Formal modelling of the electricity markets: the example of the load reduction of electricity mechanism “NEBEF”

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Abstract. The liberalisation of the electricity market initiated at the beginning of the 21st century has opened it to new parties. To ensure the growth of participants’ number will support the system’s balance, the EU regulation 2019/943 confirms that “all market participants should be financially responsible of the imbalances they cause”. In their respective area, the transmission system operators develops the regulation in compliance with this condition. However, as the regulation takes into account the new realities of the market such as renewables, the interactions between the participants become more complex. One of the risks is that the imbalance of an actor may not be due to its own actions, not complying with the EU regulation then. To analyse this kind of implicit condition, we propose a formal approach to model the exchanges of energy. Using the French regulation as a base, we model the participants and their interactions in the form of symbolic equations using the energy-related terms as variables. In this paper, to illustrate the model we will use to analyse the entire electricity market, we apply it to the NEBEF mechanism only. This mechanism is dedicated to the selling of demand response in France and introduces a third party between the final producer and the final consumer: the demand response operator. We model the mechanism and analyse how the mechanism complies with the balancing responsibility. Our results demonstrate that the mechanism complies with the regulation but there are some limits due to the calculation method of the reference consumption.

1. Introduction

Electricity is a singular good that must be consumed at the time it is produced. When there is as much electricity injected as electricity extracted from the grid, the electricity system is balanced. When it is not the case, the frequency deviates from the operating value and if the deviation is too large, it may damage the electricity devices connected to the grid.

The transmission system operators (TSOs) are charged by the government with management of the electricity system in the area they operate. To perform this task, they can propose changes of the national regulation, and/or new rules to take into account the realities of the market. As part of the European internal market for electricity, the French regulation must comply with the European “Network Codes”, a framework drafted by the European Network of Transmission System Operators for Electricity (ENTSO-E) with parties relevant to its development: EU institutions, regulators, European Union Agency for the Cooperation of Energy Regulations (ACER). The objective of this framework evolves from the liberalisation of the market at the beginning of the 21st century to the transition to a more sustainable energy system with the last package called the “Clean energy for all Europeans” package. To ensure the support of the system’s balance by all actors, the EU Parliament and the EU Council stated...
that “all markets participants should be financially responsible for the imbalance they cause in the system, representing the difference between the allocated volume and the final position in the market” [1].

At the same time, as more and more actors are willing to take part in this market and the regulation takes into account the new realities of the market such as renewables, demand response or real time control, the interactions between the participants become more complex and the domain of responsibility of each of them less distinct. We think that applying the methodology defined by the TSOs to calculate the position of all actors may create relations that pair the actions of an actor to the imbalance of another. The entry of new technologies and their impacts on the stability of the grid has been widely study from an economic point of view to the physical management of the electricity transportation. The economic studies have mainly addressed the balancing mechanisms as a whole with studies on the imbalancing price [2] or from a firm point of view with the optimisation of a portfolio by participating in the balancing mechanisms [3]. These approaches are based on the simulation of the behaviour of the actors. Simulation does not suit the analysis of the TSO’s methodology because the pairing of actions might be hidden in the data. Moreover, the models that support the simulations are rarely explicit.

Consequently, we propose an approach which consists first to model, from the network codes, the exchanges of energy between the electricity market actors and, second, to analyze, from this model, the possible relations that may pair the actions of an actor to the imbalance of another. To illustrate our approach, we apply it to a recent mechanism dedicated to provide the flexibility of consumers to the energy markets thanks to load reductions of consumption. This mechanism is called “Notification d’Échanges de Blocs d’Effacement” (NEBEF) in French and was questioned for its design.

The paper is divided into 3 sections: the presentation of the electricity system, the description of the model and the analysis of the NEBEF mechanism.

2. Electricity System

2.1. Network & actors

The electricity system refers essentially to two layers: the first one is the component layer and the second one is the business layer.

The component layer represents all the physical entities, from the actors to the devices [4]. It consists of the infrastructures to produce, to consume and to transport electricity. The transmission of electricity over long distance at a high voltage is called the transport system whereas the distribution to residential and small industrial consumers is called the distribution system.

