Characterization and Trading of Energy Level and Energy Shift Considering Virtual Power Plant

Shuai Fan, Jucheng Xiao, Zuyi Li, and Guangyu He

***Abstract*—The capability of shifting the electricity generation or consumption to proper time of the day, also defined as energy shift (ES), is the key factor to ensure the power balance, especially under high penetration of variable renewable energy (VRE). However, the ES is not characterized and traded as an independent product in current market mechanisms. In this letter, the marginal utility of an ES is assessed and leveraged to characterize the effective ES, while a novel market scheme is proposed considering the trading of both ES and energy level (EL). The proposed scheme can well integrate ES producers such as virtual power plants that cannot be rewarded sufficiently to actively participate in the current market because they are principally labeled as EL consumers. Finally, the novel concept and mechanism are illustrated by a numerical study and verified to outperform the existing price schemes on integrating the ES resources and VRE.**

***Index Terms*—Energy level, energy shift, variable renewable energy, virtual power plant, marginal utility.**

I. INTRODUCTION

VARIABLE renewable energy (VRE) such as solar and wind power has posed a huge balancing burden to the power systems. For instance, the well-known duck curve that emerged in California, USA, illustrates steep ramping needs and overgeneration risks [1]. The capability of shifting the electricity generation or consumption to proper time of the day, also defined as energy shift (ES) in this letter, is the key factor to satisfy the balance constraints of renewable power systems.

In current power systems, conventional generating units are the major energy producers. On the one hand, conventional units create electricity by burning fossil fuels, while the real generated energy can be defined as energy level (EL) to characterize how much energy is produced. On the other hand, the power outputs of conventional units are adjusted to ensure the real-time balance, which corresponds to the ES defined in this letter. With the retirement of conventional units and development of renewables, VRE will replace the conventional units to provide the EL but cannot supply the ES since their outputs are usually intermittent and not adjustable. In contrast, the virtual power plant (VPP) that aggregates diverse behind-the-meter distributed energy resources has emerged as a promising candidate for the provision of ES with low cost and high effectiveness [2]. However, in the current locational marginal price (LMP) based market, the ES is not independently characterized as a product but attached in the transaction of EL for the producers [3]. Since most of the VPPs are EL consumers, the huge ES capability of VPPs cannot be well traded and utilized [4]. Although some recent works such as [5] present the price-taker-based scheme to incentivize VPPs to offer the ES, drawbacks including overshoot, undershoot, and rebound are unavoidable, especially under high penetration of VPPs [6]. In summary, the ES is increasingly valuable but still not an independent measurable and tradeable product, which hinders the market entry of many ES producers.

These shortcomings motivate the search for a novel market scheme that can independently characterize and price the ES while complying with the current marginal cost-based LMP schemes for the trading of EL. Therefore, this letter decomposes the normal electric power vector into the EL and ES components. The contributions include: ① the ES product is characterized based on the marginal utility (MU) of the ES and pertinent effective ES; ② the ES product is transactive among entities in the proposed scheme following the cost causation principle. It helps integrate ES producers such as VPPs that cannot be rewarded sufficiently to actively participate in the current market because they are principally labeled as EL consumers.

The remainder of this letter is organized as follows. Section II characterizes the ES with the MU metric. Section III formulates the ES price and market mechanism. Case studies and benchmarks are described in Section IV. Concluding remarks are summarized in Section V.

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II. Characterization of ES

A. Amount of ES

Consider a power vector of generation or load $\boldsymbol{X} \in \mathbb{R}^H$. Firstly, the EL vector is denoted by $\bar{\boldsymbol{X}}$ and used to represent how much energy is generated or consumed by $\boldsymbol{X}$ if the variation at each time is absent. Thus, every entry of $\bar{\boldsymbol{X}}$ is the arithmetic mean of all the entries of $\boldsymbol{X}$. Then, the difference between the original vector $\boldsymbol{X}$ and the EL vector $\bar{\boldsymbol{X}}$, denoted by vector $\boldsymbol{x}$, corresponds to the definition of ES in this letter. Hence, a power vector $\boldsymbol{X}$ can be decomposed by the operator $S(\cdot)$ into the summation of the EL vector and ES vector, given by:

$$S(\boldsymbol{X}) = \bar{\boldsymbol{X}} + \boldsymbol{x} \tag{1}$$

The schematic diagram of concepts of EL and ES is presented in Fig. 1. It is straightforward that the upward ES balances the downward ES, i.e., $\boldsymbol{1}^{\mathrm{T}}\boldsymbol{x}=0$, which is similar to the charge and discharge of the battery operated in a specified state of charge. Note that generations are denoted by positive value while the consumptions are negative in this letter.

