IET Generation, Transmission & Distribution

Research Article

# Provision of flexible ramping product by battery energy storage in day-ahead energy and reserve markets

ISSN 1751-8687
Received on 28th September 2017
Revised 18th December 2017
Accepted on 13th February 2018
E-First on 6th April 2018
doi: 10.1049/iet-gtd.2017.1522
www.ietdl.org

*Jiahua Hu*[1], *Mushfiqur R. Sarker*[2], *Jianhui Wang*[2], *Fushuan Wen*[1] ✉, *Weijia Liu*[1]
[1]*School of Electrical Engineering, Zhejiang University, Hangzhou 310027, People's Republic of China*
[2]*Energy Systems Division, Argonne National Laboratory, IL 60439, USA*
✉ *E-mail: fushuan.wen@gmail.com*

**Abstract:** The variability and uncertainty of renewable energy resources introduce significant challenges to power system operation. One particular example is the occurrence of ramp capability shortage in real-time dispatch, which can cause power balance violations and price spikes. To meet the increasing need for ramp capability, some independent system operators in the USA have led initiatives to promote the implementation of flexible ramping product (FRP). More potential FRP providers, apart from conventional generators, are being explored, among which battery energy storage (BES) appears to be a feasible option owing to its good controllability and fast responsive characteristics. This study proposes an optimisation model for a BES aggregator to optimally provide FRP in day-ahead energy and reserve markets, aiming to maximise its monetary benefits. The basic concept of FRP is first introduced, including comparisons with traditional ancillary services, pricing mechanisms, and the extensions of market models to integrate FRP. The modes and strategies for BES aggregators to participate in the electricity markets are then addressed. Case studies indicate that an aggregator can gain more profit by optimally allocating its resources among various products than only providing energy and reserves. A sensitivity analysis on several key factors is also conducted.

## Nomenclature

### Sets

| | |
|---|---|
| $B$ | set of BES with index $b$ |
| $T$ | set of time periods with index $t$ |

### Parameters

| | |
|---|---|
| $\mathrm{BC}_b$ | capacity of BES $b$, MWh |
| $C_b^{\mathrm{bat}}$ | capital cost of BES $b$, \$ |
| $m_b$ | linear approximated slope of the life of BES $b$ as a function of number of cycles |
| $\psi_b$ | profit guarantee factor required by the owner of BES $b$ |
| $P_b^{\max}$ | maximum power of BES $b$, MW |
| $\mathrm{Soc}_b^{\min}$ | minimum energy SOC of BES $b$, MWh |
| $\mathrm{Soc}_b^{\max}$ | maximum energy SOC of BES $b$, MWh |
| $\mathrm{Soc}_b^{\mathrm{init}}$ | initial energy SOC of BES $b$, MWh |
| $\eta_b^{\mathrm{chg}}/\eta_b^{\mathrm{dsg}}$ | charge/discharge efficiency of BES $b$ |
| $\zeta_{t,b}$ | availability of BES $b$ in period $t$ (1 if available, 0 otherwise) |
| $\mathrm{Ramp}^{\mathrm{up}}$ | upward ramp rate of the BES aggregator, MW/h |
| $\mathrm{Ramp}^{\mathrm{dn}}$ | downward ramp rate of the BES aggregator, MW/h |
| $\Delta t$ | DA market clearing interval, h |
| $\beta$ | demand price of FRP, \$/MWh |
| $\lambda_t^{\mathrm{DA}}$ | DA energy market price, \$/MWh |
| $\lambda_t^{\mathrm{RT}}$ | RT energy market price, \$/MWh |
| $\lambda_t^{\mathrm{regup}}$ | capacity price for upward regulation service in the DA market, \$/MW |
| $\lambda_t^{\mathrm{regdn}}$ | capacity price for downward regulation service in the DA market, \$/MW |
| $\pi^{\mathrm{regup}}/\pi^{\mathrm{regdn}}$ | expected probability of upward/downward regulation service being accepted in the DA |
| $\pi^{\mathrm{raup}}/\pi^{\mathrm{radn}}$ | expected probability of upward/downward FRP being accepted in the DA |
| $\rho^{\mathrm{regup}}/\rho^{\mathrm{regdn}}$ | expected probability of upward/downward regulation service being deployed in the RT |
| $\rho^{\mathrm{raup}}/\rho^{\mathrm{radn}}$ | expected probability of upward/downward FRP being deployed in the RT |
| $\omega^{\mathrm{regup}}/\omega^{\mathrm{regdn}}$ | conditional probability of over-offering upward/downward regulation service |
| $\omega^{\mathrm{raup}}/\omega^{\mathrm{radn}}$ | conditional probability of over-offering upward/downward FRP |

### Variables

| | |
|---|---|
| $R^{\mathrm{en}}$ | revenue for providing energy, \$ |
| $R^{\mathrm{reg}}$ | revenue for providing regulation services, \$ |
| $R^{\mathrm{ra}}$ | revenue for providing FRP, \$ |
| $C^{\mathrm{reg}}$ | risk cost of over-offering regulation services, \$ |
| $C^{\mathrm{ra}}$ | risk cost of over-offering FRP, \$ |
| $C^{\mathrm{deg}}$ | battery degradation cost compensated to the BES owners, \$ |
| $p_{t,b}^{\mathrm{emdsg}}/p_{t,b}^{\mathrm{emchg}}$ | charge/discharge power of BES $b$ scheduled for the energy market in period $t$, MW |
| $p_t^{\mathrm{regup}}/p_t^{\mathrm{regdn}}$ | upward/downward regulation capacity offered by the aggregator in period $t$, MW |
| $p_t^{\mathrm{raup}}/p_t^{\mathrm{radn}}$ | upward/downward FRP capacity offered by the aggregator in period $t$, MW |
| $S_t^{\mathrm{regup}}/S_t^{\mathrm{regdn}}$ | upward/downward regulation shortage when over-offering materialises in period $t$, MW |
| $S_t^{\mathrm{raup}}/S_t^{\mathrm{radn}}$ | upward/downward FRP shortage when over-offering materialises in period $t$, MW |
| $e_{t,b}^{\mathrm{regup}}/e_{t,b}^{\mathrm{regdn}}$ | expected energy deployment of BES $b$ for upward/downward regulation service in period $t$, MWh |
| $e_{t,b}^{\mathrm{raup}}/e_{t,b}^{\mathrm{radn}}$ | expected energy deployment of BES $b$ for upward/downward FRP in period $t$, MWh |
| $E_b$ | total energy charged and discharged by BES $b$, MWh |
| $\mathrm{Soc}_{t,b}$ | energy SOC of BES $b$ in period $t$, MWh |

$\sigma_{t,b}$ auxiliary variable to allow charging or discharging for BES $b$ in period $t$ (1 if discharging, 0 if charging)

## 1 Introduction

The growing penetration of generation from renewable energy resources (RESs) has introduced great challenges to the reliable and secure operation of a given power system, among which the scarcity of ramp capability is one of the major concerns for load balancing violations. Current market practices to address the issue of ramp capability shortage include increasing reserve margins, adding an offset value to the forecasted load, and utilising look-ahead dispatch in the real-time (RT) market. However, the above solutions are incapable of remedying the issue to its full scale and may cause undesirable market distortion to some extent [1]. To this end, flexible ramping product (FRP) is proposed by some researchers and has been initially implemented by two independent system operators (ISOs) in the USA – California ISO (CAISO) and Midcontinent ISO (MISO) [2, 3]. FRP specifically refers to the ramping capability of a system over a specified response time to meet the potential net load movement in RT dispatch. As a new market product, FRP is distinguished from the existing ancillary services (ASs) in mainly two aspects [3]: (i) FRP is the only market product targeting net system load changes between two dispatch intervals; (ii) FRP is integrated into the RT dispatch function and thus is deployed very frequently and almost continuously [4].