The business layer is the representation of the information exchanges from a business point of view. It consists of the different electricity markets. It is usually subdivided into the energy markets that concerns the wholesale markets in one part and into the balancing mechanisms that ensure the stability of the grid in the other part.

The main several actors involved in the electricity market are:

- The producers generate electricity and sell it to suppliers,
- The electricity suppliers buy electricity from producers or other suppliers and sell it to consumers,
- The consumers use electricity and pay suppliers via their bills,
- The market operators provide a service whereby the offers to sell electricity are matched with bids to buy electricity,
- The distribution system operators (DSO) are paid for delivering electricity to consumer and must ensure the stability of the grid in their area. They are in charge of the data in their area,
- The transmission system operator (TSO) is paid for the long-distance transmission of electricity and is charged by the government to ensure the stability of the grid at a national level, according to [5]
- The balance responsible parties (BRP) are financially in charge of the imbalance of their customers.
2.2. System balancing
The stability translates in a nearly perfect equality between the energy injected and the energy extracted every second. The French TSO, called Réseau de Transport d’Électricité (RTE), manages the process to ensure the stability with the involvement of all the others actors, from the long-term grid investments to the invoicing of imbalances.

Between long-term investments and real-time delivery, actors participate to ensure the stability of the grid. Each actor is responsible for the imbalance of his perimeter, defined as the difference between the sum of its injections and the sum of its extractions over periods of thirty minutes. An actor may delegate this responsibility by joining the perimeter of a balance responsible party [6]. Because the actors cannot forecast their consumption and/or cannot control perfectly the production of their plants, the TSO compensates the global residual imbalance by reserving capacities from power plants and activating them when needed.

The actors pays back both the procurement and the activation of the reserves through the billing of their imbalances. They are encouraged to balance their perimeter as much as possible by a higher cost for the use of reserves than the provision of electricity from the wholesale market. The process to determine the imbalance is divided into 3 phases:

1. The planning period or ex-ante period is the period prior to the real-time period of several years before up to one hour before only. The actors forecast their production and consumption and can trade electricity to balance their perimeter as well as possible. The TSO provisions the reserves that will compensate the forecasted imbalance.

2. The real-time period or delivery is a 30-minute period during which each actor tries to produce or consume as he planned to do. During this period, the TSO is the only actor who can intervene to maintain the global balance of the electricity system: he can call actors to activate the reserves they agree to provide.

3. The invoicing period or ex-post period is the period following the delivery period. The TSO calculates the cost of the actions that he made during the real-time period to balance the grid. He also retro-estimates the imbalance of all parties to charge them for the balancing actions.

2.3. A market for consumer flexibilities in France: the NEBEF mechanism
Since 2007 in France, it is possible to sell demand response to the TSO through the adjustment mechanism (“mécanisme d’ajustement”), which is a subpart of the recovery reserve. In 2013, it was enlarged to the markets of energy by the creation of the NEBEF mechanism in order to increase the use of demand response.

The main actor is the demand response operator (DRO) who manages the consumption of his customers and sells the volume that they do not consume thanks to his actions. The DRO operates as a third party between the final producer (the one who produce the electricity for the consumer who offers his flexibility), and the final consumer (the one who buys the volume offered by the operator). The mechanism was designed to respect the process of reserves procurement, i.e. the operator is not necessarily in contract with the same balance responsible party of the consumers that he manages. Consequently, his actions may affect the imbalance of the balance responsible party of the consumers. In this paper, we analyse the relations between the parties involved in the NEBEF mechanism thanks to the model we developed.

3. Modelling

3.1. Introduction: system studied
The proposed model is a simplified representation of the management of the electricity system by RTE. Only the business layer of the system is modelled and a special focus on the imbalance of the parties is made.