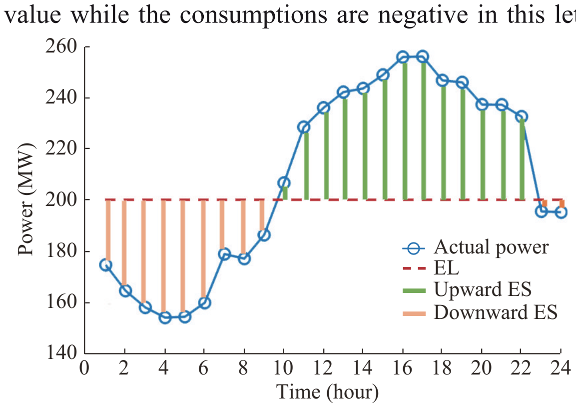

Fig. 1. Schematic diagram of concepts of EL and ES.

Definition 1: the amount of ES is defined as the l-2 norm of the ES vector $\boldsymbol{x} \in \mathbb{R}^H$, i.e., $\|\boldsymbol{x}\|_2$.

As the l-2 norm can assess the increasing marginal cost that is normal for entities such as conventional units, it is selected to appropriately characterize the ES amount. However, the effective ES offered or requested by $\boldsymbol{x}$ needs to be further characterized by its MU.

B. MU of ES

In power systems, the uncontrollable entities including VRE and inelastic load (IneL) usually cannot remain a flat output and thereby cause the ES demand. Let $\boldsymbol{r}_i$ and $\boldsymbol{d}_i$ denote the ES vectors of VRE i and IneL i from VRE set $\mathcal{R}$ and IneL set $\mathcal{D}$, respectively. Also, some dispatchable resources might introduce ES demand occasionally due to their operating constraints such as the ramping and capacity. Unlike the ES demand of VRE and IneL, the ES requested by those dispatchable resources cannot be obtained directly and thus is denoted by a variable vector $\boldsymbol{\eta}$. Therefore, the system-wide ES demand denoted by vector $\boldsymbol{e}$ can be formulated as:

$$\boldsymbol{e} = -\left(\sum_{i\in\mathcal{R}} \boldsymbol{r}_i + \sum_{i\in\mathcal{D}} \boldsymbol{d}_i + \boldsymbol{\eta}\right) \tag{2}$$

Definition 2: the profile of an ES vector $\boldsymbol{x}$, denoted by $\hat{\boldsymbol{x}}$, is defined as the ES vector normalized by its ES amount, i.e., $\hat{\boldsymbol{x}} = \boldsymbol{x}/\|\boldsymbol{x}\|_2$.

Therefore, the system-wide required profile of ES (RPES) can be represented by $\hat{\boldsymbol{e}} = \boldsymbol{e}/\|\boldsymbol{e}\|_2$. In the real world, adjustable resources such as units and VPPs will contribute to meeting the ES. To evaluate such contribution of power vector $\boldsymbol{x}$, we define the MU as follows: MU is the change in the system-wide amount of ES demand, i.e., $\|\boldsymbol{e}\|_2$, when the quantity produced by vector $\boldsymbol{x}$ is incremented by one unit. According to this definition, the Gâteaux derivative is leveraged to mathematically represent it, given by:

$$MU(\boldsymbol{x}) = \lim_{\delta\to 0} \frac{\|\boldsymbol{e}+\delta\hat{\boldsymbol{x}}\|_2 - \|\boldsymbol{e}\|_2}{\delta} \tag{3}$$

where $MU(\boldsymbol{x})$ is the MU of vector $\boldsymbol{x}$. The definition of the MU function can be interpreted as follows: we proportionally subtract a very small perturbation δ from the original ES demand $\boldsymbol{e}$ according to the profile of the vector $\boldsymbol{x}$, i.e., $\hat{\boldsymbol{x}}$, and subsequently calculate the marginal change of the amount of ES.

Lemma 1: the MU of vector $\boldsymbol{x}$ equals the inner product of the profile of vector $\boldsymbol{x}$ and RPES $\boldsymbol{e}$, i.e., $MU(\boldsymbol{x}) = \hat{\boldsymbol{e}}^{\mathrm{T}}\hat{\boldsymbol{x}}$.

Proof: the proof straightforwardly follows the definition of the derivative, given by (4).