So far, only conventional generators are eligible sources for providing FRPs in most practically operating electricity markets [5]. However, any RT dispatchable resource with an economic energy bid can provide FRP [3], and some recent research publications have already explored the feasibility of new FRP suppliers in [6–8]. By far, very limited efforts have been made on the provision of FRP by battery energy storages (BESs). The BES is widely considered to be the key to promoting the future deployment of renewable energy [9] by being able to alleviate the volatility caused by RESs and maintain the power balance. In an electricity market, a BES can provide multiple products in energy markets [10], reserve markets [11], or both markets [12]. Owing to the small capacity of a single BES unit, an aggregator is normally introduced to act as the agent of multiple BESs in the markets [11].

A number of publications [6, 13–16] focus on incorporating FRP in the RT market since the main purpose of FRP is to improve RT dispatch flexibility. However, it is pointed out in [3] that ISOs may intend to procure some of the ramping capability in the day-ahead (DA) market so as to meet the ramp capability requirements in the RT. The DA market is distinguished from the RT market in clearing granularity and ramp capability requirement. In RT dispatch, the ramp capability requirement is calculated every 5 min, representing the ability to respond over the following 5 or 10 min interval. On the other hand, the DA market, which is normally cleared on an hourly basis, aims at managing the inter-hour variations and uncertainty for the next day based on anticipated RT operation conditions. Cornelius [17] presents a good demonstration of different ramp capability requirements for the two markets, and point out that the RT net load is more volatile than that of the forecasted one in DA market. Statistical operation data in MISO show that the per-minute value of the 10 min variation is 25–30% higher than the per-minute value of the hourly variation [18]. This increased level of intra-hour variability should be considered in determining the DA ramp capability requirement.

This paper focuses on the optimal provision of FRP by a BES aggregator in the DA joint energy and ancillary service markets. Aiming to maximise the monetary benefit, an optimisation model is proposed for the aggregator to make optimal decisions on the provisions of various products in the so-called multiproduct market defined in this paper. The aggregator participates in both the energy market and reserve market as a price-taker, and provides FRP at the demand price set by the ISO. Furthermore, the aggregator's offers for energy, regulation, and FRP are co-optimised by considering both the acceptance probability and the deployment probability. The former represents the expected probability of the offers being accepted in the DA market, and the latter represents the expected probability of the accepted offers to be deployed in the RT. These expected probabilities have significant impacts on the aggregator's revenues and costs.

It should be pointed out that the focus of this paper is to formulate and solve the problem of the optimal participation strategies of a BES aggregator in the DA multiproduct market rather than to certify the clearing and deployment results in actual power systems. This is because some crucial parameters, such as the acceptance and deployment probabilities, may vary significantly from different power systems, and even in the same power system with different operation conditions. The main contributions of this paper are threefold:

i. Analyse the potential modes of a BES to participate in the multiproduct market as well as the associated revenues and costs.
ii. Propose an optimisation model for the BES aggregator to make optimal decisions on the offers of various products, with the risk of over-offering and the cost of battery degradation taken into account.
iii. Assess the expected profit a BES aggregator can attain by participating in the multiproduct market and conduct sensitivity analyses on several key factors.

The remainder of this paper is organised as follows. The concept of FRP is introduced in Section 2. The BES participation modes and the aggregator's bidding strategy are presented in Section 3, with an optimisation model for the aggregator formulated. Case studies are carried out in Section 4, followed by the conclusions in Section 5.

## 2 Flexible ramping product

FRP is deemed as the ramping capability within a specified response time interval (e.g. 10 min in MISO [2] or 5 min in CAISO [3]) targeting the net system load movement. The net system load is characterised as variable and uncertain due to intermittent RES outputs, load forecast errors, arbitrary behaviours of users, among others. The ISO builds up the system-wide ramping capability requirements [19] and procures FRPs from eligible suppliers to accommodate the forecasted variability of the net load and the uncertainty of the net load forecast in the following interval [6]. Fig. 1 depicts the requirements for both upward and downward ramping capabilities, which can be enumerated, respectively, as:

- *Upward:* max{[upper level of the net load at $t+1$]−[net load at $t$], 0}
- *Downward:* max{[net load at $t$]−[lower level of the net load at $t+1$], 0}

The main benefit of FRP lies in the reduction in the probability of power balance violations. This is because by considering FRP, the system is better positioned to respond to the potential load movement. Navid and Rosenwald [1] provide an illustrative example of the employment of FRP in avoiding power balance violations. Besides, the occurrence of penalty prices due to ramp scarcity is reduced [6]. Other benefits include improved management of ramp capacity from controllable resources, reduction in the deployment on regulation service, and enhancement of system flexibility [19]. The cost–benefit studies in MISO show the tangible annual cost savings are estimated to be in the range of \$3.8–5.4 million after the implementation of FRPs [2].

### 2.1 Comparing FRP with traditional ASs

Prior to the proposal of FRP, an array of ASs have been and are still in use to ensure the balance of power supply and demand, among which regulation and operating reserve are well-designed market-based products. However, FRP can be easily distinguished from both the regulation and operating reserve services as described below.

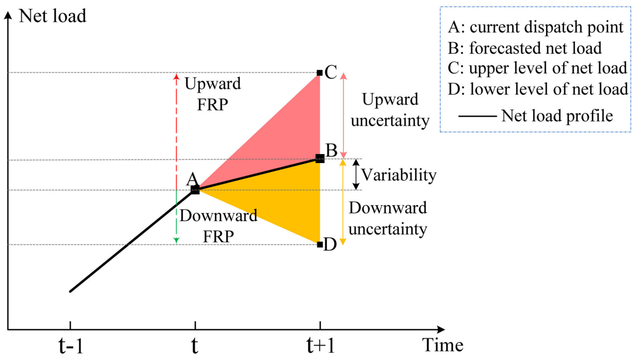
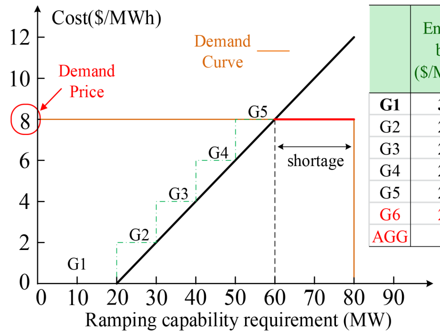



**Fig. 1** *Illustration of system-wide ramping capability requirement*




| | Energy bid ($/MWh) | Opportunity cost ($/MWh) | Upward FRP capability (MW) |
|---|---|---|---|
| **G1** | **30** | **0** | **20** |
| G2 | 28 | 2 | 10 |
| G3 | 26 | 4 | 10 |
| G4 | 24 | 6 | 10 |
| G5 | 22 | 8 | 10 |
| G6 | 20 | 10 | 10 |
| AGG | 0 | 30 | 20 |

**Fig. 2** *Demand curve and pricing process of FRP*

Regulation is designed to manage the instantaneous difference between the actual net load and the forecasted one and is deployed by automatic generation control (AGC) in a matter of seconds. On the contrary, FRP addresses the net load movement in future dispatch intervals (5 or 10 min ahead) and is deployed every 5 min by an RT dispatch model.

Operating reserve, also known as contingency reserve [20], is maintained in response to a sudden loss of generation or an unexpected increase in demand. It is activated only when a contingency event materialises, which is unlikely to occur but has significant impacts. Operating reserve is typically classified into two categories (i.e. spinning reserve and non-spinning reserve) according to the on/off status of the resource. It can only be modelled in the upward directions [21], while FRP is designed for both upward and downward.

The prices of regulation and operating reserve are generally higher than the price of FRP in current electricity markets, resulting in higher total supply costs. The FRP proposal from MISO [2] pointed out that, increasing the regulation requirement or the operating reserve requirement and using it for FRP renders a significant increase in total production cost compared to the proposed FRP. Wang and Hodge [19] also give credit to FRP as a cost-effective fashion to maintain power balance.

### *2.2 Pricing FRP and demand curve*

In contrast to traditional AS whose prices are based on separate offers, FRP is priced at the opportunity cost, namely the forgone profit a resource could have been earned by providing energy instead of FRP. The demand curve is adopted to indicate the scarcity price of FRP when insufficient ramping capability is cleared in the system. MISO employs a single-step curve with only one-segment demand price [19], and this work follows this MISO's practice.

