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► **To cite this version:**

Hélène Le Cadre, Jean-Sébastien Bedo. Distributed Learning versus Information Sharing in the Smart Grid: A Learning Game Approach. 2012. hal-00740893v2

HAL Id: hal-00740893

<https://hal.science/hal-00740893v2>

Preprint submitted on 6 Mar 2013 (v2), last revised 15 Mar 2016 (v9)

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Distributed Learning versus Information Sharing in the Smart Grid: A Learning Game Approach

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Abstract

In this article, the smart grid is modeled as a decentralized and hierarchical network, made of three categories of agents: producers, providers and microgrids. To optimize their decisions concerning the energy prices and the traded quantities of energy, the agents need to forecast the energy productions and the demand of the microgrids. The biases resulting from the decentralized learning heavily affect the smart grid performance. Indeed, at their individual level, providers and producers incur additional costs in case where they cannot meet their consumer demand. We prove that there exist prices that provide to the producers a guarantee to avoid penalties, reporting all the risk on the providers. Furthermore, the providers can minimize their average regret by sharing information and coordinating forecasts. The results on a toy network confirm the theory: information sharing between the intermediary agents minimizes the average regret. As output of the simulations, we observe that the convergence rates of the collaborative learning strategy, where providers share their information through a grand coalition, are clearly superior to rates resulting from distributed learning, using external and internal regret minimization.

Keywords: Distributed Learning; Information; Regret; Learning Game Theory

1 Introduction

Smart grids are networks enabling a decentralized storage of the energy and involving bidirectional energy flows which are controlled by a complex, global and secured communication network. The network is said to be smart because it is capable of integrating

efficiently each agent's action (producers, providers and end users) in order to guarantee a sustainable and secure supply at lower cost. The main challenges associated with the smart grid operation are:

- *To facilitate the integration of the decentralized and intermittent productions such as renewable energies.* Examples of renewable energy sources are wind, solar, geothermal, biomass, small hydroelectric facilities, etc. Their productions are highly unpredictable since they depend on uncontrollable exogenous factors like level of wind, sunshine, strength of the ocean currents, etc.
- *To get active the end user within the electrical system by allowing him to become a producer.* The electrical network based on the smart grid model is composed of a multitude of microgrids. Microgrids are modern, small-scale versions of the centralized electrical system [10], [13]. They can be either sellers in case where they have a surplus of power to transfer, or buyers in case where they need to buy additional power to meet their demand [22], [23].
- *To provide the end user with a set of signals allowing its effective steering consumption.* The end user consumption can be adapted online, by following the variations of the energy price, through an interface such as a smart phone or boxes deployed in houses, or, automatically. In this latter case, end users define in their contract, the price level above which the provider should trigger demand response.
- *To significantly reduce the environmental footprint of the electrical system.* This requires the optimization of the energy mix so as to reduce the carbon emissions [7] and the efficient planning of investments in capacities and research and development effort [27].

In Europe and in France especially, traditional electrical networks rely on nuclear based energies [10]. In case of non renewable energies, the production level can be adapted by the plant operator who alternates openings and closings and optimizes the duration of the switches between both modes. The objective then, is to adapt the production level so as to meet the uncertain demand level. We have built a first model in [12], where two learning strategies based on tit for tat and fictitious play are used to adapt the production level to meet the demand level. In this context, the distributed learning algorithms can be used as distributed control algorithms. They provide analytical expressions of the service providers' loss resulting from their predictions.

In case of renewable energies, the production level can be partially controlled, for instance, by adapting the windturbine speed. Wind energy is the fastest growing renewable energy source in the world [2]. It is increasingly apparent that current forecasting technology cannot properly handle extreme situations corresponding to either extreme weather phenomena or critical periods for power system operation. Forecasting methods used to predict windpower were mostly designed to provide point forecasts of expected productions. Only recently, probabilistic methods have been introduced to provide estimations of the entire distribution of future productions [2]. In such methods, forecasts may take the form of either quantile estimations or density estimations [5], [9]. In this latter case, the justification of the fitting of a specific parametric density

function requires the game designer to learn at least its parameters. In the statistical learning literature, there are three major learning approaches, each one of them corresponding to a particular abstract learning task. These are: supervised learning, unsupervised learning and reinforcement learning [4], [26]. Learning based on regret minimization as described in [4], belongs to this category. These learning approaches are particularly efficient. Indeed, the performance criterion being based on regret, it enables to handle extraordinary general processes called random individual sequences which need not to have a probabilistic structure. Furthermore, we observe in [11], [14] that the performance resulting from learning based on regret minimization tested on real data bases measuring household energy consumption and road occupancy rates, are clearly superior to the ones obtained using supervised learning approaches. The method provides as an output a density function which associates a weight to each possible outputs (here, the levels of production). The density function is updated by merging informations from various sensors which measurement data take into account exogenous events. As a result, it is more robust to extreme events and appears as particularly well suited to model quite erratic processes such as renewable energy production.

Taking an engineering point of view, the management of the smart grid requires the exchange of big data flows resulting from the monitoring of the end user consumption, from the online updates of the energy price, from the negotiations which occur in the market place, etc. The decentralized structure of the smart grid increases further the quantity of exchanged data. Information and Communication Technologies (ICTs) will be used to retrieve the most pertinent information from the big data flows and train forecasters to provide efficient predictions about the end users' demand and about the energy productions. These predictions will then be used as inputs to optimize the smart grid behavior. It seems fundamental to address the following research questions:

- How will the biases, introduced by the errors made by the agents in their predictions, affect the smart grid behavior ?
- Will information sharing improve the whole smart grid performance and should therefore be encouraged by the regulator ?

There is a number of well-understood reasons why regulator often does not allow horizontal collaboration in industries like the telecommunications or the energy sector. If service providers are allowed to coordinate, they might collude to raise the price i.e., reducing quantity below the efficient baseline, and create market power [6]. Alternatively, service providers might collude to reduce quality of service. Courts punish explicit agreements whose objectives are clearly to decrease the competition [1]. Most coordination mechanisms studied in the literature, leads to price or quality of service alignment. To our knowledge the impact of information sharing and the forecast alignment while prices are individually determined, has not been studied so far. Besides, collaboration might not be possible due to the agents' natural incentives to cheat and to deviate from the cooperative equilibrium.

The existing literature on distributed learning primarily focuses on distributed learning algorithms that are suitable for implementation in large scale engineering systems [15], [20], [26]. The results mainly concentrate on a specific class of games, called games of potential [24]. This class of games is of particular interest since they have

inherent properties that can provide guarantees on the convergence and stability of the system. However, there exist some limitations to this framework. The most striking one is that it is frequently impossible to represent the interaction framework of a given system as a potential game [17]. The learning game studied in this paper belongs to the category of repeated uncoupled games since one player cannot predict the forecasts and so actions of the other agents at a given time period. To take his decision i.e., optimal prices and energy orders, each agent is aware of the history of forecasts of all the agents and of his utility. Recent work has shown that for finite games with generic payoffs there exists completely uncoupled learning rules i.e., rules where the agents observe only their own prediction history and their utility, that lead to Nash equilibria that are Pareto optimal [20]. Marden et al. exhibit a different class of learning procedures that lead to Pareto optimal vector of actions that do not necessarily coincide with Nash equilibria [17]. A well-known illustration of the practical interest of Pareto optimality can be found in the prisoner dilemma where the Nash equilibrium is inefficient compared to the Pareto optimum that would be obtained if the prisoners had cooperated [18]. However, one serious concern regarding Pareto optimality is that the optimum is generally not unique and deciding which one should be implemented by the system might in some cases, require contracts, communication or bargaining mechanisms to be designed at the beginning of the game. Of course this is not always the case, as proved in [17] and [20].

The article is organized as follows. In Section 2, we introduce the economic basis of our model, the agents and their utilities. Then the complete information Stackelberg game is solved in Section 3 proceeding by backward induction. We derive analytically the optimal prices and energy orders for the agents. Partial information is introduced in Section 4 where the interacting agents learn in a distributed fashion hidden individual sequences. Using the theoretical results obtained in the previous sections, we explain how to simulate the smart grid behavior in Section 5 and an illustration of the previously derived theoretical results is provided for a toy network.