According to paragraph C.15.1 of [7], the imbalance of an actor equals the difference between the sum of his injections and the sum of his extractions over periods of thirty minutes.
\[ Imb_{\text{Actor}A} = \sum_{i \in \text{Injections}} (I_i') - \sum_{e \in \text{Extractions}} (E_e') \] (1)

Injection and extraction are defined at the same paragraph in [7]. It can be one of the following energy-related term:

- Production of electricity noted \( P \).
- Consumption of electricity noted \( C \).
- Energy activated for FCR noted \( V_{\text{FCR}} \).
- Energy activated for FRR noted \( V_{\text{FRR}} \).
- Energy activated for RR noted \( V_{\text{RR}} \).
- Energy corresponding to load reduction actions (NEBEF) noted \( V_{\text{LR}} \).
- Energy exchanged through the mechanism designed to declare bilateral exchange of energy. In France, the mechanism is “Programme d’Échanges de Blocs” (PEB). We abbreviate it by \( V_{\text{PEB}} \).
- Energy exchanged at the future markets noted \( V_{\text{FM}} \).
- Energy exchanged at the spot markets noted \( V_{\text{SM}} \).

The model is designed to study how the interactions may affect the balancing position. Therefore, rather than using numeric variables that may result in singular cases, we use symbolic variables. Consequently, the representation of the system by our model is a set of symbolic equations using the energy-related terms as variables.

3.2. Temporal modelling

The RTE’s management is a constant monitoring of the system’s imbalance within different timeframes (from long-term to real-time). RTE takes actions during the ex-ante period to ensure the stability whereas he takes actions during the ex-post period to allocate the volumes to the actors according to the regulation. At the same time, the actors participate in the markets and exchange volumes of electricity. Although these processes are continuous, our model only considerate the electricity system time base in a discrete way, in accordance with the MA-RE rules [7]. We look at the system at two key times of the RTE’s management:

1. The balancing gate closure time, which closes the planning period. At that time, the submission or update of a bid is no longer permitted [8]. The actors have announced their position in the markets and their balance position cannot be modified.
2. The end of the invoicing process for the imbalances of the actors. The actors’ data of energy production and energy consumption have been transmitted to RTE. Then, they were processed to determine the balancing position of all parties. At the end of this process, all the electricity produced and consumed during a thirty-minute period has been divided among the actors.

In our model, when the variables refer to their use in the ex-ante period, they are preceded by the term “ea” (ea_Var as example). When they are in the ex-post period, the term “ep” precedes the name of the variables. Some variables are not related to a specific period. In these cases, the variable is not preceded by any term.

3.3. Actors, Interactions & Mathematical representation for the use case

Our model represents only two groups of entities defined by the legislation. The first group is the actors and the second one, the markets.

In our use case nine actors participates in the system through two markets. There are two producers, two consumers and a demand response operator. All of them delegate their balancing responsibility to three different balance responsible parties. Some of them participate in a spot market and only the demand response operator participates in the NEBEF mechanism. They also are all supervised by RTE, the transmission system operator. Figure 1 resumes the interactions between the actors.
3.3.1. **Actors.** For each actor, one or several equations represent how the different volumes of energy are accounted in his perimeter and how they are calculated. When two actors have a different vision of a variable, the abbreviation of the actor is added to the subscript of the variable. For example, if the actor A determines the value of the variable VAR, we refer to it as VAR\textsubscript{A} and if the actor B forecasts another value for the variable, we refer to it as VAR\textsubscript{B}.

We name the two producers Producer 1 and Producer 2. The balancing position of a producer X is represented by the equation:

\[ Imb_{PX} = +PX \]  

They produce electricity for the two consumers. The consumer 1 is a consumer who is in charge of several sites. The consumer 1 offers the flexibility that one of his site can provide. The following equation represents the consumer 1:

\[ F1 = C1_O + C1_{SA\text{adj}} \]  

C\textsubscript{1O} and C\textsubscript{1SA\text{adj}} represent respectively the physical consumption of the other sites and the adjusted consumption of the site who offers his flexibility. The adjusted consumption represents the sum of the physical consumption and of the calculated adjustments made. An adjustment is a voluntary change in consumption in order to provide balancing resources or to offer flexibility through the NEBEF mechanism. In the use case, we abbreviate the flexibility offered by the consumption site by C\textsubscript{1F}.