An illustrative example is presented in Fig. 2 to demonstrate the pricing process of FRP and the function of demand curve. The table on the right side of Fig. 2 lists the energy bids of different participants, of which AGG stands for the aggregator, and G1 is assumed to be the marginal unit for energy and thus sets the market clearing price (MCP) to 30 $/MWh. According to the MCP, the opportunity costs of different participants for reserving energy to provide FRP are calculated and listed in the third column of the table. The last column enumerates the upward FRP capability of each participant.

For each dispatch interval, upward and downward ramping capability requirements are enforced independently with separate constraints. Only upward FRP is considered in this example for clarity. As observed in Fig. 2, if the requirement is <20 MW, the capacity of G1 is sufficient to meet the requirement, thus deriving zero opportunity cost. If the requirement is between 20 and 30 MW, G2 is called upon as an additional FRP provider and thus sets the marginal opportunity cost. The rest of the cases can be analysed in the same way. However, if the opportunity cost of a participant is larger than the demand price, which is set to 8 $/MWh in this example, the participants (e.g. G6 and AGG) will not be selected to provide FRP even if there is a ramp shortage.

It is notable that the expected demand price used at the initial stage in MISO is 5–20 $/MWh, which is well below the scarcity prices of operating reserve and regulation [2]. This is because the ISO prefers not to pay high premium now for something that may change in the future.

### *2.3 Involving FRP in the current market clearing models*

The joint co-optimisation model of energy and reserve [22] is extended to include FRP. The change to the objective function is to add the total supplying cost for all awarded FRPs, which is expressed as:

$$C^{\rm FRP} = \sum_{t \in T}\left(p_t^{\rm UFRP}\sum_{i \in I} Q_{t,i}^{\rm UFRP} + p_t^{\rm DFRP}\sum_{j \in J} Q_{t,j}^{\rm DFRP}\right) \tag{1}$$

where the total cost $C^{\rm FRP}$ is composed of the payments for upward FRPs and downward FRPs, $p_t^{\rm UFRP}$ and $p_t^{\rm DFRP}$ are the marginal opportunity costs of upward and downward FRPs at time interval $t$, respectively. $Q_{t,i}^{\rm UFRP}$ is the quantity of the upward FRPs provided by resource $i$, and $Q_{t,j}^{\rm DFRP}$ is the quantity of the downward FRPs provided by resource $j$. Note that certain resources can provide upward and downward FRPs at the same time.

New constraints are enforced that FRPs procured from all eligible resources are reserved to meet the system-wide ramping capability requirements:

$$\sum_{i \in I} Q_{t,i}^{\rm UFRP} \ge R_t^{\rm UFRP}, \quad \forall t \in T \tag{2}$$

$$\sum_{j \in J} Q_{t,j}^{\rm DFRP} \ge R_t^{\rm DFRP}, \quad \forall t \in T \tag{3}$$

where $R_t^{\rm UFRP}$ and $R_t^{\rm DFRP}$ are the upward and downward system-wide ramping capability requirements at time interval $t$, respectively. RT ramping capability requirements are calculated in each dispatch interval based on short-term load forecast with uncertainty considered, whereas DA requirements are established hourly based on forecasted RT ramp needs. The requirements enforced in the DA and RT markets impose great impacts on the acceptance probability and the deployment probability of the aggregator's offers on FRP. A higher requirement increases the likelihood of the aggregator's offer to be accepted in the DA market and to be deployed in the RT market.

Other changes to the existing constraints include the ramping up/down limits and maximum/minimum active power limits [3]. For example, the ramp capability is shared between FRP and others ASs. As to the active power, a capacity margin is required when considering FRP.

## 3 BES participation in the multiproduct market

### *3.1 BES participation modes*

The aggregator only manages the BESs rather than owns them and thus, it must benefit the BES owners while seeking its own profit. It is assumed that each BES owner requires an extra payment over the battery degradation cost and the ratio is denoted by a profit

**Table 1** Participation modes of a BES in the multiproduct market

| Modes | Physical action | Services | Revenues | Costs |
|---|---|---|---|---|
| *emdsg* | discharge | energy | energy provision in DA | degradation |
| *regup* | discharge | upward regulation | 1. up-regulation capacity in the DA2. energy deployment in the RT | degradation |
| *raup* | discharge | upward FRP | 1. up ramp capacity in the DA2. energy deployment in the RT | degradation |
| *emchg* | charge | energy | none | 1. degradation2. charge fee |
| *regdn* | charge | downward regulation | down-regulation capacity in the DA | degradation |
| *radn* | charge | downward FRP | down ramp capacity in the DA | degradation |

guarantee factor. Moreover, the BES owners inform the aggregator of the availability for each BES at each time period.

An available BES can provide various types of services in the multiproduct market according to its physical actions, as shown in Table 1, which also classifies the associated revenues and costs. It should be noted that although the mode *emchg* makes no revenue and even causes degradation cost and charge fee, it is an important manner to keep an appropriate state-of-charge (SOC) in the BES and the energy charged can be used for future arbitrage. Furthermore, the aggregator may also schedule no actions for the BES in certain periods without incurring any revenues or costs.

### *3.2 Optimal participation strategy of the aggregator*

In this work, it is assumed that the aggregator bids quantity-only offers in both energy market and reserve market, in which the aggregator acts as a price-taker. Since the capacity managed by the aggregator is generally small compared to the total power demand and the regulation requirement of the system, it is significant to guarantee that the whole offered quantities will be accepted. The ISO always selects the least priced offers under the uniform pricing scheme in the DA market, and hence the aggregator will be given priority as its bid price is zero. Moreover, the aggregator receives an additional payment if it is called upon to deploy the regulation up services in the RT. The deployment on regulation down services, by contrary, is not paid because the energy charged during down-regulation can be stored for future arbitrage.

Apart from the energy and regulation service, the aggregator may intend to leave a capacity margin for FRPs. Since the aggregator bids zero-price for energy, the opportunity cost of the aggregator is equal to the MCP, which is normally higher than the demand price (i.e. the ceiling price) according to Fig. 2. Thus, the aggregator is not selected to provide FRP. However, it is assumed that the aggregator is willing to provide FRP at the demand price. This makes sense for the aggregator because it can receive capacity rewards in the DA market and additional deployment payment if it is called upon in the RT. Furthermore, along with the increasing penetration level of intermittent RESs, the issue of ramp shortage is exacerbated. This motivates the ISO to procure more FRPs, rendering a higher demand price. The demand price is set by the ISO and directly reflects the revenues the aggregator can collect by providing FRPs.

In summary, the aggregator allocates its resources among energy, regulation, and FRPs, and optimises its participation strategies through the following steps: (i) first, the aggregator estimates various market prices (i.e. the DA and RT energy prices, the DA regulation prices) based on historical data; (ii) next, the aggregator estimates the acceptance and deployment probabilities of FRP and regulation; (iii) finally, the aggregator runs the optimisation model (detailed in Section 3.3) and obtains its optimal participation strategies, including energy, regulation capacity, and flexible ramp capacity for the hourly DA market.

### *3.3 Optimisation model of the aggregator*

The optimisation model is modified based on [23] by including the FRPs in both objective function and constraints. The objective function of the aggregator is to maximise the total profits and can be formulated as:

$$\max \{R^{\text{en}} + R^{\text{reg}} + R^{\text{ra}} - C^{\text{reg}} - C^{\text{ra}} - C^{\text{deg}}\} \tag{4}$$

where $R^{\text{en}}$, $R^{\text{reg}}$, and $R^{\text{ra}}$ are the revenues for providing energy, regulation services, and FRPs, respectively; $C^{\text{reg}}$ and $C^{\text{ra}}$ are the risk costs of over-offering regulation services and FRPs, respectively; $C^{\text{deg}}$ is the battery degradation cost compensated to the BES owners.