2 The model

The number of agents interacting in the smart grid is large. In this article, we model the smart grid as a three layer hierarchical network which evolution depends on the interactions between the agents composing each layer and also, on the ability of the agents to cope with unexpected random events resulting in renewable energy production and microgrid demand variations. We detail the three main categories of agents and the economic relations between them in Subsection 2.1. Then, we go deeper in the agents individual characterization to identify the decision variables, the information available to each agent and their utility. The mathematical formulations of the agents' optimization programs are set in Subsection 2.2. Finally, the repeated game which captures the interactions between the three layers of the hierarchical network, is described in Subsection 2.3.

2.1 Description of the agents

We model the smart grid through three categories of agents: the microgrids, the service providers and the energy producers.

The end users generate some energy demand, and fulfill it either by buying energy to a service provider or by finding alternatives (solar panels, more efficient appliances, etc.). Each service provider has the possibility to buy energy to all energy producers, transport and resell it to the end users. Each energy producer produces and sells energy to all service providers.

We assume that each end user contracts with only one service provider and does not churn from one service provider to another during all the period of our study. This assumption holds well if we consider local or regional utility companies for example. In this sense, the set made of end users attached to a single service provider can be seen as an individual microgrid, as defined in [13], [22], [23] and recalled in the Introduction. We denote by $(s_i)_i$, with i varying between 1 and n , the i -th service provider and by \mathcal{M}_i the corresponding group of end users. The energy producers are denoted $(e_k)_k$ with k varying between 1 and K . The energy producers can be associated with nuclear plants, photovoltaic park managers, wind farm administrators, etc. The produced energy is supposed renewable. Non-renewable energy producers like nuclear plants might be integrated into the grid. It requires to use distributed control rules as the ones described in [12], [17]. In this article, we consider exclusively renewable energy producers.

The economic relations between the agents in the grid is pictured in Figure 1. The symbol \$ is used to represent the directed financial transfers between the involved agents.

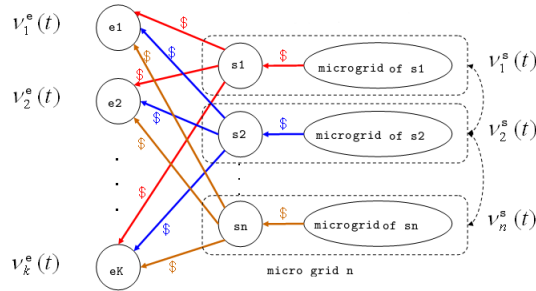


Figure 1: Economic relations between the agents in the grid.

2.2 Optimization program for each agent

In this subsection, we describe the decision variables, the available information and, finally, the utilities for each category of agents. The optimization program for each agent is presented using a mathematical formulation.

2.2.1 Programs of the microgrids

The only decision variable for microgrid \mathcal{M}_i is the quantity of energy that it decides to get from alternative sources: $a_i(t)$. We assume that the microgrid has no lever to influence its random demand: $\nu_i^s(t)$. We define the consumption of microgrid \mathcal{M}_i as the difference between its demand and the production that it gets from alternative sources i.e.: $\nu_i^s(t) - a_i(t)$. This is the quantity that it needs to buy to provider s_i .

The information available to microgrid \mathcal{M}_i is the price of an energy unit from service provider s_i , $p_i(t)$, and its demand $\nu_i^s(t)$ for the time period.

We assume that finding alternative energy sources rather than buying it to the service provider has some cost for the microgrid. More precisely, finding $a_i(t)$ energy units through alternatives, costs them $c(a_i(t))$ per time period. As a result, the total cost of energy for microgrid \mathcal{M}_i is:

$$p_i(t)\left(\nu_i^s(t) - a_i(t)\right) + c\left(a_i(t)\right) \quad (1)$$

We assume that the cost is quadratic in the alternatives i.e., $c(a_i(t)) = \frac{a_i(t)^2}{2}$. This assumption is not restrictive and constants or more complicated cost functions can be introduced. The main advantage of this choice is that it is generic enough and allows to solve a large part of the game analytically.

Microgrid \mathcal{M}_i chooses $a_i(t)$ in order to minimize its total energy cost. Its decision depends on the energy price $p_i(t)$ fixed by service provider s_i .

2.2.2 Programs of the service providers

The decision variables for each service provider s_i are the unit energy price $p_i(t)$ and the energy orders $(q_{ik}(t))_k$ for each energy producer e_k .

The only information available to service provider s_i when he makes his decision are the energy unit prices $(\tilde{p}_k(t))_k$ of the energy producers. He has to forecast the demand of microgrid \mathcal{M}_i and the energy productions of all the energy producers, $(\nu_k^e(t))_k$.

Throughout the article, we will use the notation: $x_+ = \max\{x; 0\}$ to denote the positive part of the real number x .

Following our description of the interplay between the agents, the utility for service provider s_i at time period t is:

$$\begin{aligned} \pi_i(t) &= p_i(t)\left(\nu_i^s(t) - a_i(t)\right) - \sum_{k=1, \dots, K} q_{ik}(t)\tilde{p}_k(t) - \gamma_i\left(\nu_i^s(t) - a_i(t)\right) \\ &\quad - \sum_{k=1, \dots, K} \alpha_{ki}(t)\nu_k^e(t)_+ \end{aligned} \quad (2)$$

where $\alpha_{ki}(t) \geq 0$ denotes the proportion of his production that producer e_k allocates to provider s_i , with the normalization constraint: $\sum_{i=1, \dots, n} \alpha_{ki}(t) = 1$. Service provider

s_i incurs the cost $\gamma_i \left(\nu_i^s(t) - a_i(t) - \sum_k \alpha_{ki}(t) \nu_k^e(t) \right)_+$ where $\gamma_i > 0$ is the price per missing energy unit in case of negative energy balance. The cost is proportional to the difference between the microgrid consumption and the delivered quantity of energy, measured a posteriori. It is paid to the electricity transmission network operator. In France, the electricity transmission network operator has defined some rules to give incentives to the agents to become balance operators [29]. According to these rules, a positive energy balance is paid the spot price and a negative balance is paid on the basis of the price defined through the adjustment mechanism. This latter is implemented by the electricity transmission operator who compensates the negative balances to ensure the electrical network reliability¹.

Service provider s_i chooses his energy unit price and his energy orders toward energy producers so that $\pi_i(t)$, as defined in Equation (2), is maximized.

2.2.3 Programs of the energy producers

The only decision variable for each energy producer e_k is the energy unit price $\tilde{p}_k(t)$ that he proposes to the service providers. We assume that the energy producer cannot influence directly the energy he produces at each time period. This assumption holds well if, for example, we look at a wind turbine farm without any investment in an additional wind turbine during the study period. The variation of the wind intensity will make vary the produced energy without any lever for the energy producer.

When energy producer e_k makes his decision, he has no information because he is the first player to play in the time period as it will be described in Subsection 2.3. He has to forecast the energy quantity that he will produce and the energy orders of all the service providers.

Then the utility of energy producer e_k at time period t equals:

$$\tilde{\pi}_k(t) = \tilde{p}_k(t) \sum_{i=1, \dots, n} q_{ik}(t) - \sum_{i=1, \dots, n} \tilde{\gamma}_i \left(q_{ik}(t) - \alpha_{ki}(t) \nu_k^e(t) \right)_+$$

He incurs the penalty $\sum_{i=1, \dots, n} \tilde{\gamma}_i \left(q_{ik}(t) - \alpha_{ki}(t) \nu_k^e(t) \right)_+$ with $(\tilde{\gamma}_i)_i > 0$ coefficients characterizing the price per missing energy unit in case of negative energy balances. The price discrimination based on the destination provider is justified by the fact that depending on its geographic location, a negative energy balance can be easily corrected in densely interconnected areas² whereas it is much more difficult in isolated ones due to the high cost of electricity transmission. As a result, $(\tilde{\gamma}_i)_i$ is higher for providers serving isolated locations than over densely interconnected areas. The penalty is proportional to the sum of the differences between the energy orders and the quantities of energy delivered by each service provider, measured a posteriori. It is paid to the

¹In this article, while negative energy balances at the microgrid level are compensated by the transmission network operator, this is not the case at the provider level where negative energy balances are not compensated by the transmission network operator. However, this will be the role of the feedback mechanism proposed as a possible enforcement of the Nome law [27].