The consumer 2 does not offer the flexibility of his consumption sites to the markets. The variable C\textsubscript{2} represents the whole consumption from these sites. The balancing position of both consumers is:

\[ Imb_{C1} = -F1 \text{ for the consumer 1} \]  
\[ Imb_{C2} = -C2 \text{ for the consumer 2} \]  

The consumer 1 delegates the load-reduction management to a DRO. The DRO, when it is financially attractive, sells the energy not consumed thanks to the load-reduction actions to the energy market. The global volume of load reduction, noted V\textsubscript{LR}, is considered as an injection and the volume sold, noted V\textsubscript{SM}, as an extraction in his balancing perimeter. It gives the equation:

\[ Imb_{DRO} = V_{LR} - V_{SM} \]  

In our use case, the demand response operator is in charge of one site only. Consequently, the volume of energy not consumed thanks to his actions equals the volume of flexibility offered by the site. It means:

\[ V_{LR} = C1_F \]

The balancing position of a balance responsible party equal the sum of the imbalances of the parties who delegate it to him.

\[ Imb_{BRP} = \sum_{imb \, x \in \text{actor } X} Imb_{x} \]  

For the use case, we suppose that three balance responsible parties are involved. The producer 1 and consumer 1 have the same BRP. We name it BRP\textsubscript{1}. It gives the equation:
\begin{equation}
I_{mb}^{BRP1} = P1 - F1
\end{equation}

The producer 2 and consumer 2 have the same balance responsible party, named BRP 2. We suppose that the producer 2 cannot produce as much as the consumer 2 needs, the BRP 2 has to buy the missing volume to the market. We suppose that BRP2 buys the volume \( V_{SM} \) to the DRO to this aim. The volume bought counts as an injection. It gives the equation:
\begin{equation}
I_{MB}^{BRP2} = P2 + V_{SM} - C2
\end{equation}

We suppose that the BRP 3 is in charge of the demand response operator only. Thus, his balancing position is the same as the demand response operator. Despite the activation by RTE of the reserves, noted RES, there is still a global residual imbalance, abbreviated NET. From a global point of view, the systems imbalance is summed up by the equation:
\begin{equation}
NET = \sum_{BRP \in BRPs} I_{mb}^{BRP} - RES
\end{equation}

For the use case, we divide the sum above in two parts. One represents the imbalance of the BRPs participating in the use case. We use the abbreviation \( I_{mb}^{BRP123} \) in the model. The other one represents the imbalance of all the other BRPs who are active in one of the electricity markets. We use the abbreviation \( I_{mb}^{BRPs} \). We obtained the following equation:
\begin{equation}
Net = I_{mb}^{BRP123} + I_{mb}^{BRPs} - Res
\end{equation}

3.3.2. Markets & mechanisms. The second part of our model is the markets. A market defines specific relations between the actors that are modelled by one or several equations.

The first market we look at is the spot markets, throughout which actors can sell load reduction declared by the NEBEF mechanism. On these markets, the producers offer to sell electricity and the consumers bid to buy electricity. Once there is a match between an offer and a bid for a certain quantity at a certain price, the contract cannot be modified. In particular, the quantity of energy used for the calculation of the imbalance during the invoicing process is the same as the one contracted. In term of equation, it means:
\begin{equation}
e_{a} \cdot V_{SM} = e_{p} \cdot V_{SM}
\end{equation}

The other market we look at is the NEBEF mechanism. The mechanism links the consumption of the consumers and the volume produced by the operator. During the ex-ante period, the demand response operator determines the electricity that will be consumed by the site, \( C_{1s} \), according to the reference consumption, \( C_{1ref} \) and the reduction of consumption he plans to do, \( C_{1f} \). It means:
\begin{equation}
e_{a} \cdot C_{1s} = e_{a} \cdot C_{1_{ref, DRO}} - e_{a} \cdot C_{1f}
\end{equation}

For the invoicing process, the calculation is based on the physical data and the reference consumption. It means:
\begin{equation}
e_{p} \cdot C_{1f} = C_{1_{ref}} - e_{p} \cdot C_{1s}
\end{equation}

There are three different configurations for the invoicing process of the consumer site. We assume the site is in the “télérélevé au modèle régulé” configuration. “Télérélevé” means that the data are issued from TSO’s certified metering installations with a real-time transmission. “Régulé” is the method to compensate the load reduction to the supplier financially.