The DA energy market revenue $R^{\text{en}}$ can be expressed as:

$$R^{\text{en}} = \Delta t \sum_{t \in T} \sum_{b \in B} \lambda_t^{\text{DA}} (\eta_b^{\text{dsg}} p_{t,b}^{\text{emdsg}} - p_{t,b}^{\text{emchg}}) \tag{5}$$

where $\Delta t$ is the DA market clearing interval, $\lambda_t^{\text{DA}}$ the DA energy market price, $\eta_b^{\text{dsg}}$ the discharge efficiency of BES $b$, $p_{t,b}^{\text{emdsg}}$ and $p_{t,b}^{\text{emchg}}$ are the discharge and charge power levels scheduled for the energy market and are regarded as power generation and load demand, respectively.

The expected revenue for providing regulation services $R^{\text{reg}}$ consists of the capacity payment from the DA regulation market and the expected additional revenue for energy deployment in RT, as indicated in (6):

$$\begin{aligned} R^{\text{reg}} = & \sum_{t \in T} (\pi^{\text{regup}} \lambda_t^{\text{regup}} p_t^{\text{regup}} + \pi^{\text{regdn}} \lambda_t^{\text{regdn}} p_t^{\text{regdn}}) \\ & + \Delta t \rho^{\text{regup}} \sum_{t \in T} \lambda_t^{\text{RT}} \eta^{\text{dsg}} \pi^{\text{regup}} p_t^{\text{regup}} \end{aligned} \tag{6}$$

where $\lambda_t^{\text{regup}}/\lambda_t^{\text{regdn}}$ is the DA regulation up/down capacity price, $p_t^{\text{regup}}/p_t^{\text{regdn}}$ the corresponding capacity offered by the aggregator; $\pi^{\text{regup}}/\pi^{\text{regdn}}$ the expected probability of upward/downward regulation service being accepted in the DA, which is equal to 1 as aforementioned (i.e. the aggregator's offer on regulation services is fully accepted); $\rho^{\text{regup}}$ is the expected probability of upward regulation service being deployed in RT market, and $\lambda_t^{\text{RT}}$ the RT energy market price.

Similarly, the expected revenue for providing FRP $R^{\text{ra}}$ is presented as follows:

$$\begin{aligned} R^{\text{ra}} = & \Delta t \sum_{t \in T} (\pi^{\text{raup}} \beta p_t^{\text{raup}} + \pi^{\text{radn}} \beta p_t^{\text{radn}}) \\ & + \Delta t \rho^{\text{raup}} \sum_{t \in T} \lambda_t^{\text{RT}} \eta^{\text{dsg}} \pi^{\text{raup}} p_t^{\text{raup}} \end{aligned} \tag{7}$$

where $p_t^{\text{raup}}/p_t^{\text{radn}}$ is the upward/downward FRP capacity offered by the aggregator in the DA market; the demand price $\beta$ is specified by the ISO and known by the aggregator; $\pi^{\text{raup}}$ and $\pi^{\text{radn}}$ denote the acceptance probabilities of upward and downward FRP, respectively; $\rho^{\text{raup}}$ is the expected probability of upward FRP being deployed in RT market.

The first part in the right hand of (7) represents the expected compensation to the aggregator for FRP provision in the DA market. Unlike regulation services which are fully accepted, the acceptance probabilities of FRP depend on the ramp capability requirements in the DA market and vary with different operating days. The second part represents the profit of deployed FRP in RT market, and $\rho^{\text{raup}}$ is closely related to the RT operation conditions of the system. It should be noted that $p_t^{\text{raup}}$, $p_t^{\text{radn}}$, and $\rho^{\text{raup}}$ impose remarkable impacts on the aggregator's strategies and profit. The estimation accuracy of these probabilities will be enhanced along with the development of the FRP market mechanism and the accumulation of historical data.

In RT deployment, the ISO can call upon the aggregator to provide regulation service at any level between zero and the accepted capacity in the DA market. The aggregator optimises its offers in the DA market based on the expected probability of deployment. Thus, the aggregator needs to consider the case that actual deployment requirement in the RT market is larger than its expectation. Over-offering materialises when the aggregator is deployed more than it anticipates in the DA market. In this case, it is assumed that the aggregator purchases from the energy market at the RT energy market price to cover the shortage. The associated risk cost of over-offering regulation services is modelled to make a risk-averse decision and can be expressed as:

$$C^{\text{reg}} = \omega^{\text{regup}} \sum_{t \in T} \lambda_t^{\text{RT}} S_t^{\text{regup}} + \omega^{\text{regdn}} \sum_{t \in T} \lambda_t^{\text{RT}} S_t^{\text{regdn}} \tag{8}$$

$$\omega^{\text{regup}} = \pi^{\text{regup}} \rho^{\text{regup}} (1 - \rho^{\text{regup}}) \tag{9}$$

$$S_t^{\text{regup}} = p_t^{\text{regup}} - \pi^{\text{regup}} \rho^{\text{regup}} p_t^{\text{regup}} \tag{10}$$

$$\omega^{\text{regdn}} = \pi^{\text{regdn}} \rho^{\text{regdn}} (1 - \rho^{\text{regdn}}) \tag{11}$$

$$S_t^{\text{regdn}} = p_t^{\text{regdn}} - \pi^{\text{regdn}} \rho^{\text{regdn}} p_t^{\text{regdn}} \tag{12}$$

where the first part in the right hand of (8) denotes the risk cost of over-offering upward regulation, of which $\omega^{\text{regup}}$ is the conditional probability of over-offering, as shown in (9). This is the case because over-offering materialises based on the realisation of three independent events: (i) accepted in the DA market with the probability of $\pi^{\text{regup}}$; (ii) deployed in the RT with the probability of $\rho^{\text{regup}}$; (iii) deployed more than anticipated with an associated probability of $(1 - \rho^{\text{regup}})$ based on [23].

$S_t^{\text{regup}}$ represents the expected shortage of upward regulation, and is determined by the difference between the offered capacity and the expected deployment level, as shown in (10). The expected deployment level, donated as $D_t^{\text{regup}}$, is equal to $\pi^{\text{regup}} \rho^{\text{regup}} p_t^{\text{regup}}$. The over-offering upward regulation materialises when the actual deployment requirement $A_t^{\text{regup}}$ in the RT is larger than $D_t^{\text{regup}}$, and $A_t^{\text{regup}}$ can be any value between 0 and $p_t^{\text{regup}}$ after the aggregator submits its offers into the DA market. The aggregator must consider the possibility of shortage in order to make a risk-averse decision. The extreme case where $A_t^{\text{regup}}$ equals $p_t^{\text{regup}}$ is considered by fully taking the over-offering risk into account, and thus, the optimisation results are hedge against.

The risk cost of over-offering downward regulation, as expressed by the second part in the right hand of (8), is defined in a similar way. The probabilities of over-offering downward regulation $\omega^{\text{regdn}}$ and the expected shortage $S_t^{\text{regdn}}$ are presented in (11) and (12), respectively.

Similar rationale applies for the risk cost of over-offering FRPs, as expressed in (13)–(17). $\omega^{\text{regup}}/\omega^{\text{regup}}$ is the conditional probability of over-offering upward/downward FRP, and $S_t^{\text{raup}}$/$S_t^{\text{radn}}$ is the upward/downward FRP shortage when over-offering materialises in period $t$

$$C^{\text{ra}} = \omega^{\text{raup}} \sum_{t \in T} \lambda_t^{\text{RT}} S_t^{\text{raup}} + \omega^{\text{radn}} \sum_{t \in T} \lambda_t^{\text{RT}} S_t^{\text{radn}} \tag{13}$$

$$\omega^{\text{raup}} = \pi^{\text{raup}} \rho^{\text{raup}} (1 - \rho^{\text{raup}}) \tag{14}$$

$$S_t^{\text{raup}} = p_t^{\text{raup}} - \pi^{\text{raup}} \rho^{\text{raup}} p_t^{\text{raup}} \tag{15}$$

$$\omega^{\text{radn}} = \pi^{\text{radn}} \rho^{\text{radn}} (1 - \rho^{\text{radn}}) \tag{16}$$

$$S_t^{\text{radn}} = p_t^{\text{radn}} - \pi^{\text{radn}} \rho^{\text{radn}} p_t^{\text{radn}} \tag{17}$$