$$\begin{aligned}
MU(\boldsymbol{x}) &= \lim_{\delta\to 0} \frac{\|\boldsymbol{e}+\delta\hat{\boldsymbol{x}}\|_2 - \|\boldsymbol{e}\|_2}{\delta} = \\
&\lim_{\delta\to 0} \frac{\sqrt{\|\boldsymbol{e}\|_2^2 + \|\delta\hat{\boldsymbol{x}}\|_2^2 + 2\delta\boldsymbol{e}^{\mathrm{T}}\hat{\boldsymbol{x}}} - \|\boldsymbol{e}\|_2}{\delta} = \\
&\lim_{\delta\to 0} \frac{\|\boldsymbol{e}\|_2^2 + \|\delta\hat{\boldsymbol{x}}\|_2^2 + 2\delta\boldsymbol{e}^{\mathrm{T}}\hat{\boldsymbol{x}} - \|\boldsymbol{e}\|_2^2}{\delta\left(\sqrt{\|\boldsymbol{e}\|_2^2 + \|\delta\hat{\boldsymbol{x}}\|_2^2 + 2\delta\boldsymbol{e}^{\mathrm{T}}\hat{\boldsymbol{x}}} + \|\boldsymbol{e}\|_2\right)} = \lim_{\delta\to 0}\left(\frac{\delta\hat{\boldsymbol{x}}\|_2^2 + 2\delta\boldsymbol{e}^{\mathrm{T}}\hat{\boldsymbol{x}}}{\delta}\cdot\right. \\
&\left.\frac{1}{\sqrt{\|\boldsymbol{e}\|_2^2 + \|\delta\hat{\boldsymbol{x}}\|_2^2 + 2\delta\boldsymbol{e}^{\mathrm{T}}\hat{\boldsymbol{x}}} + \|\boldsymbol{e}\|_2}\right) = \lim_{\delta\to 0} 2\boldsymbol{e}^{\mathrm{T}}\hat{\boldsymbol{x}}\frac{1}{2\|\boldsymbol{e}\|_2} = \boldsymbol{e}^{\mathrm{T}}\hat{\boldsymbol{x}}
\end{aligned} \tag{4}$$

Hence, the MU is in fact the cosine similarity of $\boldsymbol{x}$ and $\boldsymbol{e}$ that is between −1 and 1. A positive value of MU means a positive contribution to reducing the ES demand and is entitled to proper credit. In contrast, the entity that has a negative MU should be charged. An ES vector can obtain the maximal MU value 1 only when it has the same shape as the RPES. As the MU characterizes the actual contribution of the ES supply, we have the following definition that is essential in the proposed market mechanism.

Definition 3: the effective ES of a vector $\boldsymbol{x}$ is defined as the product of its MU and ES amount, i.e., $MU(\boldsymbol{x})\cdot\|\boldsymbol{x}\|_2$.

Since the effective ES characterizes the actual contribution, the entity is entitled to credits or payments based on the effective ES and the ES price generated by the market, as discussed in Section III.

III. ES Price and Market Mechanism

A. Assumptions

We use a basic economic dispatch model to illustrate the novel market mechanism based on ES with the following assumptions.

1) Assumption 1: network loss and transmission congestion are neglected.

2) Assumption 2: reserves for uncertainty and contingency are not considered.

With assumption 1, prices will be consistent among all the nodes, which enables us to focus on the proposed mechanism. Note that reserves in assumption 2 have been addressed by the uncertainty marginal price presented in [7].

B. EL and ES Decomposed Economic Dispatch

The normal power balance constraint in the economic dispatch model is decomposed into the EL and ES parts in the proposed mechanism.

First of all, the objective function minimizes the operating cost composed of the EL cost and ES cost, given by:

$$C^{OP}=\underbrace{\sum_{i\in\mathcal{G}}C_i^G(\bar{\boldsymbol{G}}_i)+\sum_{i\in\mathcal{V}}C_i^V(\bar{\boldsymbol{V}}_i)}_{\text{EL cost}}+\underbrace{\sum_{i\in\mathcal{G}}C_i^g(\boldsymbol{g}_i)+\sum_{i\in\mathcal{V}}C_i^v(\boldsymbol{v}_i)}_{\text{ES cost}} \tag{5}$$

where $C_i^G(\cdot)$, $C_i^V(\cdot)$, $C_i^g(\cdot)$, and $C^v(\cdot)$ are the cost functions related to vectors of unit EL $\bar{\boldsymbol{G}}_i$, VPP EL $\bar{\boldsymbol{V}}_i$, unit ES $\boldsymbol{g}_i$, and VPP ES $\boldsymbol{v}_i$, respectively; and $\mathcal{G}$ and $\mathcal{V}$ are the sets of units and VPPs, respectively.

To calculate the RPES and ES price, the ES balance is considered as the penalty in the objective function instead of constraints. In detail, a virtual battery (VB) is assumed to accommodate the ES along with other entities. Based on the ES balance requirement, the ES supplied by the VB denoted by vector $\boldsymbol{b}$ is formulated as:

$$\boldsymbol{b}=-\left(\sum_{i\in\mathcal{R}}\boldsymbol{r}_i+\sum_{i\in\mathcal{D}}\boldsymbol{d}_i+\sum_{i\in\mathcal{G}}\boldsymbol{g}_i+\sum_{i\in\mathcal{V}}\boldsymbol{v}_i\right) \tag{6}$$

where $\boldsymbol{b}$ is the deficiency in ES supply in the system. If there is sufficient ES supply, $\boldsymbol{b}$ would be equal to $\boldsymbol{0}$. According to definition 3, the effective ES of the VB is $MU(\boldsymbol{b})\cdot\|\boldsymbol{b}\|_2$ and the payment for the VB is further given by:

