Capacity and Intra-Hour Ramp Reserves for Wind Integration

Elis Nycander, *Student Member, IEEE*, Germán Morales-España, *Senior Member, IEEE*, and Lennart Söder, *Senior Member, IEEE*

***Abstract*—We propose a power-based unit commitment formulation with capacity and intra-hour ramp reserves for dealing with intra-hour wind power variability and uncertainty. Although the formulation has an hourly resolution, the intra-hour ramp requirements capture wind power ramp excursions with a time duration below one hour, and thus allows the formulation to consider intra-hourly wind variability and uncertainty. This increases the security of the formulation compared to using hourly ramp reserves and allows more efficient scheduling of units with high ramp rates. We test the formulation with different durations for the intra-hour reserves, and using both hourly and intra-hourly ramp reserves, to find the best reserve formulation. The formulations are evaluated using a 5-min economic dispatch, which simulates the real-time operation of the system, for hundreds of out-of-sample realizations of wind power production. The proposed formulations are then compared to two hourly stochastic formulations and a stochastic formulation with 5-min time resolution. The proposed formulations outperform the stochastic formulations in terms of security, showing that they provide a scheduling which is more robust against intra-hour wind power variations. The proposed formulations also outperform the hourly stochastic formulations in terms of total costs, giving a better trade-off between scheduling costs and security.**

***Index Terms*—Power-based unit commitment, ramp reserves, intra-hour variability, wind power.**

NOMENCLATURE

Indexes

$\mathcal{B}^D$, $\mathcal{B}^W$	- buses with load/wind power, indexed b.
$\mathcal{G}, \mathcal{G}^f, \mathcal{G}^s$	- all/fast/slow generator units, indexed g.
$\mathcal{L}$	- transmission lines, indexed l.

Parameters

$c^F_{gt}(\cdot), c^V_{gt}(\cdot)$	- fixed/variable costs of unit g for time t [\$].
C^{NL}_g	- no load cost of unit g [\$/h].
C^{LV}_g	- variable cost of unit g [\$/MWh].
C^{SU}_g, C^{SD}_g	- startup/shutdown cost of unit g [\$].
D_{bt}	- load at bus b at end of hour t [MW].
$\overline{F}_l$	- capacity limit of line l [MW].
$\overline{P}_g, \underline{P}_g$	- max/min production of unit g [MW].
P^{SU}_{gi}, P^{SD}_{gi}	- production of unit g at the end of the i^{th} hour of the startup/shutdown period [MW].
RU_g, RD_g	- ramp up/down capability of unit g [MW/h].
SU_g, SD_g	- startup/shutdown ramp capability of unit g [MW/h].
SU^D_g, SD^D_g	- startup/shutdown duration of unit g [h].
T	- number of hours in planning period.
TU_g, TD_g	- minimum up/down time of unit g [h].
$W_{bt}, \overline{W}_{bt}, \underline{W}_{bt}$	- nominal/max/min value for forecasted wind power at bus b at end of hour t [MW].
W_{bst}	- wind power at bus b at end of hour t for scenario s [MW].
W^R_{bst}	- hourly wind ramp for bus b, hour t, and scenario s [MW].
W^{R+}_{bt}, W^{R-}_{bt}	- max upward/downward forecasted wind ramp for bus b and hour t [MW].
W^{IHR}_{bsit}	- wind ramp during hour t, interval i for scenario s [MW].
$W^{IHR+}_{bt}, W^{IHR-}_{bt}$	- max upward/downward forecasted intra-hour wind ramp for bus b and hour t [MW].
Δ	- number of intra-hour intervals per hour.
Γ_{lb}	- PTDF of line l for injections at bus b [p.u.].
Γ_{lg}	- PTDF of line l for injections from unit g [p.u.].

Binary variables

u_{gt}	- commitment variable for unit g at hour t.
v_{gt}	- startup variable for unit g at hour t.
z_{gt}	- shutdown variable for unit g at hour t.

Continuous variables

p_{gt}	- power output above $\underline{P}_g$ of unit g at end of hour t [MW].
$\overline{r}_{gt}, \underline{r}_{gt}$	- upper/lower capacity reserves at end of hour t [MW].
r^{R+}_{gt}, r^{R-}_{gt}	- up/down hourly ramp reserves for hour t [MW].
$r^{IHR+}_{gt}, r^{IHR-}_{gt}$	- up/down intra-hour ramp reserves for hour t [MW].

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Elis Nycander and Lennart Söder are with the Division of Electric Power and Energy Systems, KTH Royal Institute of Technology, 10044 Stockholm, Sweden (e-mail: elisnycander@gmail.com; lsod@kth.se).

Germán Morales-España is with Energy Transition Studies, ECN part of TNO, 1043 NT Amsterdam, The Netherlands (e-mail: german.morales@tno.nl).

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$w_{bt}, \overline{w}_{bt}, \underline{w}_{bt}$ - nominal/upper/lower wind power dispatch for bus b at end of hour t [MW].

w^{R+}_{bt}, w^{R-}_{bt} - maximum up/down wind ramp possible within wind dispatch range [MW].

$w^{IHR+}_{bt}, w^{IHR-}_{bt}$ - maximum possible up/down intra-hour wind ramp possible within dispatch range [MW].

I. Introduction

To ENABLE efficient integration of variable renewable energy (VRE) sources such as wind in power systems, new methods for power system scheduling are needed that can manage: 1) the uncertainty, and, 2) the variability of VRE production. The unit commitment (UC) problem is recognized to be one of the most efficient methods for power system operation planning [1], [2] and is used by system operators world-wide for market operation and power system scheduling [3]–[5]. Thus, there is a considerable literature on adapting the UC problem to deal with high levels of VRE.

Regarding 1), uncertainty, a lot of effort has been put into developing UC methods that are able to deal with uncertainty in an efficient manner [6], [7]. These methods include scenario-based methods that represent wind uncertainty using a discrete set of scenarios [8]–[10] and robust methods [11]–[15] that represent the uncertainty using a continuous uncertainty range.

The drawbacks of scenario-based formulations include a high sensitivity to the underlying scenarios as well as a high computational burden [10], [16], which can make these formulations intractable for large systems. This creates the need for scenario reduction techniques [8], [9] to represent the uncertainty distribution with sufficient accuracy, while at the same time not imposing a too large computational burden. On the other hand, robust formulations are smaller in size but can be overly conservative. Various approaches have been proposed to overcome the inherent conservativeness of the robust approach, such as unified stochastic and robust optimization [11], min-max regret robust optimization [12], and distributionally robust optimization [14]. Robust formulations often require specialized solution techniques, such as decomposition [11]–[13], which can increase the computational burden and do not always guarantee optimality [13].

A third type of formulations are chance-constrained stochastic formulations [17]–[21]. These use stochastic variables representing the wind power uncertainty inside the constraints, and then require the violation probability of the constraints to be below some threshold. In this way, chance-constrained formulations avoid the large problem size of scenario-based methods and the conservativeness of robust formulations. On the other hand, these formulations either require stricter assumptions on the probability distribution of uncertainty, such as assuming a normal distribution [17]–[19], or they need specialized solution techniques such as sample-average approximation, which also increases the computational complexity [20], [21].

There has also been significant work related to dealing with 2), the variability of VRE. As the net load becomes more variable,

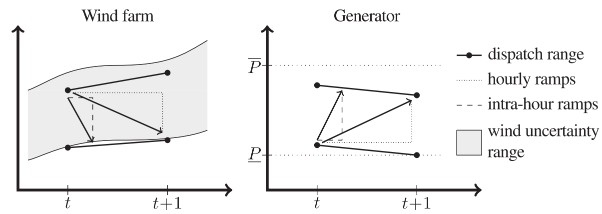

Fig. 1. Dispatch range for a wind farm and generator in the formulation. The ramp reserves held by conventional units must cover the maximum ramp excursions by the wind farms which are possible within the wind dispatch trajectory, both for hourly and intra-hourly ramps. By decreasing the wind dispatch range the wind power variability can be reduced.

this increases the frequency and unpredictability of large ramp events in the system, thus increasing the ramping requirements of conventional units [22]–[24], and adversely affecting power system security [25]. To deal with the increased variability it is possible to increase the time resolution of UC formulations, what is known as sub-hourly unit commitment, thereby improving the modelling of intra-hour variability [24], [26]–[28]. However, using sub-hourly UC formulations comes at increased computational cost [27], [28]. In [29] a time-adaptive UC formulation is proposed, in which the size of time steps are varied during the planning period, so that the time resolution is higher during times when the variation in the net load is higher. However, this method may be less effective dealing with wind power variability, since it is not known beforehand when the wind power ramps will occur.

Another way to ensure the system has enough flexibility to deal with wind power variability is by using reserve formulations. For example, flexible ramp products have been proposed [30]–[32] and adopted by system operators such as MISO [33] and CAISO [34]. The possibility of wind power to provide ramping products has been studied in [35] and [36] considered non-deterministic procurement of flexible ramp reserves.

Morales-España *et al.* [37] proposed a deterministic power-based UC formulation with capacity reserves and hourly ramp reserves for dealing with both wind power uncertainty and variability. Since the power-based formulation allows an accurate representation of the ramp rates of units, it can be ensured that online units have enough ramping capability to deal with wind power fluctuations.