²In densely interconnected areas, importations from neighboring areas is possible. It can be modelled by adding an importation cost in the providers' utilities defined in Equation (2).

regulator of the capacity market that should be implemented to equilibrate energy production and demand in the smart grid [27]. To guarantee the viability of the capacity market, it might be necessary to implement a feedback mechanism where the regulator compensates the negative energy balances of the producers by investing himself in capacity [21]. The costs of these investments would be recovered from the penalties imposed to the producers in case of negative energy balances. To define the sharing coefficients $\left(\alpha_{ki}(t)\right)_i$, we consider a weighted proportional allocation of resource that allows producers to discriminate energy allocation by providers. This framework is a generalization of the well-known proportional allocation [23] to weighted energy orders with penalty coefficients as weights. Such a resource sharing mechanism has already been introduced by Nguyen and Vojnović, in [19]. This means that between two providers with identical energy orders, the one having the highest penalty coefficient will receive the largest part of the producer's available energy. Indeed, the producer wants to minimize his overall penalty and therefore allocates larger parts of his production to providers serving isolated areas where failure of electricity supply may be critical. We set:

$$\alpha_{ki}(t) = \frac{\tilde{\gamma}_i q_{ik}(t)}{C_k(t)} \quad (3)$$

where $C_k(t) = \sum_{j=1,\dots,n} \tilde{\gamma}_j q_{jk}(t)$. Using Equation (3), energy producer e_k 's utility at time period t can be rewritten:

$$\tilde{\pi}_k(t) = \tilde{p}_k(t) \sum_{i=1,\dots,n} q_{ik}(t) - \sum_{i=1,\dots,n} \tilde{\gamma}_i q_{ik}(t) \left(1 - \frac{\tilde{\gamma}_i}{C_k(t)} \nu_k^e(t)\right)_+ \quad (4)$$

Energy producer e_k chooses his energy unit price so that $\tilde{\pi}_k(t)$, as defined in Equation (4), is maximized.

2.3 Repeated game setting

We model the interplay between all the agents through a repeated game. At each time period t , the following game is played:

Basic Game Description $G(t)$

- (1) The energy producers e_k communicate their prices $\tilde{p}_k(t) > 0$ for one energy unit (i.e., *Wh*) to the service providers. The energy prices are fixed independently and simultaneously by each energy producer so as to maximize Equation (4)
- (2) The service providers s_i place energy quantity orders to energy producers: the quantity ordered by s_i to e_k is denoted by $q_{ik}(t)$. The service providers s_i communicate their prices $p_i(t) > 0$ for one energy unit to their microgrid. The orders and the energy prices are fixed independently and simultaneously by each service provider so as to maximize Equation (2)
- (3) Microgrid \mathcal{M}_i demand reaches $\nu_i^s(t)$ energy units for the period³. It decides to find

³It could depend on weather, cooking, etc.

alternative sources of energies for $a_i(t)$ energy units and buys the rest $\left(\nu_i^s(t) - a_i(t)\right)_+$ to service provider s_i

(4) *The production of energy producer e_k reaches $\nu_k^e(t)$ energy units. They distribute their production to the service providers: e_k delivers $\alpha_{ki}(t)\nu_k^e(t)$ energy units to service provider s_i . Supplementary costs and penalties are undertaken by both service providers and energy producers if they cannot satisfy the entire demand of their consumers*

In the above game setting, the random events, modelled by individual sequences, are in italics. The game will be repeated over a finite time horizon $0 < T < +\infty$, in Section 4.

3 Complete information game resolution

The game setting described in Section 2.3 implies that in the relation producers-providers, producers appear as leaders whereas providers are followers. Identically, in the relation providers-microgrids, providers appear as leaders whereas microgrids are mere followers. Under such a setting, the game is called a Stackelberg game and, as usual, it should be solved using backward induction [13], [18].

Additionally, we make the assumption that each energy producer receives at least one energy order from a service provider guaranteeing that the Stackelberg game admits non trivial solutions.

3.1 Optimization of the microgrids' decision

To minimize their total cost of energy defined by Equation (1), microgrid \mathcal{M}_i has to choose $a_i(t)$ so that the differentiate of the total cost of energy equals 0 which means:

$$a_i(t) = p_i(t) \quad (5)$$

3.2 Optimization of the service providers' decisions

To find his optimal price and energy orders, service provider s_i has to replace $a_i(t)$ by its optimal value in $\pi_i(t)$ defined in Equation (2), and to differentiate the result in $p_i(t)$ and in $q_{ik}(t)$. This differentiation raises two cases.

3.2.1 Case 1: the energy production fulfills the energy demand of the microgrid

It is the case when:

$$\nu_i^s(t) - p_i(t) \leq \sum_{k=1, \dots, K} \alpha_{ki}(t)\nu_k^e(t) \quad (6)$$

Then differentiating the service provider's utility in $q_{ik}(t)$ leads to:

$$\frac{\partial \pi_i(t)}{\partial q_{ik}(t)} = -\tilde{p}_k(t)$$

which means that s_i will try to minimize all his energy orders to maximize his utility. As a result, s_i will tend to break the inequality defining Case 1 in Inequality (6) because $\alpha_{ki}(t)$ will tend toward zero. This implies in turn, that the optimal decision for s_i will always fall in Case 2 described below or on the frontier between Case 1 and Case 2. The frontier between these two cases is defined by the equation:

$$\nu_i^s(t) - p_i(t) = \sum_{k=1, \dots, K} \alpha_{ki}(t) \nu_k^e(t) \quad (7)$$

3.2.2 Case 2: the energy production does not fulfill the energy demand of the microgrid

It is the case when $\nu_i^s(t) - p_i(t) \geq \sum_{k=1, \dots, K} \alpha_{ki}(t) \nu_k^e(t)$. Then differentiating s_i 's utility gives us:

$$\begin{aligned} \frac{\partial \pi_i(t)}{\partial p_i(t)} &= \nu_i^s(t) + \gamma_i - 2p_i(t) \\ \frac{\partial \pi_i(t)}{\partial q_{ik}(t)} &= -\tilde{p}_k(t) + \gamma_i \nu_k^e(t) \frac{\partial \alpha_{ki}(t)}{\partial q_{ik}(t)} \end{aligned} \quad (8)$$

By using the definition of $\alpha_{ki}(t)$ given in Equation (3), we obtain:

$$\frac{\partial \alpha_{ki}(t)}{\partial q_{ik}(t)} = \tilde{\gamma}_i \frac{C_k(t) - \tilde{\gamma}_i q_{ik}(t)}{C_k(t)^2}$$

Then going back to the system of Equations (8), we conclude that the differentiates equal 0 when:

$$p_i(t) = \frac{\nu_i^s(t) + \gamma_i}{2} \quad (9)$$

$$\tilde{p}_k(t) C_k(t)^2 = \gamma_i \nu_k^e(t) \tilde{\gamma}_i (C_k(t) - \tilde{\gamma}_i q_{ik}(t)) \quad (10)$$

On the one side, we obtain directly the price for which the differentiate of $\pi_i(t)$ equals 0 through Equation (9). On the other side, Equation (10) can be rewritten as follows:

$$\tilde{\gamma}_i q_{ik}(t) = C_k(t) - \frac{\tilde{p}_k(t) C_k(t)^2}{\nu_k^e(t) \gamma_i \tilde{\gamma}_i} \quad (11)$$

If s_i anticipates that the other service providers will make the same optimization program, replicating Equation (11) for the n service providers and summing them all, results in the following equality:

$$C_k(t) = n C_k(t) - \frac{\tilde{p}_k(t) C_k(t)^2}{\nu_k^e(t)} \sum_{j=1, \dots, n} \frac{1}{\gamma_j \tilde{\gamma}_j}$$

by definition of $C_k(t)$.

