation cost [9] due to the relatively cheap wind generation cost.

Unit commitment needs to consider stochastic instead of deterministic optimization to account for the uncertainty of non-dispatchable generation. Stochastic optimization has been used for unit commitment problems with wind generation. These models jointly schedule energy generation and reserves in order to meet demand under any wind scenario [8], [10]–[14]. Pumped storage was incorporated in some of these works [8], [13], [14] to address the relevance of storage devices in case of having large amounts of wind.

Despite the fact that there is a rich body of literature focused on hourly unit commitment with renewable energy resources and storage device models, a real-time unit commitment with ideal and generic storage devices and high renewable penetration has not been presented yet. One of the main values of our paper is to include storage units in a real-time (sub-hourly) dispatch embedded in an hourly stochastic unit commitment.

Comparing energy storage technologies is rather difficult because, among other things, their levels of development vary greatly. Reference [15] studies the efficiency of pumped hydro storage. Reference [16] performs a similar study for the compressed air energy storage technology. The efficiency of flow batteries, fuel cells, and other chemicals to storage energy is analyzed in [17]. Flywheel systems, which consist of an alternator that uses electric energy during off-peak hours to accelerate a heavy rotating disk, are studied in [18]. Reference [19] analyzes the efficiency of superconducting magnetic energy storage systems. In [20], the authors study two types of thermal energy storage systems, one using sensible heat and the other using latent heat.

The benefits of energy storage rely on smoothing the load pattern by lowering on-peak and increasing off-peak generation loads. Reference [21] analyzes how the use of the storage energy depends on the agent that owns the facility. They find that, for most storage device efficiencies, merchant ownership of storage is welfare-maximizing compared to the alternatives of consumer or generator ownership.

C. Paper Contributions and Organization

The main contribution of this paper is to formulate a unit commitment that simultaneously considers scheduled and real-time power balances, including energy storage devices and intermittent renewable energy resources. Firstly, a unit commitment model is proposed as a deterministic optimization problem, and, secondly, the model is rewritten as a two-stage stochastic optimization problem. Both of them are cast as mixed integer linear programming (MILP) models. We also quantify the benefits of using stochastic and real-time unit commitment instead of conventional stochastic and hourly unit commitment.

The remainder of the paper is organized as follows: Section II provides a definition of an ideal and generic storage device in both a deterministic and an stochastic real-time setting. Section III delineates the mathematical model for a deterministic unit commitment with storage devices, while Section IV expands the mathematical model for the stochastic real-time unit commitment. Section V quantifies the value of solving a stochastic real-time unit commitment problem instead of a stochastic hourly unit commitment one. The main results are illustrated in Section VI for a 24-node system. Conclusions are presented in Section VII.

II. Ideal and Generic Storage Devices

We define a *generic storage device* as any device with the capability of transforming and storing energy, and reverting the process by injecting back the stored energy to the system.

On the other hand, an *ideal storage device* assumes certain simplifications in its technical and economic operation. Such simplifications allow us to include a storage device model into more complex systems. Then, an ideal and generic storage device unit is defined with the following assumptions:

1) There are no up or down ramps. A unit can go from not producing anything to full power instantly.
2) There are no stored energy losses. For example, losses by evaporation or filtration in pumping stations or load losses in batteries.
3) There is no hysteresis in loading or discharging, i.e., no loops due to a dynamic lag between storage and production.
4) Storage devices have conversion losses. This means there are efficiency rates of direct (production) and reverse (storage) energy transformation. These rates are given with respect to the energy measured at the node connected to the storage unit.
5) There are only production and storage costs. In general, production costs tend to be close to zero and storage costs should be related with the market price at the time that the energy is purchased to be stored in the unit.
6) Storage/production costs are the same for any level of storage/production.
7) Energy storage/production occurs at constant power for the minimum period of study (typically one hour).

A. Deterministic Energy Storage Model

Under the above assumptions, and assuming perfect information of demand and renewable production, an ideal and generic storage device j is modeled by (1)–(5). Equations (1) and (2) refer to the minimum and maximum limits of the power storage (withdrawal from the network), s^s_{jh}, and production (injection into the network), s^p_{jh}, respectively. Equation (3) sets the minimum and maximum energy capacities of the storage device. Equation (4) shows the storage transition function. Thus, the state of charge, x_{jh}, at the end of hour h depends on the previous state of charge, $x_{j,h-1}$, and the power storage/production during the current hour, h. The symbols η^s_j, η^p_j model the power storage/production efficiencies, respectively. The remaining energy in the storage device at the end of the study horizon is bounded by the limits defined in (5):

$$\underline{s}^s_j \le s^s_{jh} \le \overline{s}^s_j, \quad \forall j,h \tag{1}$$
$$\underline{s}^p_j \le s^p_{jh} \le \overline{s}^p_j, \quad \forall j,h \tag{2}$$
$$\underline{x}_j \le x_{jh} \le \overline{x}_j, \quad \forall j,h \tag{3}$$
$$x_{jh} = x_{j,h-1} + \eta^s_j s^s_{jh} - \frac{1}{\eta^p_j} s^p_{jh}, \quad \forall j,h \tag{4}$$
$$\underline{x}^{end}_j \le x_{jH} \le \overline{x}^{end}_j, \quad \forall j. \tag{5}$$

B. Stochastic Real-Time Energy Storage Model

The last assumption in Section II, 7), is neglected when the storage units are required for ancillary services. In this case, a real-time response of the conventional units and storage devices is required due to the real-time demand and intermittent production imbalances. In this framework, real time is represented as time slot division t to capture the intermittence of renewable energies and demand deviations during the scheduled values of each hour.