The configuration also specifies how the load reduction is accounted in the perimeter of the balance responsible party in charge of the consumer. In terms of modelling, it means that the reduction of consumption is added to the physical consumption \( C_{1s} \), and not directly to the imbalance of the BRP. It gives us the equation:
\begin{equation}
e_{p} \cdot C_{SA_{ Adj u}} = e_{p} \cdot C_{S} + e_{p} \cdot C_{1f}
\end{equation}

Moreover, the NEBEF mechanism was designed to ensure the demand response operators can work independently from the supplier. In our use case, one consequence is the information about a load reduction is not transmitted to the supplier. But we suppose that the supplier has access to the historical data of the sites that he supplies.

Figure 2 summarises the relations between the actors from a business point of view.
3.4. Method of analysis
The model aims at providing a base for a formal analysis of the exchanges of energy between the parties involved. We formalise the balancing responsibility of an actor into mathematical conditions that have to be observed.

3.4.1. Formalisation of Balancing Responsibility. The balancing responsibility means that an actor is responsible financially for the actions he takes. We state that it corresponds to two conditions. The first condition that must be observed is the possibility for the actor to be perfectly balanced at the end of the invoicing process. It means his balancing position must be equal to zero in the case of perfect actions (i.e. he acts “perfectly”). The actions are the forecasts for the ex-ante periods and the production and consumption according to his forecasts/schedules for the real-time period. The second condition refers to the actions of an actor to another. It means the actions of an actor must not imbalance another one. To verify the condition, we introduce the concept of error. An error is either a forecast different from the consumption physically extracted, either a consumption or production different from the schedule. We state that the condition is verified if the error is contained in the perimeter of the actor and of his balance responsible party. In particular, the error must not spread to other actors.

3.4.2. Steps of the NEBEF analysis. To analyse the compliance of the NEBEF with the balancing responsibility, we broke down the analysis into two phases. In the first one, we assume all the actors act perfectly. If the NEBEF is well designed, the imbalances of the balance responsible parties should equal zero. In that case the NEBEF complies with the first condition. In the second one, we focus our analysis to the actions of the demand response operator because of his position as a third party. We assume all the actors act perfectly, except the demand response operator. The mechanism complies with the second condition if the error is contained to the imbalance of the BRP.

4. Results
To analyse the system, the set of equations that represents the system must be determined. The choice of the variables as parameter imitates the actor’s management. For the two periods, the parameters are the injections and extractions of all parties except C1S for the ex-ante period and VLR for the ex-post
period. Consequently, the dependent variables are the imbalances of the balance responsible parties and the residual imbalance.

Table 1 summarises the variables that are used for the use case.

| Variable | Definition | Variable | Definition |
|----------|------------|----------|------------|
| P1       | Electricity generated by P1’s power plants | P2       | Electricity generates by P2’s power plants |
| F1       | Electricity supplied to consumer 1 | C2       | Electricity supplied to consumer 2 |
| C1O      | Electricity consumed by the sites not offering flexibility | ImbBRPs | Sum of the imbalances of the BRPs who are not involved in the use case |
| C1S      | Electricity consumed by the site providing flexibility | ImbBRP123 | Sum of the imbalances of the BRPs 1, 2 and 3 |
| C1Adju   | Adjusted consumption of the site providing flexibility | ImbBRP1 | Imbalance of the balance responsible party 1 |
| C1F      | Volume of flexibility provided by the site offering its flexibility | ImbBRP2 | Imbalance of the balance responsible party 2 |
| VLR      | Global volume of load reduction made by the DRO | ImbBRP3 | Imbalance of the balance responsible party 3 |
| Res      | Reserves activated by the TSO to stabilise the grid | Net | Global residual imbalance on the grid |