Then as $C_k(t)$ is not zero because each producer e_k receives at least one order of energy otherwise he would be out of the game, by dividing the previous equation by $C_k(t)$ and reordering we obtain:

$$C_k(t) = \frac{\nu_k^e(t) n - 1}{\tilde{p}_k(t) \delta}$$

where $\delta = \sum_{j=1, \dots, n} \frac{1}{\gamma_j \tilde{\gamma}_j}$. By replacing $C_k(t)$ in Equation (11), we obtain the energy orders for which the differentiates of $\pi_i(t)$ equals 0:

$$q_{ik}(t) = \frac{\nu_k^e(t) n - 1}{\tilde{p}_k(t) \delta \tilde{\gamma}_i} L(i) \quad (12)$$

where we have introduced the notation $L(i) = 1 - \frac{n-1}{\delta \gamma_i \tilde{\gamma}_i}$ to simplify future calculations.

Presently, we have to check that the price and energy orders for which the differentiates of $\pi_i(t)$ equal 0 satisfy the conditions of Case 2.

First, it is easy to check that the price is positive through Equation (9). However, the energy orders defined in Equation (12) are non-negative if, and only if, $1 \geq \frac{n-1}{\delta \gamma_i \tilde{\gamma}_i}$ which is equivalent to:

$$\gamma_i \tilde{\gamma}_i \geq \frac{n-1}{\delta} \quad (13)$$

This inequality means that the penalties related to s_i are close to the penalties related to the other service providers. Indeed, if all penalties are equal to γ , then $\delta = \frac{n}{\gamma^2}$ and Inequality (13) is true for all service providers. On the contrary, if all penalties are equal to γ except for s_1 which has a penalty of $\frac{\gamma}{n-1}$, then $\delta = \frac{(n-1)n}{\gamma^2}$ and Inequality (13) becomes $n \geq (n-1)^2$ which is false as soon as $n > 2$.

Second, by replacing the energy orders defined by Equation (12) in Equation (3), we obtain $\alpha_{ki}(t) = \frac{L(i)}{\sum_{j=1, \dots, n} L(j)} = L(i)$ meaning that the total energy delivered

to microgrid \mathcal{M}_i , attached to s_i , is $\sum_{k=1, \dots, K} \alpha_{ki}(t) \nu_k^e(t) = L(i) \sum_{k=1, \dots, K} \nu_k^e(t)$. As a result, the price and energy orders for which the differentiates of $\pi_i(t)$ equal 0 verify the inequality defining Case 2 if, and only if:

$$\nu_i^s(t) \geq \gamma_i + 2L(i) \sum_{k=1, \dots, K} \nu_k^e(t) \quad (14)$$

This inequality states that the total production of energy by energy producers should not be too large compared to the demand of the microgrid.

If Inequalities (13) and (14) are true, the optimum for s_i is reached for $p_i(t)$ defined by Equation (9) and $q_{ik}(t)$ defined by Equation (12). If one of these inequalities is not true, then the optimum for s_i is reached on the frontier defined by Equation (7).

In the rest of the article, the game parameters and random events (demands of the microgrids, energy productions and penalties) will be chosen so that we are always in energy shortage, in the sense that Inequality (14) will always be true, and with fair penalties, in the sense of Inequality (13). As a result, the optimal price for s_i is defined by Equation (9) and the optimal orders for s_i are defined by Equation (12).

3.3 Optimization of the energy producers' decision

After substituting $q_{ik}(t)$ and $C_k(t)$ by the expressions found in the previous section in energy producer e_k 's utility as defined in Equation (4), we obtain:

$$\tilde{\pi}_k(t) = \nu_k^e(t) \frac{n-1}{\delta} \left(\sum_{i=1, \dots, n} \frac{L(i)}{\tilde{\gamma}_i} - \sum_{i=1, \dots, n} \left(\frac{L(i)}{\tilde{p}_k(t)} \left(1 - \frac{\tilde{p}_k(t) \tilde{\gamma}_i \delta}{n-1} \right)_+ \right) \right)$$

The only part of this equation depending on $\tilde{p}_k(t)$ has always a negative impact on the profit of the energy producer under the assumption of fair penalties. Indeed, in that case, as raised in the previous section, we have: $L(i) \geq 0$ for all service providers $(s_i)_i$. As a result, to maximize his profit, the energy producer has to choose $\tilde{p}_k(t)$ such that the part depending on $\tilde{p}_k(t)$ in the above equation equals 0. It implies that the term $1 - \frac{\tilde{p}_k(t) \tilde{\gamma}_i \delta}{n-1}$ is inferior to 0 for all $i = 1, \dots, n$. It is equivalent to: $\tilde{p}_k(t) \geq \frac{n-1}{\delta \tilde{\gamma}_i}$. Consequently, the optimal price for the energy producer with fair penalties is defined by:

$$\tilde{p}_k(t) = \frac{n-1}{\delta \min_{i=1, \dots, n} \{\tilde{\gamma}_i\}}$$

In theory, the price could be higher than this value and it would change nothing for the utility of the energy producer. But the energy producer has an incentive to be moderate on his price to avoid competition from other energy producers and to receive at least one energy order from a service provider. This last point was set as an assumption at the beginning of Section 3.

4 Distributed learning game

In this section, we assume that the microgrids demand $(\nu_i^s(t))_i$ and the energy productions $(\nu_k^e(t))_k$ are random individual sequences. As explained in the Introduction, this means that the underlying random processes generating the sequences do not necessarily have a probabilistic structure. They can be quite erratic [3], [4].

In the previous section, we have defined the optimal decisions for each agent at time period t . We have proved that these decisions do depend neither on the microgrids demand $\nu_i^s(t)$ nor on the energy productions $\nu_k^e(t)$ except for the service providers. To guarantee the optimal operation of the whole system, it is fundamental for the service providers to elaborate efficient learning strategies about the demand of the microgrids and about the productions of the energy producers.

To simplify, we will consider a common space \mathcal{X}_e of possible values for the production of each energy producer and a common space \mathcal{X}_s of possible values for the microgrids demand. $\mathcal{X}_e, \mathcal{X}_s \subseteq \mathbb{R}$ are supposed to be of finite dimension i.e., their cardinals $|\mathcal{X}_e|$ and $|\mathcal{X}_s|$ are such that $|\mathcal{X}_e| < +\infty$ and $|\mathcal{X}_s| < +\infty$. In the description of the generic learning algorithm, we will use the notation \mathcal{X} to name indifferently \mathcal{X}_s or \mathcal{X}_e .

Service providers should optimize their prices and ordered quantities at each time period, having no information about the produced energy and the demands of the mi-

crogrids at this instant. As a result, the game can be considered as having *partial information* [4]. Each service provider s_i has to forecast $\nu_i^s(t)$ and $\nu_k^e(t)$ for all $k = 1, \dots, K$, at each time period, in order to optimize his decisions. We will denote by $f_i(X, t)$ the forecast of service provider s_i about the variable X at time period t . We will also use the simplifying notations:

- $f_i(t) = \left\{ f_i(\nu_i^s, t), f_i(\nu_1^e, t), \dots, f_i(\nu_K^e, t) \right\}$ to denote the predictions made by service provider s_i about microgrid \mathcal{M}_i demand and about the production of each energy producer e_k , $k = 1, \dots, K$.
- $f(t) = \left\{ f_1(t), \dots, f_n(t) \right\}$ which contains the forecasts of all the service providers.
- $f_{-i}(y, t) = \left\{ f_1(t), \dots, f_{i-1}(t), y, f_{i+1}(t), \dots, f_n(t) \right\}$ which contains the forecasts of all the service providers except s_i which prediction is set equal to y .
- $\nu(t) = \left\{ \nu_1^s(t), \dots, \nu_n^s(t), \nu_1^e(t), \dots, \nu_K^e(t) \right\}$ which contains the microgrids' demand and the production of each energy producer e_k , $k = 1, \dots, K$.
- $\delta = \sum_{j=1, \dots, n} \frac{1}{\gamma_j \tilde{\gamma}_j}$
- $L(i) = 1 - \frac{n-1}{\delta \gamma_i \tilde{\gamma}_i}$

