# Evolving New Market Structures

Amin Shokri Gazafroudi[1], Miadreza Shafie-khah[2], Francisco Prieto-Castrillo[1,3,4],
Saber Talari[2], Juan Manuel Corchado[1,5], João P.S. Catalão[2,6,7]

1 BISITE Research Group, University of Salamanca, Edificio I+D+i, 37008 Salamanca, Spain

2 C-MAST, University of Beira Interior, Covilhã 6201-001, Portugal

3 Media Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA

4 Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA 02115, USA

5 Osaka Institute of Technology, Asahi-ku Ohmiya, Osaka 535-8585, Japan

6 INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465

7 INESC-ID, Instituto Superior Técnico, University of Lisbon, Lisbon 1049-001, Portugal

shokri@usal.es; miadreza@ubi.pt; franciscop@usal.es; saber.talari@ubi.pt; corchado@usal.es;
catalao@fe.up.pt

***Abstract*****—** In conventionally structured of power systems, electricity markets usually consist of day-ahead and balancing markets which are cleared sequentially and independently. However, since stochastic and non-dispatchable renewable energy resources participate in the electricity market, they inject power generation uncertainty. Thus, new services such as ancillary services are required to equilibrate balancing markets. Hence, simultaneous clearing of joint energy and reserve day-ahead and balancing markets makes this process more efficient. In this chapter, sequential and simultaneous approaches are used to study a two-stage stochastic joint energy and reserve market-clearing problem. In the sequential model, the day-ahead and balancing stages are solved autonomously. Moreover, this chapter evaluates the impact that electrical loads' flexibility behaviors has on the provision of operating reserves.

***Keywords—Demand response; Energy flexibility; Market clearing; Operating reserve; Stochastic programming; Wind power integrating.***

## 1. Introduction

### 1.1. Motivation

Conventional electricity markets usually consist of day-ahead and real-time markets. The day-ahead market is required in order to allocate generating units that have slow ramp-rate and need advance planning. The clearing of the real-time market allows the energy to maintain a balance between the supply and the demand during the decision-making period. Also, the real-time market is needed because of quick output and stochastic producers, e.g., wind farms.

In the conventionally structured electricity markets, day-ahead and balancing markets are cleared sequentially and independently. However, the participation of stochastic generation of non-dispatchable renewable energy resource, injects power generation uncertainty in the electricity

market problem. In this way, new services as called ancillary services, e.g., operating reserves, are required to make balancing in the real-time markets. Hence, the simultaneous clearing of joint energy and reserve day-ahead and real-time markets makes this process more efficient.
In addition, central energy management systems are not good strategies for resolving issues related to distributed energy resources' real and fair price in medium- and low-voltage distribution network locations. Finally, centralized energy management strategies in electricity markets are transferred to decentralized approaches.

### 1.2. Literature review and background

Electricity markets have experienced many changes over the past thirty years, their evolution has been aimed at increasing the efficiency of the power system [1]. These changes have formed the foundation of the restructured electricity market in terms of design and architecture. However, rapid technological development in the area of renewable energy generation caused these resources to become cost-competitive in comparison to conventional energy. This was due to lower variable cost in the electricity markets, in addition to providing clean and eco-friendly power [2], [3]. On this basis, in many power systems, an essential evolution has been formed. It should be noted that the high penetration of renewable energy can have a negative effect on the operation and planning of power systems [1]. In addition, the implementation of several environmental policies combined with renewable energies have contributed to considerable changes [4]. The share of renewable resources, e.g., wind and solar energy, has been advancing, while the thermal units have been losing their contributions in power systems [5], [6]. The thermal units can be replaced with these resources that leads to a decrease in the short-term market prices.

Despite the benefits of renewable energy, their high penetration can jeopardize the secure operation of the power system because of their intermittent output and uncertain nature [7], [8]. The effect of different renewable support mechanisms on the performance of the power market was investigated in [9]. Similarly, [10] proposed a green power system and designed an electricity market that would support renewable energies. In [11], the integration of large-scale renewable resources in the electricity market was analyzed.

Moreover, as a result of the changes in the power system, it is necessary to make changes in the electricity markets as well. Some proposals in the state of the art have already made an effort to redesign the market. J.L. Sawin et al. [12] studied the changes in the electricity markets due to the increase in renewable energies. In [13] the capacity market was modified to make the generation of renewable energy dependent on weather conditions. In [14], [15], the Flexiramp market was introduced to decrease the negative impact of solar generation on California ISO.

To overcome the insecurity of renewable-based power systems, a larger number of backup units is needed, as well as some flexible units to supply ancillary services, e.g., regulation and reserve markets. These flexible units can cover the uncertainty of renewable resources and ensure the balance between supply-demand in real-time [16], [17]. It should be pointed out that by increasing the share of renewable energy resources, the demand for the described regulation and reserve services increases [18].

The main flexibility services are currently provided by the thermal units, and there will be no major changes to this situation in the future. However, a large part of the profit obtained by thermal units comes from participation in the energy markets, not from the ancillary services. Consequently, the thermal units prefer to supply energy, not to deliver regulation or reserve services. Since the requirement for energy is much greater than the ancillary service, the profit of thermal units resulting from a regulation/reserve service is approximately one percent of the total profit [19].

However, a higher penetration of renewable resources can cause a drastic drop in energy prices, what will result in less motivation to invest in backup plants. This would be similar to the current situation in the Danish electricity market [20], where the energy prices may have zero or negative values. Therefore, the conventional thermal units should decide to participate more in the regulation and reserve markets in order to gain more incomes. This will allow them to survive on the renewable-based electricity markets and compete with renewable resources which are supported by a variety of policies [21].