In this paper, we extend the UC formulation from [37] to consider intra-hour ramp reserves with a time duration of less than one hour, as illustrated in Fig. 1. This allows the formulation to consider wind power fluctuations with a shorter time duration, thereby ensuring the obtained commitment schedule can face short but steep (in MW/h) wind power fluctuations. Also, this allows more efficient scheduling of units with high ramp rates. To see this, consider the unit in Fig. 2, which has an hourly ramp rate that is twice the capacity operating range ($\overline{P} - \underline{P}$). If the ramp reserves are specified hourly, the maximum hourly ramp reserves, r^{R+}_t, that can be held by the unit is $\overline{P} - \underline{P}$, since the ramp reserve must fit within the capacity operating range. However, this represents only half the maximum ramp rate of

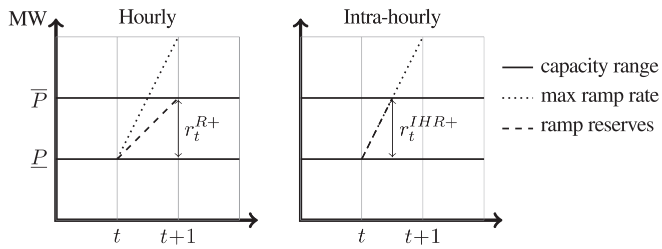

Fig. 2. Hourly and intra-hourly ramp reserves.

the unit. If instead, as in the right side of Fig. 2, intra-hour ramp reserves are specified with a deployment time of half of an hour, the maximum amount of intra-hour ramp reserves, r_t^{IHR+}, is still $\overline{P} - \underline{P}$. However, this intra-hour ramp reserve corresponds to a higher ramp rate, thus being of higher value to the system and utilizing the full ramping capability of the unit. Though the proposed is UC intended for day-ahead scheduling, the proposed reserve formulations may be adapted to UC formulations with different time horizons.

Notice that even though the proposed formulation considers intra-hour variability of wind power and intra-hour reserves, it is specified as an hourly formulation, meaning that all variables and constraints use an hourly time resolution. As explained in Section II, the linear nature of the dispatch trajectories used in the formulation means that the constraints which should hold for every intra-hour interval only need to be enforced for the first and last interval of each hour. Thus, compared to sub-hourly UC formulations such as [27], [29] our formulation has the advantage of not requiring increased time resolution to capture intra-hour wind variability. Compared to most formulations with flexible ramp reserves [30], [32], the formulation in this paper is different since it determines the needed ramp capability endogenously, and not as an input to the optimization. And compared to previous formulations with endogenously determined ramp reserves [36], [37], the formulation is different because it uses ramp reserves with two different time durations simultaneously, i.e., both hourly and intra-hourly ramp reserves.

To find the best formulation for intra-hour reserves we test different durations for the intra-hour intervals. Also, we test formulations with a combination of hourly and intra-hourly ramp reserves as well as formulations with only intra-hourly ramp reserves. The formulations are evaluated using wind power production scenarios from the model presented in [38]. The scenarios have 5-min time resolution and are based on data from real wind farms, thus capturing the empirical distribution of forecast errors and correlation between wind farms. Finally, we compare the proposed formulations with different stochastic UC formulations, demonstrating the high performance of the proposed formulations. The proposed formulations out-perform hourly stochastic formulations in terms of cost and security, and also outperform a stochastic formulation with 5-min time-resolution in some cases.

The 5-min formulation used for comparison is a stochastic power-based formulation with 5-min dispatch decisions and hourly commitment decisions which also includes the startup and shutdown trajectories of units. It gives the optimal scheduling decisions that can be achieved given the wind representation used in the evaluation of the formulations, since it is stochastic and has perfect information of the 5-min wind variability. This formulation is also new and is provided in Appendix A.

Thus, the main contributions of this paper are as follows:

1) We propose an hourly UC formulation with intra-hour ramp reserves. The intra-hour ramp reserves ensure the formulation can face steep intra-hour changes (in MW/h) in wind power production and allows more efficient scheduling of fast-ramping units.
2) We investigate different versions of the proposed formulation with intra-hour reserves, varying the intra-hour period duration and using a combination of hourly and intra-hourly reserves, or only intra-hourly reserves, to find the best formulation for the reserves.
3) The proposed formulations are compared to three different stochastic UC formulations, two hourly formulations and a stochastic formulation with 5-min dispatch decisions and hourly commitment decisions proposed in this paper, showing the high robustness of the proposed formulations.

The remainder of the paper is organized as follows: Section II describes the representation of wind uncertainty in the UC and specifies the proposed UC formulations. Section III evaluates the formulations using case studies for two different test systems, and Section IV concludes.

II. Formulation

A. Wind Uncertainty and Variability

The wind uncertainty and variability is represented by the nominal wind forecast W_{bt}, the forecasted wind capacity range $\underline{W}_{bt} \leq W_{bt} \leq \overline{W}_{bt}$ and the maximum forecasted hourly and intra-hourly ramps, W_{bt}^{R+}, W_{bt}^{R-} and W_{bt}^{IHR+}, W_{bt}^{IHR-}, respectively. Notice that the forecasted capacity values are given in terms of power, i.e., as instantaneous values at the end of each hour. Both the wind capacity range and the maximum ramps are inputs to the formulation, and can be tuned to achieve the desired robustness.

Fig. 3 shows how the hourly and intra-hourly wind ramps are calculated for a given wind power profile. Given the hourly and intra-hourly wind ramps for all scenarios, the maximum ramps used to define the ramp reserve requirements are then calculated as

$$W_{bt}^{R+} = \max_{s \in \mathcal{S}} W_{bst}^{R} \tag{1}$$

$$W_{bt}^{R-} = -\min_{s \in \mathcal{S}} W_{bst}^{R} \tag{2}$$

$$W_{bt}^{IHR+} = \max_{s \in \mathcal{S}, i \in \Delta} W_{bsit}^{IHR} \tag{3}$$

$$W_{bt}^{IHR-} = -\min_{s \in \mathcal{S}, i \in \Delta} W_{bsit}^{IHR} \tag{4}$$

For each scenario, the hourly wind power profile is obtained by fitting a piecewise linear profile W_{bst} that minimizes the deviation between the 5-min profile and the hourly profile. The hourly profiles are then used to determine the wind power

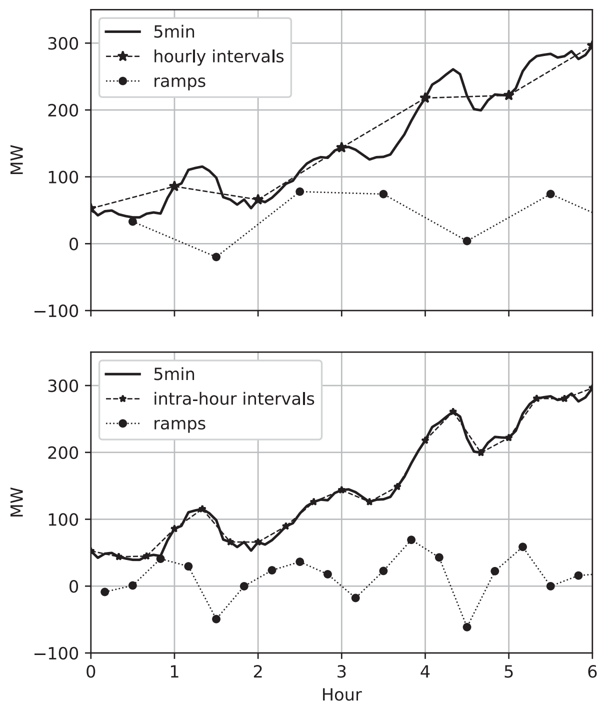

Fig. 3. Calculation of wind power ramp excursions for hourly ramps W^R_{bst} (top) and intra-hourly ramps W^{IHR}_{bsit} with three intra-hour periods (bottom).

capacity range:

$$\underline{W}_{bt} = \min_{s\in\mathcal{S}} W_{bst} \tag{5}$$

$$\overline{W}_{bt} = \max_{s\in\mathcal{S}} W_{bst} \tag{6}$$

$$W_{bt} = 0.5 \cdot (\underline{W}_{bt} + \overline{W}_{bt}) \tag{7}$$

Thus, the formulations proposed in this paper take the set of wind power scenarios as input, and then calculate the wind power ramps and capacity ranges for characterizing the uncertainty and variability using (1)–(7). This facilitates the comparison with stochastic formulations using the same input scenarios, which is carried out in Section III.

B. Hourly Ramp Reserves

This section describes the formulation with hourly ramp reserves. It is similar to the formulation proposed in [37], but simplified since it uses only one set of variables for describing the capacity operating range of the units, i.e., we do not have separate variables for capacity reserves and the capacity dispatch range. The core of the formulation is based on the tight and compact power-based formulation from [39]. For the sake of brevity, we give a relatively concise description of the hourly formulation, and refer the reader to [37] for more elaboration.

1) Objective: The cost to be minimized is given by

$$\sum_{t=1}^{T}\sum_{g\in\mathcal{G}}\Bigg[c^F_{gt}(u_{gt},v_{gt},z_{gt}) + (1-\alpha)c^V_{gt}(p_{gt}) + \alpha\left(\frac{c^V_{gt}(p_{gt}+\overline{r}_{gt}) + c^V_{gt}(p_{gt}-\underline{r}_{gt})}{2}\right)\Bigg] \tag{8}$$

where c^F_{gt} represents commitment costs which are fixed day-ahead (including the energy cost incurred from the minimum generation level) and c^V_{gt} are the variable dispatch costs which change depending on the wind dispatch. These are given by

$$c^F_{gt}(u_{gt},v_{gt},z_{gt}) = C^{NL}_g u_{gt} + C^{LV}_g \underline{P}_g u_{gt} + C^{SU}_g v_{gt} + C^{SD}_g z_{gt} \tag{9}$$

$$c^V_{gt}(p_{gt}) = C^{LV}_g \cdot \frac{p_{gt} + p_{g,t-1}}{2} \tag{10}$$

Notice that the energy produced during startup and shutdown is not explicitly included in the objective, since the cost for this energy is internalized in C^{SU}_g and C^{SD}_g. The parameter α can be tuned to give the relative weight of the upper and lower dispatch compared to the nominal dispatch, and was set to 0.1 as this was found to be the best value in [37].

2) Unit Commitment Logic: The unit commitment logic and minimum up/down times are enforced by

$$u_{gt} - u_{g,t-1} = v_{gt} - z_{gt} \quad \forall g,t \tag{11}$$

$$\sum_{j=t-TU_g+1}^{t} v_{gj} \le u_{gt} \quad \forall g, t\in[TU_g,T] \tag{12}$$

$$\sum_{j=t-TD_g+1}^{t} z_{gj} \le 1 - u_{gt} \quad \forall g, t\in[TD_g,T] \tag{13}$$

with initial conditions implemented as described in [40].