By substitution of the forecasters in the Stackelberg game solution at equilibrium as obtained in Section 3, we infer the optimal decisions for service provider s_i at each time period t :

$$\begin{aligned} p_i(t) &= \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \\ q_{ik}(t) &= \frac{f_i(\nu_k^e, t) L(i) n - 1}{\tilde{p}_k(t) \tilde{\gamma}_i \delta} \end{aligned}$$

As a result, the utility of service provider s_i at each time period t is:

$$\begin{aligned} \pi_i(t) &= \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \right) \\ &- \frac{L(i) n - 1}{\tilde{\gamma}_i \delta} \sum_{k=1, \dots, K} f_i(\nu_k^e, t) - \gamma_i \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \right) \\ &- \sum_{k=1, \dots, K} \frac{f_i(\nu_k^e, t) L(i)}{\sum_{j=1, \dots, n} f_j(\nu_k^e, t) L(j)} \nu_k^e(t) \end{aligned} \quad (15)$$

4.1 Loss, external regret and Hannan consistency definitions

Provider s_i 's loss is defined as:

$$l_i(f(t), \nu(t)) = \left(\pi_i^0(t) - \pi_i(t) \right)$$

where $\pi_i^0(t)$ corresponds to provider s_i 's utility evaluated in $f_i(\nu_i^s, t) = \nu_i^s(t)$ and $f_i(\nu_k^e, t) = \nu_k^e(t)$, $\forall k = 1, \dots, K$. It means that $\pi_i^0(t)$ contains the utility that provider s_i would have received if his forecasts were perfectly aligned with microgrid \mathcal{M}_i demand and with the production of each energy producer.

Having no a priori information about the dynamic evolution of the produced renewable energies and about the microgrids' demand, we assume that everything happens as if the system were in the worst case: Nature and microgrids allie together to form a *meta-player* who is supposed to be the most unfavorable to the service providers. It means that the meta-player tries to maximize the sum of the providers' losses. His loss can be expressed as the opposite of the sum of all the providers' losses. Therefore, it takes the form:

$$l(f(t), \nu(t)) = \sum_{i=1, \dots, n} (\pi_i(t) - \pi_i^0(t))$$

The agents' external regret over the sequence of time periods $1, \dots, T$, is expressed as the realized difference between the cumulative loss and the loss of the best prediction i.e., pure strategy (in the sense that this prediction minimizes their cumulative loss).

To be more precise, for service provider s_i , it coincides with the difference between s_i 's truly observed cumulative loss and the cumulative loss that would be obtained in case where s_i made the best constant prediction over time interval $[1; T]$. It takes the form:

$$\mathcal{R}_i(T) = \sum_{t=1}^T l_i(f(t), \nu(t)) - \min_{y \in \mathcal{X}_s \times \mathcal{X}_e^K} \sum_{t=1}^T l_i(f_{-i}(y, t), \nu(t))$$

Finally, for the meta-player, the regret coincides with the difference between his cumulative loss and the loss of the constant predictions over $[1; T]$ about the unknown sequences minimizing his cumulative loss or equivalently maximizing the sum of the providers' losses over the interval. We have:

$$\mathcal{R}(T) = \sum_{t=1}^T l(f(t), \nu(t)) - \min_{z \in \mathcal{X}_s^n \times \mathcal{X}_e^K} \sum_{t=1}^T l(f(t), z)$$

The service providers and the meta-player try to determine randomized strategies such that asymptotically their external regrets remain in $o(T)$ where T is the number of time periods which have been played. It means that with probability 1:

$$\lim_{T \rightarrow +\infty} \sup \frac{1}{T} \sum_{t=1}^T \mathcal{R}_i(t) = 0$$

for provider s_i , $i = 1, \dots, n$ and

$$\lim_{T \rightarrow +\infty} \sup \frac{1}{T} \sum_{t=1}^T \mathcal{R}(t) = 0$$

for the meta-player. Forecasters satisfying these inequalities are said Hannan consistent [4].

In the following lemma, we prove that it is possible to construct learning strategies for the service providers which minimize their external regret asymptotically.

Lemma 1. *A Hannan consistent learning strategy exists for each service provider s_i .*

Proof of Lemma 1. In our case setting, at the end of each time period, service provider s_i knows the energy quantity bought by the microgrid \mathcal{M}_i and he can infer $\nu_i^s(t)$ from that quantity. s_i also knows the energy which has been delivered by each energy producer e_k to him. He can infer from that the energy which could have been delivered to him, if he had ordered a different quantity $q_{ik}(t)$, all other providers ordering the same energy quantities. As a result, s_i can calculate his loss for all his possible actions. In [4], it is proved that a Hannan consistent learning strategy always exists when the player can calculate his loss for each possible action at the end of each time period. \square

4.2 Analysis of s_i 's loss function upper bounds

In this subsection, we unfold sequentially results enabling us to obtain upper bounds on the provider s_i 's loss function. We will then study the upper bounds on the meta-player's loss in next subsection. Last subsection will cover collaborative learning strategies.

We start by upper bounding provider s_i 's loss through the identification of upper bounds in Proposition 2. This upper bound is represented as the sum of a loss function depending only on provider s_i 's predictions and on another one relying exclusively on the disagreement between provider s_i and the other providers on the predictions of producer e_k 's production in renewable energy. Then properties of these upper bounds are studied in Corollary 3.

We introduce:

$$d_{ij}^k(t) = f_i(\nu_k^e, t) - f_j(\nu_k^e, t), \quad i, j = 1, \dots, n, \quad k = 1, \dots, K$$

It is a measure of the disagreement between provider s_i and provider s_j for $i \neq j$, in the prediction of e_k 's energy production, at time period t .

Proposition 2. *Provider s_i 's loss can be upper-bounded by the sum of two functions: the first one $l_i^{(1)}(\cdot)$ depending only on his forecasts $f_i(t)$ and the second one $l_i^{(2)}(\cdot)$ depending on his disagreement with the other providers' predictions exclusively. Formally, we have: $\forall i = 1, \dots, n, l_i(f(t), \nu(t)) \leq l_i^{(1)}(f_i(t), \nu(t)) + l_i^{(2)}((d_{ij}^k(t))_{j,k}, \nu(t))$.*

Proof of Proposition 2. The proof can be found in Appendix.

We now demonstrate functional properties for provider s_i 's upper bounds which lead us to the following observations concerning the provider's strategic learning behavior.

Corollary 3. *To minimize his loss, provider s_i should:*

- *Have no bias in his forecast of microgrid \mathcal{M}_i demand*
- *Minimize his energy production forecasts and his disagreements with the other providers in the energy production forecasts at the same time*

Proof of Corollary 3. Judging by the form of function $l_i^{(1)}(\cdot)$ as obtained in the proof of Proposition 2 which is detailed in Appendix, it is linear increasing in $f_i(\nu_k^e, t)$, $\forall k = 1, \dots, K$ since $L(i) \geq 0$ as proved in Section 3.2. Therefore, to reduce his loss, s_i has incentives to choose small values for $f_i(\nu_k^e, t)$, $\forall k = 1, \dots, K$.

Furthermore, the differentiate of $l_i^{(1)}(\cdot)$ in $f_i(\nu_i^s, t)$ equals 0 when $f_i(\nu_i^s, t) = \nu_i^s(t)$. Since $l_i^{(1)}(\cdot)$ is a second order polynomial in $f_i(\nu_i^s, t)$ with a positive first coefficient, the minimum of $l_i^{(1)}(\cdot)$ is reached in $\nu_i^s(t)$. As a result, to reduce his loss, s_i has incentives to choose $f_i(\nu_i^s, t) = \nu_i^s(t)$.