Physical charge or discharge in multiproduct (i.e. energy, regulation, and FRP) markets causes battery degradation cost. For simplicity, battery degradation cost is assumed to relate to the total number of cycles only [24], as expressed in (18):

$$C^{\text{deg}} = \sum_{b \in B} \psi_b C_b^{\text{bat}} \left| \frac{m_b}{100} \right| \frac{E_b}{\text{BC}_b} \tag{18}$$

$$E_b = \sum_{t \in T} \left[ \underbrace{\Delta t \left( p_{t,b}^{\text{emdsg}} + p_{t,b}^{\text{emchg}} \right)}_{\text{(i) energy}} + \underbrace{\left( e_{t,b}^{\text{regup}} + e_{t,b}^{\text{regdn}} \right)}_{\text{(ii) regulation}} + \underbrace{\left( e_{t,b}^{\text{raup}} + e_{t,b}^{\text{radn}} \right)}_{\text{(iii) FRP}} \right] \tag{19}$$

where $\psi_b$, $C_b^{\text{bat}}$, $m_b$, and $\text{BC}_b$ are the profit guarantee factor, capital cost, the linear approximated slope [23], and battery capacity of BES $b$. These BES-related parameters are confirmed in the agreement between the owners of the BESs and the aggregator. Note that $\psi_b$ is >1. A large $\psi_b$ indicates more profit for the BES owner but also more compensation cost for the aggregator, which may affect the optimal strategies made by the aggregator.

$E_b$ is the total energy charged and discharged by BES $b$, and consists of three terms with respect to different products, as expressed in (19). $e_{t,b}^{\text{regup}}/e_{t,b}^{\text{regdn}}$ represents the expected energy deployment for regulation up/down service, while $e_{t,b}^{\text{raup}}/e_{t,b}^{\text{radn}}$ is the expected energy deployment for upward/downward FRP, respectively.

The relevant constraints for the BES aggregator are categorised as follows:

- Expected RT energy deployment from regulation services

$$\sum_{b \in B} e_{t,b}^{\text{regup}} = \Delta t \pi^{\text{regup}} \rho^{\text{regup}} p_t^{\text{regup}}, \quad \forall t \in T \tag{20a}$$

$$\sum_{b \in B} e_{t,b}^{\text{regdn}} = \Delta t \pi^{\text{regdn}} \rho^{\text{regdn}} p_t^{\text{regdn}}, \quad \forall t \in T \tag{20b}$$

- Expected RT energy deployment from FRP

$$\sum_{b \in B} e_{t,b}^{\text{raup}} = \Delta t \pi^{\text{raup}} \rho^{\text{raup}} p_t^{\text{raup}}, \quad \forall t \in T \tag{21a}$$

$$\sum_{b \in B} e_{t,b}^{\text{radn}} = \Delta t \pi^{\text{radn}} \rho^{\text{radn}} p_t^{\text{radn}}, \quad \forall t \in T \tag{21b}$$

- Energy state-of-charge (Soc) limits

$$\text{Soc}_{t,b} = \text{Soc}_{t-1,b} + \eta_b^{\text{chg}} p_{t,b}^{\text{emchg}} \Delta t - p_{t,b}^{\text{emdsg}} \Delta t, \quad \forall t \in T, \forall b \in B \tag{22}$$

$$e_{t,b}^{\text{regup}} + e_{t,b}^{\text{raup}} \le \text{Soc}_{t,b} - \text{Soc}_b^{\text{min}}, \quad \forall t \in T, \forall b \in B \tag{23a}$$

$$e_{t,b}^{\text{regdn}} + e_{t,b}^{\text{radn}} \le \text{Soc}_b^{\text{max}} - \text{Soc}_{t,b}, \quad \forall t \in T, \forall b \in B \tag{23b}$$

$$\text{Soc}_b^{\text{min}} \le \text{Soc}_{t,b} \le \text{Soc}_b^{\text{max}}, \quad \forall t \in T, \forall b \in B \tag{24}$$

$$\text{Soc}_{t=|T|,b} = \text{Soc}_b^{\text{init}}, \quad \forall b \in B \tag{25}$$

- Rated power and ramp limits

$$p_{t,b}^{\text{emdsg}} \Delta t + e_{t,b}^{\text{regup}} + e_{t,b}^{\text{raup}} \le \zeta_{t,b} (P_b^{\text{max}} \Delta t) \sigma_{t,b}, \quad \forall t \in T, \forall b \in B \tag{26a}$$

**Table 2** BES characteristics in four different groups

| Group | Number of BESs | $BC_b$, MWh | Unit capital cost, \$/kWh | $\eta_b^{dsg}$, % | $\eta_b^{chg}$, % | $m_b$ | $Soc_b^{min}$, MWh | $Soc_b^{max}$, MWh | $P_b^{max}$, MW |
|---|---|---|---|---|---|---|---|---|---|
| A | 15 | 1.5 | 500 | 95 | 95 | −0.01 | 0.15 | 1.35 | 1.5 |
| B | 15 | 1.5 | 400 | 95 | 95 | −0.006 | 0.15 | 1.35 | 1.5 |
| C | 15 | 1.5 | 300 | 95 | 95 | −0.003 | 0.15 | 1.35 | 1.5 |
| D | 15 | 1.5 | 200 | 95 | 95 | −0.0013 | 0.15 | 1.35 | 1.5 |

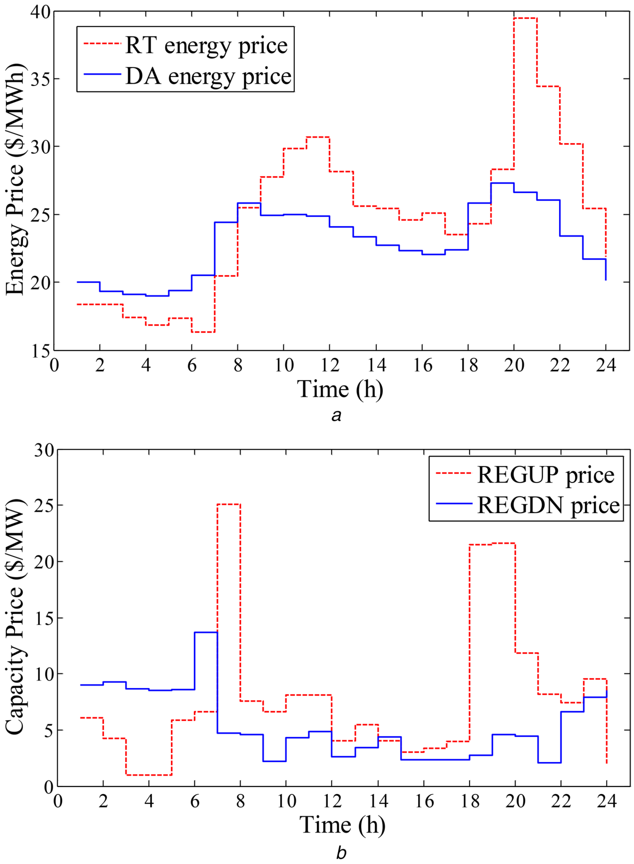



**Fig. 3** *Market prices*
***(a)*** Energy prices in the DA and RT markets, ***(b)*** Upward/downward regulation capacity prices

$$p_{t,b}^{\text{emchg}}\Delta t + e_{t,b}^{\text{regdn}} + e_{t,b}^{\text{radn}} \le \zeta_{t,b}(P_b^{\max}\Delta t)(1-\sigma_{t,b}), \quad \forall t \in T, \forall b \in B \tag{26b}$$

$$p_t^{\text{regup}} + p_t^{\text{raup}} \le \text{Ramp}^{\text{up}}\Delta t, \quad \forall t \in T \tag{27a}$$

$$p_t^{\text{regdn}} + p_t^{\text{radn}} \le \text{Ramp}^{\text{dn}}\Delta t, \quad \forall t \in T \tag{27b}$$

$$e_{t,b}^{\text{regup}}, e_{t,b}^{\text{regdn}}, e_{t,b}^{\text{raup}}, e_{t,b}^{\text{radn}}, p_{t,b}^{\text{emdsg}}, p_{t,b}^{\text{emchg}}, p_t^{\text{regup}}, p_t^{\text{regdn}}, p_t^{\text{raup}}, p_t^{\text{radn}} \ge 0 \tag{28}$$

Constraints (20) establish the relationship between the total deployed energy in the RT market of all BESs and the aggregator's offered regulation capacities. Note that the aggregator considers the general situation over a whole hour rather than exploring the intra-hour details on a 5 min basis. The aggregator can dispatch its managed BESs to meet the RT requirements and provide upward and downward regulations at the same time. However, it needs to estimate the values of $p_t^{\text{regup}}$ and $p_t^{\text{regdn}}$ based on the deployment probabilities in case there is insufficient energy for practical use. Similar constraints for FRP are defined in constraints (21).