For the ex-ante period, we obtain the relations between the variables presented in the Table 2.

| Variable | Value at the gate closure time | Variable | Value at the gate closure time |
|----------|--------------------------------|----------|--------------------------------|
| P1       | ea_P1                          | P2       | ea_P2                          |
| F1       | ea_C1O + ea_C1Adju            | C2       | ea_C2                          |
| C1O      | ea_C1O                         | C1Adju   | ea_C1Adju                      |
| C1S      | ea_C1Adju                      | VLR      | VSM                            |
| VLR      | ea_VLR                         | C1ref    | C1refDRO                       |
| C1ref    | C1ref                          | ImbBRP   | ea_Res                         |
| ImbBRPs  | ea_ImbBRPs                    | ImbRE1   | ea_C1O + ea_C1Adju + ea_P1    |
| ImbRE2   | ea_C2 + ea_P2 + ea_VSM        |         |                                |

Table 2 shows that the imbalance of the balance responsible parties depends on different variables for each of them at the gate closure time.

For the BRP 1, the electricity supplied to consumer 1 and the electricity production scheduled to producer 1 are the variables that determine the forecast of the imbalance of the balance responsible 1.
For the BRP2, the electricity supplied to consumer 2, $C_2$, the electricity production scheduled by producer 2, $P_2$, and the electricity bought during the short-market period, $V_{SM}$ are the variables that determine the imbalance of the balance responsible 2.

Finally, the electricity sold to a spot market, $V_{LR}$, and the reduction of consumption that the DRO plans to do, $V_{SM}$, are the variables that determine the imbalance of the BRP3.

Table 3. System of equations solved for the ex-post period

| Variable | Value at the end of the invoicing process | Variable | Value at the end of the invoicing process |
|----------|------------------------------------------|----------|------------------------------------------|
| $P_1$    | $ea_{-P_1}$                              | $P_2$    | $ea_{-P_2}$                              |
| $F_1$    | $ea_{-F_1}$                              | $C_2$    | $ea_{-C_2}$                              |
| $C_1_{o}$| $ea_{-C_1_{o}} + ea_{-C_1_{ref}}$        | $C_1_{s}$| $ea_{-C_1_{s}}$                          |
| $C_1_{r}$| $ea_{-C_1_{r}}$                          | $C_1_{f}$| $ea_{-C_1_{f}}$                          |
| $V_{LR}$ | $ea_{-V_{LR}}$                           | $V_{SM}$ | $ea_{-V_{SM}}$                           |
| Imb_{BRP} | $ea_{-Imb_{BRP}}$                        | Res      | $ea_{-Res}$                             |
| Imb_{BRP} | $ea_{-Imb_{BRP}} + ea_{-P_1}$             | Imb_{BRP} | $ea_{-Imb_{BRP}} - ea_{-P_1}$ + ea_{-P_2} + ea_{-V_{SM}} |

Table 3 summarises the relations at the end of the invoicing process. The imbalances of the balances responsible parties do not depend on the same variables.

For the balance responsible party 1, the electricity produced by producer 1, $P_1$, the electricity consumed by the other sites, $C_{1_{o}}$ and the reference consumption, $C_{1_{ref}}$ are the variables that determine the imbalance of the balance responsible 1.

For the balance responsible party 2, the electricity consumed by consumer 2, $C_2$, the electricity produced by producer 2, $P_2$, and the electricity bought during the short-market period, $V_{SM}$, are the variables that determines the imbalance of the balance responsible 2.

Finally, the electricity sold to a spot market, $V_{SM}$, the reference consumption, $C_{1_{ref}}$, and the energy extracted by the site offering flexibility, $C_{1_{s,c1}}$, are the variables that determines the imbalance of the balance responsible 3.