Some articles in the literature consider the evolution of market design. In [22], which has been published in 2009, reviewed the electricity market in terms of architecture and design. In that year the main market design issues were related to electricity price forecast, bilateral contracts, and auction designs. Therefore, [22] did not study the effects of the upcoming power system on electricity markets. In [23], [24], a market splitting framework was proposed for future integration in day-ahead markets in Europe. In [25], a model was proposed for the electricity markets' clearing process, it had high computational efficiency. This model enabled the system operator to consider the supply orders and ramping limits. In [26], the efficiency of the balancing market in Germany was studied in terms of electricity market design. The authors of [27] investigated the problem of market design from a conventional thermal power plant's point of view. The work examined various market designs in order to achieve the optimal participation and success of such power plants.

### 1.3. Contributions

In this chapter, sequential and simultaneous approaches are used to solve and analyze the stochastic market-clearing problem of joint energy and reserve. Then, the influences of electrical consumers' flexibility behaviors on our proposed market-clearing model is evaluated. The rest of the chapter is organized as follows. In Section 2, the proposed restructured electricity market model is presented. Simulation results are described in details in Section 3. Finally, Section 5 concludes this chapter.

## 2. Restructured electricity market model

### 2.1. Nomenclature

#### A. *Indices and Numbers*

| | |
|---|---|
| $n$ | Index of system buses, from 1 to $N_B$. |
| $i$ | Index of conventional generating units, from 1 to $N_G$. |
| $j$ | Index of loads, from 1 to $N_L$. |
| $t$ | Index of time periods, from 1 to $N_T$. |
| $m$ | Index of energy blocks offered by conventional generating units, from 1 to $N_{Oit}$. |
| $\omega$ | Index of wind power, electrical load and power grid scenarios, from 1 to Ω. |

#### B. *Continuous Variables*

| | |
|---|---|
| $C_{it}^{SU}$ | Scheduled start-up cost ($). |
| $P^{S}{}_{it}$ | Power output of units in the day-ahead market (MW). |
| $p_{itm}^{G}$ | Power output from the $m$-th block of energy offered by unit in day-ahead market (MW). |
| $L^{S}{}_{jt}$ | Power consumed of load in day-ahead market (MW). |
| $P_t^{S,WP}$ | Wind power in day-ahead market (MW). |
| $C^{A}{}_{it\omega}$ | Start-up cost due to change in commitment status of units in day-ahead market and balancing market ($). |
| $P^{G}{}_{it\omega}$ | Power output of unit in balancing market (MW). |
| $L^{C}{}_{jt\omega}$ | Electrical consumed in balancing market (MW). |
| $r^{U}{}_{it\omega}$ | Up-spinning reserve in balancing market (MW). |
| $r^{D}{}_{it\omega}$ | Down-spinning reserve in balancing market (MW). |
| $r^{NS}{}_{it\omega}$ | Non-spinning reserve in balancing market (MW). |
| $r^{U}{}_{jt\omega}$ | Up-spinning reserve from demand-side in balancing market (MW). |
| $r^{U}{}_{jt\omega}$ | Down-spinning reserve from demand-side in balancing market (MW). |

| | |
|---|---|
| $r^{G}_{itm\omega}$ | Reserve deployed from the $m$-th block of energy offered in balancing market (MW). |
| $L^{shed}_{jt\omega}$ | Load shedding (MW). |
| $S_{t\omega}$ | Wind power generation spillage (MW). |
| $f_{t\omega(n,r)}$ | Power flow through line $(n, r)$ (MW). |
| $\delta_{t\omega n}$ | Voltage angle at node . |

### C. Binary Variables

| | |
|---|---|
| $u_{it}$ | Commitment status of units in day-ahead market. |
| $v_{it\omega}$ | Commitment status of units in balancing market. |

### D. Random Variables

| | |
|---|---|
| ${P^{WP}}_{t\omega}$ | Wind power generation in balancing market (MW). |

### E. Constants

| | |
|---|---|
| $\lambda^{SU}_{it}$ | Start-up offer cost of unit ($). |
| $\lambda^{G}_{itm}$ | Marginal cost of the $m$-th block of energy offered ($/MWh). |
| $\lambda^{L}_{jt}$ | Utility of electrical load ($/MWh). |
| ${\lambda^{WP}}_{t}$ | Marginal cost of the energy offer submitted by the wind producer ($/MWh). |
| $VOLL_{jt}$ | Value of loss load for load ($/MWh). |
| ${V^{S}}_{t}$ | Wind spillage cost ($/MWh). |
| $\pi_{\omega}$ | Probability of scenarios. |
| $\bar{P}_{\mathrm{i}}$ | Maximum capacity of units (MW). |
| $\underline{P_i}$ | Minimum power output of generation units (MW). |
| $B_{(n,r)}$ | Absolute value of the imaginary part of the admittance of line $(n, r)$ (p.u.). |
| $\bar{f}_{(n,r)}$ | Maximum capacity of line $(n, r)$ (MW). |

## 2.2. Modeling description

This section is an introduction to the restructured electricity market. As stressed before, electricity markets include new services, they are called ancillary services. In this chapter, only spinning and non-spinning reserves are modeled in the proposed market-clearing problem. Also, two different approaches are used to solve the two-stage stochastic market-clearing problem. The first stage represents a day-ahead market-clearing problem, and the balancing market-clearing problem is described in the second stage. As mentioned before, two approaches were utilized to model the electricity market-clearing problem. In the first one, market-clearing problem is solved sequentially. In this way, the day-ahead electricity market is cleared first, then the balancing market is cleared according to the outputs of the day-ahead market. In the second one, the day-ahead and balancing markets are cleared simultaneously. It should be noted that the uncertainty of decision-making variables is seen only in the second -balancing- stage. In the following subsections, day-ahead and balancing stages of the market-clearing problem are described.

