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Flexibility management in sustainable power systems: An energy-centric approach

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Abstract: Currently, power system operations planning practices are undergoing various transformations in an attempt to integrate efficiently significant amounts of sustainable low-carbon power generation technologies. At the heart of this efficient integration lies the need to plan for and exploit the available flexibility in power systems. Flexibility is a relatively new concept addressing the issue of increased variability and uncertainty in power systems admitting high penetration levels of renewable energy sources. To that end, we previously introduced the concept of flexible power envelopes to capture flexibility requirements and flexibility availability from power system resources in terms of time-constrained power deployment. Here, we extend this concept to flexible energy envelopes, thus giving rise to the notion of flexibility assessment in terms of time-constrained energy deployment. This approach is more appropriate for considering flexibility resources like energy storage and demand response. We demonstrate the advantages of planning with flexible energy envelopes with a receding-horizon economic dispatch example integrating energy storage assets.

Key Words: Energy storage, flexibility, power generation operations planning, renewable power generation.

Résumé : Partout dans le monde, les pratiques de planification des réseaux électriques sont en mutation dans le but d'intégrer de manière efficace un parc de production qui se veut plus faible en carbone. Au cœur de cette intégration se trouve le besoin de planifier et d'exploiter les flexibilités présentes dans les réseaux. Le concept de flexibilité des réseaux électriques est relativement nouvelle et elle cherche à adresser les défis associés à la variabilité et à l'incertitude des sources d'énergie faibles en carbone telles que l'éolien et le solaire. À cet effet, nous avons proposé auparavant le concept des enveloppes de flexibilité en terme de puissance. Celles-ci permettent de capturer dans le temps les exigences de flexibilité du réseau ainsi que les flexibilités disponibles venant des ressources de puissance du réseau. Dans cet article, nous étendons l'applicabilité du concept aux enveloppes de flexibilité énergétiques, qui nous permettent de considérer la flexibilité en termes d'énergie livrée dans le temps. Cette nouvelle approche est appropriée pour la considération des ressources de flexibilité comme les systèmes de stockage d'énergie et les applications de pilotage de charge. Nous démontrons les avantages à planifier la flexibilité via les enveloppes de flexibilité énergétique avec un exemple détaillé d'un problème de dispatching économique à horizon fuyant intégrant de la production renouvelable et des moyens de stockage d'énergie.

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1 Introduction

The recently emerging concept of *power system flexibility* [1,2] is an attempt at modernizing the traditional operating reserve paradigm. The traditional reserve paradigm is mostly concerned with capacity planning, while assuming ample ramping capability of resources. At best, ramping is planned for the 10 (primary/secondary) and 60-minute (tertiary) reserve requirements. On the other hand, power system flexibility puts as much emphasis on ramping as it does on capacity planning. It ensures that the planned reserve capacity can be deployed (*i.e.* ramped up or down) in due time, to provide frequency control and load following as dictated by the capacity and ramping behavior of the net load, *i.e.*, load less non-dispatchable renewable energy sources (RES). Recently as well, there has been an increasing interest in energy storage and energy-constrained demand response as flexibility providers, thus adding a third equally-important dimension to the emerging flexibility concept.

In recent work [3], we reviewed the state of the art on operational flexibility, which focused on assessing capacity and ramping capability of resources, while assuming no constraints on energy. To summarize, quantifying flexibility requirements, in the form of flexible operating reserve, has been addressed in recent literature on three main frontiers. First, earlier literature emerged to quantify flexibility requirements with respect to the current industry-based categorization of reserve types: primary/instantaneous, secondary/fast, and tertiary/slow [4–7]. The main emphasis was on optimizing flexibility requirements statistically [8, 9], stochastically [10], reliability-wise [4, 11–13], and via cost/benefit analysis [13–15]. Although these methods fell short of addressing the complete intra-hourly spectrum of flexibility requirements, they still provided a valuable set of tools that could be extended to the remaining intra-hourly durations. Second, more recent literature addressed the full spectrum of intra-hourly flexibility requirements by statistical analysis of step changes applied to the net load time series for a range of intra-hourly durations. The more notable approaches, which also incorporated intra-hourly flexibility in scheduling mechanisms, are our proposed flexibility envelope in [3], the flying brick in [16], and the probability box in [17]. Third, stochastic-based methodologies, surveyed in [10], managed operating reserve implicitly via the power balance imposed on the stochastic scenarios. Stochastic-based approaches, however, suffer from the curse of dimensionality rendering them computationally intractable even for tertiary reserve management.

Moreover, for the most part, the state of the art catered to traditional power systems that are dominated by thermal generation. In contrast, sustainable power systems are increasingly admitting various energy-constrained flexible resources to help mitigate the impact of variability and uncertainty arising from higher penetration levels of RES. The two main types are energy storage and demand response devices, which are capable of providing ample ramping (*i.e.* quasi-instantaneous on/off switching) but limited energy capacity. Thus, we argue here that it is also beneficial to address the concept of power system flexibility from an energy-centric perspective, to explicitly manage energy deployment of these types of resources. To this end, we extend our previous work in [3] to managing energy flexibility in lieu of power flexibility.

In [3], we proposed the concept of flexibility requirement envelopes to capture the capacity and ramping requirements over some operational time, as dictated by net load variability and uncertainty. Likewise, we used envelopes to constrain flexibility deployment by resources in terms of their capacity and ramping limitations. The approach was that, to provide adequate system flexibility, dispatch levels of flexibility resources have to be prepositioned appropriately such that their aggregate *flexible power envelope* encloses the *flexible power requirement envelope* arising from the variable and uncertain net load.

On the other hand, the inclusion of energy-constrained devices in planning would require prepositioning their energy state levels, rather than their power dispatch levels. Therefore, here we extend the flexibility envelope approach them from an energy standpoint. In other words, we argue in favor of replacing the flexible power requirement envelope by the flexible energy requirement envelope, while we replace the flexible power envelopes of resources by their flexible energy envelopes. Such envelopes are capable of capturing energy, power, and ramp altogether in a single envelope. This way, the energy states of energy-constrained resources can be prepositioned—along with the power dispatch levels of other conventional resources—such that the aggregate flexible energy envelope of all resources encloses the flexible energy requirement envelope arising from the net load. This poses a paradigmatic shift in the way we look at operating reserve as flexible deployable energy, rather than flexible deployable power.

2 Quantifying operational energy flexibility requirements

In [3], we obtained the *flexible power requirement envelope* from net load power step changes. The envelope's height and slope determines how much power capacity and ramping, respectively, over the envelope's horizon are needed to cover appropriately plausible net load variability and uncertainty. This idea is re-iterated here followed by its extension to calculating the *flexible energy requirement envelope*. We will show two approaches to obtaining the flexible energy requirement envelope. One approach first integrates the net load power step changes to obtain the net load energy step changes. Subsequently, the flexible energy requirement envelope is calculated statistically from those net load energy step changes by adapting the procedure from [3]. The second approach obtains the flexible energy requirement envelope directly by integrating the flexible power requirement envelope from [3].