$$C^{VB}=\pi^{ES}\cdot MU(\boldsymbol{b})\cdot\|\boldsymbol{b}\|_2=\pi^{ES}\hat{\boldsymbol{e}}^{\mathrm{T}}\boldsymbol{b} \tag{7}$$

where π^{ES} is the ES price to be solved. It is worth noting that the RPES $\hat{\boldsymbol{e}}$ is a variable vector with the constraint $\|\hat{\boldsymbol{e}}\|_2=1$. Based on (5) and (7), the objective function is formulated as:

$$\min_{\{\bar{\boldsymbol{G}}_i,\boldsymbol{g}_i,\bar{V}_i,\boldsymbol{v}_i,\forall i\}}\left(C^{OP}+\max_{\{\pi^{ES},\hat{\boldsymbol{e}}\}}C^{VB}\right) \tag{8}$$

In the outer-level problem, the operating cost and VB penalty are minimized over the feasible region of VPPs and conventional units. Since the RPES $\hat{\boldsymbol{e}}$ and ES price π^{ES} are unknown, the inner-level problem is required to minimize the maximum (or worst-case) penalty cost C^{VB} by properly adjusting the value of π^{ES} and $\hat{\boldsymbol{e}}$ with the constraints $0\le\pi^{ES}\le\pi^{ES}_{\max}$ and $\|\hat{\boldsymbol{e}}\|_2=1$, so that the system-wide ES demand is adequately characterized while $\boldsymbol{b}$ is minimized and even equals zero.

Remark 1: when the ES supply in the system is insufficient or the bidding price of ES supply is too high so that the ES price exceeds the predefined price ceiling denoted by $\pi^{ES}_{\max}$, the ES of VB would not be zero. In this case, the curtailment of VRE or IneL is unavoidable. Note that the ES price π^{ES} may not be zero even if $\boldsymbol{b}$ is equal to zero.

Besides the ES part, EL balance constraint is formulated as:

$$\sum_{i\in\mathcal{G}}\bar{\boldsymbol{G}}_i+\sum_{i\in\mathcal{R}}\bar{\boldsymbol{R}}_i+\sum_{i\in\mathcal{D}}\bar{\boldsymbol{D}}_i+\sum_{i\in\mathcal{V}}\bar{\boldsymbol{V}}_i=\boldsymbol{0}:\lambda \tag{9}$$

where $\bar{\boldsymbol{R}}_i$ and $\bar{\boldsymbol{D}}_i$ are the ELs of the VRE and IneL, respectively. Since the entries of the EL vector are time-invariant, a scalar λ is used to denote the dual variable for every EL balance constraints.

In addition to the system-wide constraints illustrated above, the optimization model involves the local constraints for units and VPPs such as the ramping and capacity constraints. For example, the capacity constraints of units can be formulated as $\boldsymbol{G}_i^{\min}\le\bar{\boldsymbol{G}}_i+\boldsymbol{g}_i\le\boldsymbol{G}_i^{\max}$, where $\boldsymbol{G}_i^{\min}$ and $\boldsymbol{G}_i^{\max}$ are the lower and upper bounds of units, respectively. Also, the ES variables of VPPs and units should satisfy the constraints $\boldsymbol{1}^{\mathrm{T}}\boldsymbol{v}_i=\boldsymbol{0}$ and $\boldsymbol{1}^{\mathrm{T}}\boldsymbol{g}_i=\boldsymbol{0}$, respectively.

Remark 2 (solution method): although there exists a bilinear product term $\pi^{ES}\hat{\boldsymbol{e}}^{\mathrm{T}}$ in the objective function, it can be replaced by an ancillary vector in the solution process. Then, the results of π^{ES} and $\hat{\boldsymbol{e}}$ are recovered based on the constraint $\|\hat{\boldsymbol{e}}\|_2=1$. Therefore, the global optimum can be obtained by the standard primal-dual gradient algorithm for the saddle point problems [8].

C. Market Mechanism and Equilibrium

The credit and payment of the EL and ES follow the cost causation principle and are discussed below.

1) Credit and Payment of EL

Generally, units and VRE are EL producers entitled to the EL credit while VPPs and IneL are EL consumers to be charged. The EL price π^{EL} depends on the dual variable associated with the EL balance constraints in (9), i.e., $\pi^{EL}=\lambda$. Hence, the market mechanism for the EL is similar to the existing marginal cost-based LMP scheme although there is only one time-invariant price in a day since the time-varying ES is traded separately as another product.

2) Credit and Payment of ES

The system-wide single ES price π^{ES} is revealed from the objective function in (8). Hence, the ES price depends on the adequacy of ES supply as well as the bidding prices. Also, the settlement of the ES depends on the effective ES while the sign of the MU determines whether the entity will be credited or charged. Therefore, an ES producer can reshape its output for a more similar profile relative to the RPES to obtain a higher MU in the ES trading.