4.1. Feasibility to balance its perimeter

The first phase of the analysis is to verify the first condition. In this phase, we assume the actors act perfectly. It mean that:

- The producer produces the exact quantity contracted with the suppliers.
  \[ ea_{-P_1} = ea_{-F_1} \]  
  \[ ea_{-P_1} = ea_{-P_1} \]  
  \[ ea_{-P_2} = ea_{-C_2} \]  
  \[ ea_{-P_2} = ea_{-P_2} \]  

- The consumption of the consumer 2 equals the forecast made in the ex-ante period.
  \[ ea_{-C_2} = ea_{-C_2} \]  

- The demand response operator plans to reduce the consumption of its customers as much as he sells to the market.
  \[ ea_{-V_{LR}} = ea_{-V_{SM}} \]
Moreover, he perfectly reduces the consumption according to his schedule.

\[ e_p \_C1 \_s = e_{a \_C1 \_s} \]  

- The BRP 2 buys the quantity of electricity missing between its production and its consumption

\[ e_{a \_C2} = e_{a \_P2} + e_{a \_VSM} \]  

- RTE forecasts the imbalance of the others BRPs perfectly and the procurement and the activation of reserves compensates the sum of their imbalance

\[ e_{a \_RES} = e_{a \_Imb_{BRPs}} \]

Table 4 presents the value of the BRPs’ imbalance after the simplifications that have been applied to the system.

| Variable | Value at the end of the invoicing process |
|----------|------------------------------------------|
| Imb_{BRP1} | \( e_{a \_C1 \_SAdj} - C1_{ref} \) |
| Imb_{BRP2} | 0 |
| Imb_{BRP3} | 0 |

When all the actors act perfectly, the balance responsible party 2 and 3 are perfectly balanced. It means that other actors do not affect them and the first condition is observed for both actors.

This is not the case for the balance responsible party 1. The imbalance is the difference between the forecast made by the supplier, \( e_{a \_C1 \_SAdj} \), and the reference consumption, \( C1_{ref} \). To study how it may affect the balance responsible 1, we discuss the four manners the reference consumption is determined and what it changes for the balance responsible 1.

4.2. Discussion about the reference consumption

There are four methods to calculate the reference consumption. All of them are based on the previous consumption of the site and differ mainly on the period considered to calculate the reference consumption. Each method and the conditions are explained in [9].

4.2.1. Reference consumption by forecast. In that case, the reference consumption is a scheduled consumption sent to the TSO by the demand response operator. There are no restrictions for the power values but it is compared to the historic consumption. If it deviates too much from the reality, the operator loses the possibility to send schedules. Therefore, there are no law-based relations between the reference consumption, \( C1_{ref} \), and the forecast made by the supplier, \( C1_{SAdj} \).

The difference between both values is considered the responsibility of the supplier even though he does not manage both. If he perfectly performs as he planned but his planning is different from the operator’s schedule, he will be imbalanced. Consequently, the first condition is not respected.

4.2.2. By average or median. In that case, the reference consumption is the average or median of previous periods. It could be the same period of the week for the four previous weeks or the same period of the day for the ten previous days.

In this case, the supplier cannot balance his position in the ex-ante period because his forecast is not necessarily equal to the average/median of the previous periods.

The mechanism does not comply with the first condition. To solve it, the supplier must know that a load reduction will happen during the week and must only buy the quantity corresponding to the reference consumption.

4.2.3. Double-corrected reference rectangle method. In that case, the reference consumption is the minimum between the average power over the period preceding the load reduction period and the average power over the period following the load reduction period.
The first condition is respected as long as the reference consumption is typical of the consumption that would have happened without the load reduction.

4.2.4. **Algebraic rectangle site-by-site method.** This method is applied to demand response aggregators only. The reference consumption is calculated over the period of 10 minutes preceding the period of load reduction and the reference value is the average power. The period of load reduction is either several 10-minute periods separated by a 20-minute period, or a 30-minute period.

Like the previous method, it is based on the consumption close to the period of load reduction. Consequently, it respects the first condition as long as the reference is typical of the consumption.