2.1 Flexible power requirement envelope, [3]

The net load measurement at present time k is used as a constant forecast (reference) level for the upcoming short-term operational horizon. This is referred to as a *persistence forecast* and is believed to be the most accurate under high penetration of renewable energy sources [18]. More importantly, it is by deviating from the present net load level (*i.e.* the persistence forecast) that a need to deploy flexibility over the operational horizon arises—at least from our perspective in this work and [3].

Consider a net load power time series $\ell(k)$, $k = 1, \ldots, K$. From $\ell(k)$, we can obtain the step change in the net load at time τ as seen from the present time k

$$\Delta P(\tau; k) = \ell(k + \tau) - \ell(k) \tag{1}$$

which represents deviation from the persistence forecast $\ell(k)$, τ units of time later. By fixing τ and sweeping through k, we obtain k realizations of the net load step change $\Delta P_k(\tau)$ as a function of τ only. These realizations can then be used to obtain the standard deviation $\sigma_P(\tau)$ as a function of τ, as well. From this, the flexible power requirement envelope can be defined as a multiple of the standard deviation $\sigma_P(\tau)$, depending on the desired percentile coverage of flexibility requirements. For example, if the step change realizations at τ are fitted to a Laplace distribution [19], multiplying $\sigma_P(\tau)$ by a factor of 1.63 covers the 90^{th} percentile of all plausible net load power deviations, τ units of time later. The decision maker must choose the appropriate multiplication factor, to cover the desired percentile of the distribution.

For example, consider the net load time series obtained for the Bonneville Power Authority for the year 2014 [20], which contains roughly 89 000 data points. The sampling period is $T = 5$ minutes, and the operational horizon is set to one hour (*i.e.*, 12 sub-hourly time steps). The method outlined above is applied to all $\tau = nT$, where $n = 1, \ldots, 12$. Fig. 1 plots the normalized histogram (gray area) of $\Delta P_k(\tau)$ for $\tau = 60$ minutes, which is also fitted to a Laplace distribution (red line). Assuming a Laplace distribution at every τ allows us to calculate the standard deviation $\sigma_P(\tau)$, as shown in Fig. 2. The plot of $\sigma_P(\tau)$ resembles the shape of an envelope over the horizon $\tau = [0, 60]$ minutes, as desired. Fig. 3 reinforces the concept visually by ploting several envelopes for integer multiples of the standard deviation $\sigma_P(\tau)$.

2.2 Flexible energy requirement envelope—1st approach

First, we integrate the net load power step change (1) to obtain the net load energy step change $\Delta E(\tau; k)$

$$\Delta E(\tau; k) = T \sum_{i=1}^{\tau/T} \ell(k + i) - \tau \ell(k) \tag{2}$$

$\Delta E(\tau; k)$ represents the energy deviation in the net load τ units of time later, as seen from the present time k. Next, following the methodology in Section 2.1, we can obtain the energy standard deviation $\sigma_E(\tau)$ as

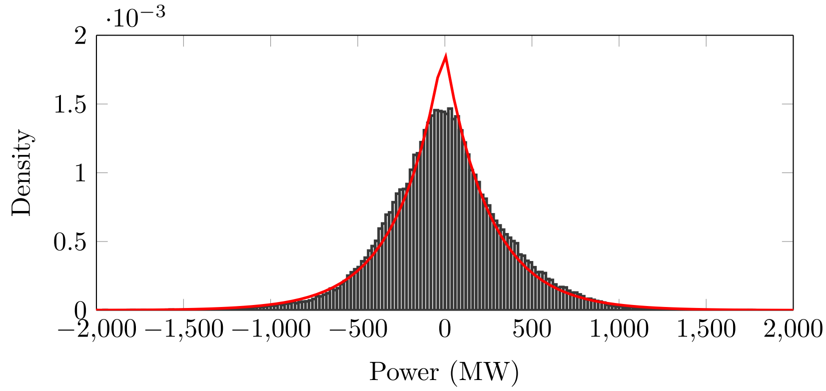

Figure 1: Laplace PDF fitted to power step changes at $\tau = 60$ minutes.

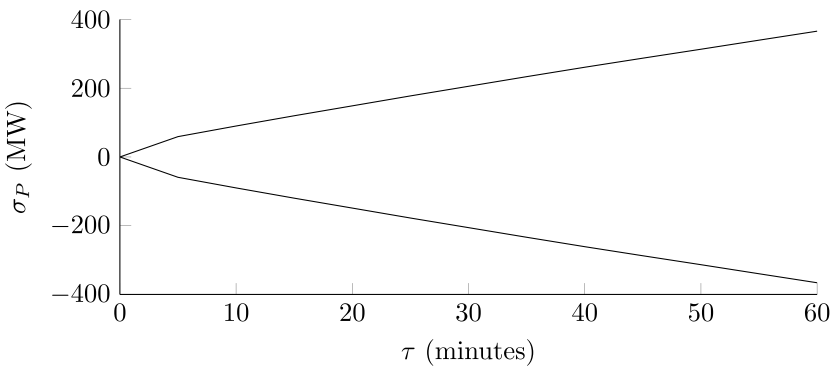

Figure 2: Standard deviation of power step changes as a function of τ.

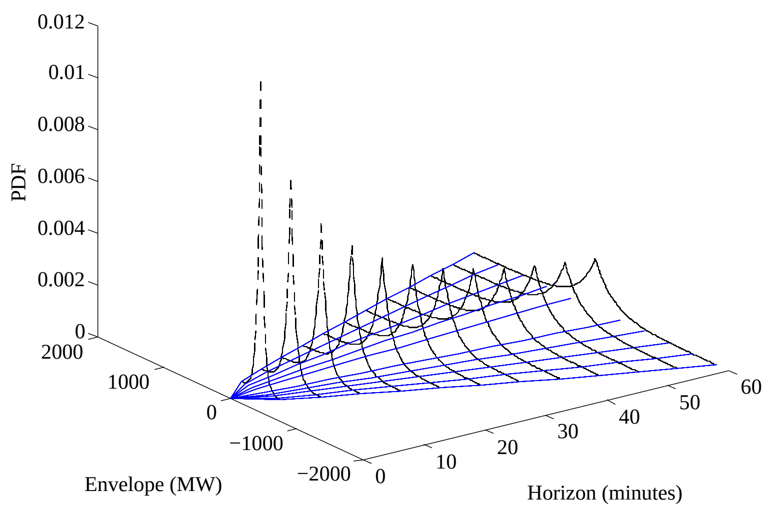

Figure 3: Flexible power requirement envelopes plotted as integer multiples of the standard deviation σ_P.

a function of τ, from which we obtain the flexible energy requirement envelope by multiplying $\sigma_E(\tau)$ by a pre-determined factor.