### 2.3. Day-ahead stage

In the proposed day-ahead electricity market model, only energy is cleared between market players as an electricity commodity. Besides, uncertainty is not seen in the day-ahead stage. Thus, an objective function is defined as the social welfare's expected cost which should be minimized in the day-ahead market-clearing problem.

$$EC_{da} = \sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C_{it}^{SU} + \sum_{t=1}^{N_T}\left[\sum_{i=1}^{N_G}\sum_{m=1}^{N_{Oit}} \lambda_{itm}^{G}.\, p_{itm}^{G} - \sum_{j=1}^{N_L} \lambda_{jt}^{L}.\, L_{jt}^{S} + \sum_{k=1}^{N_W} \lambda^{WP}{}_{kt}.\, P_{kt}^{S,WP}\right] \tag{1}$$

The expected cost of the day-ahead market is expressed in Eq. (1) in four terms. The first term represents the start-up cost of units and the second the energy cost of units. The utility of electricity customers and the cost of wind farm energy generation are expressed in third and fourth terms, respectively. Also, there are constraints related to different players of the electricity market that are represented in the following:

Eqs. (2) - (4) represent constraints linked to the power generation of the conventional generation units in the day-ahead electricity market. Specifically, Eq. (2) states maximum and minimum limitations of conventional units' power scheduling. The constraints related to the generation units' energy blocks are expressed in Eq. (3). Moreover, the total scheduled power of a conventional unit in each time period is represented in Eq. (4), its power is equal to the sum of its energy blocks.

$$\underline{P_i}.\, u_{it} \le P^{S}{}_{it} \le \bar{P}_{\mathrm{i}}.\, u_{it}, \quad \forall i, \forall t \tag{2}$$

$$0 \le p_{itm}^{G} \le \bar{p}_{itm}^{G}, \quad \forall m, \forall i, \forall t \tag{3}$$

$$P^{S}{}_{it} = \sum_{m=1}^{N_{Oit}} p_{itm}^{G}, \quad \forall i, \forall t. \tag{4}$$

The following Eqs. (5) - (7) present constraints linked to the start-up cost of the conventional units.

$$C_{it}^{SU} \ge \lambda_{it}^{SU}.\left(u_{it} - u_{i(t-1)}\right), \quad \forall i, \forall t > 1 \tag{5}$$

$$C^{SU}_{i(t=1)} \geq \lambda^{SU}_{i(t=1)}.\left(u_{i(t=1)} - u_{i(0)}\right), \quad \forall i, t = 1 \tag{6}$$

$$C^{SU}_{it} \geq 0, \quad \forall i, \forall t. \tag{7}$$

As seen in Eqs. (2) - (7), conventional units only provide energy as a commodity that can be cleared in the day-ahead market. Moreover, these constraints show that conventional units can be committed by the market operator. Hence, these units are called dispatchable generation units. Eq. (8) expresses the balancing equation between conventional generation units, wind farms, and electrical loads.

$$\sum_{i=1}^{N_G} P^S{}_{it} + \sum_{k=1}^{N_W} P^{S,WP}_t = \sum_{i=1}^{N_L} L^S{}_{jt}, \forall t. \tag{8}$$

As highlighted before, the uncertainty of stochastic variables such as wind power generation is not considered in the day-ahead stage. Therefore, the scheduled power of the wind farm is modeled in a way that limits its maximum and minimum power generation, as represented in Eq. (9).

$$\underline{P}^{WP}_{kt} \leq P^{S,WP}_{kt} \leq \bar{P}^{WP}_{kt}, \quad \forall k, \forall t. \tag{9}$$

### 2.4. Balancing stage

In this stage, both energy and operating reserve services are provided. Energy is supplied by wind farms. However, operating reserves are provided by generation units and electrical customers. In this chapter, only spinning and non-spinning reserves are modeled. Spinning reserves are classified as up-ward and down-ward spinning reserves that can be provided by generation-side and demand-side. However, the non-spinning reserve can be provided only by generation units. Moreover, the uncertainty of stochastic parameters is considered in the balancing stage. Eq. (10) represents the balancing stage's objective function. This objective function expresses the expected social welfare cost of the system in the balancing electricity market.

$$\begin{aligned} EC_b = \sum_{\omega=1}^{N_\Omega} \pi_\omega . \Bigg\{ & \sum_{t=1}^{N_T} \sum_{i=1}^{N_G} C^A{}_{it\omega} \\ & + \sum_{t=1}^{N_T} \sum_{i=1}^{N_G} \sum_{m=1}^{N_{Oit}} \left( C^{R^U}{}_i . r^U{}_{it\omega} + C^{R^D}{}_i . r^D{}_{it\omega} + C^{R^{NS}}{}_i . r^{NS}{}_{it\omega} \right) \\ & + \sum_{j=1}^{N_L} \left( C^{R^U}{}_j . r^U{}_{jt\omega} + C^{R^D}{}_j . r^D{}_{jt\omega} + VOLL_{jt} . L^{shed}_{jt\omega} \right) + \sum_{k=1}^{N_W} V^S{}_t . S_{kt\omega} \Bigg\} \end{aligned} \tag{10}$$

As expressed in Eq. (10), the social welfare's expected cost in the balancing stage includes 8 terms. First line represents the cost caused by changes in the start-up states of generation units in day-ahead and balancing stages. The second line states costs linked to the generation sides up-ward, down-ward spinning, and non-spinning reserves, respectively. Finally, the third line lists the costs of up-ward and down-ward spinning reserves from the demand-side, the load shedding cost, and the spillage cost of wind power generation.

The power generation constraint of generation units in the balancing market is expressed by Eq. (11).

$$\underline{P}_i . v_{it\omega} \leq {P^G}_{it\omega} \leq \bar{P}_{\mathrm{i}} . v_{it\omega}, \quad \forall i, \forall t, \forall \omega. \tag{11}$$

Eq. (12) expresses the balancing of allocated energy in the generation units in the day-ahead and balancing electricity markets, and the operating reserves from the generation-side in the balancing market. As seen in Eq. (12), if the power provided by the generation units in the balancing market is greater than their committed power in the day-ahead market, up-ward spinning, or non-spinning reserves should be committed in the balancing stage. Otherwise, down-ward spinning reserve should be provided by generation units in the balancing stage. It should be noted that non-spinning reserve can be committed only from units that are "OFF" in the day-ahead market as represented in Eq. (15). In other words, spinning reserves can be dispatched when the commitment status of generation units is "ON". Eqs. (15) - (17) state the constraints related to the operating reserve of generation units in the balancing stage.