Since the differentiate of $l_i^{(2)}(\cdot)$ in $d_{ij}^k(t)$ is always positive, $l_i^{(2)}(\cdot)$ increases when the disagreement with the other providers $d_{ij}^k(t)$ increases. \square

In the rest of the paper, functions $l_i^{(1)}(y, \nu(t))$ will be denoted the *partial losses* for provider s_i , this latter making predictions $y \in \mathcal{X}_s \times \mathcal{X}_e^K$ while the meta-player chooses $\nu(t) \in \mathcal{X}_s^n \times \mathcal{X}_e^K$. We start by introducing lower and upper bounds on the disagreements between provider s_i and the other providers about the predictions of the energy productions:

$$\underline{D}_{ss}(i) = \min_{t=1, \dots, T} \min_{j \neq i, k} d_{ij}^k(t)$$

and

$$\overline{D}_{ss}(i) = \max_{t=1, \dots, T} \max_{j \neq i, k} d_{ij}^k(t)$$

They contain the extreme disagreement values between the providers, about the estimated energy productions.

Lemma 4. *If provider s_i plays according to a Hannan consistent strategy for his loss upper bound then, there exists an upper bound for the external regret associated with s_i 's partial loss which depends only on the extreme disagreement values between the providers about the estimated energy productions $\underline{D}_{ss}(i)$ and $\overline{D}_{ss}(i)$.*

Proof of Lemma 4. The proof can be found in Appendix.

4.3 Analysis of the sum of service providers loss functions upper bounds

The repetition of the Stackelberg game introduced in Section 3 in a context of partial information can be rewritten by introducing randomization in the strategies. We denote by $d_t(f_i) : \mathcal{X}_s \times \mathcal{X}_e^K \rightarrow [0; 1]$ and $d_t(\nu) : \mathcal{X}_s^n \times \mathcal{X}_e^K \rightarrow [0; 1]$ the randomized strategies for service provider s_i and for the meta-player respectively at time period t . We then have to cope with a repeated learning game. At each time period t , the basic game $G(t)$ introduced in Section 3 is updated according to the following rules, $(R_l)_{1 \leq l \leq 5}$, to incorporate the forecasting tasks of the providers:

Learning Game Description

R₁ : Each service provider s_i makes his forecasts $f_i(\nu_i^s, t)$, $\{f_i(\nu_k^e, t)\}_k$, following the distribution $d_t(f_i)$ for $i = 1, \dots, n$

Step (1) of $G(t)$ is played

Step (2) of $G(t)$ is played

R₃ : The meta-player chooses $(\nu_i^s(t))_i$ and $(\nu_k^e(t))_k$ following the distribution $d_t(\nu)$.

R₄ : Each service provider s_i obtains his profit $\pi_i(t)$, the demand of microgrid \mathcal{M}_i and the quantities of energy delivered by the producers $(e_k)_k$

R₅ : Each service provider s_i updates his forecasting strategies $d_t(f_i)$ for $i = 1, \dots, n$ and the meta-player updates his forecasting strategy $d_t(\nu)$ depending on the value of the expected utilities

We define $\tilde{l}_g(\cdot)$ as the sum of the providers' partial losses:

$$\tilde{l}_g(f(t), \nu(t)) = \sum_{i=1, \dots, n} l_i^{(1)}(f_i(t), \nu(t)) \quad (16)$$

If the repeated learning game described above, reaches a stable state i.e., an equilibrium for the generating density functions, the randomized strategy becomes time invariant for t large enough:

$$\begin{aligned} d_t(f_i) &\rightarrow d(f_i) \\ d_t(\nu) &\rightarrow d(\nu) \end{aligned}$$

We let F_s be the set of all the predictors (i.e., discrete density function set or alternatively, randomized prediction set) for each service provider and F_m the set of all the predictors for the meta-player. It will be used to properly introduce the value of the game. The value of the game where the providers consider their partial losses as utilities is defined as:

$$\tilde{V}_g = \min_{\otimes_{i=1, \dots, n} d(f_i) \in F_s^n} \max_{d(\nu) \in F_m} \tilde{l}_g^E(\otimes_{i=1, \dots, n} d(f_i), d(\nu))$$

where $\tilde{l}_g^E(\cdot)$ represents the expectation of function $\tilde{l}_g(\cdot)$ as defined in Equation (16).

Theorem 5. *Assume that all service providers play according to Hannan consistent strategies for their loss upper bound. Then:*

$$\limsup_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T \tilde{l}_g(f(t), \nu(t)) \leq \tilde{V}_g + \frac{1}{T} \sum_{t=1}^T \sum_{i=1, \dots, n} \psi(\underline{D}_{ss}(i), \overline{D}_{ss}(i)) \sum_{k=1, \dots, K} \nu_k^e(t)$$

where we have defined the function $\psi(\cdot, \cdot)$ from \mathbb{R}^2 to \mathbb{R} such that:

$$\psi(\underline{D}_{ss}(i), \overline{D}_{ss}(i)) = \gamma_i L(i) \sum_{k=1, \dots, K} \nu_k^e(t) \left(\frac{1}{g(\underline{D}_{ss}(i))} - \frac{1}{g(\overline{D}_{ss}(i))} \right) \quad (17)$$

with $g(x) = 1 - \frac{x}{\max\{\mathcal{X}_e\}} \mathbf{1}_{x \geq 0} - \frac{x}{\min\{\mathcal{X}_e\}} \mathbf{1}_{x < 0}$, $\mathbf{1}_E = 1$ if E is true and 0 otherwise.
Proof of Theorem 5. The proof can be found in Appendix.

Corollary 6. *Assume that the meta-player plays according to a Hannan consistent strategy for his loss upper bound. Then:*

$$\lim_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T \tilde{l}_g(f(t), \nu(t)) \geq \tilde{V}_g - \frac{1}{T} \sum_{t=1}^T \sum_{i=1, \dots, n} \psi(\underline{D}_{ss}(i), \overline{D}_{ss}(i)) \sum_{k=1, \dots, K} \nu_k^\varepsilon(t)$$

Proof of Corollary 6. Applying Theorem 5 to the meta-player i.e, by symmetry, considering that the meta-player's loss upper bound is the opposite of the sum over i of s_i 's loss upper bounds, and using von Neuman-Morgenstern's minimax theorem [18] for \tilde{V}_g , we derive the proposed inequality. \square

We let:

$$l_g(f(t), \nu(t)) = \sum_{i=1, \dots, n} l_i(f(t), \nu(t)) \quad (18)$$

be the sum of the providers' losses. Using the definitions settled in Equations (16) and (18), we derive the following inequality:

$$l_g(f(t), \nu(t)) \leq \tilde{l}_g(f(t), \nu(t)) + \sum_{i=1, \dots, n} l_i^{(2)}\left((d_{ij}^k(t))_{j,k}, \nu(t)\right)$$

where j browses all the values in the set $\{1, \dots, n\}$ and k , all the values in the set $\{1, \dots, K\}$. By substitution in Theorem 5, we obtain the following result:

Corollary 7. *If all service providers play according to a Hannan consistent strategy for their loss upper bounds then, their average loss cannot be larger than:*

$$\begin{aligned} & \tilde{V}_g + \frac{1}{T} \sum_{t=1}^T \sum_{i=1, \dots, n} \psi(\underline{D}_{ss}(i), \overline{D}_{ss}(i)) \sum_{k=1, \dots, K} \nu_k^\varepsilon(t) \\ & + \frac{1}{T} \sum_{t=1}^T \sum_{i=1, \dots, n} l_i^{(2)}\left((d_{ij}^k(t))_{j,k}, \nu(t)\right) \end{aligned}$$

whatever strategy is chosen by the meta-player.

The objective of the next subsection is to determine which conditions to impose on the gaps between the providers' predictions, in order to minimize the upper bound of the agents' average loss.

4.4 Collaborative learning strategy

Collaboration takes place within coalitions. In cooperative game theory literature, a coalition is a group of agents who have incentives to collaborate by sharing resource access, information, etc., in the hope to increase their revenue, knowledge, social welfare

(in case of altruism), etc., compared to the case where they behave non-cooperatively [1], [18], [23]. Adapted to our hierarchical learning context, we define coalitions of agents as follows:

Definition 8. • *A coalition of agents is a group of agents who share their information and coordinate their predictions on a common value.*

- *Agents who belong to the same coalition are said to collaborate.*

Forecasts of the shared information contain the energy productions. However, the providers still predict independently their microgrid demand since each microgrid adapts independently the quantity of energy that it needs to buy, to the dynamic price fixed by the service provider.