An ideal and generic storage device j under a stochastic and real-time timeframe is represented by (6)–(13):

$$\underline{s}^s_j \le s^s_{jh} + r^s_{jh} \le \overline{s}^s_j, \quad \forall j,h \tag{6}$$
$$\underline{s}^p_j \le s^p_{jh} + r^p_{jh} \le \overline{s}^p_j, \quad \forall j,h \tag{7}$$
$$0 \le \hat{r}^p_{jht}(\omega) \le r^p_{jh}, \quad \forall j,h,t,w \tag{8}$$
$$0 \le \hat{r}^s_{jht}(\omega) \le r^s_{jh}, \quad \forall j,h,t,w \tag{9}$$
$$\underline{x}_j \le \hat{x}_{jht}(\omega) \le \overline{x}_j, \quad \forall j,h,t,\omega \tag{10}$$
$$\begin{aligned}\hat{x}_{jht}(\omega) = {} & \hat{x}_{j,h,t-1}(\omega) + \Delta\left[\eta^s_j s^s_{jh} - \frac{1}{\eta^p_j} s^p_{jh}\right] \\ & + \Delta\left[\eta^s_j \hat{r}^s_{jht}(\omega) - \frac{1}{\eta^p_j}\hat{r}^p_{jht}(\omega)\right], \\ & \forall j,h,\omega,t=\{2,\dots,T\}\end{aligned} \tag{11}$$
$$\begin{aligned}\hat{x}_{jht}(\omega) = {} & \hat{x}_{j,h-1,T}(\omega) + \Delta\left[\eta^s_j s^s_{jh} - \frac{1}{\eta^p_j} s^p_{jh}\right] \\ & + \Delta\left[\eta^s_j \hat{r}^s_{jht}(\omega) - \frac{1}{\eta^p_j}\hat{r}^p_{jht}(\omega)\right], \quad \forall j,h,\omega,t=1\end{aligned} \tag{12}$$
$$\underline{x}^{end}_j \le \mathbb{E}[\hat{x}_{jHT}(\omega)] \le \overline{x}^{end}_j, \quad \forall j. \tag{13}$$

Equations (6) and (7) refer to the minimum and maximum limits of power storage (withdrawal from the network), and production (injection into the network). Note that (6) (and, similarly (7)), has two terms: the first one, s^s_{jh}, helps to smooth the power production curve; the second one, r^s_{jh}, commits part of the storage (charge) capacity to use it to meet the real-time power balance. Equations (8) and (9) limit the actual deployed real-time reserves, $\hat{r}^s_{jht}(\omega)$/$\hat{r}^p_{jht}(\omega)$, to the maximum reserves

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committed, r^s_{jh}/r^p_{jh}. Equation (10) sets the minimum and maximum energy capacities of the storage device and (11) and (12) show the storage transition function. Equation (13) limits the expected energy left in the storage units.

III. Deterministic Unit Commitment

The scheduled energy cost is defined by function Φ in (14). It is composed of two terms. The first term describes the total hourly production cost, start-up, shut-down and fixed costs for the conventional generating units. The second term depicts the overall hourly cost of storing and producing energy from the storage units:

$$\Phi = \sum_{h,i}\left(c^g_{ih}p_{ih} + C^{su}_{ih} + C^{sd}_{ih} + c^u_i u_{ih}\right) + \sum_{h,j}\left(c^s_{jh}s^s_{jh} + c^p_{jh}s^p_{jh}\right) \quad (14)$$

where the start-up/shut-down cost functions are defined by (15) and (16):

$$0 \le C^{su}_{ih} \ge c^{su}_i(u_{ih} - u_{i,h-1}), \quad \forall i, h \quad (15)$$
$$0 \le C^{sd}_{ih} \ge c^{sd}_i(u_{i,h-1} - u_{i,h}), \quad \forall i, h. \quad (16)$$

Therefore, the deterministic unit commitment (D–UC), with ideal and generic storage devices is defined by (17). The objective function consists of the scheduling cost minus the value of the remaining energy in the storage devices at the end of the time horizon. The future value of the stored energy, γ_j, represents an opportunity cost of saving energy in unit j for the future, instead of using it now. This opportunity cost is a parameter for our model and it is not easy to obtain, especially for long-term problems. Because our model is framed for a short-time horizon, γ_j could be defined as the marginal fuel cost of a conventional generating unit that would be replaced by storage unit j the day after the scheduled plan:

$$\begin{aligned}&\text{(D–UC)}\\ &\underset{\Xi,\mathbf{X}}{\text{minimize}} \quad \Phi - \sum_j \gamma_j x_{jH}\\ &\text{subject to:} \quad \text{Scheduling equations (18)–(23),}\\ &\qquad\qquad \text{Deterministic storage equations (1)–(5)}\end{aligned} \quad (17)$$

where $\Xi = \{p_{ih}, q_{nh}, u_{ih}, s^s_{jh}, s^p_{jh}\}$ is the set of scheduling decision (control) variables and $\mathbf{X} = \{x_{jh}\}$ is the set of state variables. Constraints (18)–(23) are defined in the following subsection.

The deterministic problem (17), is stated as a MILP optimization problem. The set of constraints is defined as follows.

A. Scheduled Power Balance

The power balance is made hour by hour with perfect information of the inelastic demand, d_{nh}, and the non-dispatchable energy resources, w_{nh}. Then, the demand in each node and each hour is equal to the scheduled conventional power generation connected to node n, plus the energy produced at node n by the storage units connected to this node, minus the energy stored, plus the net flow coming into this node:

$$d_{nh} = w_{nh} + \sum_{i\in\Omega_{in}} p_{ih} + \sum_{j\in\Omega_{jn}}\left(s^p_{jh} - s^s_{jh}\right) + q_{nh}, \quad \forall n, h. \quad (18)$$

B. Scheduled Constraints for Conventional Units

The maximum/minimum technical production constraints and the up/down and start-up/shut-down ramps for conventional generators are represented by (19)–(21) with a single on/off binary variable:

$$\underline{p}_i u_{ih} \le p_{ih} \le \overline{p}_i u_{ih}, \quad \forall i, h \quad (19)$$
$$p_{i,h-1} - p_{ih} \le RD_i u_{ih} + SD_i(1 - u_{ih}), \quad \forall i, h \quad (20)$$
$$p_{ih} - p_{i,h-1} \le RU_i u_{i,h-1} + SU_i(1 - u_{i,h-1}), \ \forall i, h. \quad (21)$$