$${P^G}_{it\omega} - {P^S}_{it} = {r^U}_{it\omega} + {r^{NS}}_{it\omega} - {r^D}_{it\omega}, \quad \forall i, \forall t, \forall \omega. \tag{12}$$

$$0 \leq {r^U}_{it\omega} \leq \overline{R^U}_i . u_{it}, \quad \forall i, \forall t, \forall \omega. \tag{13}$$

$$0 \leq {r^D}_{it\omega} \leq \overline{R^D}_i . u_{it}, \quad \forall i, \forall t, \forall \omega. \tag{14}$$

$$0 \leq {r^{NS}}_{it\omega} \leq \overline{R^{NS}}_i . (1 - u_{it}), \quad \forall i, \forall t, \forall \omega. \tag{15}$$

$${r^U}_{it\omega} + {r^{NS}}_{it\omega} - {r^D}_{it\omega} = \sum_{m=1}^{N_{Oit}} r^G_{itm\omega}, \quad \forall i, \forall t, \forall \omega. \tag{15}$$

$$r^G_{itm\omega} \leq \bar{p}^G_{itm} - p^G_{itm}, \quad \forall i, \forall t, \forall \omega. \tag{16}$$

$$r^G_{itm\omega} \geq -p^G_{itm}, \quad \forall m, \forall i, \forall t, \forall \omega. \tag{17}$$

In the balancing stage, the uncertainty of the power system causes generation units to make new commitments which increase start-up costs in the system. The start-up equation and limitations in the balancing stage are represented with Eqs. (18) - (21).

$${C^A}_{it\omega} = {C^{SU}}_{it\omega} - {C^{SU}}_{it}, \quad \forall i, \forall t, \forall \omega. \tag{18}$$

$${C^{SU}}_{it\omega} \geq \lambda^{SU}_{it} . \left(v_{it\omega} - v_{i(t-1)\omega}\right), \quad \forall i, \forall t > 1, \forall \omega. \tag{19}$$

$$C^{SU}_{i(t=1)\omega} \geq \lambda^{SU}_{i(t=1)} . \left(v_{i(t=1)\omega} - u_{i(0)}\right), \quad \forall i, t = 1 \tag{20}$$

$$C^{SU}{}_{it\omega} \geq 0, \quad \forall i, \forall t, \forall \omega. \tag{21}$$

In Eq. (22), the power balance equation in the balancing stage is represented considering line power flow. In this chapter, the market-clearing is modeled according to the DC optimal power flow problem. In this way, Eqs. (23) and (24) express constraints related to obtaining power flow and its transmission line's capacity, respectively.

$$\sum_{i:(i,n)} P^{G}{}_{it\omega} - \sum_{j:(j,n)} \left(L^{C}{}_{jt\omega} - L^{shed}_{jt\omega}\right) + \sum_{k:(k,n)} \left(P^{WP}{}_{kt\omega} - S_{kt\omega}\right) - \sum_{r:(n,r)} f_{t\omega(n,r)} = 0, \qquad \forall n, \forall t, \forall \omega. \tag{22}$$

$$f_{t\omega(n,r)} = B_{(n,r)}.\left(\delta_{t\omega n} - \delta_{t\omega r}\right), \quad \forall t, \forall \omega. \tag{23}$$

$$-\bar{f}_{(n,r)} \leq f_{t\omega(n,r)} \leq \bar{f}_{(n,r)}, \quad \forall \mathrm{t}, \forall \omega. \tag{24}$$

As pointed out, wind farms are renewable energy resources which are modeled as stochastic power generation units. Although wind power generation in the day-ahead market is modeled on the basis of its maximum and minimum limitation, wind power generation is modeled as a stochastic parameter in the balancing market. Besides, wind power can be spilled in the balancing stage due to economic and technical concerns, as expressed in Eq. (25).

$$0 \leq S_{kt\omega} \leq P^{WP}{}_{kt\omega}, \quad \forall k, \forall t, \forall \omega. \tag{25}$$

In the balancing electricity market, electrical loads can act as interruptible agents. In this case, they present their flexible behavior to decrease or increase their consumption in the balancing stage. Hence, if customers increase their consumption in the balancing market, they act as virtual generation units which decrease their power generation. Hence, this flexible behavior of electrical loads is called down-ward spinning reserve from demand-side. On the other hand, if they decrease their electrical demand in the balancing market, they provide up-ward spinning reserve from the demand-side. The above definitions are represented in Eqs. (26) - (28).

$$0 \leq r^{U}{}_{jt\omega} \leq \overline{R^{U}}_{j}, \quad \forall j, \forall t, \forall \omega. \tag{26}$$

$$0 \leq r^{D}{}_{jt\omega} \leq \overline{R^{D}}_{j}, \quad \forall j, \forall t, \forall \omega. \tag{27}$$

$$L^{C}{}_{jt\omega} - L^{S}{}_{jt} = r^{D}{}_{jt\omega} - r^{U}{}_{jt\omega}, \quad \forall j, \forall t, \forall \omega. \tag{28}$$

Moreover, the portion of loads that is decreased non-voluntarily in the balancing market is called the shed load. The load shedding limitation is represented in Eq. (29).

$$0 \leq L^{shed}_{jt\omega} \leq L^{C}{}_{jt\omega}, \quad \forall j, \forall t, \forall \omega. \tag{29}$$

## 3. Simulation results

This section presents the two approaches that were used to solve the proposed two-stage stochastic market-clearing problem: a sequential approach and a simultaneous approach. A modified 3-bus test system from [28-29] is used to evaluate our study as shown in Fig. 1. Tables 1 and 2 present generation units and system data, respectively. Table 3 shows transmission lines' power capacity. The day-ahead scheduled load is presented in Table 4. Wind power generation, its scenarios and their corresponding probabilities are outlined in Tables 5 and 6, respectively. It should be noticed that uncertainty of the power grid is considered in this case study that its scenarios come from ORR which equals 0.02 for conventional generation units and 0.01 for transmission lines. Besides, the Value Of Lost Load (VOLL) of consumers is supposed to equal 1000. Our stochastic market-clearing problem is model by Mixed Integer Linear Programming (MILP) to solve in GAMS 24.7.4 [31] that has been linked with MATLAB software [32].