3) Market Equilibrium

Entities such as conventional units and VPPs in the market are credited or charged based on their supply/demand of EL and ES. Without loss of generality, the profit maximization problem of unit i is formulated as (10), while the optimized variables are confined in the feasible set considering constraints such as ramping and capacities.

$$\max_{\{\bar{\boldsymbol{G}}_i,\boldsymbol{g}_i\}}\left(\underbrace{\pi^{EL}\boldsymbol{1}^{\mathrm{T}}\bar{\boldsymbol{G}}_i}_{\text{EL credit}}+\underbrace{\pi^{ES}\cdot MU(\boldsymbol{g}_i)\cdot\|\boldsymbol{g}_i\|_2}_{\text{ES credit/payment}}-\underbrace{C_i^G(\bar{\boldsymbol{G}}_i)}_{\text{EL cost}}-\underbrace{C_i^g(\boldsymbol{g}_i)}_{\text{ES cost}}\right) \tag{10}$$

It can be proven that unit i is not inclined to change its EL and ES outputs as it can get the maximum profit by following the optimal solutions to the economic dispatch model of independent system operator (ISO). The proof based on the Karush-Kuhn-Tucker (KKT) conditions is neglected here.

IV. Case Study

We illustrate the proposed mechanism on a 3-unit and 3-VPP system with VRE penetration. The normal quadratic cost function for units can be equivalently reformulated as the summation of EL cost and ES cost, i. e., $C_i^G(\bar{\boldsymbol{G}}_i)=\bar{\boldsymbol{G}}_i^{\mathrm{T}}(a_i\boldsymbol{I})\bar{\boldsymbol{G}}_i+b_i\boldsymbol{1}^{\mathrm{T}}\bar{\boldsymbol{G}}_i+Hc_i$ and $C_i^g(\boldsymbol{g}_i)=a_i\|\boldsymbol{g}_i\|_2^2$, where a_i, b_i, and c_i are the cost coefficients, while $\boldsymbol{I}$ and $\boldsymbol{1}$ are the H-dimension identity matrix and vector, respectively. The derivation straightforwardly comes from replacing the power vector in the normal quadratic cost function by the summation of EL and ES vectors:

$$
\begin{aligned}
&(\bar{\boldsymbol{G}}_i+\boldsymbol{g}_i)^{\mathrm{T}}(a_i\boldsymbol{I})(\bar{\boldsymbol{G}}_i+\boldsymbol{g}_i)+b_i\boldsymbol{1}^{\mathrm{T}}(\bar{\boldsymbol{G}}_i+\boldsymbol{g}_i)+Hc_i=\\
&\quad\underbrace{\bar{\boldsymbol{G}}_i^{\mathrm{T}}(a_i\boldsymbol{I})\bar{\boldsymbol{G}}_i+b_i\boldsymbol{1}^{\mathrm{T}}\bar{\boldsymbol{G}}_i+Hc_i}_{:=C_i^G(\bar{\boldsymbol{G}}_i)}+\underbrace{a_i\|\boldsymbol{g}_i\|_2^2}_{:=C_i^g(\boldsymbol{g}_i)}+2\bar{\boldsymbol{G}}_i^{\mathrm{T}}(a_i\boldsymbol{I})\boldsymbol{g}_i+b_i\boldsymbol{1}^{\mathrm{T}}\boldsymbol{g}_i=\\
&\quad C_i^G(\bar{\boldsymbol{G}}_i)+C_i^g(\boldsymbol{g}_i)+(2a_i\bar{\boldsymbol{G}}_i^{\mathrm{T}}\boldsymbol{1}+b_i)\underbrace{\boldsymbol{1}^{\mathrm{T}}\boldsymbol{g}_i}_{=\boldsymbol{0}}=\\
&\quad C_i^G(\bar{\boldsymbol{G}}_i)+C_i^g(\boldsymbol{g}_i)
\end{aligned}
\tag{11}
$$

The VPPs are set as EL consumers with given parameters and the ESs of three VPPs are optimized with the cost being $C_i^v(\boldsymbol{v}_i)=k_i\|\boldsymbol{v}_i\|_2^2$, and k_i is the cost coefficient for VPP. The total demand is set to be $M=209.28$ MW at each hour based on the data in [7]. To adjust the penetration of VRE and VPPs, we define two adjustable parameters R and V as the percentage of the EL of aggregated VRE and VPPs in the total demand, respectively. The data setup is detailed in Table I, where $\bar{\boldsymbol{V}}_1$, $\bar{\boldsymbol{V}}_2$, and $\bar{\boldsymbol{V}}_3$ are EL of V1, V2, and V3, respectively. Note that V1, V2, and V3 represent VPP1, VPP2, and VPP3, respectively; and G1, G2, and G3 represent generator 1, generator 2, and generator 3, respectively