C. Scheduled Line Constraints

The Kirchhoff's laws are represented by (22)–(23) using the elements of the power transfer distribution factors matrix (PTDF), φ_{ln}, in a lossless linear DC approximation. Equation (22) limits the power flow and (23) states that the total net flow must be equal to zero:

$$-\overline{f}_l \le \sum_n \varphi_{ln} q_{nh} \le \overline{f}_l, \quad \forall l, h \quad (22)$$
$$\sum_n q_{nh} = 0, \quad \forall h. \quad (23)$$

IV. Stochastic and Real-Time Unit Commitment

In this section, the demand and non-dispatchable resources are considered stochastic parameters with intermittent variations along each hour. These variations occur in real time, indexed by the symbol t. Each scenario realization is represented by ω, the demand by $\hat{d}_{nht}(\omega)$ and the non-dispatchable power generation by $\hat{w}_{nht}(\omega)$.

Accommodating the scheduled generation to the real-time demand and the intermittent renewable generation has an associated cost. This cost comes from scheduling spinning reserves, deploying them for each plausible scenario. Furthermore, storage devices can be used for replacing the conventional thermal spinning reserves.

Then, the cost associated with the scheduled reserves, Υ, is stated in (24). The first part of the equation accounts for the cost of scheduling the up and down spinning reserves. The second part of the equation accounts for the cost of scheduling the storage units, using them as reserves:

$$\Upsilon = \left\{\sum_{h,i}\left(c^{r,up}_{ih}r^{up}_{ih} + c^{r,dw}_{ih}r^{dw}_{ih}\right) + \sum_{h,j}\left(c^{r,s}_{jh}r^s_{jh} + c^{r,p}_{jh}r^p_{jh}\right)\right\}. \quad (24)$$

The corrective actions for each scenario, ω, (i.e., the actual reserves deployment of conventional and storage units) have an associated cost given by function $\Theta(\omega)$:

$$\Theta(\omega) = \left\{ \sum_{h,t,i} \left(\hat{c}_{ih}^{r,up} \hat{r}_{iht}^{up}(\omega) + \hat{c}_{ih}^{r,dw} \hat{r}_{iht}^{dw}(\omega) \right) + \sum_{h,t,j} \left(\hat{c}_{jh}^{r,s} \hat{r}_{jht}^{s}(\omega) + \hat{c}_{jh}^{r,p} \hat{r}_{jht}^{p}(\omega) \right) \right\} \Delta \quad (25)$$

where parameter Δ represents the real-time slot hour subdivision.

The stochastic real-time unit commitment (SRT–UC) problem is modeled by the two-stage stochastic optimization (26). The model is stated as a MILP problem:

$$\begin{aligned} &\text{(SRT–UC)} \\ &\underset{\Xi,\mathbf{\Gamma},\mathbf{X}}{\text{minimize}} \quad \Phi + \Upsilon + \mathbb{E}[\Theta(\omega)] - \sum_j \gamma_j \mathbb{E}\left[\hat{x}_{jHT}(\omega)\right] \\ &\text{subject to:} \quad \text{Scheduling equations (18)–(23)} \\ &\qquad\qquad\quad \text{RT operation equations (27)–(40)} \\ &\qquad\qquad\quad \text{Stochastic RT storage equations (6)–(13)} \end{aligned} \quad (26)$$

where $\Xi = \{p_{ih}, q_{nh}, u_{ih}, s_{jh}^s, s_{jh}^p, r_{ih}^{up}, r_{ih}^{dw}, r_{jh}^s, r_{jh}^p\}$ is the set of scheduling decision (first stage) variables, $\mathbf{X} = \{\hat{x}_{jht}(\omega)\}$ is the set of stochastic state decision variables, $\mathbf{\Gamma} = \{\hat{q}_{nht}(\omega), \hat{r}_{jht}^s(\omega), \hat{r}_{jht}^p(\omega), \hat{r}_{iht}^{up}(\omega), \hat{r}_{iht}^{dw}(\omega)\}$ is the second stage variables set.

The objective function of the SRT–UC (26), consists of the sum of four terms: 1) the scheduling costs, Φ, including the cost of scheduling all conventional generating units and storage devices, 2) the reserve scheduling costs, Υ, 3) the expected cost associated with the deployment of reserves, $\Theta(\omega)$, and 4) the expected value of the remaining energy left in the storage units.

The set of constraints defining the RT operations is detailed as follows.

A. *Real-Time Power Balance*

The real-time operation of a power system requires that the power must be balanced for all plausible demand and renewable scenarios, ω, at any time t. Equation (27) depicts the real-time power balance. Note that p_{ih}, s_{jh}^p and s_{jh}^s are decided prior to the scenario realization. Then, after realization of uncertainty, reserves (from storage and thermal units) are deployed to meet demand and renewable energy imbalances:

$$\begin{aligned} \hat{d}_{nht}(\omega) = {} & \hat{w}_{nht}(\omega) + \sum_{i\in\Omega_{in}} p_{ih} + \sum_{j\in\Omega_{jn}} \left(s_{jh}^p - s_{jh}^s \right) + \hat{q}_{nht}(\omega) \\ & + \sum_{j\in\Omega_{jn}} \left(\hat{r}_{jht}^p(\omega) - \hat{r}_{jht}^s(\omega) \right) \\ & + \sum_{i\in\Omega_{in}} \left(\hat{r}_{iht}^{up}(\omega) - \hat{r}_{iht}^{dw}(\omega) \right), \quad \forall n,h,t,\omega. \end{aligned} \quad (27)$$