3) Total Production: The total production of units, used to enforce demand balance and transmission constraints, is given by (14) for slow-start units and by (15) for fast-start units.

$$\hat{p}_{gt} = \underline{P}_g(u_{gt}+v_{g,t+1}) + p_{gt} + \sum_{i=1}^{SU^D_g} P^{SU}_{gi} v_{g,t-i+SU^D_g+2} + \sum_{i=2}^{SD^D_g+1} P^{SD}_{gi} z_{g,t-i+2} \quad \forall\, g\in\mathcal{G}^s, t \tag{14}$$

$$\hat{p}_{gt} = \underline{P}_g(u_{gt}+v_{g,t+1}) + p_{gt} \quad \forall\, g\in\mathcal{G}^f, t \tag{15}$$

4) Wind Dispatch: The limits for the wind dispatch are given by (16)–(18) and (19) makes sure the nominal wind dispatch is within the wind dispatch range.

$$0 \le \underline{w}_{bt} \le \underline{W}_{bt} \quad \forall b,t \tag{16}$$

$$0 \le w_{bt} \le W_{bt} \quad \forall b,t \tag{17}$$

$$0 \le \overline{w}_{bt} \le \overline{W}_{bt} \quad \forall b,t \tag{18}$$

$$\underline{w}_{bt} \le w_{bt} \le \overline{w}_{bt} \quad \forall b,t \tag{19}$$

5) Capacity Constraints: The capacity constraints are given by

$$p_{gt} + \overline{r}_{gt} \le (\overline{P}_g - \underline{P}_g)u_{gt} - (\overline{P}_g - SD_g)z_{g,t+1} + (SU_g - \underline{P}_g)v_{g,t+1} \quad \forall g,t \tag{20}$$

$$p_{gt} - \underline{r}_{gt} \geq 0 \quad \forall g, t, \tag{21}$$

where the startup and shutdown ramp capabilities for slow start units are set to $SU_g = SD_g = \underline{P}_g$.

6) Ramp Constraints: The ramp constraints are given by (22)–(23). Notice that the ramp reserves r_{gt}^{R+} and r_{gt}^{R-} must also be feasible with respect to the ramp limits of units.

$$p_{gt} - p_{g,t-1} + r_{gt}^{R+} \leq RU_g u_{gt} + (SU_g - \underline{P}_g) v_{g,t+1} \quad \forall g, t \tag{22}$$

$$p_{g,t-1} - p_{gt} + r_{gt}^{R-} \leq RD_g u_{gt} + (SD_g - \underline{P}_g) z_{gt} \quad \forall g, t \tag{23}$$

7) Envelope Ramp Constraints: The upper and lower dispatch trajectories must also respect the ramp limits of units. Notice that since units are not expected to deploy their ramp reserves when operating at the upper/lower dispatch trajectory it is not necessary to include the ramp reserves when enforcing these constraints. Hence the envelope ramp limits are given by (24)–(25) for the upper dispatch trajectory and by (26)–(27) for the lower dispatch trajectory.

$$p_{gt} + \overline{r}_{gt} - (p_{g,t-1} + \overline{r}_{g,t-1}) \leq RU_g u_{gt} + (SU_g - \underline{P}_g) v_{g,t+1} \forall g, t \tag{24}$$

$$p_{g,t-1} + \overline{r}_{g,t-1} - (p_{gt} + \overline{r}_{gt}) \leq RD_g u_{gt} + (SD_g - \underline{P}_g) z_{gt} \forall g, t \tag{25}$$

$$p_{gt} - \underline{r}_{gt} - (p_{g,t-1} - \underline{r}_{g,t-1}) \leq RU_g u_{gt} + (SU_g - \underline{P}_g) v_{g,t+1} \forall g, t \tag{26}$$

$$p_{g,t-1} - \underline{r}_{g,t-1} - (p_{gt} - \underline{r}_{gt}) \leq RD_g u_{gt} + (SD_g - \underline{P}_g) z_{gt} \forall g, t \tag{27}$$

As described in [37] these constraints may be enforced by

$$-r_{gt}^{R-} \leq \overline{r}_{gt} - \overline{r}_{g,t-1} \leq r_{gt}^{R+} \quad \forall g, t \tag{28}$$

$$-r_{gt}^{R-} \leq \underline{r}_{g,t-1} - \underline{r}_{gt} \leq r_{gt}^{R+} \quad \forall g, t \tag{29}$$

8) Ramp Reserve Deployment Feasibility: To ensure that ramp reserves can be dispatched within the capacity range we enforce:

$$r_{gt}^{R+} \leq \underline{r}_{g,t-1} + \overline{r}_{gt} \quad \forall g, t \tag{30}$$

$$r_{gt}^{R-} \leq \overline{r}_{g,t-1} + \underline{r}_{gt} \quad \forall g, t \tag{31}$$

9) Ramp Capability Reserves: To ensure there is sufficient ramp reserves we enforce the constraints

$$\sum_{g \in \mathcal{G}} r_{gt}^{R+} \geq \sum_{b \in \mathcal{B}^W} \inf \left(\tilde{W}_{bt}^{R-}, w_{bt}^{R-} \right) \quad \forall t \tag{32}$$

$$\sum_{g \in \mathcal{G}} r_{gt}^{R-} \geq \sum_{b \in \mathcal{B}^W} \inf \left(\tilde{W}_{bt}^{R+}, w_{bt}^{R+} \right) \quad \forall t, \tag{33}$$

where $\tilde{W}_{bt}^{R-}$ and $\tilde{W}_{bt}^{R+}$ are the exogenously calculated wind ramps (in excess of the nominal wind trajectory):

$$\tilde{W}_{bt}^{R-} = W_{bt}^{R-} - (W_{b,t-1} - W_{bt}) \tag{34}$$

$$\tilde{W}_{bt}^{R+} = W_{bt}^{R+} - (W_{bt} - W_{b,t-1}) \tag{35}$$

and w_{bt}^{R-} and w_{bt}^{R+} are the maximum wind ramps (in excess of the nominal wind dispatch) that can fit within the wind dispatch trajectory:

$$w_{gt}^{R-} = \overline{w}_{b,t-1} - \underline{w}_{bt} - (w_{b,t-1} - w_{bt}) \tag{36}$$

$$w_{bt}^{R+} = \overline{w}_{bt} - \underline{w}_{b,t-1} - (w_{bt} - w_{b,t-1}) \tag{37}$$

Thus, by curtailing wind power it is possible for the formulation to decrease the ramp requirements imposed by wind power fluctuations, if this is economical. The inf functions in (32)–(33) are implemented as described in [37].

10) Demand Balance: Demand balance is enforced for the nominal wind dispatch:

$$\sum_{g \in \mathcal{G}} \hat{p}_{gt} = \sum_{b \in \mathcal{B}^D} D_{bt} - \sum_{b \in \mathcal{B}^W} w_{bt} \quad \forall t, \tag{38}$$

and for the upper and lower dispatch trajectories:

$$\sum_{g \in \mathcal{G}} \overline{r}_{gt} = \sum_{b \in \mathcal{B}^W} (w_{bt} - \underline{w}_{bt}) \quad \forall t \tag{39}$$

$$\sum_{g \in \mathcal{G}} \underline{r}_{gt} = \sum_{b \in \mathcal{B}^W} (\overline{w}_{bt} - w_{bt}) \quad \forall t \tag{40}$$

11) Transmission Constraints: Transmission constraints are enforced for the lower and upper wind dispatch trajectories:

$$-\overline{F}_l \leq \sum_{g \in \mathcal{G}} \Gamma_{lg}^P (\hat{p}_{gt} + \overline{r}_{gt}) + \sum_{b \in \mathcal{B}^W} \Gamma_{lb} \underline{w}_{bt} - \sum_{b \in \mathcal{B}^D} \Gamma_{lb} D_{bt} \leq \overline{F}_l \forall l, t \tag{41}$$

$$-\overline{F}_l \leq \sum_{g \in \mathcal{G}} \Gamma_{lg}^P (\hat{p}_{gt} - \underline{r}_{gt}) + \sum_{b \in \mathcal{B}^W} \Gamma_{lb} \overline{w}_{bt} - \sum_{b \in \mathcal{B}^D} \Gamma_{lb} D_{bt} \leq \overline{F}_l \forall l, t \tag{42}$$

C. Intra-Hourly Ramp Reserves

In this paper we now propose intra-hourly ramp reserves r_{gt}^{IHR+} and r_{gt}^{IHR-}, i.e., ramp reserves with a deployment time which is less than one hour. We let Δ be the number of intra-hour intervals corresponding to the ramp deployment time so that, e.g., $\Delta = 2$ corresponds to the case with two intra-hour intervals and a ramp deployment time of 30 min. Adding intra-hour ramp reserves requires modification of the hourly formulation as described in this section.