Using the same net load time series from [20], Fig. 4 plots the normalized histogram (gray area) of $\Delta E_k(\tau)$ for $\tau = 60$ minutes, which also fits well to a Laplace distribution (red line). Assuming a Laplace distribution at every τ, Fig. 5 plots the standard deviation $\sigma_E(\tau)$. Likewise, the plot of $\sigma_E(\tau)$ resembles the shape of an envelope over the horizon $\tau = [0, 60]$ minutes, as expected.

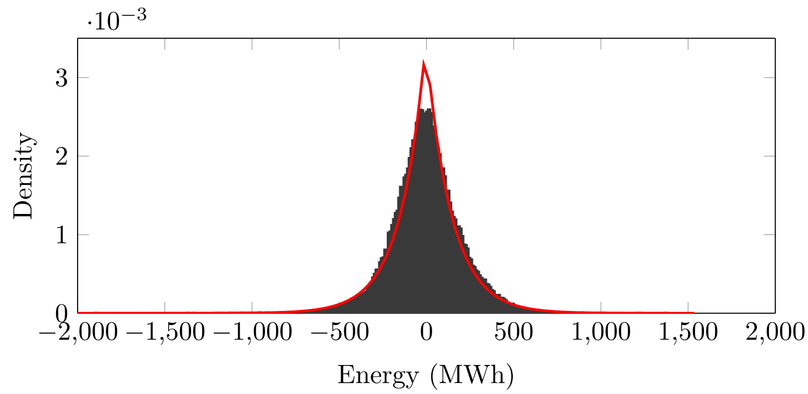

Figure 4: Laplace PDF fitted to energy step changes at $\tau = 60$ minutes.

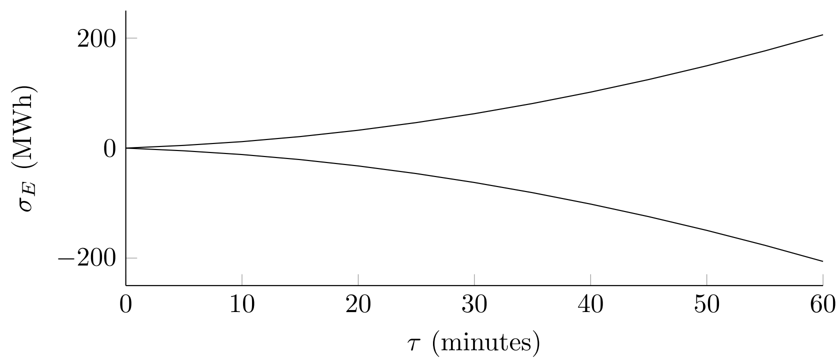

Figure 5: Standard deviation of energy step changes as a function of τ.

2.3 Flexible energy requirement envelope—2nd approach

In this case we obtain the flexible energy requirement envelope directly by integrating the original flexible power requirement envelope:

$$\sigma_{\Sigma P}(\tau) = T \sum_{i=1}^{\tau/T} \sigma_P(i) \tag{3}$$

2.4 Comparison of flexible energy requirement envelopes

Next, we compare the flexible energy requirement envelopes obtained by both approaches. To do so, we start by taking the square of both sides of (3)

$$\begin{aligned}
\sigma^2_{\Sigma P}(\tau) &= \left(T \sum_{i=1}^{\tau/T} \sigma_P(i) \right)^2 \\
&= T^2 \sum_{i=1}^{\tau/T} \sigma^2_P(i) + T^2 \sum \sum_{j \neq i} \sigma_P(i)\sigma_P(j) \\
&\geq T^2 \sum_{i=1}^{\tau/T} \sigma^2_P(i) + T^2 \sum \sum_{j \neq i} \sigma_P(i,j)
\end{aligned} \tag{4}$$

through the application of the Cauchy-Schwarz inequality. Furthermore, taking the variance of both sides of (2) yields

$$\begin{aligned} Var\left(\Delta E(\tau;k)\right) &= Var\left(T \cdot \sum_{i=1}^{\tau/T} \Delta P(i;k)\right) \\ &= T^2 \cdot \sum_{i=1}^{\tau/T} Var\left(\Delta P(i;k)\right) \\ &\quad + T^2 \cdot \sum_{i \neq j}^{\tau/T} Cov\left(\Delta P(i;k), \Delta P(j;k)\right) \end{aligned} \tag{5}$$

Replacing $Var\left(\Delta E(\tau;k)\right)$ by $\sigma_E^2(\tau)$, $Var\left(\Delta P(\tau;k)\right)$ by $\sigma_P^2(i)$, and $Cov\left(\Delta P(i;k), \Delta P(j;k)\right)$ by $\sigma_P(i,j)$ gives

$$\sigma_E^2(\tau) = T^2 \sum_{i=1}^{\tau} \sigma_P^2(\tau) + T^2 \sum_{j \neq i}\sum \sigma_P(i,j) \tag{6}$$

Comparing (4) to (6), we conclude that

$$\sigma_E^2(\tau) \leq \sigma_{\Sigma P}^2(\tau) \tag{7}$$

This result implies that the flexible energy requirement envelope obtained via the first approach, $\sigma_E(\tau)$, is less stringent than the one obtained via the second approach, $\sigma_{\Sigma P}(\tau)$. Intuitively, summing of the power step changes to obtain the energy step changes is a form of smoothing (*i.e.* a moving-average filter). Consequently, one can use the integral of the flexible power requirement envelope, $\sigma_{\Sigma P}(\tau)$, as an *upper bound* on the flexible energy requirement envelope $\sigma_E(\tau)$.

3 Flexible energy envelope of power system resources

In line with the previous section, a planned deviation from the present (scheduled) power level of a power system resource is what constitutes flexibility (power) deployment. In the context of this paper, we now seek to quantify the energy associated with a power system resource when its power output is deviating over the operational horizon. Let $y(k)$ represent the power output level at present time k. The output power can undergo step changes as flexibility is deployed over forward time τ

$$\Delta P(\tau;k) = y(k+\tau) - y(k) \tag{8}$$

For example, consider a thermal generation unit with minimum output level of 10 MW, maximum output level of 50 MW, and a maximum upward/downward ramp rate of 1 MW/minute. Given an initial output of 30 MW, Fig. 6 plots the *flexible power envelope* of the thermal generation unit. In contrast, consider a lossless energy storage device that can deliver or absorb energy at a rated power of 10 MW and can hold up to 10 MWh of energy. Given an initial state of charge of 5 MWh, Fig. 7 plots the *flexible power envelope* of the lossless energy storage asset. In both examples, the sampling period T is 5 minutes and τ varies from 0 to 60 minutes. Integrating (8) yields energy step change at τ:

$$\Delta E(\tau;k) = T \sum_{i=1}^{\tau/T} y(k+i) - \tau y(k) \tag{9}$$

where this quantity represents the amount of energy a resource can deliver by τ units of time later, as seen from the present time k.