B. *Power and Reserve Constraints for Conventional Units*

Equations (28) and (29) depict the minimum and maximum generation limits including reserves. Equations (30) and (31) represent the up and down reserve limit constraints. Equations (32) and (33) provide the bounds for the deployed up and down reserves:

$$p_{ih} + r_{ih}^{up} \le \overline{p}_i u_{ih} \qquad \forall i,h \quad (28)$$
$$p_{ih} - r_{ih}^{dw} \ge \underline{p}_i u_{ih} \qquad \forall i,h \quad (29)$$
$$\underline{r}_i^{up} u_{ih} \le r_{ih}^{up} \le \overline{r}_i^{up} u_{ih} \qquad \forall i,h \quad (30)$$
$$\underline{r}_i^{dw} u_{ih} \le r_{ih}^{dw} \le \overline{r}_i^{dw} u_{ih} \qquad \forall i,h \quad (31)$$
$$0 \le \hat{r}_{iht}^{up}(\omega) \le r_{ih}^{up} \qquad \forall i,h,t,\omega \quad (32)$$
$$0 \le \hat{r}_{iht}^{dw}(\omega) \le r_{ih}^{dw} \qquad \forall i,h,t,\omega. \quad (33)$$

C. *Real-Time Ramp Constraints*

A new auxiliary real-time power variable $\hat{p}_{iht}(\omega)$, is defined to represent the real production in each scenario realization ω, hour h and real-time slot t for every conventional generator i. Then, the real-time ramp constraints are (35)–(38). Note that the ramps are defined in MW/h, so the ramp limits are multiplied by Δ:

$$\hat{p}_{iht}(\omega) = p_{ih} + \hat{r}_{iht}^{up}(\omega) - \hat{r}_{iht}^{dw}(\omega) \; \forall i,t,h,\omega \quad (34)$$

$$\hat{p}_{iht}(\omega) - \hat{p}_{ih,t-1}(\omega) \le \Delta \left(RU_i u_{i,h-1} + SU_i (1 - u_{i,h-1}) \right) \quad \forall i,h,w,t = \{2,\ldots,T\} \quad (35)$$

$$\hat{p}_{iht}(\omega) - \hat{p}_{i,h-1,T}(\omega) \le \Delta \left(RU_i u_{i,h-1} + SU_i (1 - u_{i,h-1}) \right) \quad \forall i,h,w,t = \{1\} \quad (36)$$

$$\hat{p}_{ih,t-1}(\omega) - \hat{p}_{iht}(\omega) \le \Delta \left(RD_i u_{ih} + SD_i (1 - u_{ih}) \right) \quad \forall i,h,w,t = \{2,\ldots,T\} \quad (37)$$

$$\hat{p}_{i,h-1,T}(\omega) - \hat{p}_{iht}(\omega) \le \Delta \left(RD_i u_{ih} + SD_i (1 - u_{ih}) \right) \quad \forall i,h,w,t = \{1\}. \quad (38)$$

D. *Real-Time Line Constraints*

The real-time Kirchhoff's laws are represented by (39) and (40):

$$-\overline{f}_l \le \sum_n \varphi_{ln} \hat{q}_{nht}(\omega) \le \overline{f}_l, \quad \forall l,h,t,\omega \quad (39)$$

$$\sum_n \hat{q}_{nht}(\omega) = 0, \quad \forall h,t,\omega. \quad (40)$$

V. VALUE OF REAL-TIME INFORMATION

The main drawback of hourly unit commitment models to solve the joint energy generation and reserves scheduling with large amounts of uncertainty (as in [8], [10]–[14]) is that reserves are underestimated. This happens especially for large demands and/or wind changes from one hour to the next. For example, it usually happens from peak-to-valley or valley-to-peak hourly transitions. This is because hourly models use a single average value for the entire hour. In this section we quantify the value of scheduling energy and reserves with an hourly unit commitment model instead of a real-time unit commitment model.

A. Stochastic and Hourly Unit Commitment

The stochastic and hourly unit commitment (SH–UC) with storage units is a simplification of the problem (26) where $t = 1$, i.e., there are no hourly subdivisions and wind and demand scenario realizations are given on an hourly basis.

B. Real-Time Corrective Actions

Hourly scheduled reserves are obtained as a solution for the SH–UC model. They are used as corrective actions to meet real-time demand with real-time wind production. But, if there are not enough reserves, they would require emergency corrective actions such as load shedding or wind spillage. We define four possible emergency corrective actions to measure the impact of not having real-time information in the unit commitment problem. They are load shedding, wind spillage, fast response generation (such as diesel generation) and power spillage. Without loss of generality we assume that fast response generation units and power spillage are available in all nodes without limits. This is a conservative assumption in favor of hourly models.

Then, the real-time power balance with emergency corrective actions is defined in (41):

$$\begin{aligned}&\hat{d}_{nht}(\omega) - \hat{ls}_{nht}(\omega)\\ &\quad = \hat{w}_{nht}(\omega) - \hat{ws}_{nht}(\omega) + \hat{p}^{fast\text{-}r}_{nht}(\omega) - \hat{p}^{spill}_{nht}(\omega)\\ &\qquad + \sum_{i\in\Omega_{in}} p_{ih} + \sum_{j\in\Omega_{jn}} \left(s^p_{jh} - s^s_{jh}\right) + \hat{q}_{nht}(\omega)\\ &\qquad + \sum_{j\in\Omega_{jn}} \left(\hat{r}^p_{jht}(\omega) - \hat{r}^s_{jht}(\omega)\right)\\ &\qquad + \sum_{i\in\Omega_{in}} \left(\hat{r}^{up}_{iht}(\omega) - \hat{r}^{dw}_{iht}(\omega)\right), \quad \forall n,h,t,\omega. \end{aligned} \tag{41}$$

Note that the reserves deployed can not exceed the values obtained from the SH–UC solution in every real-time slot and scenario, i.e., (32)–(33) for conventional generators and (8)–(9) for storage units.