1) Ramp Constraints: The ramp constraints (43)–(44), which replace (22)–(23), now also include intra-hourly ramp reserves, multiplied by Δ to get hourly ramp rates.

$$p_{gt} - p_{g,t-1} + r_{gt}^{R+} + \Delta \cdot r_{gt}^{IHR+} \leq RU_g u_{gt} + (SU_g - \underline{P}_g) v_{g,t+1} \quad \forall g, t \tag{43}$$

$$p_{g,t-1} - p_{gt} + r_{gt}^{R-} + \Delta \cdot r_{gt}^{IHR-} \leq RD_g u_{gt} + (SD_g - \underline{P}_g) z_{gt} \quad \forall g, t \tag{44}$$

2) Envelope Ramp Constraints: The ramp constraints for the dispatch trajectories (24)–(27) are the same as before, but they

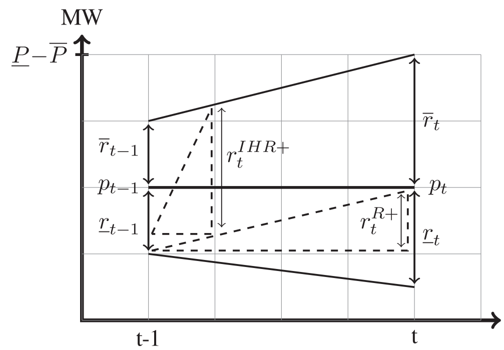

Fig. 4. Example of ramp reserve deployment feasibility for upward ramp reserves. In this case both the hourly constraint (47) and the intra-hourly constraint (49) are binding.

can now be enforced by:

$$-r_{gt}^{R-} - \Delta \cdot r_{gt}^{IHR-} \leq \overline{r}_{gt} - \overline{r}_{g,t-1} \leq r_{gt}^{R+} + \Delta \cdot r_{gt}^{IHR+} \forall g,t \quad (45)$$

$$-r_{gt}^{R-} - \Delta \cdot r_{gt}^{IHR-} \leq \underline{r}_{g,t-1} - \underline{r}_{gt} \leq r_{gt}^{R+} + \Delta \cdot r_{gt}^{IHR+} \forall g,t \quad (46)$$

3) Ramp Reserve Deployment Feasibility: Both hourly and intra-hourly ramp reserves must be dispatchable within the capacity range of the units during the course of one hour:

$$r_{gt}^{R+} + r_{gt}^{IHR+} \leq \underline{r}_{g,t-1} + \overline{r}_{gt} \quad \forall g,t \quad (47)$$

$$r_{gt}^{R-} + r_{gt}^{IHR-} \leq \overline{r}_{g,t-1} + \underline{r}_{gt} \quad \forall g,t \quad (48)$$

Additionally, the intra-hour ramp reserves must now be dispatchable within each intra-hour interval, assuming that the hourly ramp reserves are also being dispatched. Since the dispatch range changes linearly during the hour, it is enough to ensure that the ramp reserves can be dispatched in the first and last intra-hour interval each hour. Thus the constraints for intra-hour reserve feasibility are given by:

$$\frac{1}{\Delta} r_{gt}^{R+} + r_{gt}^{IHR+} \leq \underline{r}_{g,t-1} + \frac{(\Delta-1)\overline{r}_{g,t-1} + \overline{r}_{gt}}{\Delta} \quad \forall g,t \quad (49)$$

$$\frac{1}{\Delta} r_{gt}^{R+} + r_{gt}^{IHR+} \leq \frac{\underline{r}_{g,t-1} + (\Delta-1)\underline{r}_{gt}}{\Delta} + \overline{r}_{gt} \quad \forall g,t \quad (50)$$

$$\frac{1}{\Delta} r_{gt}^{R-} + r_{gt}^{IHR-} \leq \overline{r}_{g,t-1} + \frac{(\Delta-1)\underline{r}_{g,t-1} + \underline{r}_{gt}}{\Delta} \quad \forall g,t \quad (51)$$

$$\frac{1}{\Delta} r_{gt}^{R-} + r_{gt}^{IHR-} \leq \frac{\overline{r}_{g,t-1} + (\Delta-1)\overline{r}_{gt}}{\Delta} + \underline{r}_{gt} \quad \forall g,t \quad (52)$$

Fig. 4 illustrates how (47)–(52) limit the amount of upward ramp reserves. Since the capacity reserve range is narrowest at t-1, the most restrictive intra-hourly constraint will be the constraint for the first intra-hour interval, i.e., (49). However, whether or not it will be binding depends on if it is more restrictive than the hourly reserve deployment constraint (47). In the case shown in Fig. 4 both the hourly constraint (47) and the intra-hourly constraint (49) are binding. However, if the share of hourly reserves relative to intra-hourly reserves increases, only (47) will be binding, and similarly if the share of intra-hourly reserves increases only (49) will be binding.

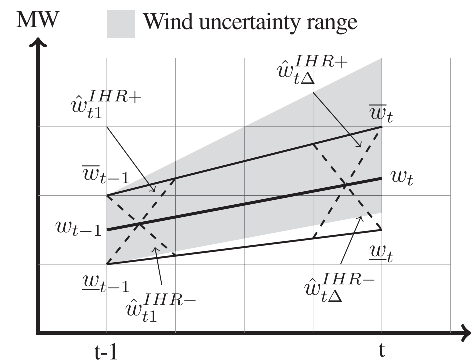

Fig. 5. Wind uncertainty range and dispatch range. In this case the dispatch range at t is reduced compared to the uncertainty range, meaning that there might be wind curtailment in real time. This decreases the ramp rate of the nominal dispatch $w_t - w_{t-1}$ and the wind excursions $\hat{w}_{t\Delta}^{IHR+}$, $\hat{w}_{t\Delta}^{IHR-}$, thus decreasing the flexibility needed from conventional generators. Since the dispatch range changes linearly, it is enough to ensure that the intra-hour ramp reserves can cover the intra-hour wind ramps in the first and the last interval of each hour.

4) Ramp Capability Reserves: As before, there is an hourly requirement for the amount of ramp reserves, but now both the hourly and intra-hourly reserves can contribute to fulfilling this requirement:

$$\sum_{g\in\mathcal{G}} \left(r_{gt}^{R+} + r_{gt}^{IHR+}\right) \geq \sum_{b\in\mathcal{B}^W} \inf\left(\tilde{W}_{bt}^{R-}, w_{bt}^{R-}\right) \quad \forall t \quad (53)$$

$$\sum_{g\in\mathcal{G}} \left(r_{gt}^{R-} + r_{gt}^{IHR-}\right) \geq \sum_{b\in\mathcal{B}^W} \inf\left(\tilde{W}_{bt}^{R+}, w_{bt}^{R+}\right) \quad \forall t \quad (54)$$

Additionally, there is a requirement for the amount of intra-hour ramp reserves:

$$\sum_{g\in\mathcal{G}} r_{gt}^{IHR+} \geq \sum_{b\in\mathcal{B}^W} \inf\left(\tilde{W}_{bt}^{IHR-}, \max_{i\in\Delta} w_{bti}^{IHR-}\right) \quad \forall t \quad (55)$$

$$\sum_{g\in\mathcal{G}} r_{gt}^{IHR-} \geq \sum_{b\in\mathcal{B}^W} \inf\left(\tilde{W}_{bt}^{IHR+}, \max_{i\in\Delta} w_{bti}^{IHR+}\right) \quad \forall t \quad (56)$$

where $\tilde{W}_{bt}^{IHR-}$, $\tilde{W}_{gt}^{IHR+}$ are the exogeneously calculated intra-hour ramp excursions, i.e., deviations from nominal wind trajectory, and w_{bti}^{IHR-}, w_{bti}^{IHR+} are the maximum intra-hour ramp excursions possible within the wind power dispatch range, where i is the index of the intra-hour period. Since the wind dispatch range is changing linearly it is enough to ensure that there is enough ramp reserves for the first and last intra-hour interval, as illustrated in Fig. 5. Thus the constraints used to enforce (55)–(56) are:

$$\sum_{g\in\mathcal{G}} r_{gt}^{IHR+} \geq \sum_{b\in\mathcal{B}^W} \inf\left(\tilde{W}_{bt}^{IHR-}, w_{bt1}^{IHR-}\right) \quad \forall t \quad (57)$$

$$\sum_{g\in\mathcal{G}} r_{gt}^{IHR+} \geq \sum_{b\in\mathcal{B}^W} \inf\left(\tilde{W}_{bt}^{IHR-}, w_{bt\Delta}^{IHR-}\right) \quad \forall t \quad (58)$$

$$\sum_{g\in\mathcal{G}} r_{gt}^{IHR-} \geq \sum_{b\in\mathcal{B}^W} \inf\left(\tilde{W}_{bt}^{IHR+}, w_{bt1}^{IHR+}\right) \quad \forall t \quad (59)$$

$$\sum_{g\in\mathcal{G}} r_{gt}^{IHR-} \geq \sum_{b\in\mathcal{B}^W} \inf\left(\tilde{W}_{bt}^{IHR+}, w_{bt\Delta}^{IHR+}\right) \quad \forall t \tag{60}$$

The maximum intra-hour ramp excursions are given by

$$w_{bt1}^{IHR-} = \hat{w}_{bt1}^{IHR-} - \frac{w_{b,t-1} - w_{bt}}{\Delta} \tag{61}$$

$$w_{bt\Delta}^{IHR-} = \hat{w}_{bt\Delta}^{IHR-} - \frac{w_{b,t-1} - w_{bt}}{\Delta} \tag{62}$$

$$w_{bt1}^{IHR+} = \hat{w}_{bt1}^{IHR+} - \frac{w_{bt} - w_{b,t-1}}{\Delta} \tag{63}$$

$$w_{bt\Delta}^{IHR+} = \hat{w}_{bt\Delta}^{IHR+} - \frac{w_{bt} - w_{b,t-1}}{\Delta} \tag{64}$$

where the maximum possible ramps $\hat{w}_{bt1/\Delta}^{IHR-/+}$ can be obtained from Fig. 5 and are given by:

$$\hat{w}_{bt1}^{IHR-} = \overline{w}_{b,t-1} - \frac{(\Delta-1)\underline{w}_{b,t-1} + \underline{w}_{bt}}{\Delta} \tag{65}$$

$$\hat{w}_{bt\Delta}^{IHR-} = \frac{\overline{w}_{b,t-1} + (\Delta-1)\overline{w}_{bt}}{\Delta} - \underline{w}_{bt} \tag{66}$$

$$\hat{w}_{bt1}^{IHR+} = \frac{(\Delta-1)\overline{w}_{b,t-1} + \overline{w}_{bt}}{\Delta} - \underline{w}_{b,t-1} \tag{67}$$

$$\hat{w}_{bt\Delta}^{IHR+} = \overline{w}_{bt} - \frac{\underline{w}_{b,t-1} + (\Delta-1)\underline{w}_{bt}}{\Delta} \tag{68}$$

The exogenous intra-hour ramps are calculated as the maximum intra-hour ramp during one hour, in excess of the ramp rate for the nominal forecast:

$$\tilde{W}_{bt}^{IHR-} = W_{bt}^{IHR-} - \frac{W_{b,t-1} - W_{bt}}{\Delta} \tag{69}$$

$$\tilde{W}_{bt}^{IHR+} = W_{bt}^{IHR+} - \frac{W_{bt} - W_{b,t-1}}{\Delta} \tag{70}$$

D. Complete Formulations

The formulation specified in Section II-C includes both hourly and intra-hourly ramp reserves. However, it is straightforward to adjust the formulation to include only intra-hourly reserves. Thus three distinct formulations can be implemented:

1) Hourly ramp reserves (**HR**), (8)–(23), (28)–(33), (38)–(42).
2) Combined hourly and intra-hourly ramp reserves (**CR**), (8)–(21), (38)–(42), (43)–(54), (57)–(60).
3) Only intra-hourly ramp reserves (**IR**). This is obtained by removing the hourly ramp reserves from the previous formulation, i.e., (8)–(21), (38)–(42), (57)–(60), and the following constraints with $r_{gt}^{R+} = r_{gt}^{R-} = 0$: (43)–(46) and (49)–(52).