Fig. 8 plots the *flexible energy envelope* of the thermal generation unit, given $y(k) = 30$ MW, and Fig. 9 plots the flexible energy envelope of the lossless energy storage for the initial state of charge of 5 MWh. In

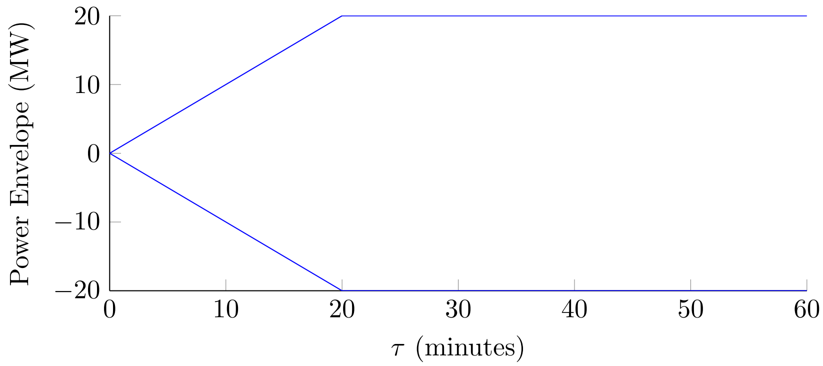

Figure 6: Sample power envelope of a thermal generation unit.

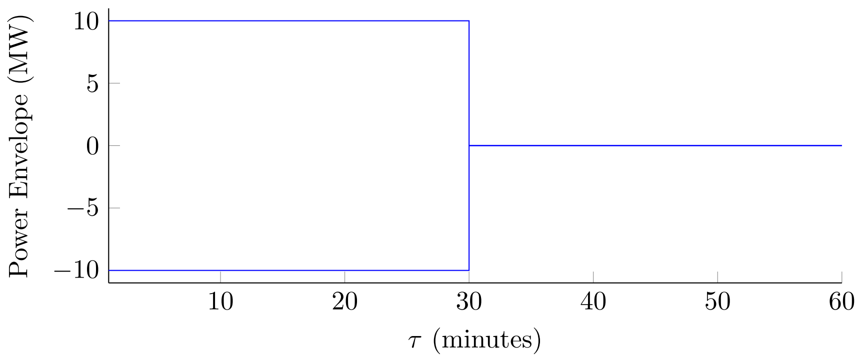

Figure 7: Sample power envelope of an energy storage unit.

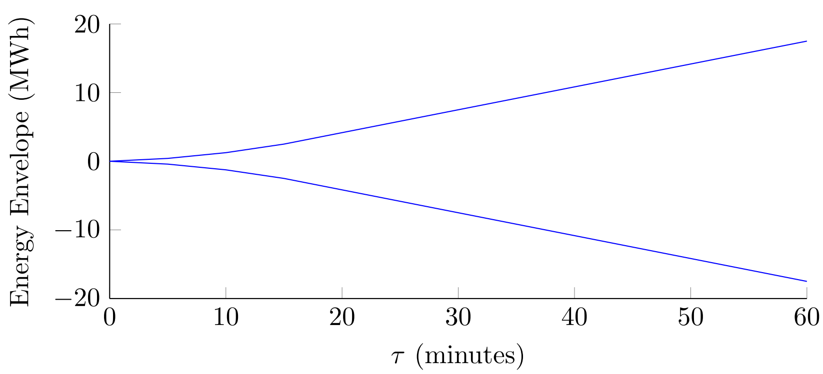

Figure 8: Energy envelope of the thermal generation unit as a function of τ.

the case of the storage unit, the rising/falling slopes of the energy envelope is its rated power of 10 MW. Moreover, the envelope is set to saturate at $\tau = 30$ minutes, due to depletion of upward or downward energy flexibility—*i.e.* the energy store is either fully charged or fully discharged, respectively. In contrast, the flexible energy envelope of the thermal generation unit continues to ramp up/down, albeit at different rates, even once it reaches its maximum and minimum power output levels.

The key observation here is that the flexible power envelope of the storage unit is not the most appropriate to perform operational flexibility planning. As is stands, the flexible power envelope in Fig. 7 is myopic in the sense that it neglects the fact that the storage asset could provide flexibility well beyond the time where its state of charge limits are attained. When one turns to the flexible energy envelope of the storage asset in Fig. 9, it is clear that the corresponding envelope is such that the storage unit state of charge

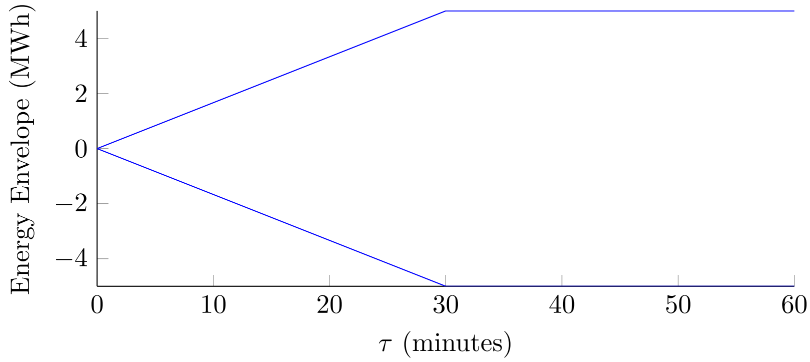

Figure 9: Energy envelope of the energy storage unit as a function of τ.

can evolve in a range well beyond the time at which state of charge limits are attained for rated power charging/discharging. In fact, one sees readily that the shape of the flexible energy envelope of the storage unit is similar to the flexible power envelope of the generating unit. It has been shown in [3] that this envelope is appropriate to conduct forward-looking flexibility planning. By using flexible energy envelopes, power system operators could break away from the myopic character of flexible power envelopes associated with energy-limited resources. In addition, energy envelopes are still consistent for modeling the flexibility of conventional generation. Therefore, energy-based flexibility planning, being more resource-inclusive than power-based flexibility planning, should have more potential at leveraging the available flexibility in a power system.

We show next how flexible energy envelopes can provide an appropriate operations planning mechanism to best exploit the flexibility of storage or other energy-limited assets. Flexible energy envelopes allow for simultaneous asset state of charge and power output positioning, something not possible with flexible power envelopes.