TABLE I
Data Setup of 3-unit and 3-VPP System

Type	EL	ES	Cost coefficient
V1	$\bar{\boldsymbol{V}}_1=(-0.5VM)\times\boldsymbol{1}$	$1.5\bar{\boldsymbol{V}}_1\le\boldsymbol{v}_1\le-1.5\bar{\boldsymbol{V}}_1$	$k_1=0.05$
V2	$\bar{\boldsymbol{V}}_2=(-0.25VM)\times\boldsymbol{1}$	$3\bar{\boldsymbol{V}}_2\le\boldsymbol{v}_2\le-3\bar{\boldsymbol{V}}_2$	$k_2=0.10$
V3	$\bar{\boldsymbol{V}}_3=(-0.25VM)\times\boldsymbol{1}$	$0.5\bar{\boldsymbol{V}}_3\le\boldsymbol{v}_3\le-0.5\bar{\boldsymbol{V}}_3$	$k_3=0.05$
G1	$10\le\bar{\boldsymbol{G}}_1\le\boldsymbol{g}_1\le150$	$10\le\bar{\boldsymbol{G}}_1\le\boldsymbol{g}_1\le150$	$a_1=0.11$, $b_1=5$, $c_1=50$
G2	$10\le\bar{\boldsymbol{G}}_2\le\boldsymbol{g}_2\le50$	$10\le\bar{\boldsymbol{G}}_2\le\boldsymbol{g}_2\le50$	$a_2=0.085$, $b_2=1.2$, $c_2=150$
G3	$10\le\bar{\boldsymbol{G}}_3\le\boldsymbol{g}_3\le50$	$10\le\bar{\boldsymbol{G}}_3\le\boldsymbol{g}_3\le50$	$a_3=0.1225$, $b_3=1$, $c_3=135$
VRE	$\bar{\boldsymbol{R}}_i=(RM)\times\boldsymbol{1}$	Follow profiles in [7]	
IneL	$\bar{\boldsymbol{D}}_i=-(1-V)M\times\boldsymbol{1}$		

A. Case 1

1) Payments and Credits

In Case 1, the penetrations of VRE and VPPs are set to be $R=35\%$ and $V=30\%$, respectively. The results of the market clearing are demonstrated in Table II.

The EL price is obtained as 13.59 \$/MWh. Due to the negligible operating cost, the VRE offers the EL according to its maximum available capacity. The units are other EL producers. As G2 is the cheapest unit, its output remains at the upper limit. Since the marginal cost of G1 is higher than G3, the EL of G1 is lower than that of G3. VPPs and IneL are EL consumers to be charged based on the EL price.

TABLE II
Results of Market Clearing

Type	EL (MW)	EL payment/ credit (\$)	ES amount (MW)	MU	ES payment/ credit (\$)
V1	–31.39	–10238	115.43	1.0000	1332
V2	–15.70	–5119	57.71	1.0000	666
V3	–15.70	–5119	39.95	0.8970	413
G1	39.04	12733	51.11	0.9955	587
G2	50.00	16307	0	0	0
G3	46.99	15326	17.49	0.7564	153
VRE	73.25	23889	190.08	–0.9382	–2058
IneL	–146.50	–47779	123.00	–0.7702	–1094

ES is the second part of the market clearing and the ES price is derived as 11.54 \$/MWh. Conventional units and VPPs are crucial candidates for the provision of ES. The amounts of ES supplied by VPPs and units mainly depend on their marginal ES costs and capacities. Hence, the ES amount of V1 is the largest one due to its cheapest cost and sufficient capacity. As for the units, G2 cannot produce any ES since it supplies the EL at the upper limit. G1 offers more amount of ES than G3 due to the larger capacity and lower marginal cost.

In addition to the amount, the ES will be characterized by the pertinent MU for further payment or credit. Firstly, the RPES that depicts the most effective ES profile is demonstrated in Fig. 2(a) by the red solid line. Note that the presence of the variable $\boldsymbol{\eta}$ in (2) makes some differences between the ES demand profile that only considers the VRE and IneL (blue dashed line) compared with the RPES. As discussed in lemma 1, the MU of an entity is essentially the cosine similarity of its ES profile and the RPES. Since the ES profiles of V1 and V2 in Fig. 2(c) coincide with the RPES, they achieve the largest MU, i. e., $MU=1$. G1 has a very similar ES profile to the RPES and gets the magnitude of MU being 0.9955. However, the ES profiles of G3 and V3 are constrained by the upper and lower limits and thereby less similar to the RPES. For instance, when the system needs considerable upward ES from 17^{th} to 21^{st} hour, G3 and V3 cannot follow the trend of demand due to their upper limits and contribute less to flatten the RPES, which renders relatively smaller values of MU compared with those of V1 and V2. The VRE and IneL both have negative MU due to their reverse ES profiles relative to the RPES and will be charged based on the cost causation principle. In summary, although the IneL and VPPs are both EL consumers to make EL payments, VPPs are ES producers that are entitled to ES credit. Also, the VRE and units are EL producers but VRE is the ES consumer to be charged.