Constraints (22)–(25) specify the limits related to the energy SOC of each BES. The change in the SOC of a BES between two contiguous time intervals is associated with its present discharging/charging power, as imposed in constraint (22). Constraints (23) stipulate that the overall expected energy deployed in the RT market does not exceed the available energy stored in a BES. Constraint (24) defines the SOC bounds for all time periods and constraint (25) emphasises the SOC of a BES should be identical to its initial value at the end of the optimisation horizon.

The rated power constraints are expressed in (26), in which the binary parameter $\zeta_{t,b}$ indicates the availability of BES $b$ in period $t$. From the physical perspective, a BES is unable to be charged and discharged at the same time. The binary variable $\sigma_{t,b}$ ensures only single-direction services be activated in a certain time period. Constraints (27) impose that the amount of services the aggregator can provide is limited by its ramp rate $\text{Ramp}^{\text{up}}/\text{Ramp}^{\text{dn}}$. However, these constraints are usually unbinding in practice since BESs are fast-acting devices with large ramp rates (e.g. 500 W per 0.1 s [11]) compared with their restricted power and energy capacity. As such, constraints (27) can be relaxed from the model, whereas potential studies can focus on the intentional bids where the aggregator strategically submits its ramp rate into the following market clearing model in order to seek more profits. Such intentional bids, however, entail more market information and are beyond the scope of this work.

Finally, constraint (28) points out the positive variables of this model.

## 4 Case studies and numerical results

An aggregator managing a fleet of 60 BESs is employed to demonstrate the features of the proposed model. The BESs are divided equally into four groups based on their characteristics. The physical parameters of the BESs in the same group are assumed to be identical and are shown in Table 2 [9]. The tendency from group A to group D can be observed as the decreasing unit capital cost and corresponding flatter slope, which represent the reduction in battery cost and technological improvement in the battery cycle-life [25]. Owing to the electrochemical constraints on the battery, the SOC bounds ($Soc_b^{min/max}$) are, respectively, specified to be 10 and 90% of the battery capacity. The initial SOC is randomised within the upper and lower bounds and different from each other. For simplicity, the profit guarantee factors required by different BES owners are assumed to be identical and equal to 1.2. All BESs are assumed to be available in every time interval.

Referring to the ERCOT [26], the hourly energy market prices in the DA and RT markets are estimated and shown in Fig. 3, along with the capacity prices for regulation services. Note that the hourly RT energy price is the average of the 5 min-based RT prices in the according hour. The demand price of FRP is assumed to be 10 \$/MWh [19]. The deployment probability of upward/downward regulation is assumed to follow $\rho^{\text{regup}} = \rho^{\text{regdn}} = 0.3$ [23]. In terms of FRP, the acceptance probabilities $\pi^{\text{raup}}$ and $\pi^{\text{radn}}$ are set to 0.5 and the deployment probabilities $\rho^{\text{raup}}$ and $\rho^{\text{radn}}$ are both set to 0.3. To take a further step, detailed sensitivity analysis will be conducted on these probability-related parameters to show their impacts on the aggregator's optimal strategy and overall profit. The proposed model is implemented in GAMS [27] as a mixed-integer linear program and all cases are solved using CPLEX.

### *4.1 Aggregator's offering strategies in the DA and its profit components*

The aggregator's offering strategies are shown in Fig. 4, with various streams of revenues and costs presented. As observed, the aggregator barely offers in the energy market. This is because the charging and discharging power levels specifically targeted for the energy market will definitely introduce the degradation cost, which

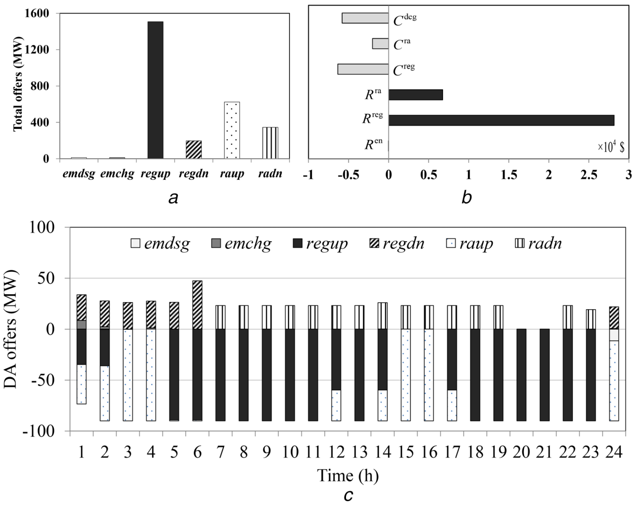



**Fig. 4** *Aggregator's offering strategies and profit components*
***(a)*** Total offers of various products, ***(b)*** Revenue streams and cost streams, ***(c)*** Itemised breakdown of various products

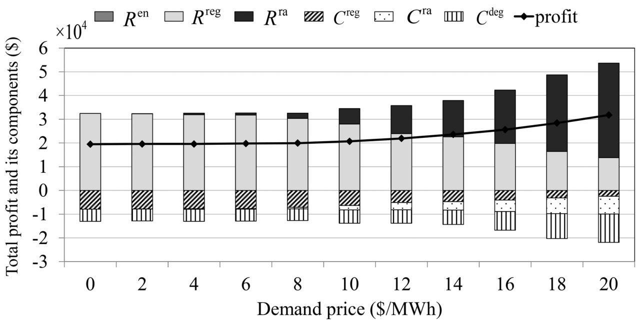



**Fig. 5** *Impacts of FRP demand price on the total profit of the BES aggregator and its components*

is unfavourable for the aggregator. In contrast, by offering regulation services and FRP, the aggregator can receive the capacity revenues in the DA market and has a chance that it will not be deployed in the RT.

As aforementioned, the aggregator can provide both upward regulation (regup) and upward FRP (raup) by physically discharging. As shown in Fig. 4*a*, the aggregator favours upward regulation because it is fully accepted in the DA market. Thus, the offers on upward regulation are more likely to be deployed in the RT market and result in more deployment payments. Besides, the capacity price of upward regulation is generally higher than the demand price of FRP. On the other hand, regarding charging-related services, the aggregator tends to schedule more resources for downward FRP (radn) compared to downward regulation (regdn). This is because the capacity price of downward regulation is lower than the demand price of FRP most of the time. Furthermore, unlike discharging-related services, the deployment on regdn and radn will not result in additional payments. It is in the aggregator's best interest to make sure that the offers are accepted in the DA market and on-standby in the RT market, thus receiving capacity revenues as well as avoiding degradation cost.

Subsequently, Fig. 4*c* shows the DA hourly offers on various products in different time slots. In terms of upward services, the aggregator prefers upward FRP during hours with low upward regulation capacity prices (3–4, 15–16, 24). It provides both regulation and FRP simultaneously in some hours (1–2, 12, 14, 17) by different groups of BESs. On the other hand, when the downward regulation capacity price is relatively low (7–19, 22–23), the aggregator chooses downward FRP rather than downward regulation. Note that in hours 20–21, the aggregator schedule no actions without incurring any revenues or costs. Specifically, Table 3 compares the expected energy deployment for regulation and FRP by different BES groups. Results show that the BESs in group A are not used for providing any services because they are the least cost-effective. The BESs in group B are scheduled to provide downward regulation and upward FRP in a few hours. As a contrast, the aggregator takes full advantage of the BESs in groups C and D, most of which are allocated for upward services (i.e. regup and raup). This is because with upward services, the aggregator may potentially obtain two revenue sources, DA capacity reward, and RT deployment payment.