4 Flexibility planning: A detailed example

Planning with flexible power envelopes has been proposed in [3]. Here, however, the use of flexible energy envelopes will allow us to preposition energy states of energy-constrained resources, to optimize their deployment moving forward. The following example formulates a mixed-integer linear program integrating energy storage in a receding-horizon economic dispatch problem. Two energy storage strategies will be compared. The first strategy deploys energy storage resources myopically without planning their potential use moving forward. The second strategy deploys energy storage assets anticipatorily, by planning their use according to their flexible energy envelopes. The two strategies are benchmarked against a case without storage to compare their relative performance.

4.1 Receding horizon operation

As illustrated by Fig. 10, the power system is running during the h^{th} hour, at the k^{th} economic dispatch step. The decision maker must re-dispatch the committed resources to match the new forecast net load $\ell(k)$ by ramping these resources from their previous output levels at step $k-1$ subject to ramping constraints. Concurrently, the decision maker must preposition these resources at step k, such that their projected aggregate flexibility envelope encloses the flexibility requirement envelope over the upcoming operational horizon $k+n$, where $n = 1, \ldots, H$ is the receding horizon. In this example, we assume there are 12 economic dispatch steps k within the unit commitment hour h, such that the sampling period is $T = 5$ minutes and $k = 1, \ldots, 12$. The projected horizon of the envelopes is set to be one hour as well, such that $H = 12$ and $n = 1, \ldots, 12$, while, equivalently, $\tau = 5, \ldots, 60$ minutes.

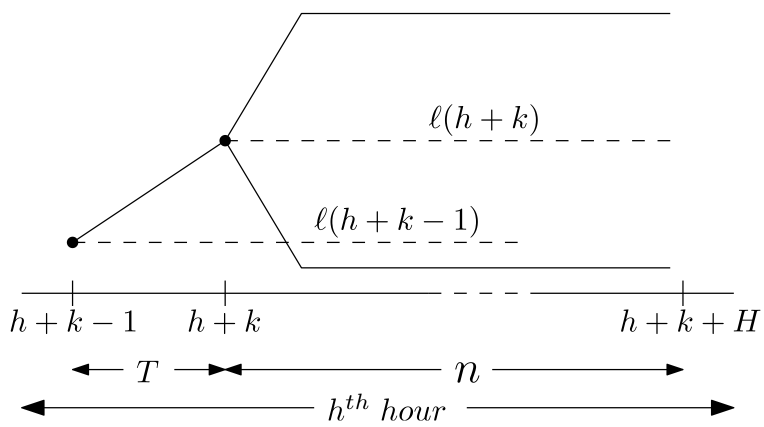

Figure 10: Schematic illustration of a single decision making epoch [3].

4.2 Net load model

A series of twelve 5-minute step changes, $\{w_k\}_{k=1}^{12}$, is generated randomly from a symmetric Laplace distribution that is characterized by $\beta = 1$ MW/minute. The random step changes are used to update the net load at each economic dispatch step k. The step changes are assumed to be independent and identically distributed (i.i.d.), while $\sqrt{2}\beta$ is the standard deviation, and $1.63\sqrt{2}\beta$ is the 90^{th} percentile for the Laplace distribution. A cap is placed on the realizations of w_k such that

$$w(k) \leftarrow \min(1.63\sqrt{2}\beta, w(k)) \quad k = 1, \ldots, 12 \tag{10}$$

Taking the initial net load forecast $\ell(1)$ to be 30 MW for economic dispatch step $k = 1$, the net load forecasts for the remaining economic dispatch steps are generated by subsequently adding the random step changes w_k. In addition, a cap is placed on the net load maximum and minimum

$$\ell(k+1) \leftarrow \min(50, \ell(k) + w(k)) \quad k = 1, \ldots, 12 \tag{11}$$

$$\ell(k+1) \leftarrow \max(10, \ell(k) + w(k)) \quad k = 1, \ldots, 12 \tag{12}$$

The power deviation step changes, as a function of the receding horizon step n, are

$$\Delta P(n) = \sum_{i=1}^{n} w(i) \quad n = 1, \ldots, 12 \tag{13}$$

while the energy deviation step changes, as a function of n, are

$$\Delta E(n) = 5 \sum_{i=1}^{n} \sum_{j=1}^{i} w(j) \quad n = 1, \ldots, 12 \tag{14}$$

4.2.1 Flexible power requirement envelope

The standard deviation envelope $\sigma_P(n)$ is computed by taking the variance of (13) and, noting the i.i.d. property of $\{w_n\}_{n=1}^{12}$, yields[1]

$$\sigma_P(n) = \sqrt{n}\sqrt{2}\beta \quad n = 1, \ldots, 12 \tag{15}$$

For example, multiplying (15) by a factor of 1.63 gives the flexible power requirement envelope covering the 90% confidence region. As mentioned earlier, establishing the optimal coverage level remains an open research question; we shall not address it formally here. Also, the Laplace distribution is assumed to hold for all n, as an approximation of the actual distributions.

[1] We recall that the covariance of i.i.d. random variables is zero.

4.2.2 Flexible energy requirement envelope

The standard deviation envelope $\sigma_E(n)$ is found by taking the variance of both sides of (14)

$$\sigma_E(n) = 5\sqrt{2}\beta\sqrt{\frac{n^3}{3} + \frac{n^2}{2} + \frac{n}{6}} \quad n = 1, \ldots, 12 \tag{16}$$

by applying the i.i.d. property of $\{w_n\}_{n=1}^{12}$ and an elementary series sum result. Multiplying (16) by 1.63 yields the flexible energy requirement envelope covering the 90% confidence region. Here again the Laplace distribution is assumed to hold for all n. Fig. 11 plots (16) along with the integral of (15), which confirms the flexible energy envelope is less stringent than the flexible power envelope.

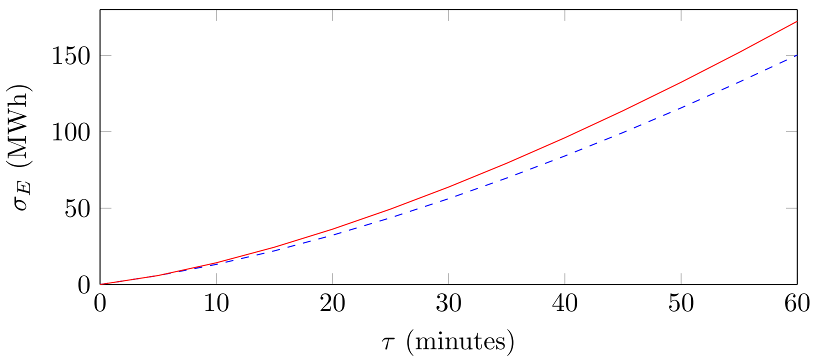

Figure 11: σ_E (dashed) compared to $\sigma_{\Sigma P}$ (solid).