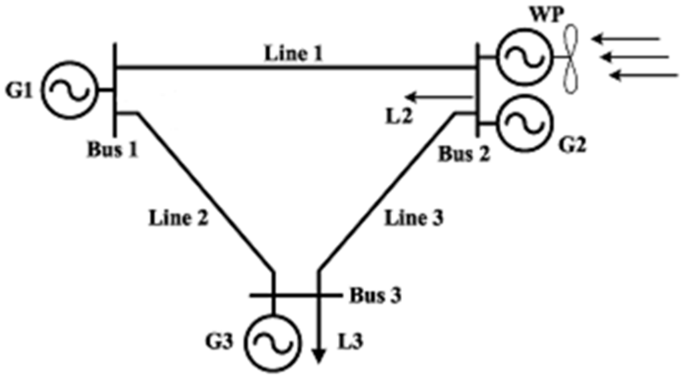

**Figure 1** The 3-bus test system [28-29].

**Table 2** System data in a 3-bus test system [28-30].

| | |
|---|---|
| ${C^{R^U}}_{jt}$ (\$/MWh) | 70 |
| ${C^{R^D}}_{jt}$ (\$/MWh) | 70 |
| $VOLL_{base}$ (\$/MWh) | 1000 |
| Lines reactance (p.u.) | 0.13 |
| Lines capacity (MW) | 55 |
| $P_{base}$ (MW) | 41 |
| $V_{base}$ (kV) | 120 |

**Table 3** Line capacities [28-30].

| Transmission lines | Capacity (MW) |
|---|---|
| Line (1,2) | 10 |
| Line (1,3) | 28 |
| Line (2,3) | 24 |

**Table 4** Day-ahead electrical demand of consumers [28-30].

| | | Time (Hour) | | | |
|---|---|---|---|---|---|
| Consumer (MW) | | t 1 | t 2 | t 3 | t 4 |
| L2 | ${L^S}_{jt}$ | 20 | 60 | 90 | 30 |
| L3 | ${L^S}_{jt}$ | 30 | 80 | 110 | 40 |

**Table 5** Scenarios of wind power generation [28-30].

| Period t | ${P^{WP}}_{t\omega}$ (MW) | | |
|---|---|---|---|
| | As forecasted | High | Low |
| 1 | 6 | 9 | 2 |
| 2 | 20 | 30 | 13 |
| 3 | 35 | 50 | 25 |
| 4 | 8 | 12 | 6 |

**Table 6** Scenarios probabilities of wind Power generation [28-30].

| | ${P^{WP}}_{t\omega}$ (MW) | | |
|---|---|---|---|
| | As forecast | High | Low |
| Probability | 0.6 | 0.2 | 0.2 |

### 3.1. Case 1: Sequential market-clearing model

In case 1, the day-ahead and balancing electricity markets are cleared sequentially. In this way, the day-ahead market-clearing problem is solved independently. Then, the balancing market is cleared according to the outputs of the day-ahead market-clearing problem as shown in Fig. 2. Table 7 presents the expected electrical consumption, load shedding, down-ward and up-ward spinning reserves of consumers in the balancing market. As seen in Tables 4 and 7, the expected consumption of L2 in t1, t2, and t4 in the balancing market which is lower than its scheduled load in the day-ahead market. However, for L3 the day-ahead scheduled demand is greater than its expected consumption in the balancing stage only in t3. If the consumer decreases its demand in the balancing market voluntarily, this quantity of decrement acts as an up-ward spinning reserve from the demand-side. As stated in Table 7, this decrement plays only as the up-ward spinning reserve form L2. However, load shedding occurs in t2 and t3 for L3. On the other hand, if the balancing expected consumption of the electrical consumers is greater than their day-ahead scheduled demand, they play as virtual down-ward spinning reserve providers in the market. As seen in Table 7, while L2 provides down-ward spinning reserve only in t4, the down-ward spinning reserve is provided by L3 in t1, t2 and t4.

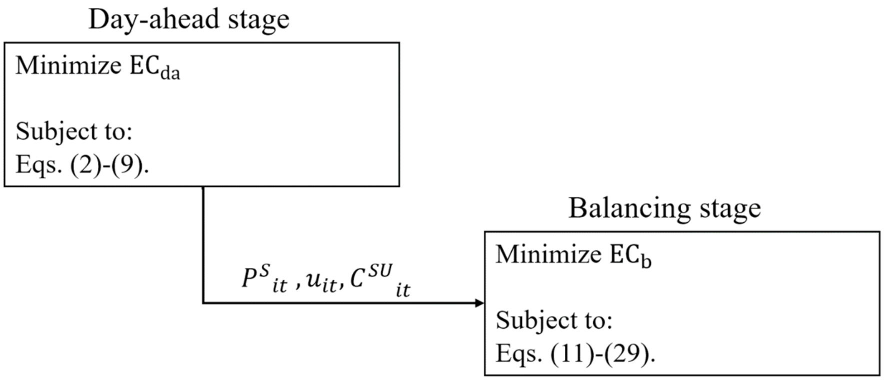

**Figure 2** Stochastic market-clearing procurement in the sequential approach.

**Table 7** Expected demand, load shedding, spinning reserves of consumers in the balancing market of the sequential market-clearing model.