Fig. 4*b* shows various streams of revenues and costs. Note that the costs are presented as the opposite values for illustration. As observed, providing regulation services is the main revenue stream, followed by the revenue stream for providing FRP. Moreover, revenue obtained from energy market is close to zero. In terms of costs, risk cost of over-offering regulation is the highest in all cost streams. This is because the aggregator prefers to provide regulation, and large provisions of regulation in the DA market increase the likelihood of the RT actual deployment on regulation to be larger than its expectation. On the other hand, degradation has significant impacts on the benefits that the aggregator may attain from providing products. The aggregator's profit is equal to the sum of all components, which is \$20.7 thousand. It is noteworthy that the profit is associated with several individual sensitive parameters. The impacts of different parameters on the total profit of the aggregator and its components are analysed in the following subsections and presented in Figs. 5–7.

### 4.2 Impacts of demand price $\beta$

As indicated in Section 3.2, the demand price $\beta$ directly reflects the revenue the aggregator can attain by providing FRP. Fig. 5 shows the aggregator's overall profit as well as its components, given the increment of $\beta$ with 2 \$/MWh per interval. As $\beta$ increases from 0 to 20 \$/MWh, the overall profit increases significantly by nearly 65%, most of which is induced by the increase in the revenues for providing FRP ($R^{\text{ra}}$). In contrast, the expected revenues for providing regulation ($R^{\text{reg}}$) decline. This is due to the constraints on the limited BES capacity, implying that the aggregator has to split its resources between FRP and regulation. Larger $\beta$ indicates that FRP is more profitable than regulation services, thus the aggregator may intend to allocate more resources for FRP and less for regulation services.

The over-offering risk of FRP ($C^{\text{ra}}$) also increases as it is proportional to $R^{\text{ra}}$ with fixed acceptance and deployment probabilities. Similar rationale accounts for the decline of the over-offering risk of regulation ($C^{\text{reg}}$). The degradation cost ($C^{\text{deg}}$) tends to be flat in the range of [0, 14] with more provision of FRP and less provision of regulation, whereas increases afterwards as much more FRP are provided due to strong economic incentives.

One thing should be noted that with a proper $\beta$, the aggregator can attain more monetary benefit by providing FRP, compared with only participating in energy and regulation markets (when $\beta$ is zero). This is because FRP offers extra options for the aggregator to make a more profitable bidding strategy based on the proposed optimisation model. If $\beta$ is specified to be very small, the model

**Table 3** Expected energy deployment for regulation and FRP by different BES groups (unit: MWh)

| Group | $\sum e_{t,b}^{\text{regup}}$ | $\sum e_{t,b}^{\text{regdn}}$ | $\sum e_{t,b}^{\text{raup}}$ | $\sum e_{t,b}^{\text{radn}}$ | Total |
|---|---|---|---|---|---|
| A | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 6.3 | 27 | 0 | 33.3 |
| C | 136 | 39.5 | 81.5 | 91.8 | 348.8 |
| D | 317.1 | 6.9 | 78.1 | 0 | 402.1 |

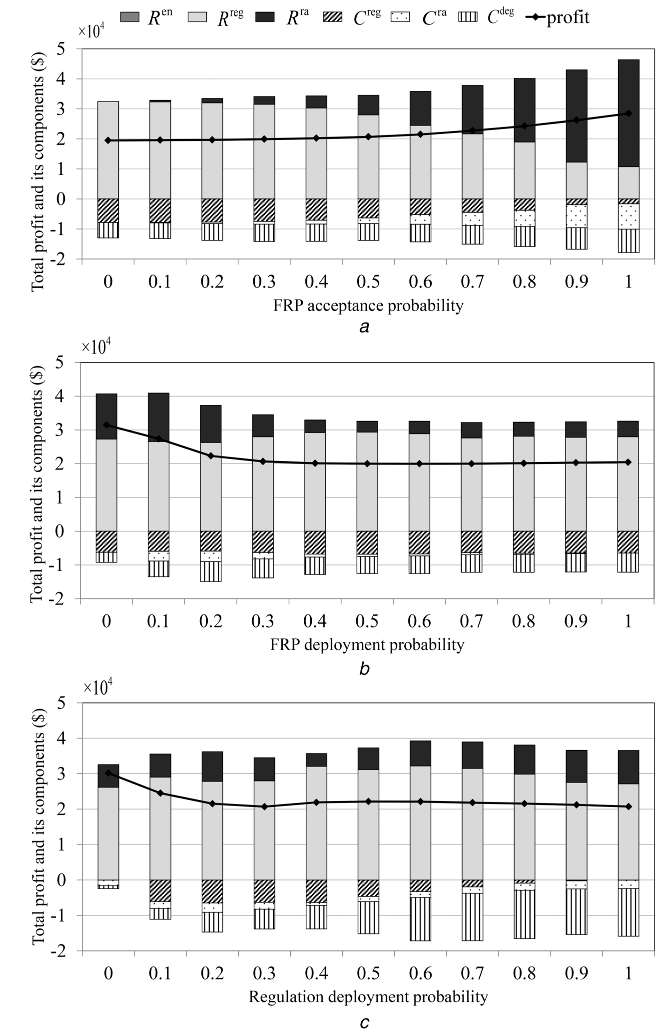



**Fig. 6** *Impacts of various probabilities on the total profit of the BES aggregator and its components*
***(a)*** $\pi^{raup}/\pi^{radn}$, ***(b)*** $\rho^{raup}/\rho^{radn}$, ***(c)*** $\rho^{regup}/\rho^{regdn}$

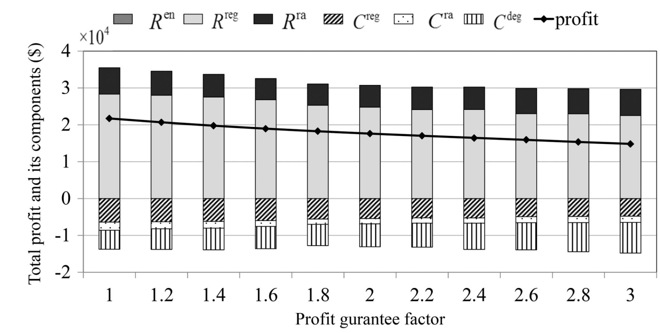



**Fig. 7** *Impacts of profit guarantee factor on the total profit of the BES aggregator and its components*

will automatically choose not to provide FRP, otherwise it will increase the provision.

### *4.3 Impacts of FRP acceptance probability $\pi^{raup}/\pi^{radn}$*

With the increase in $\pi^{raup}/\pi^{radn}$, FRPs are more likely to be accepted in the DA market. The aggregator can attain more capacity revenues by providing FRPs, thus it increases the provision of FRPs and reduces the provision of regulation due to BES capacity limitations, as shown in Fig. 6*a*. Consistent with the changes in the offers, the over-offering risk of FRP increases sharply, whereas the over-offering risk of regulation declines gradually. The degradation cost almost remains unchanged and the overall profit increases progressively. This validates that in situations where the ramp requirement is high and FRPs are more likely to be accepted, it is beneficial for the aggregator to schedule more resources for FRPs.

### *4.4 Impacts of FRP deployment probability $\rho^{raup}/\rho^{radn}$*

The FRP deployment probability has significant impacts on the FRP deployment payment in the RT market, the over-offering risk of FRP, and the degradation cost, simultaneously. With the increase in the deployment probability, FRPs are more likely to be deployed in the RT market, indicating the aggregator is subject to more deployment payment and more degradation cost at the same time. On the other hand, the over-offering risk of FRP first increases and then declines when the probability goes beyond 0.2, as presented in Fig. 6*b*. The aggregator makes optimal offering strategies taking into account the mentioned considerations. The overall profit is reduced to the minimum as the probability increases to 0.4 and then tends to be flat afterwards.