4.3 Flexibility resources

There are five identical conventional generators, $\mathcal{I}_g = \{1, 2, 3, 4, 5\}$, constrained by capacity and affine ramp limits, which provide flexibility at a fixed incremental cost. In addition, two energy storage assets included in the system, $\mathcal{I}_s = \{1, 2\}$, which do not incur any additional operational costs. Table 1 shows the cost and flexibility characteristics of the generators, whereas Table 2 shows the flexibility characteristics and efficiencies of energy storage assets. We note that storage asset 1 (the smaller one, energy capacity-wise) has a rated power charge/discharge time of 20 minutes, whereas storage asset 2 (the larger one, energy capacity-wise) has a rated power charge/discharge time of three hours. Clearly, one can see that storage asset 1 is meant for providing intra-hour bridging power, while the second asset is meant primarily for inter-hour energy management.

Table 1: Resources' capacity, ramping, and cost characteristics.

$\mathcal{I}_g$	$g^{\max}$ (MW)	$g^{\min}$ (MW)	R (MW/minute)	c (\$/MWh)
1	10	0	1.5	20
2	10	0	1.5	40
3	10	0	1.5	60
4	10	0	1.5	80
5	10	0	1.5	100

Table 2: Storage capacity, power, and efficiency characteristics.

$\mathcal{I}_s$	$E^{\max}$ (MWh)	$E^{\min}$ (MWh)	P (MW)	μ^c	μ^d
1	25	10	75	0.9	0.9
2	75	10	25	0.9	0.9

4.4 Mathematical program formulation

The following mixed-integer linear program represents the flexibility envelopes-constrained receding-horizon planning for a single economic dispatch step k. To keep the units of measurements consistent, ramp constraints are in MW/minute, power constraints are in MW, and energy constraints are in MWh. This explains the conversion factors $1/T, 60/T, T/60$, given that the discretization period is $T = 5$ minutes.

Objective: The objective here is to minimize the total dispatch cost of conventional generators. Energy storage can be used, at no cost, to reduce the operational costs of the generators.

$$\min \sum_{i \in \mathcal{I}_g} c_i g_i(k) \tag{17}$$

This is subject to:

Power balance for dispatch step k: Equation (18) ensures the power balance at the current dispatch time step k.

$$\sum_{i \in \mathcal{I}_g} g_i(k) + \frac{60}{T} \sum_{i \in \mathcal{I}_s} \left(\mu^d \left[u_i(k) s_i(k-1) - s_i^{\downarrow}(k) \right] + \frac{1}{\mu^c} \left[(1 - u_i(k)) s_i(k-1) - s_i^{\uparrow}(k) \right] \right) = \ell(k) \tag{18}$$

Multiplying by the factor $60/T$ converts the step changes in storage levels from MWh to MW. The variable u_{i_s} is binary and indicates the charging status of storage unit i, whereas $s_i(k-1)$ is the previous storage state of charge at time step $k-1$ and appears here as a parameter. The inclusion of storage efficiencies—μ^c and μ^d for charging and discharging processes, respectively—necessitates representing the storage states by two variables, $s_i^{\uparrow}$ (charge) and $s_i^{\downarrow}$ (discharge), because the storage dispatch decision (*i.e.* whether to charge or discharge at k) is unknown *a priori*.

Dispatch for generator $i \in \mathcal{I}_g$ at step k: These bound the generators by their capacity and ramp rates, respectively, as they ramp from the previous (given) power output level at time step $k-1$.

$$g_i^{\min} \le g_i(k) \le g_i^{\max} \tag{19}$$

$$-R_i \le \frac{1}{T} \Big(g_i(k) - g_i(k-1) \Big) \le R_i \tag{20}$$

Dispatch for storage $i \in \mathcal{I}_g$ at step k: Similarly, constraints (21)–(24) bound the energy storage devices by their state of charge and rated power output. The binary variable u_i ensures that charging, $s_i^{\uparrow}(k)$, and discharging, $s_i^{\downarrow}(k)$, are mutually exclusive.

$$s_i(k) = s_i^{\uparrow}(k) + s_i^{\downarrow}(k) \tag{21}$$

$$u_i(k) E_i^{\min} \le s_i^{\downarrow}(k) \le u_i(k) s_i(k-1) \tag{22}$$

$$(1 - u_i(k)) s_i(k-1) \le s_i^{\uparrow}(k) \le (1 - u_i(k)) E_i^{\max} \tag{23}$$

$$-P_i \le \frac{60}{T} \Big(s_i(k) - s_i(k-1) \Big) \le P_i \tag{24}$$

The next sets of constraints are necessary to enforce flexible energy envelope enclosure over all steps of the receding horizon $n = 1, \ldots, 12$ of any dispatch step k.

Flexible energy requirement envelope for $n = 1, \ldots, 12$: Equations (25) and (26) generate the flexible energy requirement envelope by integrating the flexible power requirement envelope (second approach in Section 2.3)

$$W^{\uparrow}(n) = \frac{T}{60}\sum_{j=1}^{n} \min(1.63\sigma_P(j), 50 - \ell(k)) \tag{25}$$

$$W^{\downarrow}(n) = \frac{T}{60}\sum_{j=1}^{n} \max(1.63\sigma_P(j), \ell(k) - 10) \tag{26}$$

We note that $W^{\uparrow}(n)$ and $W^{\downarrow}(n)$ are not optimization variables. They are parameters used next to enforce flexible energy envelope enclosure.

Flexible power envelopes for generators $i \in \mathcal{I}_g$ and $n = 1, \ldots, 12$: Constraints (27)–(32) determine for each generator two flexible power trajectories, one upward $v_i^{\uparrow}$ and one downward $v_i^{\downarrow}$, bounded by the generators' capacities and ramp rates. Here, (27) and (30) set the initial condition of the envelope to the step k dispatch levels, while (29) and (32) bound the envelope trajectories to minimum and maximum generator capacity at the end of the receding horizon. On the other hand, (28) and (31) enforce maximum ramping limitations over the duration of the receding horizon.

$$v_i^{\downarrow}(0) = g_i(k) \tag{27}$$

$$\frac{1}{T}\left(v_i^{\downarrow}(n) - v_i^{\downarrow}(n-1)\right) \leq -R_i \tag{28}$$

$$v_i^{\downarrow}(12) \geq g_i^{\min} \tag{29}$$

$$v_i^{\uparrow}(0) = g_i(k) \tag{30}$$

$$\frac{1}{T}\left(v_i^{\uparrow}(n) - v_i^{\uparrow}(n-1)\right) \leq R_i \tag{31}$$

$$v_i^{\uparrow}(12) \leq g_i^{\max} \tag{32}$$

Flexible energy envelopes for storage $i \in \mathcal{I}_s$ and $n = 1, \ldots, 12$: In a way similar to the flexible power envelopes for generation, constraints (33)–(38) induce two flexible energy trajectories, one upward $z_i^{\uparrow}$ and one downward $z_i^{\downarrow}$, bounded by the assets' storage energy capacity and rated power. Equalities (33) and eb10a enforce the initial condition of the energy flexibility envelope to the current dispatch step state of charge, while (35) and (38) guarantee that, at the end of the receding horizon, the flexible energy envelope is bounded by the minimum and maximum state of charge levels. In between, changes in the storage state of charge are limited by the rated power of storage assets, (34) and (37).