| | | Time (Hour) | | | |
|---|---|---|---|---|---|
| Consumer (MW) | | t 1 | t 2 | t 3 | t 4 |
| L2 | $L^{C}{}_{jt}$ | 18.399 | 54 | 81 | 32.349 |
| | $L_{jt}^{shed}$ | 0 | 0 | 0 | 0 |
| | $r^{D}{}_{jt\omega}$ | 0 | 0 | 0 | 2.375 |
| | $r^{U}{}_{jt\omega}$ | 1.601 | 6 | 9 | 0.025 |
| L3 | $L^{C}{}_{jt}$ | 33 | 87.909 | 101.973 | 44 |
| | $L_{jt}^{shed}$ | 0 | 0.080 | 0.355 | 0 |
| | $r^{D}{}_{jt\omega}$ | 3 | 7.952 | 0 | 4 |
| | $r^{U}{}_{jt\omega}$ | 0 | 0.044 | 8.027 | 0 |

**Table 8** Dispatched power of generation units in the day-ahead market and their expected balancing power generation in the sequential market-clearing model.

| | | Time (Hour) | | | |
|---|---|---|---|---|---|
| Gen. unit (MW) | | t 1 | t 2 | t 3 | t 4 |
| G1 | ${P^S}_{it}$ | 0 | 70 | 100 | 12 |
| | ${P^G}_{it}$ | 0.063 | 33.944 | 31.935 | 12.191 |
| G2 | ${P^S}_{it}$ | 0 | 0 | 15 | 0 |
| | ${P^G}_{it}$ | 0.027 | 37.484 | 64.982 | 8.156 |
| G3 | ${P^S}_{it}$ | 44 | 50 | 50 | 50 |
| | ${P^G}_{it}$ | 45.529 | 49.841 | 49.721 | 49.602 |

Table 8 shows the scheduled power and the expected balancing power generation of the generation units. The difference between the dispatched power of generation units in the day-ahead and balancing markets is allocated to the spinning and non-spinning reserves of the conventional generation units in the balancing stage, as expressed in Eq. (12). As seen in Table 9, G1 provides both up-ward and down-ward spinning reserves in the 4th time period. At first, it seems that these results are not true because the generation units can only provide up-ward or down-ward spinning reserves. However, the results are the expected reserves that are supplied in different scenarios. This means that G1 produces only the up-ward spinning reserve in one scenario, and it provides the down-ward spinning reserve in another one. This occurs in t1, where G1 provides both spinning and non-spinning reserves. In this case, G1 provides only a non-spinning reserve in one scenario, and a down-ward spinning reserve in another one.

**Table 9** Expected allocated operating reserves of generation units in the sequential market-clearing model.

| | | Time (Hour) | | | |
|---|---|---|---|---|---|
| Gen. unit (MW) | | t 1 | t 2 | t 3 | t 4 |
| G1 | ${r^U}_{it}$ | 0 | 0 | 0 | 0.199 |
| | ${r^D}_{it}$ | 36.056 | 0 | 68.065 | 0.008 |
| | ${r^{NS}}_{it}$ | 0.063 | 0 | 0 | 0 |
| G2 | ${r^U}_{it}$ | 0 | 0 | 49.982 | 0 |
| | ${r^D}_{it}$ | 0 | 0 | 0 | 0 |
| | ${r^{NS}}_{it}$ | 0.027 | 37.484 | 0 | 8.156 |
| G3 | ${r^U}_{it}$ | 1.597 | 0 | 0 | 0 |
| | ${r^D}_{it}$ | 0 | 0 | 0 | 0 |
| | ${r^{NS}}_{it}$ | 0 | 0 | 0 | 0 |

### 3.2. Case 2: Simultaneous market-clearing model

In case 2, the joint energy and reserve stochastic market-clearing problem is solved in the day-ahead and balancing electricity markets, simultaneously. The objective function of the simultaneous market-clearing will be total expected cost- sum of day-ahead and balancing stages' objective functions- of that should be minimized as represented in Eq. (30).

$$EC = EC_{da} + EC_b \qquad (30)$$

of that should be minimized as represented in Eq. (30). Hence, the simultaneous market-clearing problem is presented in the following:

Min. $EC$

S.t.

Eqs. (2) - (9), (11) - (29).

Table 10 shows the expected load, load shedding, down-ward and up-ward spinning reserves of consumers in the balancing stage. As seen in Tables 7 and 10, there is no difference between consumers' flexibility behavior in sequential and simultaneous market-clearing models. The dispatched power of the generation units in the day-ahead and balancing electricity markets is represented in Table 11. Also, spinning and non-spinning reserves that are provided by generation units are outlined in Table 12.

**Table 10** Expected electrical demand, load shedding, down-ward and up-ward spinning reserves of consumers in the balancing market of the simultaneous market-clearing model.

| | | Time (Hour) | | | |
|---|---|---|---|---|---|
| Consumer (MW) | | t 1 | t 2 | t 3 | t 4 |
| L2 | $L^{C}_{jt}$ | 18.399 | 55.59 | 81.014 | 32.349 |
| | $L_{jt}^{shed}$ | 0 | 0 | 0 | 0 |
| | $r^{D}_{jt\omega}$ | 0 | 0.398 | 0 | 2.375 |
| | $r^{U}_{jt\omega}$ | 1.601 | 4.807 | 8.986 | 0.025 |
| L3 | $L^{C}_{jt}$ | 33 | 87.909 | 101.973 | 44 |
| | $L_{jt}^{shed}$ | 0 | 0.080 | 0.355 | 0 |
| | $r^{D}_{jt\omega}$ | 3 | 7.952 | 0 | 4 |
| | $r^{U}_{jt\omega}$ | 0 | 0.044 | 8.027 | 0 |

**Table 11** Dispatched power of generation units in the day-ahead market and their expected balancing power generation in the simultaneous market-clearing model.

| | | Time (Hour) | | | |
|---|---|---|---|---|---|
| Gen. unit (MW) | | t 1 | t 2 | t 3 | t 4 |
| G1 | $P^{S}_{it}$ | 0 | 34 | 49 | 12 |
| | $P^{G}_{it}$ | 0.063 | 33.944 | 31.935 | 12.191 |
| G2 | $P^{S}_{it}$ | 0 | 36 | 66 | 0 |
| | $P^{G}_{it}$ | 0.027 | 39.074 | 67.996 | 8.156 |
| G3 | $P^{S}_{it}$ | 44 | 50 | 50 | 50 |
| | $P^{G}_{it}$ | 45.509 | 49.801 | 49.701 | 49.601 |

As seen in Tables 8 and 11, the difference between the day-ahead and balancing power generation of the conventional units in the simultaneous model is lower than the sequential one. Hence, generation units show smoother behavior to provide operating reserves in the simultaneous market-clearing model as shown in Table 12. Hence, this smoother behavior decreases the balancing stage's expected cost in the simultaneous market-clearing model. Furthermore, as shown in Table 13, the total expected cost in the simultaneous market-clearing model is lower than the sequential model proving that the simultaneous model is more efficient than the sequential model.