### *4.5 Impacts of regulation deployment probability $\rho^{regup}/\rho^{regdn}$*

Fig. 6*c* depicts the tendency of the overall profit and its components under different settings of $\rho^{regup}/\rho^{regdn}$, which imposes direct impacts on the regulation deployment payment, the over-offering risk of regulation, and the degradation cost. The overall profit decreases as $\rho^{regup}/\rho^{regdn}$ increases in the range of [0, 0.3] mainly due to the increase in the degradation cost and the over-offering risk of regulation. When the probability increases between 0.3 and 1, the overall profit almost keeps constant. This is because although the degradation cost increases significantly in this range, the total revenues for providing FRP and regulation increase as well, and at the same time, the over-offering risk of regulation declines with the rising of $\rho^{regup}/\rho^{regdn}$. Furthermore, the change in the over-offering risk of FRP is less insignificant and imposes little influence on the aggregator's profit.

### *4.6 Impacts of profit guarantee factor $\psi_b$*

The profit guarantee factor $\psi_b$ represents the ratio that the aggregator has to pay for the degradation cost. Fig. 7 indicates that the degradation cost rises up generally with the increase in $\psi_b$, while $R^{reg}$ declines gradually. The other components fluctuate in a small range. This results in the gradual decline of the overall profit. With further increase in $\psi_b$, the aggregator may stop providing services considering the costly payment to the BES owners for the degradation cost.

## 5 Conclusions

A BES aggregator plays an important role as the mediator between large fleets of BESs and power system operators. This paper presents an optimisation model for a BES aggregator to optimally participate in the multiproduct market with the goal of maximising its monetary benefits. The proposed model considers the over-offering risk and the reimbursement for degrading BESs in addition to the revenues for providing energy, regulation, and FRP. The numerical results and sensitivity analyses are examined in-depth with four main points concluded: (i) it is preferable for the aggregator to schedule a portion of the resources for FRP compared with participating in energy and reserve markets solely; (ii) a large demand price will incentivise the aggregator to increase the provision of FRP; (iii) the acceptance and deployment probabilities impose different impacts on the aggregator's offers; (iv) the high profit guarantee factor will harm the interest of the aggregator and cause it to cease providing services under worst situations.

The research work in this paper is mainly from the standpoint of a BES aggregator. It is our future work to extend this study to investigate the quantitative benefits the power system concerned can attain with the participation of BES aggregators.

## 6 Acknowledgments

This work is jointly supported by the National Natural Science Foundation of China (no. 51477151), the National Basic Research Program (973 Program) (no. 2013CB228202), and Postdoctoral Innovation Talent Support Program of China (no. BX201700211).

## 7 References

[1] Navid, N., Rosenwald, G.: 'Market solutions for managing ramp flexibility with high penetration of renewable resource', *IEEE Trans. Sustain. Energy*, 2012, **3**, (4), pp. 784–790

[2] Navid, N., Rosenwald, G.: 'Ramp capability product design for MISO markets', MISO, Market Development and Analysis, July 2013

[3] Xu, L., Tretheway, D.: 'Flexible ramping products', CAISO, December 2014

[4] Bushnell, J., Harvey, S.M., Stoft, S., *et al.*: 'Final opinion on payment for provision of flexible ramping', Market Surveillance Committee, CAISO, August 2011

[5] Wu, H., Shahidehpour, M., Alabdulwahab, A. A.: 'Thermal generation flexibility with ramping costs and hourly demand response in stochastic security-constrained scheduling of variable energy sources', *IEEE Trans. Power Syst.*, 2015, **30**, (6), pp. 2955–2964

[6] Chen, R., Wang, J., Botterud, A., *et al.*: 'Wind power providing flexible ramp product', *IEEE Trans. Power Syst.*, 2017, **32**, (3), pp. 2049–2061

[7] Cui, M., Zhang, J., Wu, H., *et al.*: 'Wind power ramping product for increasing power system flexibility'. Proc. IEEE Power Energy Soc. Transmission Distribution Conf. Expo., Dallas, TX, USA, May 2016, pp. 1–5

[8] Zhang, B., Kezunovic, M.: 'Impact on power system flexibility by electric vehicle participation in ramp market', *IEEE Trans. Smart Grid*, 2016, **7**, (3), pp. 1285–1294

[9] Divya, K.C., Østergaard, J.: 'Battery energy storage technology for power systems – an overview', *Electr. Power Syst. Res.*, 2009, **79**, (4), pp. 511–520

[10] Mohsenian-Rad, H.: 'Optimal bidding, scheduling, and deployment of battery systems in California day-ahead energy market', *IEEE Trans. Power Syst.*, 2016, **31**, (1), pp. 442–453

[11] Chen, S., Zhang, T., Gooi, H.B., *et al.*: 'Penetration rate and effectiveness studies of aggregated bess for frequency regulation', *IEEE Trans. Smart Grid*, 2016, **7**, (1), pp. 167–177

[12] Giuntoli, M., Poli, D.: 'Optimized thermal and electrical scheduling of a large scale virtual power plant in the presence of energy storages', *IEEE Trans. Smart Grid*, 2013, **4**, (2), pp. 942–955

[13] Wang, B., Hobbs, B.F.: 'A flexible ramping product: can it help real-time dispatch markets approach the stochastic dispatch ideal?', *Electr. Power Syst. Res.*, 2014, **109**, (4), pp. 128–140

[14] Wang, B., Hobbs, B.F.: 'Real-time markets for flexiramp: a stochastic unit commitment-based analysis', *IEEE Trans. Power Syst.*, 2016, **31**, (2), pp. 846–860

[15] Ela, E., Malley, M.O.: 'Scheduling and pricing for expected ramp capability in real-time power markets', *IEEE Trans. Power Syst.*, 2016, **31**, (3), pp. 1681–1691

[16] Wang, C., Luh, P., Navid, N.: 'Requirement design for a reliable and efficient ramp capability product'. Proc. IEEE Power Energy Soc. Gen. Meeting, Vancouver, BC, Canada, July 2013, pp. 1–5

[17] Cornelius, A.: 'Assessing the impact of flexible ramp capability products in the Midcontinent ISO'. Master's thesis, Duke University, May 2014

[18] MISO: 'Ramp product questions and answers'. Available at https://www.misoenergy.org/Library/Repository/Communication%20Material/Strategic%20Initiatives/Ramp%20Product%20Questions%20and%20Answers.pdf, accessed March 2016

[19] Wang, Q., Hodge, B.M.: 'Enhancing power system operational flexibility with flexible ramping products: a review', *IEEE Trans. Ind. Inf.*, 2017, **13**, (4), pp. 1652–1664

[20] Zhou, Z., Levin, T., Conzelmann, G.: 'Survey of US ancillary services markets', Argonne National Lab., Argonne, January 2016

[21] Holttinen, H., Milligan, M., Ela, E., *et al.*: 'Methodologies to determine operating reserves due to increased wind power', *IEEE Trans. Sustain. Energy*, 2012, **3**, (4), pp. 713–723

[22] Wu, T., Rothleder, M., Alaywan, Z, *et al.*: 'Pricing energy and ancillary services in integrated market systems by an optimal power flow', *IEEE Trans. Power Syst.*, 2004, **19**, (1), pp. 339–347

[23] Sarker, M.R., Dvorkin, Y., Ortega-Vazquez, M.A.: 'Optimal participation of an electric vehicle aggregator in day-ahead energy and reserve markets', *IEEE Trans. Power Syst.*, 2016, **31**, (5), pp. 3506–3515

[24] Ortega-Vazquez, M.A.: 'Optimal scheduling of electric vehicle charging and vehicle-to-grid services at household level including battery degradation and price uncertainty', *IET Gener. Transm. Distrib.*, 2014, **8**, (6), pp. 1007–1016

[25] Mckinsey & Compay: 'Battery technology charges ahead'. Available at https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/battery-technology-charges-ahead, accessed July 2012

[26] 'Electric Reliability Council of Texas'. Available at http://www.ercot.com/

[27] 'GAMS – a user's guide'. Available at http://www.gams.com/dd/docs/bigdocs/GAMSUsersGuide.pdf