Notice that if some units should be excluded from providing capacity and ramp reserves, this can be achieved by setting $\overline{r}_{gt} = \underline{r}_{gt} = r_{gt}^{R+} = r_{gt}^{R-} = r_{gt}^{IHR+} = r_{gt}^{IHR-} = 0$ for those units.

Conceptually, the formulations differ in the following way: HR has only hourly ramp reserves, meaning that it does not include information about the wind variability on shorter time scales than one hour. On the other hand, IR has only intra-hourly reserves, based on the intra-hour wind variability which is determined as shown in Fig. 3. Finally, CR has both hourly and intra-hourly reserves, meaning that this is expected to be the most robust formulation, but also the most computationally demanding.

TABLE I
TEST SYSTEM DATA

	IEEE 24-bus RTS	IEEE 118-bus
Nr. of units	14	54
Fixed (non-redispatchable) units	[5,6,9,10,11,12]	[4,5,10,11,27,28, 36,39,43,44,45]
Wind buses	[9,16,21]	[36,77,69]
Wind capacity [MW]	[400,500,500]	[400,600,700]
Peak load [MW]	3000	5600

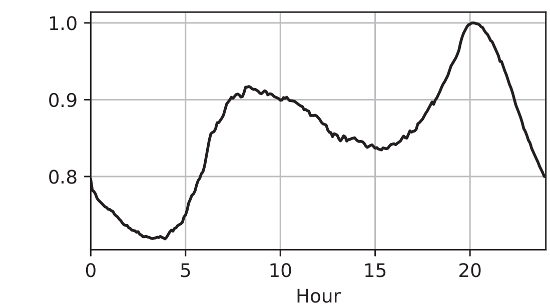

Fig. 6. Normalized CAISO load profile for 2019-10-16 [www.caiso.com].

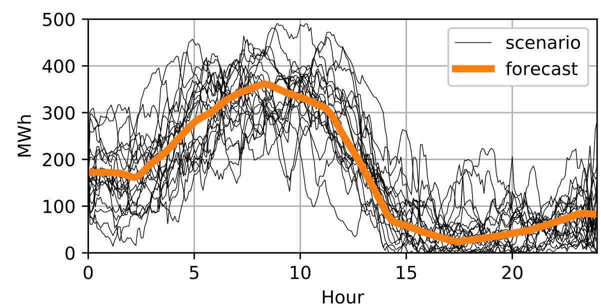

Fig. 7. Wind power scenarios for bus 16 for the 24-bus system.

III. RESULTS

A. Test Systems

Two test systems were used, a modified version of the IEEE 24-bus reliability test system and the IEEE 118-bus test system. The 24-bus system was based on [41], [42], with generator data as shown in Table II. To create binding transmission constraints, line capacities of 1000 MW, 500 MW, and 175 MW lines in [41] were reduced to, respectively, 500 MW and 400 MW, and 150 MW. The 118-bus test system was the same system as used in [37]. For both systems 5-min load and wind data were used, with capacities as shown in Table I. Fig. 6 shows the normalized demand profile, which was obtained from CAISO. The wind power production scenarios were generated using the model described in [38], and Fig. 7 shows the wind power scenarios used in the UC formulations. The wind scenarios have 5-min time resolution and are based on the empirical distribution of forecast errors, while preserving the correlation of the forecast errors between different time periods and different wind farms [38].

TABLE II
GENERATOR DATA FOR THE 24 BUS SYSTEM

	Bus	Type	$\underline{P}$	$\overline{P}$	RU	TU	TD	SU^D	SD^D	C^{NL}	C^{LV}	C^{SU}	C^{SD}	P_0	S_0
1	1	CCGT	80.0	152.0	144.0	3	2	1	1	526.8	19.0	1271.1	1271.1	80.0	2
2	1	CCGT	80.0	152.0	72.0	3	2	1	1	526.8	18.6	1271.1	1271.1	80.0	2
3	2	CCGT	80.0	152.0	144.0	3	2	1	1	526.8	18.6	1255.6	1255.6	80.0	2
4	2	CCGT	80.0	152.0	72.0	3	2	1	1	526.8	18.2	1255.6	1255.6	80.0	2
5*	7	CCGT	120.0	300.0	126.0	4	4	2	2	919.8	17.6	3949.3	3949.3	182.4	3
6*	13	CCGT	312.0	591.0	93.0	4	4	2	2	1448.6	17.2	8261.3	8261.3	591.0	3
7	15	IGCC	54.2	155.0	201.5	8	5	3	2	415.5	24.0	3164.4	2109.6	0.0	-1
8	15	IGCC	54.2	155.0	100.8	8	5	3	2	415.5	23.6	3164.4	2109.6	54.2	7
9*	16	IGCC	54.2	155.0	7.0	8	5	3	2	415.6	24.1	3204.0	2136.0	0.0	-1
10*	18	Nuclear	100.0	400.0	28.0	8	8	5	3	188.3	6.8	26449.9	1577.7	400.0	7
11*	21	Nuclear	100.0	400.0	28.0	8	8	5	3	188.3	7.2	26556.9	1641.9	234.8	7
12*	22	CCGT	156.0	300.0	72.0	2	4	2	2	3756.6	28.3	11927.0	11927.0	0.0	-1
13	23	Coal	140.0	350.0	420.0	8	5	3	2	303.8	26.7	10379.5	4277.4	0.0	-1
14	23	Coal	140.0	350.0	210.0	8	5	3	2	303.8	26.2	10379.5	4277.4	0.0	-1

Notes:
1. Ramp capability of all units is symmetrical: $RU = RD$.
2. P_0 refers to initial production and S_0 to number of hours a unit has been online (+) or offline (-) at hour 1.
3. * unit not providing reserves in the UC, i.e., with fixed production in the ED.

To obtain the initial status of units, a steady state problem was solved, which minimized the cost to satisfy the initial net load while maintaining a specified amount of upward and downward reserves and satisfying transmission limits. The amount of reserves was 500 MW for the 24 bus system and 600 MW for the 118 bus system. The initial status of the units was set so that online units could be shut down during the second hour, thus reducing the impact of the initial conditions on the optimal scheduling the remaining time span.

B. Evaluation Procedure

To evaluate the performance of the UC formulations we use an economic dispatch (ED), where all commitment decisions are fixed to the values from the UC solution. Since the ED has no binary variables, it is an LP problem. The ED is evaluated using 500 out-of-sample wind scenarios, generated by the same model used to generate the wind scenarios used in the UC. For the ED to be feasible load shedding is allowed, which is needed if, e.g., there is less wind power than was anticipated. The cost for load shedding is 10 000 $/MWh.

If all dispatch decisions in the ED can be re-optimized without extra costs, this can lead to a large amount of redispatch, as the production schedules of all units are changed to accommodate the realized wind power production. However, in real power systems all units are not usually available for redispatch. For example, in most US markets with real-time dispatch, producers are not required to participate in the real-time dispatch, but can follow their day-ahead schedules and receive the corresponding day-ahead prices for their production [3]. To simulate a system where not all units participate in the real-time balancing of the system, some units are fixed to their UC schedules in the ED, as shown in Table I. These units are also not able to provide ramp or capacity reserves in the proposed UC formulation, and for the stochastic formulations they have the same production schedule in all scenarios.

Both the UC and ED formulations were implemented in Python and solved with Gurobi 9.02 on a PC with Intel Core i7-4790 CPU @ 3.6 GHz and 32 GB of RAM. The relative MIP gap for solving the UC formulations was set to 10^{-4} for the 24-bus system and $5 \cdot 10^{-3}$ for the 118-bus system.

C. Results for 24-Bus System

In this section we first compare the performance of the different proposed ramp reserve formulations (Section III-C1) and then proceed to compare the ramp reserve formulations with different stochastic formulations (Section III-C2).

1) Hourly Versus Intra-Hourly Ramp Reserves: Section II specifies three distinct formulations, the formulation with only hourly ramp reserves (HR), the formulation with both hourly and intra-hourly ramp reserves (CR), and the formulation with only intra-hourly ramp reserves (IR). For the formulations CR and IR we try using three different intra-hour period lengths: 30 min, 20 min and 15 min, by adjusting Δ in the formulations.

Table III shows the evaluation of the formulations. The first part of the table shows the results from the unit commitment (UC) and the second part shows the average values over 500 out-of-sample scenarios for the evaluation using the economic dispath (ED). HR has the lowest costs in the UC, but it also has the largest amount of load-shedding in the ED and largest number of violations (number of 5-min loadshed events, with simultaneous events on different buses counted separately), showing that it is less secure than the other formulations. However, the average total costs for HR are still lower than for CR 15 min and IR 15 min, showing that the extra security achieved by adding the intra-hour reserves is not always economical.