The emergency corrective actions are also limited by (42)–(45):

$$0 \le \hat{ls}_{nht}(\omega) \le \hat{d}_{nht}(\omega) \qquad \forall n,h,t,\omega \tag{42}$$
$$0 \le \hat{ws}_{nht}(\omega) \le \hat{w}_{nht}(\omega) \qquad \forall n,h,t,\omega \tag{43}$$
$$0 \le \hat{p}^{spill}_{nht}(\omega) \qquad \forall n,h,t,\omega \tag{44}$$
$$0 \le \hat{p}^{fast\text{-}r}_{nht}(\omega) \qquad \forall n,h,t,\omega. \tag{45}$$

The corrective actions cost for each scenario, ω (i.e., the actual reserves deployment of conventional and storage units, load shedding, wind spillage, fast-response generators and power spillage), is given by function $\Theta'(\omega)$:

$$\begin{aligned}\Theta'(\omega) = \Bigg\{ &\sum_{h,t,i} \left(\hat{c}^{r,up}_{ih}\hat{r}^{up}_{iht}(\omega) + \hat{c}^{r,dw}_{ih}\hat{r}^{dw}_{iht}(\omega)\right)\\ &+ \sum_{h,t,j} \left(\hat{c}^{r,s}_{jh}\hat{r}^s_{jht}(\omega) + \hat{c}^{r,p}_{jh}\hat{r}^p_{jht}(\omega)\right)\\ &+ \sum_{h,t,n} \left(c^{fast\text{-}r}\hat{p}^{fast\text{-}r}_{nht}(\omega) + c^{ls}\hat{ls}_{nht}(\omega)\right)\\ &+ \sum_{h,t,n} \left(c^{ws}\hat{ws}_{nht}(\omega) + c^{p\text{-}spill}\hat{p}^{spill}_{nht}(\omega)\right)\Bigg\}\Delta. \end{aligned} \tag{46}$$

Then, the real-time corrective actions cost is minimized in the MILP model (47):

$$\begin{aligned} &(\mathrm{RTCA})\\ &\underset{\boldsymbol{\Gamma'}}{\text{minimize}} \quad \mathbb{E}[\Theta'(\omega)]\\ &\text{subject to:} \quad \text{RT power balance (41)}\\ &\qquad \text{Deployed reserves limits (32)–(33)}\\ &\qquad \text{and (8)–(9)}\\ &\qquad \text{Emergency corrective limits (42)–(45)}\\ &\qquad \text{RT line constraints (39)–(40)} \end{aligned} \tag{47}$$

where $\Gamma' = \{\hat{p}^{fast\text{-}r}_{nht}(\omega), \hat{ls}_{nht}(\omega), \hat{ws}_{nht}(\omega), \hat{p}^{spill}_{nht}(\omega)\} \cup \{\Gamma | t = 1\}$ is the set of decision variables.

C. Value of Real-Time Information

The value of real-time information (VRTI) represents the extra expected cost of solving a stochastic unit commitment on an hourly basis and afterwards use corrective actions to meet real-time demand and wind deviations, instead of solving a stochastic unit commitment on a real-time basis. This is defined by (48):

$$VRTI = z^*_{(SHUC+RTCA)} - z^*_{(SRTUC)} \tag{48}$$

where $z^*_{(SRTUC)}$ represents the optimal solution of the SRT–UC from objective function (26) and $z^*_{(SHUC+RTCA)}$ (49) represents the optimal scheduling costs from the SH–UC problem plus the optimal RT corrective actions given by problem (47) and the optimal future value of the remaining energy from the SH–UC problem:

$$z^*_{(SHUC+RTCA)} = \left\{ \Upsilon + \mathbb{E}[\Theta'(\omega)] - \sum_j \gamma_j \mathbb{E}\left[\hat{x}_{jH}(\omega)\right] \,\middle|\, \boldsymbol{\Xi}^*, \boldsymbol{\Gamma'}^*, \mathbf{X}^* \right\}. \tag{49}$$

VI. Case Study

We illustrate the proposed models using a 24-node system based on a modified version of the IEEE Reliability Test System (IEEE RTS) [22] (see Fig. 1). The system comprises 24 nodes, 32 generating units and 17 loads. We have considered a horizon of 24 hours divided into 6 periods of 10 min each to represent the real time, i.e., $\Delta = 1/6$. The cost of scheduling any kind of reserve is fixed to \$1/MWh.

For the sake of simplicity, we have considered two equal energy storage units with 400 MWh capacity each, located at nodes 8 and 9. The initial energy level of the storage units is set

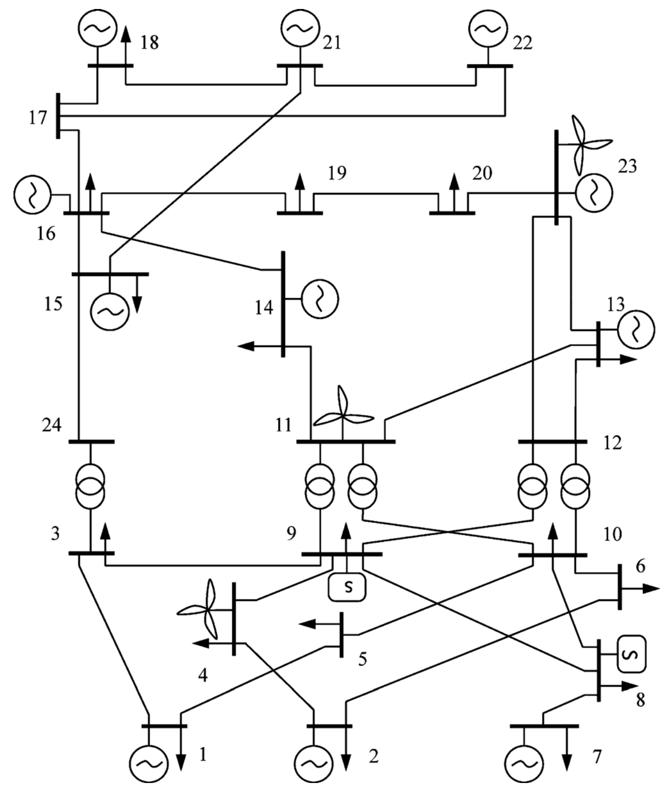

Fig. 1. 24-node system.