$$z_i^{\downarrow}(0) = s_i(k) \tag{33}$$

$$\frac{60}{T}\left(z_i^{\downarrow}(n) - z_i^{\downarrow}(n-1)\right) \leq -P_i \tag{34}$$

$$z_i^{\downarrow}(12) \geq E_i^{\min} \tag{35}$$

$$z_i^{\uparrow}(0) = s_i(k) \tag{36}$$

$$\frac{60}{T}\left(z_i^{\uparrow}(n) - z_i^{\uparrow}(n-1)\right) \leq P_i \tag{37}$$

$$z_i^{\uparrow}(12) \leq E_i^{\max} \tag{38}$$

Energy envelopes enclosure for $n = 1, \ldots, 12$: Constraints (39) and (40) serve to enclose the flexible energy requirement envelope defined in (25) and (26) using both storage and conventional generation. These constraints are only to be used with the second energy storage strategy, which plans storage deployment anticipatorily. In the case where storage use is planned myopically, the storage terms are omitted and only generation is used to ensure envelope enclosure.

$$\frac{T}{60}\sum_{j=1}^{n}\sum_{i\in\mathcal{I}_g}\left(v_i^{\uparrow}(j)-g_i(k)\right)+\sum_{i\in\mathcal{I}_s}\mu^d\left(s_i(k)-z_i^{\downarrow}(n)\right)=W^{\uparrow}(n) \tag{39}$$

$$\frac{T}{60}\sum_{j=1}^{n}\sum_{i\in\mathcal{I}_g}\left(g_i(k)-v_i^{\downarrow}(j)\right)+\sum_{i\in\mathcal{I}_s}\frac{1}{\mu^c}\left(z_i^{\uparrow}(n)-s_i(k)\right)=W^{\downarrow}(n) \tag{40}$$

Finally, the base strategy (for benchmarking the other two) does not use any storage. It uses the conventional generators only, to enclose the flexible energy requirement envelope. Hence, in this case all storage terms are out while all storage-related constraints are removed as well.

4.5 Simulations

Five hundred one-hour realizations of the net load random process were generated according to the model in Section 4.2. The no storage case, the myopic storage strategy, and the envelopes-based anticipatory storage strategy were simulated for each of the 500 net load realizations, using the mathematical programs described in Section 4.4.

4.6 Results and discussion

To compare quantitatively the three dispatch strategies, the energy dispatched (MWh) for a single realization j, EG_j, contributed by the conventional resources is

$$\mathrm{EG}_j=\frac{1}{12}\sum_{i=1}^{5}\sum_{k=1}^{12}g_{i,j}(k) \tag{41}$$

whereas the cost (\$) of dispatch fo the same single realization j, C_j, incurred by the conventional resources is

$$\mathrm{C}_j=\frac{1}{12}\sum_{i=1}^{5}\sum_{k=1}^{12}c_i g_{i,j}(k) \tag{42}$$

The expected energy (MWh) contribution by conventional resources for J realizations is

$$\mathrm{EG}_J=\frac{1}{J}\sum_{j=1}^{J}\mathrm{EG}_j \tag{43}$$

whereas the total expected cost (\$) of operating the conventional resources for J realizations is

$$\mathrm{EC}_J=\frac{1}{J}\sum_{j=1}^{J}\mathrm{C}_j \tag{44}$$

where $g_{i,j}(k)$ is the power dispatch of conventional resource i at the k^{th} dispatch step for the j^{th} economic dispatch simulation.

Fig. 12 plots the histograms of (42) for the three dispatch strategies. Deploying storage myopically shifts and tightens the cost histogram over the basecase, implying reduced energy contributions and dispatch costs from the conventional resources. On the other hand, deploying storage anticipatorily via the energy envelopes approach further shifts and tightens the histogram.

Table 3 shows the values associated to (43) and (44). The storage dispatch strategy exploiting the flexible energy envelopes improves substantially over its myopic counterpart. Moreover, it is important to see how the capabilities of the storage assets are leveraged by considering their potential deployment moving forward. We note here that no forecast beyond the net load persistence forecast was needed here.

Table 3: Expected energy dispatched and expected costs of conventional resources.

	No storage	Myopic	Δ	Envelopes	Δ
EEG (MWh)	29.6	19.6	−34%	6.7	−77%
EC ($\$ \times 10^3$)	15.8	8.63	−45%	2.50	−84%