Notice that the amount of wind curtailment also decreases when using intra-hour ramp reserves with a smaller time resolution, meaning that increased security (less load shedding) is accompanied by lower wind curtailment. This is because the conventional generators that have been scheduled by the formulations with short intra-hour intervals are better able to follow the fast wind ramps, thereby decreasing the need for curtailment. In the ED wind was treated as zero marginal cost resource. However, in many markets curtailing wind energy can

TABLE III
EVALUATION OF RAMP RESERVE FORMULATIONS FOR 24-BUS SYSTEM

	HR	CR 30min	CR 20min	CR 15min	IR 30min	IR 20min	IR 15min
Unit commitment (UC)							
Objective	1.0000	1.0117	1.0289	1.0482	1.0098	1.0248	1.0404
Commitment cost†	0.1913	0.2036	0.1980	0.1920	0.1916	0.1941	0.1908
Dispatch cost	0.8087	0.8081	0.8309	0.8562	0.8182	0.8307	0.8497
Nr. of startups	5	4	6	4	5	5	4
Solution time (s)	15.8	250.0	316.3	652.8	50.0	48.0	163.3
Economic dispatch (ED) - average from 500 evaluations							
Objective	0.0844	0.0620	0.0750	0.0900	0.0690	0.0641	0.0891
Total cost‡	1.0593	1.0463	1.0507	1.0646	1.0494	1.0534	1.0596
Loadshed (MWh)	2.92	0.82	0.51	0.28	1.82	0.44	0.29
Wind curtail (MWh)	2203.58	2018.57	1815.34	1985.41	2249.54	2047.17	1818.57
Wind curtail (%)	12.8	11.7	10.6	11.6	13.1	11.9	10.6
Nr. of violations	548	181	105	71	365	99	72
Nr. of eval. w. viol.	65	30	18	16	51	18	16

All costs are scaled to the UC objective value for HR: 762075 $.
†Sum of startup, shutdown, and no load costs.
‡Computed as sum of commitment cost and the average ED dispatch cost, including cost for load shedding.

be costly due to, e.g., negative bidding by wind producers [43]. If this were the case, it could increase the performance of the formulations with intra-hour reserves relative to HR, since the curtailment can be decreased.

The reason why the formulations with intra-hour reserves can achieve higher security than HR is not only that they can consider intra-hour wind power fluctuations, but also that they can achieve better scheduling of fast-ramping units. Notice in Table II that unit 1 and unit 2 are identical except that unit 1 has higher variable costs (C^{LV}) but also higher ramp capability (RU). Although unit 1 is more expensive than unit 2, it may be beneficial to schedule this unit instead of unit 2 if the additional ramp capability (144 MW/h vs 72 MW/h) is needed. However, if only hourly ramp reserves are used, the ramp reserves that can be provided by unit 1 are limited by its capacity operating range of 72 MW, so the additional ramping capability of unit 1 is not seen in the hourly formulation HR. The principle is the same for the unit pairs 3 and 4, 7 and 8, as well as 13 and 14, where the units differ only regarding the ramp capability and the variable costs.

Fig. 8 compares the commitment of these units (1-4,7,8,13,14) for the formulations HR and CR 30 min. As expected, in the choice between unit 1 and unit 2, HR prefers to schedule unit 2 which is cheaper, while CR 30 min schedules unit 1 during the whole planning period. During hour 11-19, HR schedules only unit 2 while CR 30 min schedules only unit 1. A similar pattern can also be observed for unit 7 and 8, where CR 30 min better appreciates the need for ramping capability from unit 7 compared to HR.

In summary, using intra-hour reserves can make the formulation more robust against intra-hour wind variability by ensuring sufficient intra-hour ramp capability is available. In the following we use an intra-hour time interval of 30 min, since this gave the best trade-off between cost and security, as observed from Table III.

2) Comparison With Stochastic Formulations: Here we compare the formulation with hourly ramp reserves (HR) and the 30 minute intra-hour ramp formulations (CR 30 min and IH 30 min) to three different stochastic formulations:

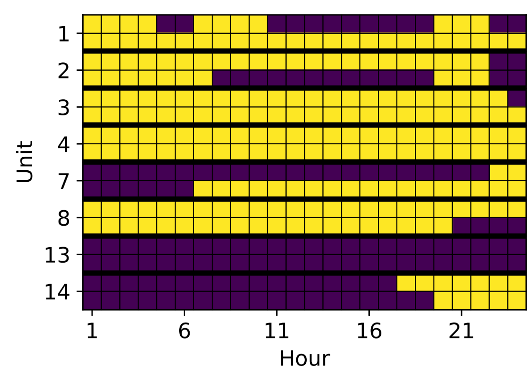

Fig. 8. Comparison of commitment schedule from HR and CR 30 min for selected units. For each unit, the first row shows the commitment from HR and the second row the commitment for CR 30 min. Bright yellow indicates an online unit ($u_{gt} = 1$) and dark purple indicates an offline unit ($u_{gt} = 0$).

1) StochEn - a conventional hourly stochastic formulation which models the average energy production during the hour, based on [44].
2) StochPw - an hourly stochastic power-based formulation, based on [39].
3) Stoch5min - a power-based formulation with hourly unit commitment decisions and 5-min resolution for the dispatch decisions. Unlike the other stochastic formulations, this formulation allows load-shedding, allowing it to reduce the security of schedule if this would be economical. The full formulation is provided in Appendix A.

The purpose of this comparison is to see how the proposed formulations perform relative to other formulations that consider uncertainty and intra-hour variability of wind. While the hourly stochastic formulations consider the uncertainty, they cannot capture the intra-hour wind variability and uncertainty due to the intrinsic nature of the hourly wind profiles. However, Stoch5min

TABLE IV
EVALUATION FOR 24-BUS SYSTEM WITHOUT SCENARIO REDUCTION

	HR	CR 30min	IR 30min	StochEn	StochPw	Stoch5min
Unit commitment (UC)						
Objective	1.0000	1.0117	1.0098	0.9705	0.9808	0.9878
Commitment cost †	0.1913	0.2036	0.1916	0.1681	0.1741	0.1743
Dispatch cost	0.8087	0.8081	0.8182	0.8024	0.8067	0.8127
Nr. of startups	5	4	5	5	4	4
Solution time (s)	14.6	247.4	44.9	13.2	15.6	6328.3
Economic dispatch (ED) - average from 500 evaluations						
Objective	0.0844	0.0620	0.0690	1.2093	0.8006	0.7515
Total cost‡	1.0593	1.0463	1.0494	2.1188	1.7218	1.6724
Loadshed (MWh)	2.92	0.82	1.82	86.30	55.84	52.19
Wind curtail (MWh)	2203.58	2018.57	2249.54	1676.79	1638.97	1661.32
Wind curtail (%)	12.8	11.7	13.1	9.8	9.5	9.7
Nr. of violations	548	181	365	12437	8380	7660
Nr. of eval. w. viol.	65	30	51	412	320	298

All costs are scaled to the UC objective value for HR: 762075 $.
†Sum of startup, shutdown, and no load costs.
‡Computed as sum of commitment cost and the avg. ED dispatch cost, incl. cost for load shedding.

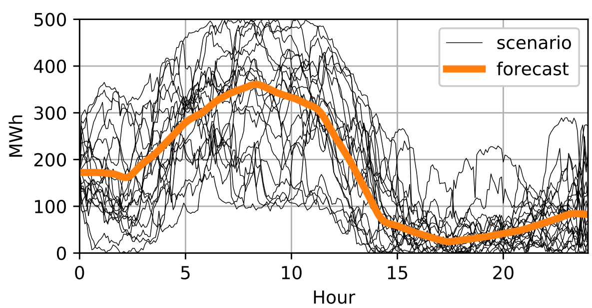

Fig. 9. Wind power scenarios fur bus 16 for the 24-bus system when using scenario reduction with 500 sample scenarios.

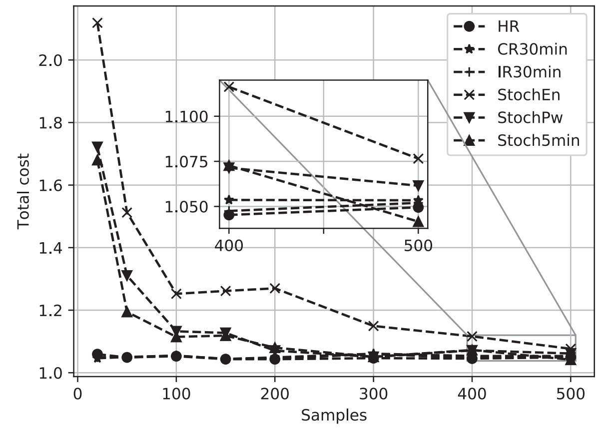

Fig. 10. Average total cost for different formulations with increasing number of samples for scenario reduction.

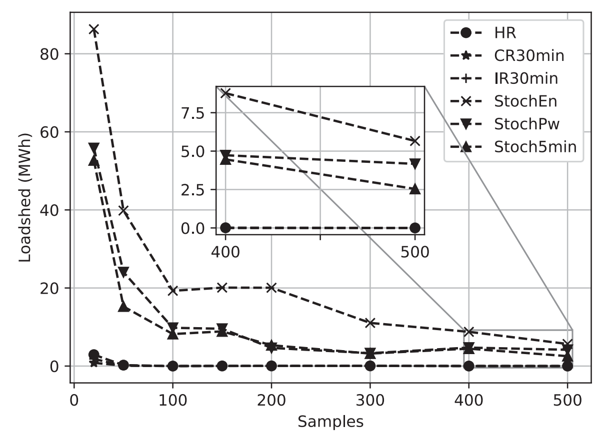

Fig. 11. Average load shedding in ED for different formulations with increasing number of samples for scenario reduction.

has complete information of the intra-hour variability since it uses 5-min resolution for the dispatch decisions.

Unlike the formulations with reserves, the stochastic formulations are very sensitive to which scenarios are included. When comparing the formulations in Section III-C1, 20 randomly generated scenarios were used in the UC formulation. Table IV evaluates HR, CR 30 min, IR 30 min, and the stochastic formulations, using the same 20 scenarios in the formulation. Notice that, in this case, the formulations with ramp reserves outperform all stochastic formulations by at least 60% in terms of average total costs. The high costs for the stochastic formulations occur due to the high load shedding required in the ED for the resulting commitment schedules to be feasible. This is the result of both wind uncertainty, which means that wind scenarios which were not anticipated in the UC can occur, and intra-hour wind variability, which is not captured by the hourly stochastic UC formulations.