2) Comparisons with Other Schemes

The purpose of this subsection is to compare the proposed mechanism with the following three schemes.

Scheme 1: the VPPs and units are jointly optimized in the centralized economic dispatch model. This scheme does not consider the market and related payments and credits but can serve as an excellent benchmark. As expected, scheme 1 offers the same solution generated by the centralized economic dispatch model, which means that the novel market mechanism can well optimize all the resources in the systems by the EL price, ES price, and RPES.

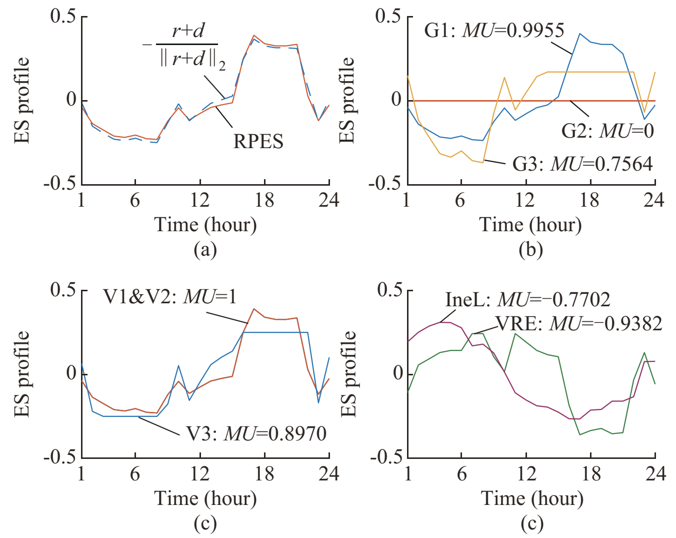

Fig. 2. ES profiles of entities. (a) ES profile of RPES. (b) ES profile of generators. (c) ES profile of VPPs. (d) ES profile of VRE and IneL.

Scheme 2: the VPPs strategically respond to the dynamic price as price takers and electricity consumers [5]. In detail, VPPs submit their hourly power for the market clearing based on the dynamic price that is generated according to the variations of IneL and VRE. Then, the EL producers such as units are scheduled in the market clearing. Also, two scenarios with different R and V are tested in this benchmark test.

The results are outlined in Table III and demonstrate that the dynamic price scheme underperforms the proposed mechanism, especially under high VRE and VPP penetration. To satisfy the system demand determined by the IneL and VRE, VPPs and units will afford more amount of ES using the dynamic price scheme compared with the proposed mechanism, which causes a larger ES cost. The reason is that the VPPs and units operate in a lower MU and effectiveness under the dynamic price scheme. In detail, VPPs are price-takers to shift the electricity consumption to the lucrative parts, where overshoot, undershoot, and rebound might occur. In the proposed mechanism, since the ES is measurable and tradeable, VPPs and units will follow the RPES to maximize their MU, allocating their ES capabilities optimally.

TABLE III
ES AMOUNT AND MU UNDER SCHEME 2 AND PROPOSED MECHANISM

Type	Scenario 1: $R=25\%$, $V=5\%$				Scenario 2: $R=35$, $V=30\%$			
	Scheme 2		Proposed		Scheme 2		Proposed	
	ES amount ($)	MU	ES amount ($)	MU	ES amount	MU	ES amount ($)	MU
V1	168.70	0.99	115.10	1.00	135.88	0.99	115.42	1.00
V2	87.66	0.99	57.55	1.00	67.95	0.99	57.71	1.00
V3	44.86	0.88	42.24	0.92	43.85	0.84	39.95	0.90
G1	36.24	–0.53	52.11	1.00	30.28	0.93	51.11	1.00
G2	17.80	0.58	0	0	0	0	0	0
G3	19.79	0.45	0	0	9.36	0.57	17.49	0.76
Cost ($)	40511		39912		32483		32313	

Scheme 3: the VRE is curtailable in the market clearing problem. In detail, the ES $\boldsymbol{r}_i$ in (6) and EL $\bar{\boldsymbol{R}}_i$ in (9) of VREs are set as variables to be solved in the optimization problem. Also, the pertinent constraints should be involved, including the basic constraint of ES $\mathbf{1}^{\mathrm{T}}\boldsymbol{r}_i=\mathbf{0}$ and the maximum available output constraint $\mathbf{0}\leq\bar{\boldsymbol{R}}_i+\boldsymbol{r}_i\leq\boldsymbol{R}_i^{\max}$. This benchmark is performed to validate the operation strategy of VREs in response to the trading of the ES product.