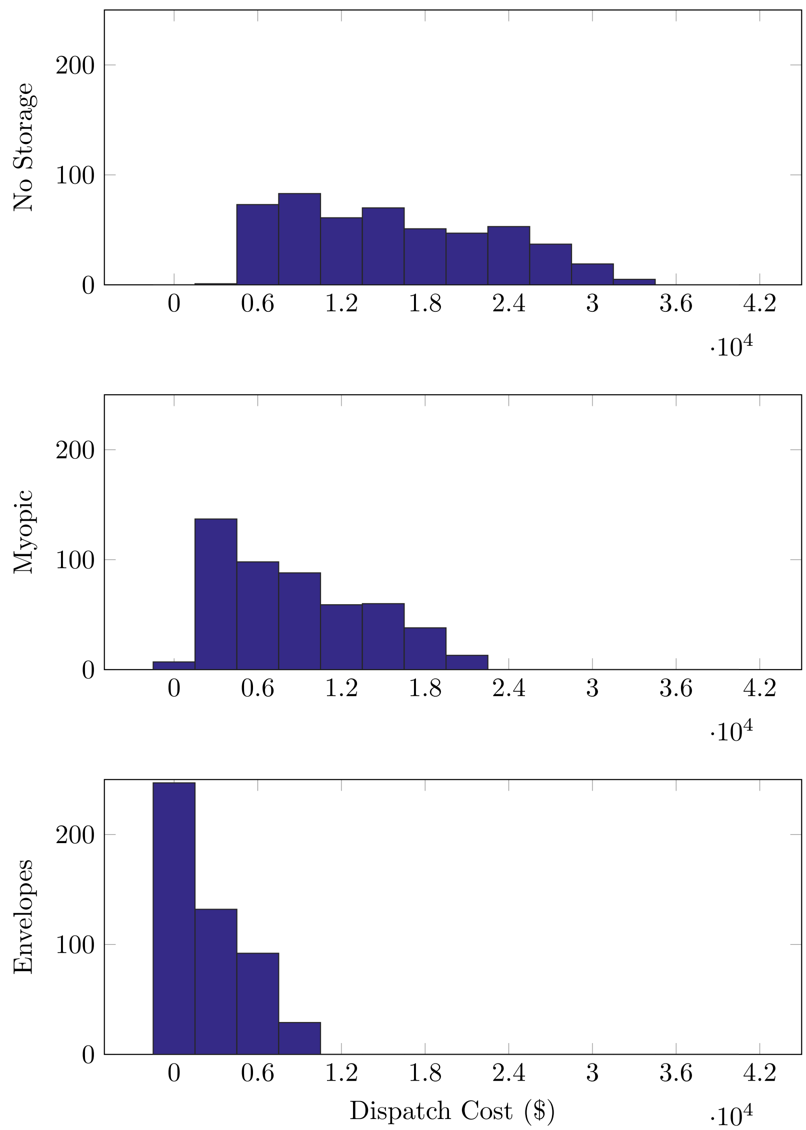

Figure 12: Histograms of generators' total dispatch cost under the three economic dispatch strategies.

Fig. 13 plots the histogram of the small (25 MWh) energy storage's intra-hourly state of charge, sampled every 5 minutes. It appears that optimal operations via the envelopes approach attempts to push the storage asset's state of charge as low as possible. This involves two simultaneous actions. One action is the discharge of the energy stored to deliver (dispatch) energy here and now, whereas the other action is the prepositioning of the state of charge at a lower level to provide potential fast-acting downward flexibility going forward.

On the other hand, Fig. 14 plots the histogram of the large (75 MWh) energy storage's intra-hourly state of charge, sampled every 5 minutes. The large storage asset has more capacity (in MWh) but a lower rate of charge/discharge (in MW), when compared to the small 25 MWh asset. Here operations via the envelopes

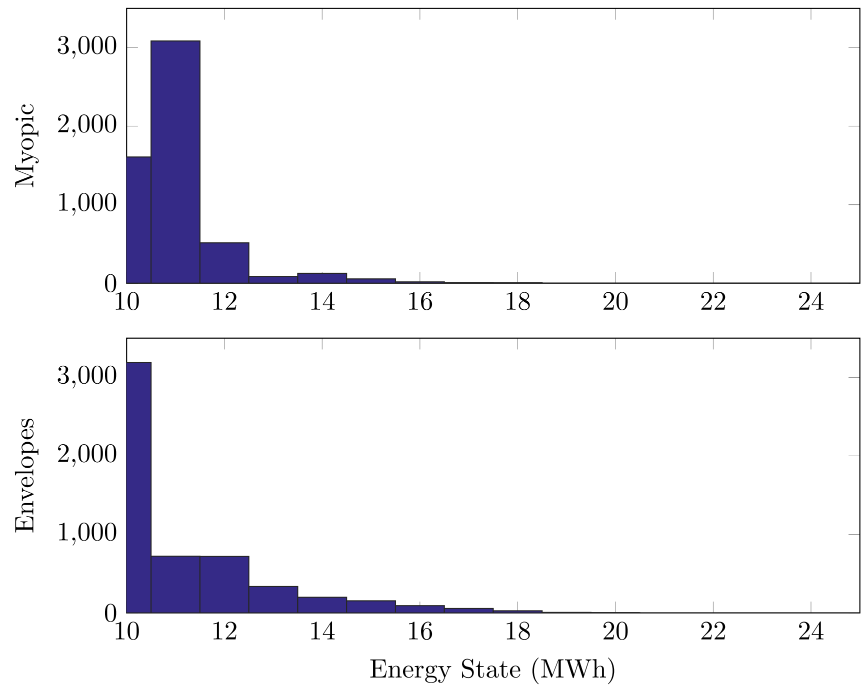

Figure 13: Histograms of the 25 MWh storage's state of charge.

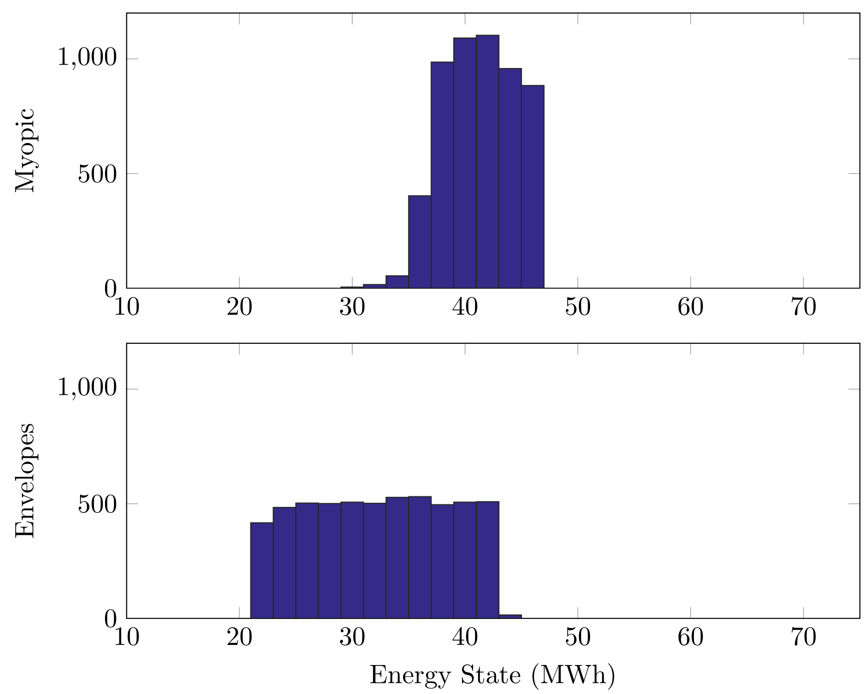

Figure 14: Histogram of the 75 MWh storage's state of charge.

approach attempts to shift the expected state of charge to a lower level, as well as flatten its distribution. As expected, this shows that the 75 MWh storage asset acts more as an energy buffer, by spending roughly equal time over a wide range of states of charge as it caters to the slower net load variations. In contrast, the 25 MWh energy storage asset returns frequently to its lowest state of charge, thus catering to the faster net load variations.

5 Conclusion

In this paper, we looked at flexibility as deployable energy, rather than the traditional view as deployable power. This prompted us to re-model the flexibility envelopes of [3] in terms of potential energy deployment. The new model facilitates the planning of energy-constrained resources (like energy storage systems and some forms of demand response). It allows for their energy levels could be prepositioned ahead of time to better optimize their potential deployment over an upcoming operational horizon. A proof of concept was performed through a receding-horizon economic dispatch problem to show how the an anticipatory storage strategy exploiting the proposed flexible energy envelope model is able to perform significantly better than with a myopic storage use strategy.

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