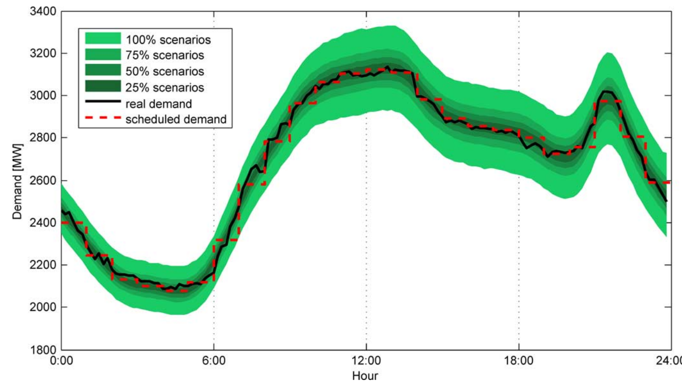

Fig. 2. Real demand, scheduled demand and predicted densities of real-time demand scenarios considering 25%, 50%, 75%, and 100% of scenarios.

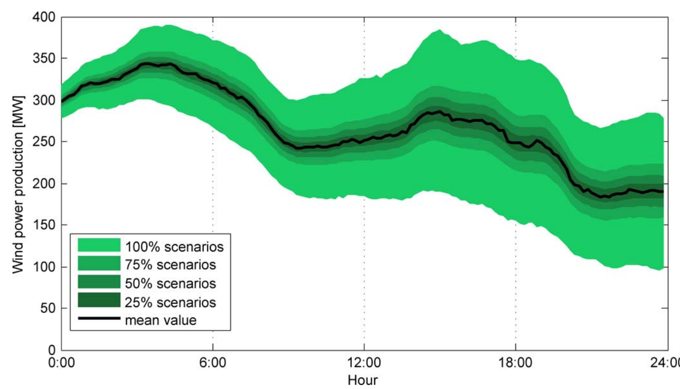

Fig. 3. Real-time wind mean value and predicted densities of real-time wind production scenarios considering 25%, 50%, 75%, and 100% of scenarios.

to 50% of their capacities (200 MWh). The maximum and minimum limits for power storage/production are both 200 MW and the future energy value is set to \$18/MWh. The cost of storage/production in the storage unit is \$0.5/MWh and \$0.1/MWh, respectively. The costs of deploying reserves to produce or store energy are set to \$0.5/MWh and $\$-0.1$/MWh, respectively. The efficiency rates are set to 90% (81% round-trip efficiency rate).

The 10-min demand data are obtained from the Iberian power system [23] and scaled according to the IEEE RTS system. Fig. 2 shows the total system demand based on data collected from the Iberian power system [23] on April 4, 2013. The solid and dark-colored line represents the actual real-time scenario. The dashed line represents the hourly demand. The scenarios have been generated based on a 10-min forecasted demand using a Normal distribution with demand errors ranging from 1% at the beginning to 2% at the end of the study horizon.

Wind is the non-dispatchable energy source selected. There are 3 wind units located at nodes 4, 11, and 23, with a constant wind production share of 30%, 20%, and 50%, respectively. The wind scenarios are generated correlated with the demand based on a Normal distribution from data of the Iberian power system [23]. The standard deviation of the wind scenarios ranges from 2% at the beginning to 15% at the end of the study horizon. Fig. 3 shows the total production wind scenarios with 10% penetration of wind, where 20 demand and wind scenarios have been generated.

Table I provides data for the generating units. Each column refers to a particular type of generation unit. The maximum and minimum technical limits are shown in rows 2 and 3. The generating capacities are divided into four blocks (rows 3 to 6) with their associated marginal production costs (rows 11 to 14). Rows 7 to 10 contain the ramp limits. Start-up, shut-down and fixed costs are shown in rows 15, 16, and 17, respectively. The last two rows show the deployed up and down reserve costs.

All case studies have been solved using CPLEX 11 under GAMS. An Intel Core i7-3770 computer at 3.4 GHz and 12 GB of RAM has been used. The average time to solve a D–UC

TABLE I
GENERATING UNITS DATA FOR THE IEEE RTS 24-BUS SYSTEM

	oil	oil	hydro	coal	oil	coal	oil	coal	nuclear
$\overline{p}_i$	12	20	50	76	100	155	197	350	400
$\underline{p}_i$	2.4	15.8	0	15.2	25	54.25	68.95	140	100
$\overline{p}_i^1$	2.4	15.8	0	15.2	25	54.25	68.95	140	100
$\overline{p}_i^2$	3.6	0.2	0	22.8	25	38.75	49.25	87.5	100
$\overline{p}_i^3$	6.6	3.8	0	22.8	30	31	39.4	52.5	120
$\overline{p}_i^4$	2.4	0.2	50	15.2	20	31	39.4	70	80
RD_i	60	180	-	120	420	180	180	240	200
RU_i	60	180	-	120	420	180	180	240	200
SD_i	30	90	-	60	210	90	90	120	100
SU_i	30	90	-	60	210	90	90	120	100
$c_i^{g,1}$	23.41	29.58	0	11.46	18.6	9.92	19.2	10.08	5.31
$c_i^{g,2}$	23.78	30.42	0	11.96	20.03	10.25	20.32	10.66	5.38
$c_i^{g,3}$	26.84	42.82	0	13.89	21.97	10.68	21.22	11.09	5.53
$c_i^{g,4}$	30.4	43.28	0	15.97	22.72	11.26	22.13	11.72	5.66
c^{su}	87.4	15	0	715.2	575	312	1018.9	2298	0
c^{sd}	0	0	0	0	0	0	0	0	0
c^u	5.25	5	0	7.5	8.5	6.25	15	20	0
$\hat{c}^{r,up}$	26.11	36.53	0	13.32	20.76	10.53	20.72	10.89	5.47
$\hat{c}^{r,dw}$	-26.11	-36.53	0	-13.32	-20.76	-10.53	-20.72	-10.89	-5.47

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

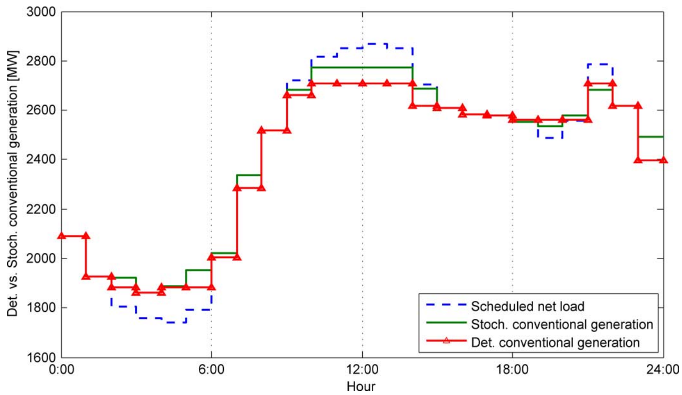

Fig. 4. Total conventional deterministic and stochastic generation.