At this stage, the objective is to identify conditions on the disagreement levels between the providers about the forecasted energy productions such that the term at the right of \tilde{V}_g defined in Corollary 7, remains as small as possible. Indeed, the smaller is the term defined in Corollary 7, the smaller is the sum of the agents' losses.

Such a strategy would satisfy the following relations, at any time period t :

$$\begin{aligned} \psi\left(\underline{D}_{ss}(i), \overline{D}_{ss}(i)\right) \sum_{k=1, \dots, K} \nu_k^e(t) &= 0, \quad \forall i = 1, \dots, n \\ \Leftrightarrow \underline{D}_{ss}(i) &= \overline{D}_{ss}(i), \quad \forall i = 1, \dots, n \end{aligned}$$

It means that service providers can decrease the upper bound of their average loss by coordinating their predictions about the produced energies $\left(\nu_k^e(t)\right)_k$, at any time period t . Providers therefore have incentive to form a grand coalition because it might enable them to decrease their total loss.

By substitution in the second part of the loss upper bounds as introduced in Propositions 2 and detailed analytically in Appendix, we let:

$$\mu_i(t) = l_i^{(2)}\left(\left(d_{ij}^k(t)\right)_{j,k}, \nu(t)\right) \Big|_{d_{ij}^k(t)=0, j=1, \dots, n, k=1, \dots, K}$$

and we obtain: $\mu_i(t) = -\gamma_i L(i) \sum_{k=1, \dots, K} \nu_k^e(t)$ which depends only on the service provider index (i) and on time period t , but not on the providers' forecasts.

Proposition 9. *When the providers collaborate through a grand coalition and play Hannan consistent strategies, the system average loss over time interval $[1; T]$ cannot*

be larger than $\tilde{V}_g + \frac{1}{T} \sum_{t=1}^T \sum_{i=1, \dots, n} \mu_i(t)$.

Proof of Proposition 9. By definition:

$$\begin{aligned}
l_g(t) &= \sum_{i=1, \dots, n} l_i(t) \\
&\leq \underbrace{\sum_{i=1, \dots, n} l_i^{(1)}(t)}_{\tilde{l}_g(t)} + \sum_{i=1, \dots, n} l_i^{(2)}(t) \\
&\leq \tilde{l}_g(t) + \sum_{i=1, \dots, n} \mu_i(t).
\end{aligned}$$

Taking the average of these values over time interval $[1; T]$, the proposition statement is straightforward. \square

5 Simulations

The aim of this section is to explain how the economic model of the hierarchical network described in Section 2 can be applied in practice to take decisions in an uncertain context and then to check that the results derived analytically in Section 4 hold, for a smart grid which structure is defined a priori.

The rest of the section is organized as follows: Subsection 5.1 deals with payoff function estimation for each forecast, Subsection 5.2 elaborates on the update of mixed strategies for each forecast and we discuss in the last part the results that we have obtained on a numerical example.

5.1 Payoff functions

As detailed in Section 4, after the energy prices have been issued by the energy producers, the service providers make their forecasts and choose a quantity to order to each producer and their optimal energy unit price according to the following system:

$$\begin{aligned}
p_i(t) &= \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \\
q_{ik}(t) &= \frac{f_i(\nu_k^e, t)}{\tilde{p}_k} \frac{L(i)}{\tilde{\gamma}_i} \frac{n-1}{\delta}
\end{aligned}$$

By substitution in Equation (2), service provider s_i 's utility can then be rewritten as:

$$\begin{aligned}
\pi_i(t) &= \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \right) - \frac{L(i)}{\tilde{\gamma}_i} \frac{n-1}{\delta} \\
&\quad \sum_{k=1, \dots, K} f_i(\nu_k^e, t) - \gamma_i \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \right) \\
&\quad - \sum_{k=1, \dots, K} \frac{L(i) f_i(\nu_k^e, t)}{\sum_{j=1, \dots, n} L(j) f_j(\nu_k^e, t)} \nu_k^e(t) \Big)_+
\end{aligned}$$

Interestingly, the profit of the service provider depends on the forecasts of the other service providers.

Each service provider has $K + 1$ forecasts to do: one for his microgrid demand and one to evaluate the productions of each of the K energy producers. As a result, each service provider should define a randomized strategy on the space $\mathcal{X}_s \times \mathcal{X}_e^K$. We recall that a randomized strategy is the classical terminology used in game theory to name a discrete density function defined over the considered set [18]. The size of the set grows very fast with K and, as a result, each probability in the randomized strategy of forecasts, is very small, which leads to rounding errors during computation. In order to overcome this issue, we have decided to cut the service providers in smaller entities, each of them making only one forecast at each time period and to consider that these entities are uncoupled. This trick results in $K + 1$ randomized strategies in the space of forecasts $\mathcal{X}_s \times \mathcal{X}_e^K$ for each service provider.

For a given forecast X , we derive the payoffs for each value $x \in \mathcal{X}$ of the forecast at each time period t by using the utilities of the service providers and keeping only the terms depending on forecast X . This is summarized in the following definition:

Definition 10. *The payoff function associated to forecast X evaluated in $x \in \mathcal{X}$ coincides with the utility of service provider s_i restricted to its terms depending on forecast X solely and evaluated in x .*

For the forecasts of microgrid \mathcal{M}_i demand, provider s_i 's payoff takes the form:

$$H_{f_i(\nu_i^s)}(x, t) = \frac{x + \gamma_i}{2} \left(\nu_i^s(t) - \frac{x + \gamma_i}{2} \right) - \gamma_i \left(\nu_i^s(t) - \frac{x + \gamma_i}{2} - \sum_{k=1, \dots, K} \frac{L(i) f_i(\nu_k^e, t)}{\sum_{j=1, \dots, n} L(j) f_j(\nu_k^e, t)} \nu_k^e(t) \right)_+$$

Concerning the forecasts of energy producer e_k 's production, provider s_i 's payoff takes the form:

$$H_{f_i(\nu_k^e)}(x, t) = -\frac{L(i)}{\tilde{\gamma}_i} \frac{n-1}{\delta} x - \gamma_i \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} - \sum_{l \neq k} \frac{L(i) f_i(\nu_l^e, t)}{\sum_j L(j) f_j(\nu_l^e, t)} \nu_l^e(t) - \frac{L(i)x}{\sum_{j \neq i} L(j) f_j(\nu_k^e, t) + L(i)x} \nu_k^e(t) \right)_+$$

As already stated in Section 4, we will also consider that the meta-player is non oblivious and plays so as to minimize the sum of the utilities of the service providers. As for the service providers, we uncouple $\nu_i^s(t)$ and $\nu_k^e(t)$ to improve the computation. More precisely the meta-player's payoffs are:

$$H_{\nu_i^s}(x, t) = \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \left(\frac{f_i(\nu_i^s, t) + \gamma_i}{2} - x \right) + \gamma_i \left(x - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} - \sum_{k=1, \dots, K} \frac{L(i) f_i(\nu_k^e, t)}{\sum_{j=1, \dots, n} L(j) f_j(\nu_k^e, t)} \nu_k^e(t) \right)_+$$

$$\begin{aligned}
H_{\nu_k^e}(x, t) &= \sum_{i=1, \dots, n} \gamma_i \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} - \sum_{l \neq k} \frac{L(i) f_i(\nu_l^e, t)}{\sum_{j=1, \dots, n} L(j) f_j(\nu_l^e, t)} \right. \\
&\quad \left. \nu_l^e(t) - \frac{L(i) f_i(\nu_k^e, t)}{\sum_{j=1, \dots, n} L(j) f_j(\nu_k^e, t)} x \right)_+
\end{aligned}$$

It is very straightforward to adapt the repeated learning game and payoffs considering that the service providers integrate a grand coalition. The grand coalition payoffs take the following forms:

$$\begin{aligned}
H_{f_C(\nu_i^s)}(x, t) &= H_{f_i(\nu_i^s)}(x, t) \\
H_{f_C(\nu_k^e)}(x, t) &= - \sum_{i=1, \dots, n} \frac{L(i)}{\tilde{\gamma}_i} \frac{n-1}{\delta} x
\end{aligned}$$

Whereas, the meta-player's payoffs become:

$$\begin{aligned}
H_{\nu_i^s}(x, t) &= \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \left(\frac{f_i(\nu_i^s, t) + \gamma_i}{2} - x \right) + \gamma_i \left(x - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \right. \\
&\quad \left. - L(i) \sum_{k=1, \dots, K} \nu_k^e(t) \right)_+ \\
H_{\nu_k^e}(x, t) &= \sum_{i=1, \dots, n} \gamma_i \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} - L(i) \left(\sum_{l \neq k} \nu_l^e(t) + x \right) \right)_+
\end{aligned}$$

5.2 Updates of forecasting strategies

In the rest of the paper, we consider two types of updates for the forecasting randomized strategies $d_t(X)$ at each time period based on the exponential forecaster for signed games: one based on the external regret and the other based on the internal regret [4]. We assume that this is a signed game because the range of values of payoff function $H_X(\cdot)$ might include a neighborhood of 0.