To get better results for the stochastic formulations, it is necessary to do a more careful selection of the scenarios used in the UC. For this purpose, a scenario reduction algorithm from [45] was used to select the 20 scenarios out of a larger number of sample scenarios, while maintaining as closely as possible the probability distribution of the original scenarios. Fig. 9 shows the 20 scenarios generated from 500 sample scenarios, and comparison with Fig. 7 shows that the scenarios now capture a much larger part of the uncertainty distribution.

Fig. 10 shows how the average total cost changes for the different formulations as the number of sample scenarios from which the 20 UC scenarios can be drawn increases from 20 to 500. It can be seen that 500 scenarios are needed before Stoch5min outperforms the ramp reserve formulations in terms of total costs. Similarly, Fig. 11 shows how the average load shedding changes with the number of scenarios. The load shedding decreases for the stochastic formulations as the number of samples increases, but it never goes to zero. On the other hand, the load shedding for the ramp reserve formulations decreases to zero already if 100 sample scenarios are used, showing high security of these formulations. This is due to the inclusion of the lower wind dispatch trajectory in the formulation, which gives the formulations robustness against low wind outcomes, as demonstrated in [15]. In fact, these formulations are “too robust” when a large number of sample scenarios are used, since they give higher total costs than Stoch5min even though they result in zero load shedding, meaning that the additional commitment and dispatch costs needed to completely guarantee that no load shedding occurs outweigh the decreased costs of load shedding in the evaluation. However, the robustness of the ramp reserve formulations can be decreased by increasing the value of α, i.e.,

TABLE V
EVALUATION FOR 24-BUS SYSTEM WITH SCENARIO REDUCTION

	HR	CR 30min	IR 30min	StochEn	StochPw	Stoch5min
Unit commitment (UC)						
Objective	1.0000	1.0070	1.0048	0.9749	0.9829	0.9912
Commitment cost†	0.1841	0.1859	0.1852	0.1727	0.1741	0.1798
Dispatch cost	0.8159	0.8212	0.8196	0.8022	0.8088	0.8114
Nr. of startups	5	5	5	3	3	2
Solution time (s)	5.0	27.3	10.9	17.6	13.0	4390.4
Complexity and computational burden						
Continuous variables	2328	3864	2760	8160	8160	195840
Binary variables	1152	1440	1296	1008	1008	1008
Constraints	7423	9355	8757	56381	56381	672557
Nodes explored	2467	4033	7802	97	41	269
Economic dispatch (ED) - average from 500 evaluations						
Objective	0.0420	0.0453	0.0450	0.1279	0.1048	0.0914
Total cost‡	1.0192	1.0230	1.0216	1.0455	1.0309	1.0115
Loadshed (MWh)	0.00	0.00	0.00	5.66	4.17	2.54
Wind curtail (MWh)	2749.23	2641.80	2623.52	2017.27	2229.06	1789.29
Wind curtail (%)	16.0	15.4	15.3	11.7	13.0	10.4
Nr. of violations	0	0	0	1042	839	534
Nr. of eval. w. viol.	0	0	0	134	98	81
Economic dispatch (ED) - insample evaluation, average of 20 scenarios						
Objective	0.0501	0.0535	0.0533	0.3609	0.1932	0.0704
Total cost	1.0273	1.0312	1.0300	1.2784	1.1192	0.9904
Loadshed (MWh)	0.00	0.00	0.00	23.05	10.28	0.00
Wind curtail (MWh)	2586.67	2481.42	2467.07	2007.06	2171.78	1765.35
Wind curtail (%)	15.0	14.4	14.3	11.6	12.6	10.2
Nr. of violations	0	0	0	176	95	0
Nr. of scen. w. viol.	0	0	0	11	10	0

All costs are scaled to the UC objective value for HR: 784729 $.
†Sum of startup, shutdown, and no load costs.
‡Computed as sum of commitment cost and the avg. ED dispatch cost, incl. cost for load shedding.

TABLE VI
EVALUATION FOR 118-BUS SYSTEM WITHOUT SCENARIO REDUCTION

	HR	CR 30min	IR 30min	StochEn	StochPw
Unit commitment (UC)					
Objective	1.0000	1.0486	1.0453	0.9793	0.9812
Commitment cost†	0.0162	0.0209	0.0211	0.0134	0.0147
Dispatch cost	0.9838	1.0277	1.0242	0.9659	0.9664
Nr. of startups	44	44	42	37	41
Solution time (s)	106	2827	1147	344	243
Economic dispatch (ED) - average of 500 evaluations					
Objective	0.2451	0.2021	0.2041	1.3825	0.7557
Total cost‡	1.0466	1.0418	1.0447	2.1797	1.5594
Loadshed (MWh)	2.55	0.03	0.07	114.79	53.82
Wind curtail (MWh)	353.81	366.00	334.35	785.22	423.53
Wind curtail (%)	1.6	1.7	1.5	3.6	2.0
Nr. of violations	728	19	39	34002	17428
Nr. of eval. w. viol.	53	6	10	443	338

All costs scaled to the UC objective value for HR: 981077 $.
†Sum of startup, shutdown, and no load costs.
‡Computed as sum of commitment cost and the average ED dispatch cost, including cost for load shedding.

increasing the weight of the upper and lower dispatch trajectories in the objective function, as shown in [37].

Table V shows the results of the evaluation when using 500 sample scenarios. In this case the total costs of Stoch5min is about 1% lower compared to the ramp reserve formulations. However, the hourly stochastic formulations have total costs which are about 1% and 2.5% higher, respectively, for the power-based and energy-based formulations. Notice also that while the ramp reserve formulations achieve a higher level of security, since they have zero load shedding on average, this comes at the cost of significantly higher wind power curtailment compared to the stochastic formulations.

Table V also shows the insample evaluation of the formulations using the same 20 scenarios as used in the UC formulations. Notably, the hourly stochastic formulations perform worse than the reserve formulations for the insample evaluation, since they have more load shedding and high total costs. This means that it is not the uncertainty representation which is limiting the performance of the stochastic formulations, but the representation of wind variability. Since the hourly wind scenarios used in the stochastic UC formulations don't give an exact representation of the wind variability of the 5-min wind scenarios used in the ED these formulations do not schedule units with enough flexibility. However, the hourly and intra-hourly reserves add more robustness to the formulations, thus eliminating the load shedding and reducing the total cost. Stoch5min, which has complete knowledge of both uncertainty and intra-hour variability, performs even better than the reserve formulations, since it is also able to eliminate load shedding but has lower commitment and dispatch costs compared to the reserve formulations.

Finally, Table V shows the complexity of the formulations. Compared to HR, the number of continuous variables in IR 30 min and CR 30 min increase by 19% and 66%, respectively, while the number of binary variables increase by 12.5% and 25%. The increase in the number of binary variables is due to the big-M implementation of the inf function in the ramp reserve constraints (57)–(60). For each time period, wind farm, and constraint there is an additional inf function and associated binary variable, which gives an additional $24 \times 3 \times 4 = 288$ binary variables for CR 30 min compared to HR 30 min. Additionally each inf function requires 2 additional continuous variables. Thus significant reductions in the model complexity could be achieved, especially for the CR and IR formulations, if it were possible to implement the ramp reserve requirements without the inf function. This would also be important to allow application of the formulation to real-world power systems.

D. Results for 118-Bus System

For the 118-bus system solving the 5 minute stochastic UC was computationally intractable. We thus compare the hourly ramp reserve formulation (HR) and the 30 minute intra-hourly ramp reserve formulations (CR 30 min and IR 30 min) to the hourly stochastic formulations (StochEn and StochPw).

Table VI and Table VII compare the formulations when using 20 and 500 scenarios in the scenario reduction, respectively, and Fig. 12 and Fig. 13 show the evolution of the total costs and load shedding as the number of scenarios increases. Overall the results are quite similar to those for the 24-bus system. When only using 20 scenarios, the formulations with intra-hour reserves provide higher security than HR, seen by the reduced load shedding in Table VI. However, as the number of scenarios increases the load shedding for all ramp reserve formulations reduces to zero, and the hourly reserve formulation ends up being more economical than the intra-hour reserve formulations. However, the intra-hour reserve formulations still give a lower amount of wind curtailment, which can be useful if curtailing wind is costly and lead to reduced emissions.

TABLE VII
EVALUATION FOR 118-BUS SYSTEM WITH SCENARIO REDUCTION

	HR	CR 30min	IR 30min	StochEn	StochPw
Unit commitment (UC)					
Objective	1.0000	1.0615	1.0566	0.9774	0.9823
Commitment cost†	0.0170	0.0234	0.0216	0.0134	0.0147
Dispatch cost	0.9830	1.0381	1.0352	0.9639	0.9676
Nr. of startups	47	44	40	36	42
Solution time (s)	98	8525	1451	445	301
Complexity and computational burden					
Continuous variables	7128	10584	7560	27360	27360
Binary variables	4032	4320	4176	3888	3888
Constraints	33366	38518	37920	272474	265394
Nodes explored	309	17452	2972	197	1
Economic dispatch (ED) - average of 500 evaluations					
Objective	0.2062	0.1946	0.1941	0.3900	0.2072
Total cost‡	1.0130	1.0472	1.0383	1.2035	1.0239
Loadshed (MWh)	0.00	0.00	0.00	20.16	2.07
Wind curtail (MWh)	312.17	250.33	260.42	798.06	443.36
Wind curtail (%)	1.4	1.1	1.2	3.7	2.1
Nr. of violations	0	0	0	10556	940
Nr. of eval. w. viol.	0	0	0	500	107
Economic dispatch (ED) - insample evaluation, average of 20 scenarios					
Objective	0.2169	0.2043	0.2037	0.5347	0.2552
Total cost	1.0236	1.0568	1.0479	1.3482	1.0718
Loadshed (MWh)	0.00	0.00	0.00	33.52	5.80
Wind curtail (MWh)	426.73	323.13	336.86	943.73	564.70
Wind curtail (%)	2.0	1.5	1.6	4.5	2.7
Nr. of violations	0	0	0	708	101
Nr. of scen. w. viol.	0	0	0	20	8

All costs scaled to the UC objective value for HR: 993041 $.
†Sum of startup, shutdown, and no load costs.
‡Computed as sum of commitment cost and the average ED dispatch cost, including cost for load shedding.