4.2.5. **Analysis of an error made by the demand response operator.** The second part of our study is the introduction of an error from the demand response operator and the analysis of its spreading into the system. The demand response operator can make two kinds of error:

1. The operator forecasts a reference consumption different from the one calculated by the TSO.

   It gives the following equation:
   \[
   C_{1ref} = C_{1ref,DRO} \pm Err
   \]  
   \(26\)

2. The operator does not control the reduction of consumption perfectly as planned.

   \[
   ep.C_{1S} = ea.C_{1S} \pm Err
   \]  
   \(27\)

The introduction of an error of prevision results in the relations presented in Table 5.

### Table 5. Propagation of the error of prevision

| Variable  | Value at the end of the invoicing process | Variable  | Value at the end of the invoicing process |
|-----------|------------------------------------------|-----------|------------------------------------------|
| P1        | ea.C1_{1,0} + ea.C1_{sadju}              | P2        | ea.P2                                    |
| F1        | ea.C1_{1,0} + ea.C1_{ref}                | C2        | ea.C2                                    |
| C1_{0}    | ea.C1_{0}                                | C1_{sadju} | C1_{ref}                                |
| C1_{S}    | C1_{ref} - ea.C2 + ep.Err + ea.P2        | C1_{f}    | ea.C2 - ep.Err - ea.P2                  |
| V_{LR}    | ea.C2 - ep.Err - ea.P2                   | V_{SM}    | ea.C2 - ea.P2                            |
| C1_{ref}  | C1_{ref}                                 | C1_{ref,DRO} | ep.C1_{ref,DRO}                        |
| Imb_{BRPs}| 0                                       | Res       | 0                                        |
| Imb_{RE1} | - C1_{ref} + ea.C1_{sadju,C1}           | Imb_{RE2} | 0                                        |

| Variable  | Value at the end of the invoicing process |
|-----------|------------------------------------------|
| Imb_{RE3} | - ep.Err                                 |
| Imb_{BRP123}| - C1_{ref} + ea.C1_{sadju,C1} - ep.Err |
| Net       | C1_{ref} - ea.C1_{sadju,C1} + ep.Err    |

Our results show that the error is contained to the responsibility domain of the demand response operator. Consequently, the NEBEF mechanism complies with the second formal condition we introduce.

### 5. Conclusion

In the paper, we present a model whose objective is to analytically study how the design of the exchanges made by the TSOs complies with the EU’s legislative framework. The model simplifies the management of the electricity system by a TSO from a business point of view.

Only two entities are defined in the model: the actors and the markets. They are represented by one or several equations with the energy-related terms as variables. The variables are symbolic in order to study how they can spread across the system because of the interactions between the actors. The equations are a translation and an interpretation of the rules and must be challenged with other models for the management of the electricity system.
Another simplification is the discrete representation of the system at two steps of the continuous process only. The first step is the gate closure time and the second one is the end of the invoicing process.

In the paper, we apply our model to the NEBEF mechanism in order to analyse its compliance with the principle of balancing responsibility. The formalisation of the principle translates into two conditions. The first condition is the possibility for a balance responsible party to balance its perimeter at the end of the invoicing process if he perfectly acts according to his schedule. The second condition is the spreading of an error made by an actor. The error should only affect the balance responsible in charge of the actor. We demonstrate that the NEBEF always complies with the second condition. The balancing position of the balance responsible party in charge of the consumer who provide his flexibility cannot be imbalanced due to an error made by the demand response operator.

However, the mechanism does not comply with the first condition because of the calculation method of the reference consumption. If the demand response operator forecasts the reference curve and the balance responsible party does not know the reference consumption, the latter cannot balance his perimeter even if he performs perfectly.

For the other methods, the limit is the adequacy of the reference consumption to be representative of the consumption that would have occurred without the reduction of consumption.

We conclude that the NEBEF mechanism reproduces the physical consumption as accurately as possible but presents some limits due to the calculation methods of the reference consumption.

6. References
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