**Table 12** Expected allocated operating reserves of generation units in the simultaneous market-clearing model.

| | | Time (Hour) | | | |
|---|---|---|---|---|---|
| Gen. unit (MW) | | t 1 | t 2 | t 3 | t 4 |
| G1 | ${r^U}_{it}$ | 0 | 0 | 0 | 0.199 |
| | ${r^D}_{it}$ | 0 | 0.056 | 17.065 | 0.008 |
| | ${r^{NS}}_{it}$ | 0.063 | 0 | 0 | 0 |
| G2 | ${r^U}_{it}$ | 0 | 3.074 | 1.996 | 0 |
| | ${r^D}_{it}$ | 0 | 0 | 0 | 0 |
| | ${r^{NS}}_{it}$ | 0.027 | 0 | 0 | 8.156 |
| G3 | ${r^U}_{it}$ | 1.597 | 0 | 0 | 0 |
| | ${r^D}_{it}$ | 0 | 0 | 0 | 0 |
| | ${r^{NS}}_{it}$ | 0 | 0 | 0 | 0 |

**Table 13** Expected Costs (ECs) in the sequential and simultaneous market-clearing models.

| | Sequential market-clearing model | Simultaneous market-clearing model |
|---|---|---|
| EC ($) | 11,428.803 | 11,243.460 |
| $\mathrm{EC_{da}}$($) | 10,240.000 | 11,110.000 |
| $\mathrm{EC_b}$ ($) | 1,188.803 | 133.460 |

### 3.3. Case 3: Flexibility analysis

In this case, the impact of electrical consumers' flexible behavior is assessed in the simultaneous stochastic joint energy and reserve market-clearing problem. Three different scenarios are studied. In Scenario 1, consumers do not join the balancing market in order to provide spinning reserves. In Scenario 2, consumers act as interruptible loads, in the same way as they did in Case 2. In Scenario 3, we consider that consumers play as shiftable loads in the balancing market as expressed in Eq. (31).

$$\sum_{t=1}^{N_T}\sum_{\omega=1}^{N_\Omega}\pi_\omega\left({r^D}_{jt\omega}-{r^U}_{jt\omega}\right)=0,\quad \forall j,\forall t,\forall\omega. \tag{31}$$

Thus, in Scenario 3 the market-clearing model is represented in the following:
Min. $EC$
S.t.
Eqs. (2) - (9), (11) - (29), and (31).

As shown in Table 14, the worst scenario is Scenario 1 where the total EC of the system is the greatest one. Also, the total expected cost in Scenario 3 in greater than the EC in Scenario 2, because shiftable load constraint gives less freedom to electrical consumers to show their desired flexibility behavior. However, the proposed market-clearing models are solved in a centralized manner by the system operator who is in charge of making policies regarding to Scenarios 1, 2 and 3. In this way, this can be concluded that the efficiency of decision-makings in the electricity markets can be improved if consumers as active agents can decide autonomously based on a decentralized way.

**Table 14** Impact of customers' flexibility behavior on the Total Expected Cost (EC) in the simultaneous market-clearing model.

| | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| EC ($) | 19,837.361 | 11,243.460 | 11,707.427 |

## 4. Conclusion

In this chapter, the two-stage stochastic joint energy and reserve market-clearing problem has been solved. The two stages of the problem are called day-ahead and balancing. Also, two different approaches - sequential and simultaneous – were used in the problem. In the sequential model, the day-ahead stage was solved independently, and the balancing stage was solved on the basis of the first stage's outputs. However, the day-ahead and balancing stages were solved together according to the coupling constraints in the simultaneous market-clearing problem. Furthermore, impacts of electrical consumers' flexibility programs have been assessed in this book chapter. According to our study, the simultaneous market-clearing model is more efficient than the sequential one. This is because the total expected cost in the simultaneous model is lower than the sequential one. Moreover, from the analysis of the flexibility programs, shiftable load constraint increases the total expected cost of the system because it decreases the electrical consumers' freedom to have their desired flexibility behavior. However, both market models with or without shiftable load constraints, improve the efficiency of the electricity market and decrease the total expected cost of the system.

## 5. Acknowledgment

Amin Shokri Gazafroudi, Francisco Prieto-Castrillo, and Juan Manuel Corchado acknowledge the support of the European Commission H2020 MSCA-RISE-2014: Marie Sklodowska-Curie project DREAM-GO Enabling Demand Response for short and real-time Efficient And Market Based Smart Grid Operation - An intelligent and real-time simulation approach ref. 641794. Moreover, Amin Shokri Gazafroudi acknowledges the support of the Ministry of Education of the Junta de Castilla y Leon and the European Social Fund through a grant from predoctoral recruitment of research personnel associated with the research project “Arquitectura multiagente para la gestión eficaz de redes de energía a través del uso de tecnicas de inteligencia artificial” of the University of Salamanca. The work of João P.S. Catalão was supported by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, and UID/EMS/00151/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