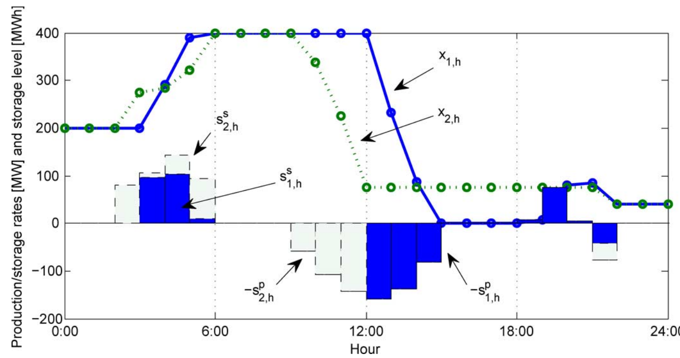

Fig. 5. Production and storage rates vs. storage level for D–UC.

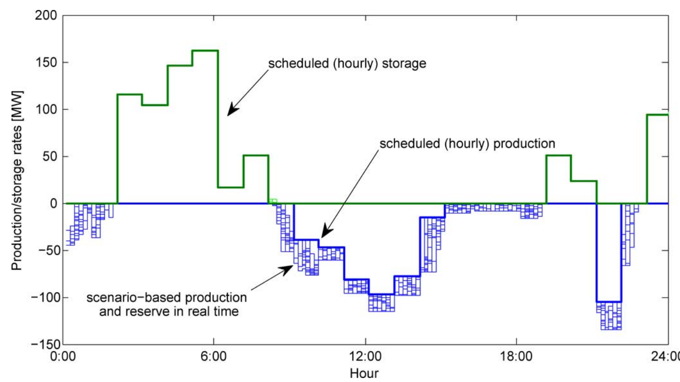

Fig. 6. Total scheduled and real time production/storage rates for SRT–UC.

problem is 3.07 s, for a SRT–UC is 1639 s, and for a SH–UC is 99.4 s.

A. D–UC and SRT–UC Solutions

The D–UC and SRT–UC problems are solved and compared considering 10% penetration of wind. The total scheduling cost for the D–UC problem, Φ, is \$486 552 and the future value of the remaining stored energy is \$1440. However, the sum of the total scheduling cost for the SRT–UC problem, $\Phi + \Upsilon$, plus the expected cost of deploying reserves, $\mathbb{E}[\Theta(\omega)]$, is \$493 540 (1.44% more expensive than the D–UC) and the future expected value of the remaining energy in storage is \$1503.

Fig. 4 shows the comparison between the deterministic, the stochastic scheduling program and the net demand (demand minus wind production). As it can be seen, the stochastic program follows a similar pattern to the deterministic one, but the stochastic curve has not the same plateaus (specially at peak hours) as the deterministic curve, due to uncertainty. In the stochastic case, part of the storage device capacities are used as reserves to meet wind imbalances, therefore, it is not possible to smooth the generating curve as in the deterministic case. Comparing the net load and generation curves, it can be seen that the storage units help to smooth the scheduled power generation profile by storing energy in valley demand hours and using it to produce in peak demand hours.

Fig. 5 reports production and storage rates against total energy storage for the D–UC solution. The values related with the first storage unit located at node 8 are in dark color, and the values related with the second storage unit located at node 9 are in light color and represented by a dashed line. Fig. 6 illustrates the total scheduled and deployed reserves for the two storage devices in all the scenarios for the SRT–UC. Similarly to the D–UC, it can be noted that the storage units are used to store energy in the valley hours to produce in the peak hours. Furthermore, the effects of using storage devices as reserves can be observed, showing a higher use of reserves as wind uncertainty increases over time.

B. Real-Time Solution vs. Hourly Solution

The SH–UC problem is solved considering the IEEE RTS-based case study described above and compared with the SRT–UC model solution. Real-time wind and demand realizations are transformed into hourly scenarios to solve the SH–UC. After solving the SH–UC, the optimal unit commitment variables and the energy generation and reserves schedules are used to optimize the real-time corrective actions (47).

The cost parameters considered are \$200/MWh for load shedding, \$50/MWh for fast-response generators, \$5/MWh for power spillage, and \$4/MWh for wind spillage. Tables II and III show the expected values for the corrective actions in terms of energy and costs for the SRT–UC, SH–UC, and RTCA problems. Note that the SH–UC problem expects to use less reserves than SRT–UC, then real-time operations need to use emergency corrective actions like wind spillage and fast response power generation. Observe that the expected costs for deploying reserves are negative in the SRT–UC and SH–UC cases, meaning that this is a cost which has been avoided. This is because the down reserves account for negative costs in the objective function. Finally, the value of VRTI is \$9095.1, which represents 1.84% extra cost for the hourly unit commitment with real-time corrective actions. This gain is relatively small in this case study because we have considered very conservative corrective emergency costs and no limitations on diesel generation and power spillage at any node.