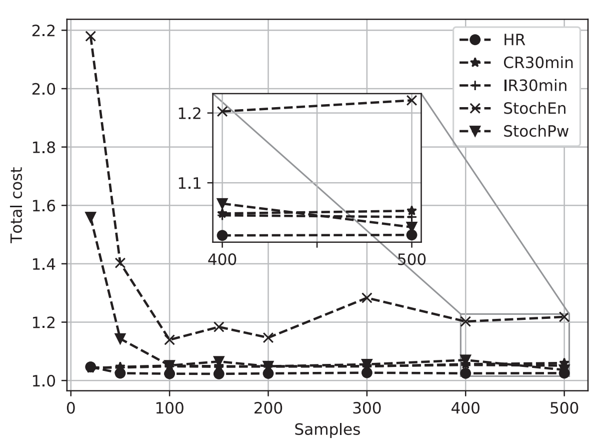

Fig. 12. Average total cost for the 118-bus system for different formulations with increasing number of samples for scenario reduction.

Compared to the stochastic formulations, the proposed formulations all have significantly higher security and lower total costs, although the power-based stochastic formulation also does quite well if the number of scenarios in the scenario reduction is increased.

IV. Conclusion

In this paper, we present a power-based unit commitment (UC) formulation with intra-hour ramp reserves for dealing with wind power uncertainty and variability. Specifying intra-hour reserves with a time duration of less than one hour allows the formulation to schedule units with enough ramping capability to balance intra-hour variations in wind power production, and produces better scheduling of fast-ramp units. Several different UC formulations with intra-hour reserves were investigated and compared to a pure hourly formulation, showing their benefit in terms of increased security and decreased wind power curtailment.

The proposed formulations were also compared to conventional stochastic formulations, including a stochastic formulation with 5-min time resolution. It was observed that the proposed formulations provided significantly higher security than the stochastic formulations. Only with a sufficiently large number of scenario samples did the 5-min stochastic formulation outperform the ramp reserve formulations in terms of total costs. However, even then some load shedding was required in the economic dispatch (ED), while the ramp reserve formulations eliminated all load shedding, thus providing full security against wind power variations.

The main drawback of the proposed intra-hourly reserves was the increase in computational complexity, mainly due to the increased number of binary and continuous variables resulting from the implementation of the inf function in the ramp reserve requirements. Thus, future research should explore alternative methods to implement the ramp reserve requirements that can avoid this increase in complexity. Also, further comparisons to other methods of dealing with wind variability and uncertainty, such as robust UC formulations, would be useful.

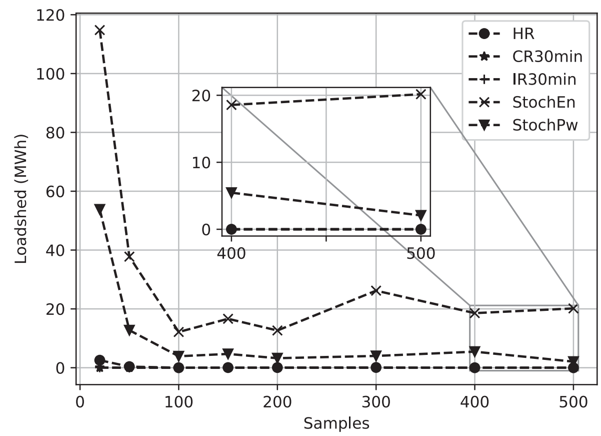

Fig. 13. Average load shedding in ED for the 118-bus system for different formulations with increasing number of samples for scenario reduction.

Appendix

A. 5-Min Stochastic Formulation

The dispatch decisions for the production of units p_{gsi}, wind power w_{bsi}, and load curtailment d_{bsi} are now modelled with 5-min time resolution. We index the 5-min intervals by $i \in \mathcal{I}$ and the hours by $t \in \mathcal{T}$, each index starting from 1. Every 5-min interval can be uniquely mapped to the hour it belongs, denoted by $t(i)$. To avoid modelling the production below $\underline{P}_g$ for fast start units it is assumed that $SU_g = SD_g = \underline{P}_g$ for all units, so that the start up and shut down trajectories are always fixed.

1) Cost Function: The cost function is given by

$$\sum_{t\in\mathcal{T}}\sum_{g\in\mathcal{G}}\left(C_g^{NL}u_{gt}+C_g^{LV}\underline{P}_g u_{gt}+C_g^{SU}v_{gt}+C_g^{SD}z_{gt}\right)$$
$$+\frac{1}{12\cdot N_s}\left(\sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}}\sum_{g\in\mathcal{G}}C_g^{LV}\tilde{p}_{gsi}+\sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}}\sum_{b\in\mathcal{B}}C^{LS}\tilde{d}_{bsi}\right) \tag{71}$$

where $\tilde{p}_{gsi}$ is average power production above $\underline{P}_g$ during the 5-min interval i and $\tilde{d}_{bsi}$ is the average demand curtailment, given by:

$$\tilde{p}_{gsi}=0.5\cdot(p_{gsi}-p_{gs,i-1}) \tag{72}$$

$$\tilde{d}_{bsi}=0.5\cdot(d_{bsi}-d_{bs,i-1}). \tag{73}$$

Notice that the scenario-dependent dispatch cost is computed as the average over the N_s scenarios and divided by 12 as the sum is over the 5-min dispatch intervals. Also notice that the energy cost for the startup and shutdown trajectories is not explicitly included in (71) but is internalized in the startup and shutdown costs.

2) 1st Stage Constraints: Enforced using hourly variables:

$$u_{gt}-u_{g,t-1}=v_{gt}-z_{gt}\quad\forall g,t \tag{74}$$

$$\sum_{j=t-TU_g+1}^{t}v_{gj}\le u_{gt}\quad\forall g,t\in[TU_g,T] \tag{75}$$

$$\sum_{j=t-TD_g+1}^{t}z_{gj}\le 1-u_{gt}\quad\forall g,t\in[TD_g,T] \tag{76}$$

3) 2nd Stage Constraints: Capacity constraints and ramp constraints are enforced every 5-min interval:

$$0\le p_{gsi}\le(\overline{P}_g-\underline{P}_g)u_{g,t(i)}\quad\forall g,s,i \tag{77}$$

$$p_{gsi}-p_{gs,i-1}\le\frac{1}{12}RU_g u_{g,t(i)}\quad\forall g,s,i \tag{78}$$

$$p_{gs,i-1}-p_{gsi}\le\frac{1}{12}RD_g u_{g,t(i)}\quad\forall g,s,i \tag{79}$$

and the wind production and load curtailment are restricted by the 5-min wind scenarios W_{bsi} and 5-min load D_{bi}:

$$0\le w_{bsi}\le W_{bsi}\quad\forall b,s,i \tag{80}$$

$$0\le d_{bsi}\le D_{bi}\quad\forall b,s,i \tag{81}$$

Demand balance and transmission constraints are enforced every 5-min interval:

$$\sum_{g\in\mathcal{G}}\hat{p}_{gsi}+\sum_{b\in\mathcal{B}^W}w_{bsi}=\sum_{b\in\mathcal{B}}(D_{bi}-d_{bsi})\,\forall s,i \tag{82}$$

$$-\overline{F}_l\le\sum_{g\in\mathcal{G}}\Gamma_{lg}^P\hat{p}_{gsi}+\sum_{b\in\mathcal{B}^W}\Gamma_{lb}w_{bsi}-\sum_{b\in\mathcal{B}}\Gamma_{lb}(D_{bi}-d_{bsi})\le\overline{F}_l\forall l,s,i \tag{83}$$

where $\hat{p}_{gsi}$ is the total power production at the end of the 5-min interval i. This is given by

$$\hat{p}_{gsi}=\underline{P}_g u_{g,t(i)}+p_{gsi}+\sum_{j=2}^{SU_g^D+1}v_{g,(t(i)-j+SU_g^D+2)}\frac{(11-\delta_i)P_{g,j-1}^{SU}+(1+\delta_i)P_{gj}^{SU}}{12}+\sum_{j=2}^{SD_g^D+1}z_{g,t(i)-j+2}\frac{(11-\delta_i)P_{g,j-1}^{SD}+(1+\delta_i)P_{gj}^{SD}}{12} \tag{84}$$

Here δ_i is an index for each 5-min interval i within the hour, which goes from 0 to 11 within each hour. This is given by

$$\delta_i=i-1-12(t(i)-1)$$

The purpose of the weighted sums in (84) is to interpolate values for the startup and shutdown trajectories. For example, for the first interval i in an hour t, $\delta_i=0$ so that the fraction for the startup trajectory becomes

$$\frac{11P_{g,j-1}^{SU}+P_{gj}^{SU}}{12},$$

which is the power 5 minutes into the j^{th} hour of the startup period.

The full formulation is given by min (71) subject to (72)–(84).

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Elis Nycander (Student Member, IEEE) received the M.Sc. degree in engineering physics from Uppsala University, Uppsala, Sweden, in 2016. He is currently working toward the Ph.D. degree with the KTH Royal Institute of Technology, Stockholm, Sweden. His research interests include planning, operation, and economics of electric power systems.

Germán Morales-España (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from the Universidad Industrial de Santander, Bucaramanga, Colombia, in 2007, the M.Sc. degree from the Delft University of Technology (TUDelft), Delft, The Netherlands, in 2010, and the Ph.D. degrees from Universidad Pontificia Comillas, Madrid, Spain, the KTH Royal Institute of Technology, Stockholm, Sweden, and TUDelft, Delft, The Netherlands, in 2014. Since 2017, he has been with the Netherlands Organisation for Applied Scientific Research (TNO), Energy Transition, as a Scientific Researcher. His research interests include planning, operation, economics, and reliability of electric systems and sector coupling.

Lennart Söder (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from the KTH Royal Institute of Technology, Stockholm, Sweden, in 1982 and 1988, respectively. He is currently a Professor of electric power systems with the KTH Royal Institute of Technology. His research interests include power system operation and planning, integration of wind and solar power, hydropower system modeling, demand side management, distribution systems, power system reliability, power markets, and regulation.