The results are demonstrated in Fig. 3. Firstly, with the increasing penetration of VPP, the share of IneL decreases accordingly. Thus, VREs contribute more to the amount of ES demand and obtain a lower value of MU with the augments of V in both curtailable or uncurtailable cases. Since the MU is decided by the cosine similarity of the ES profile and the RPES, reshaping the output profile by curtailing can help increase the MU and reduce ES payments for VREs to some extent. However, the curtailment might also decrease the EL credit, which means the VREs must control the tradeoff strategically considering the ES and EL prices. As demonstrated in Fig. 3, more amount of curtailment will be determined in the optimization problem when the VPP penetration is lower. No curtailment occurs if the share of VPP is beyond 10%. The reason is that the integration of VPPs highly improves the capacity of ES supply and reduces the ES price, where VREs will choose to pay for ES products offered by markets and ensure their own EL credits without any curtailment.

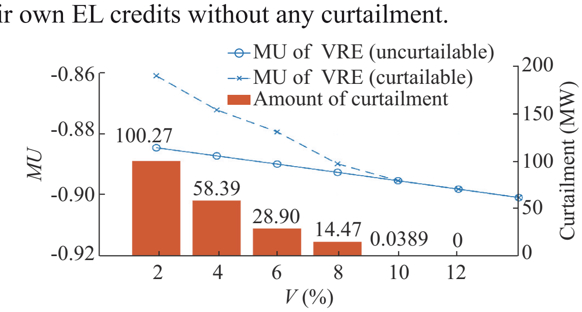

Fig. 3. MU and curtailment of VRE with different penetration of VPP.

B. Case 2

In Case 2, the penetrations of VRE and VPPs are adjusted to corroborate the essential role of ES in power systems. Figure 4(a) demonstrates the ratio of ES cost (including the potential cost of VB) to the total operating cost. Given a V, the share of ES cost grows with the increase of R. The reasons include the lower EL cost due to the cost-free VRE and the higher ES cost caused by the variation of VRE and related ES demand. For example, when R increases from 5% to 95% under the 5% VPP penetration, the ES cost increases from \$1121 to \$27072, while the EL cost decreases from \$60767 to \$8563. Nevertheless, the ES cost can be reduced if we integrate more VPPs to make the ES supply sufficient. For instance, the ES cost decreases from \$27072 to \$4287 when V increases from 5% to 90%. Concurrently, it can be observed in Fig. 4(b) that the operating cost will decrease with the increasing penetration of VRE due to the lower EL price. However, if the VPPs are not enough, the total cost will rebound due to huge ES demands and insufficient ES supply when R continues to increase. As expected, increasing the penetration of VPP can enrich the ES supply and avoid the cost rebound, which facilitates integrating more VRE.

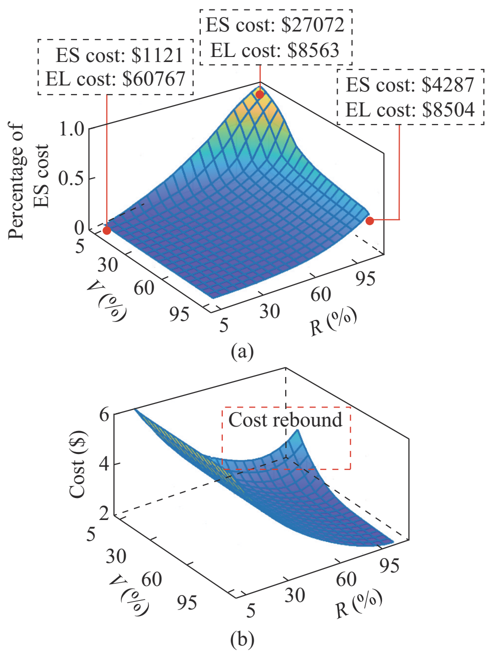

Fig. 4. Dynamics of cost with different R and V. (a) ES cost ratio. (b) Total cost.

V. Conclusion

The current electricity market does not consider the ES independently, which hinders integrating the desirable ES producers while charging the ES consumers. In the proposed mechanism: ① the trading of EL follows the normal marginal cost-based LMP scheme although with only one EL price in a day; ② the ES is characterized and priced by the RPES also with only one ES price in a day; ③ since the effective ES depends on the profile of a power curve rather than the level, more ES producers such as VPPs can participate in the market to trade the ES product even though they are EL consumers. This letter lays the groundwork for future research into the novel market with the separated consideration of the EL and ES, especially under the high penetration of VRE where the ES demand dominates the market.

In this letter, the network constraints are neglected. Thus, future work will propose the product of spatial energy shift for avoiding congestions, which characterizes and incentivizes the proper shifting of power generations or consumptions among locations. Also, ongoing efforts are analyzing the underlying differences between the time-varying LMP-based scheme and the proposed mechanism. In addition, accurate and detailed modeling algorithms for VPPs are essential and promising to be further studied.

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