C. Wind Penetration Sensitivity Analysis

In order to model the influence of renewable penetration in power systems, this section presents a sensitivity analysis for the SRT–UC. The demand is scaled to the same proportion of the wind penetration to simulate that the demand growth is covered with the new wind generators. Fig. 7 shows the total costs for different wind penetrations ranging from 0% to 60% and storage capacities ranging from 0 MWh to 3000 MWh. As the

TABLE II
EXPECTED VALUE OF REAL-TIME CORRECTIVE ACTIONS: ENERGY [MWh]

	$\hat{r}^{r,up}$	$\hat{r}^{r,dw}$	$\hat{r}^{s}$	$\hat{r}^{p}$	$\hat{ls}$	$\hat{ws}$	$\hat{p}^{fast\text{-}r}$	$\hat{p}^{spill}$
SRT–UC	373.0	3513.6	6.9	3161.1	n/a	n/a	n/a	n/a
SH–UC	89.3	274.9	0	187.8	n/a	n/a	n/a	n/a
RTCA	151.3	211.8	0	275.9	0	468.9	255.8	0

TABLE III
EXPECTED VALUE OF REAL-TIME CORRECTIVE ACTIONS: COSTS [$]

	Total costs	Total reserves	Load shedding	Wind spillage	Diesel gener.	Power spillage
SRT–UC	-8161.1	-8161.1	n/a	n/a	n/a	n/a
SH–UC	-2933.2	-2933.2	n/a	n/a	n/a	n/a
RTCA	13010.5	-1657.6	0	1875.9	12792.3	0

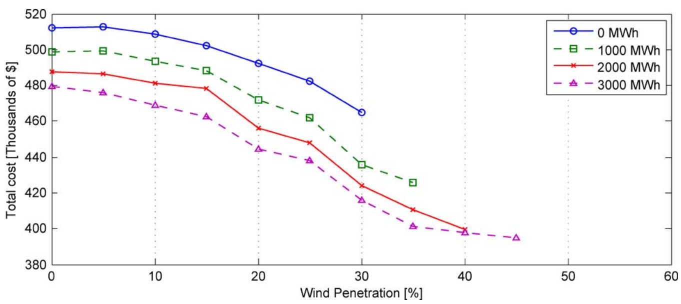

Fig. 7. Total cost sensitivity analysis vs. wind penetration.

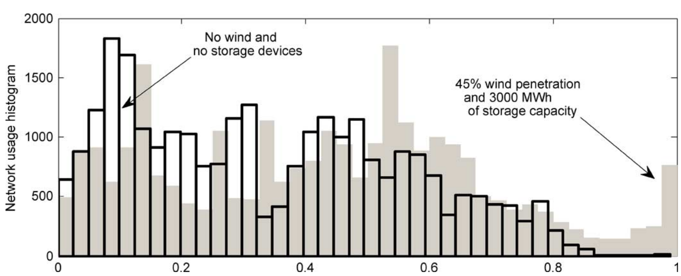

Fig. 8. Network usage histogram.

storage capacity increases, the total operating cost decreases. Furthermore, the total operational cost decreases as wind penetration increases, because of the relative low generation cost of the wind generators. The maximum wind penetration for the no storage case is 30%. However, installing two storage devices of 1500 MWh each, wind penetration can be increased by 15%.

Fig. 8 shows a network usage histogram of the no wind and no storage capacity case which is compared with a 45% wind integration histogram and 3000 MWh of storage capacity.

D. Storage Parameters Sensitivity Analysis

One of the biggest barriers to include storage technologies in power systems has been their costs and efficiencies, but, since they are constantly evolving, cost and efficiency values have improved. Although the model proposed in this paper does not represent a particular technology, in this section we perform a sensitivity analysis of the most relevant parameters of the storage units. We roughly consider that both storage and production efficiencies are rated the same. They range from 70%

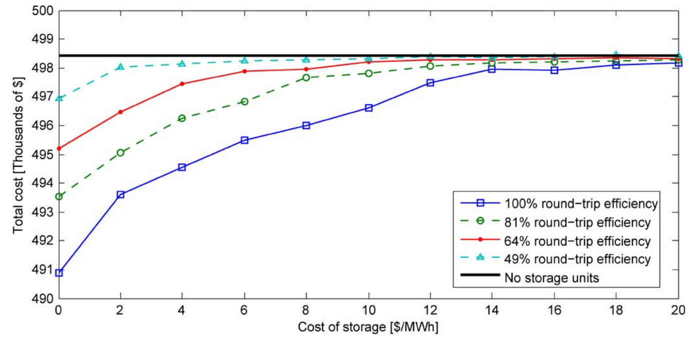

Fig. 9. Total cost sensitivity analysis vs. storage cost.

(49% round-trip efficiency) to 100%. Storage costs are considered ranging from $0/MWh to $20/MWh with $2/MWh intervals. Fig. 9 shows a sensibility analysis of the total operational costs. As the storage cost increases, the total operating cost increases. Moreover, the total operational cost decreases as efficiency rates increase. The total cost reduction from the case SRT–UC without storage devices is more significant for high efficiency rates or relatively low storage costs.

VII. CONCLUSIONS

This paper provides a linear model of an ideal and generic storage device, which includes the most important features of all electric energy storage technologies. The storage model is presented within a deterministic unit commitment model and a stochastic real-time unit commitment model. Both models have been formulated as MILP. The proposed models have been successfully tested on a case study based on the IEEE-RTS 24-bus system.

As the penetration of non-dispatchable resources increases, the total reserve cost increases due to the uncertainty of these sources. In contrast, the total operational cost decreases by including storage units in the system. Moreover, more storage capacity in power systems should help to tackle large penetration of renewable energies. It has been shown that, for a high penetration of renewable energy, the problem becomes infeasible using just conventional thermal generation.

These findings suggest that, in general, the integration of storage devices in power systems helps in tree ways: firstly, by reducing the total cost of supplying energy; secondly, by smoothing the power generation profile; and thirdly, by using storage devices as reserve devices in order to accommodate large amounts of uncertain demands and renewable energy.

Finally, further extensions with more focus on CO_2 emissions reduction, specific features for modeling storage technologies, optimal storage unit location or applying decomposition techniques should be relevant for future research.

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