## References

[1] Peng Zou, Qixin Chen, Yang Yu, Qing Xia, Chongqing Kang, Electricity markets evolution with the changing generation mix: An empirical analysis based on China 2050 High Renewable Energy Penetration Roadmap, Applied Energy, Volume 185, Part 1, 2017, Pages 56-67.
[2] Project Partner Paul Scherrer Institute of World Energy Council. World Energy Scenarios: Composing energy futures to 2050. Switzerland; Tech. Rep.; 2013.
[3] Energy Research Institute of National Development and Reform Commission. China 2050 High Renewable Energy Penetration Scenario and Roadmap Study. Beijing; Tech. Rep.; 2015.
[4] Antonio J. Conejo, Ramteen Sioshansi, Rethinking restructured electricity market design: Lessons learned and future needs, International Journal of Electrical Power & Energy Systems, Volume 98, 2018, Pages 520-530.
[5] T.R. Karl, J.M. Melillo, T.C. Peterson (Eds.), Global climate change impacts in the United States, Cambridge University Press (2009).
[6] Ardani K, Margolis R. 2010 Solar Technologies Market Report, Tech. Rep. DOE/GO-102011-3318, United States Department of Energy; November 2011.
[7] E.A. DeMeo, W. Grant, M.R. Milligan, M.J. Schuerger Wind plant integration IEEE Power Energy Mag, 3 (2005), pp. 38-46.
[8] J.C. Smith, M.R. Milligan, E.A. DeMeo, B. Parsons Utility wind integration and operating impact state of the art IEEE Trans Power Syst, 22 (2007), pp. 900-908.
[9] E.A. DeMeo, G.A. Jordan, C. Kalich, J. King, M.R. Milligan, C. Murley, et al. Accommodating wind’s natural behavior IEEE Power Energy Mag, 5 (2007), pp. 59-67.
[10] M.R. Milligan, K. Porter, E.A. DeMeo, P. Denholm, H. Holttinen, B. Kirby, et al. Wind power myths debunked IEEE Power Energy Mag, 7 (2009), pp. 89-99.
[11] Denholm P, O’Connell M, Brinkman G, Jorgenson J. Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart, Tech. Rep. NREL/TP-6A20-65023, National Renewable Energy Laboratory; November 2015.
[12] Sawin JL, Sverrisson F, Chawla K, Lins C, McCrone A, Musolino E, et al. Renewables 2014 Global Status Report, Tech. rep., Renewable Energy Policy Network for the 21st Century; 2014.

[13] H. Holttinen, M. Milligan, E. Ela, N. Menemenlis, J. Dobschinski, B. Rawn, et al. Methodologies to determine operating reserves due to increased wind power IEEE Trans Sustain Energy, 3 (October) (2012), pp. 713-723.
[14] Monitoring Analytics, LLC. State of the Market Report for PJM, Independent Market Monitor; 2015.
[15] Nord Pool Spot. Europe’s leading power market [Online]. Available: <http://www.nordpoolspot.com>.
[16] C. Weiller, Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States, Energy Policy, 39 (2011), pp. 3766-3778.
[17] R. Sioshansi, Evaluating the impacts of real-time pricing on the cost and value of wind generation, IEEE Trans Power Syst, 25 (2010), pp. 741-748.
[18] Ela E, Milligan M, Bloom A, Botterud A, Townsend A, Levin T. Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation, Tech. Rep. NREL/TP-5D00-61765, National Renewable Energy Laboratory; September 2014.
[19] Bushnell J, Harvey SM, Stoft S, Hobbs BF. Final Opinion on Payment for Provision of Flexible Ramping, Tech. rep.; 16 August 2011.
[20] B. Wang, B.F. Hobbs, A flexible ramping product: can it help real-time dispatch markets approach the stochastic dispatch ideal? Electric Power Syst Res, 109 (2014), pp. 128-140.
[21] P.N. Biskas, D.I. Chatzigiannis, A.G. Bakirtzis, European electricity market integration with mixed market designs—Part II: Solution algorithm and case studies IEEE Trans Power Syst, 29 (2014), pp. 466-475.
[22] L.C. Chien, W. Lin, Y.C. Yin, Enhancing frequency response control by DFIGs in the high wind penetrated power systems, IEEE Trans Power Syst, 26 (May) (2011), pp. 710-718.
[23] R.G. Almeida, J.A. Lopes, Participation of doubly fed induction wind generators in system frequency regulation, IEEE Trans Power Syst, 22 (August) (2007), pp. 944-950.
[24] N. Aparicio, I. MacGill, J.R. Abbad, H. Beltran, Comparison of wind energy support policy and electricity markets design in Europe, the United States, and Australia, IEEE Trans Sustain Energy, 3 (October) (2012), pp. 809-818.
[25] Y. Lin, J.X. Johnson, J.L. Mathieu, Emissions impacts of using energy storage for power reserves, Appl Energy, 168 (January) (2016), pp. 444-456.
[26] B. Kyle, P. Lincoln, P. Dalia, Economic viability of energy storage systems based on price arbitrage potential in real-time electricity markets, Appl Energy, 114 (October) (2013), pp. 512-519.
[27] G.M. Casolino, G. Liuzzi, A. Losi, Combined cycle unit commitment in a changing electricity market scenario, Int J Electric Power Energy Syst, 73 (2015), pp. 114-123.
[28] A. Shokri Gazafroudi, K. Afshar, N. Bigdeli, “Assessing the operating reserves and costs with considering customer choice and wind power uncertainty in pool-based power market”, International Journal of Electrical Power & Energy Systems, Vol. 67, May 2015, Pages 202-215.
[29] A. Shokri Gazafroudi, M. Shafie-khah, M. Abedi, S. H. Hosseinian, Gh. H. R. Dehkordi, L. Goel, P. Karimyan, J. M. Corchado, J. P.S. Catalão, “A Novel Stochastic Reserve Cost Allocation Approach of Electricity Market Agents in the Restructured Power Systems”, Electric Power Systems Research, 152(C):223–236, July 2017.
[30] Antonio J. Conejo, Miguel Carrion, Juan M. Morales, “Decision making under uncertainty in electricity markets”, International series in operations research & management science, Springer, 2010.

[31] GAMS Release 2.50. A User's Guide; GAMS Development Corporation: 1999. Available online: http://www.gams.com (Accessed 30 January 2018).
[32] The MathWorks, MATLAB. Available online: http://www.mathworks.com (Accessed 30 January 2018).