We let:

$$\begin{aligned}
\mathcal{V}_t &= \sum_{s=1}^t \text{Var} \left(H_X(X_s, s) \right) \\
&= \sum_{s=1}^t \mathbb{E} \left[\left(H_X(X_s, s) - \mathbb{E}[H_X(X_s, s)] \right)^2 \right]
\end{aligned}$$

be the sum of the variances associated with the random variable $H_X(X_t, t)$ which is the payoff for forecaster X at time period t assuming that the forecast at time period t has been set to X_t , under the mixed strategy X which is defined over space \mathcal{X} . Using the

exponential forecaster for signed games with external regret means that the randomized strategy is updated according to the algorithm described below.

External Regret Learning Algorithm: Updating of the Exponential Forecaster

Initialization. For $t = 0$, we set: $w_0(x) = \frac{1}{|\mathcal{X}|}$, $\forall x \in \mathcal{X}$.

Step 1 to T . The updating rules are the following:

$$\begin{aligned} d_t(x) &= \frac{w_t(x)}{\sum_{x \in \mathcal{X}} w_t(x)}, \forall x \in \mathcal{X} \\ w_{t+1}(x) &= \exp\left(\eta_{t+1} \sum_{s=1}^t H_X(x, s)\right) \\ &= d_t(x)^{\frac{\eta_{t+1}}{\eta_t}} \exp\left(\eta_{t+1} H_X(x, t)\right), \forall x \in \mathcal{X} \\ \eta_{t+1} &= \min\left\{\frac{1}{2 \max\{|H_X(\cdot)|\}}; \sqrt{\frac{2(\sqrt{2}-1)}{e-2}} \sqrt{\frac{\ln|\mathcal{X}|}{\mathcal{V}_t}}\right\} \\ \mathcal{V}_t &= \mathcal{V}_{t-1} + \text{Var}\left(H_X(X_t, t)\right) \end{aligned}$$

For the internal regret, it is similar but with $d_t(\cdot) = \sum_{i \neq j} d_t^{i \rightarrow j}(\cdot) \Delta_{(i,j)}(t)$ where $d_t^{i \rightarrow j}(\cdot)$ is the modified forecasting strategy obtained when the forecaster predicts j each time he would have predicted i and $\Delta_{(i,j)}(t) = \frac{\omega_{(i,j)}(t)}{\sum_{k \neq l} \omega_{(k,l)}(t)}$ with:
 $\omega_{(i,j)}(t) = \exp\left(\eta_t \sum_{s=1}^{t-1} \sum_{x \in \mathcal{X}} d_s(x) H_X(x, s)\right)$.

We see that we need to compute the maximum of the absolute value of the payoff function $|H_X(\cdot)|$ for all forecasts X to run a simulation of the game. This maximum is reached for $x = \min\{\mathcal{X}\}$ or $x = \max\{\mathcal{X}\}$ for all payoff functions except for $H_{f_i(\nu_i^s)}(\cdot)$ because their differentiate with respect to x is never equal to 0. For $H_{f_i(\nu_i^s)}(\cdot)$, the differentiate equals 0 if, and only if, $f_i(\nu_i^s, t) = \nu_i^s(t)$, so the maximum of $|H_X(\cdot)|$ is reached either for $x = \min\{\mathcal{X}\}$ or $x = \max\{\mathcal{X}\}$ or $x = \nu_i^s(t)$.

5.3 Results

For our numerical illustration, we have chosen $n = 3$ and $K = 2$. We have also used $\gamma_1 = \gamma_2 = \gamma_3 = 0.9$ and $\tilde{\gamma}_1 = 0.5$, $\tilde{\gamma}_2 = 0.4$, $\tilde{\gamma}_3 = 0.6$ and $\mathcal{X}_e = [1; 2]$, $\mathcal{X}_s = [5; 8]$ which ensure that the $L(i)$, $i = 1, 2, 3$ remain positive and that Inequality (14) is always true.

In the following pictures, we compare the cumulative regret of each player to the cumulative regret of the same player who would have forecasted the best value at each time period in terms of payoffs. More precisely, we display:

$$\frac{1}{t} \sum_{s=1}^t \sum_{X \in F} \left(H_X(X_s, s) - \max_x (H_X(x, s)) \right)$$

where F is the generic set of forecasts made by the service provider or the meta-player or the coalition considered.

We start by comparing the cumulative internal and external regrets in the case of full competition between service providers in Figures 2 (a) and 2 (b).

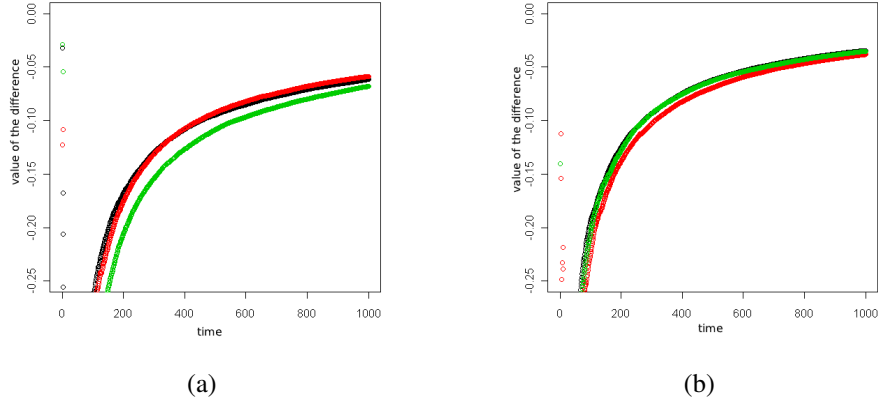


Figure 2: Difference between the best achievable cumulative regret and the one obtained with the internal regret minimization algorithm in (a) and with the external regret minimization algorithm in (b) under full competition.

The service providers are in black for s_1 , green for s_2 and red for s_3 . We can see that in all cases, the differences between regrets converge toward 0 which means that the cumulative payoff obtained at the end of the game following the exponential forecaster strategy is close to the best possible cumulative payoff. This is in coherence with the theoretical result for the internal regret but is better than what we could expect for the external regret which means that we are in a game setting which performs well for regret based learning. We also remark that the algorithm converges faster for the external regret compared to the internal regret.

We compare these graphs with the graphs obtained when service providers integrate a grand coalition in Figures 3 (a) and 3 (b).

Again, we observe that the differences between the best achievable regrets and those obtained using the learning algorithm converge toward 0. The rate of convergence under cooperative learning seems higher than in the non-cooperative case where the providers perform decentralized learning. In addition, we observe that after 400 time periods the sum of differences between regrets under collaborative learning is close to -0.2 whereas the sum of differences between regrets is close to -0.26 in the full competition case. This is in coherence with the theory which says that collaborative learning is better.

6 Conclusion

In this article, we study a model of renewable energy production in which producers, providers and microgrids are organized in a hierarchical network. Renewable energy productions are modeled by random individual sequences which need not to have a

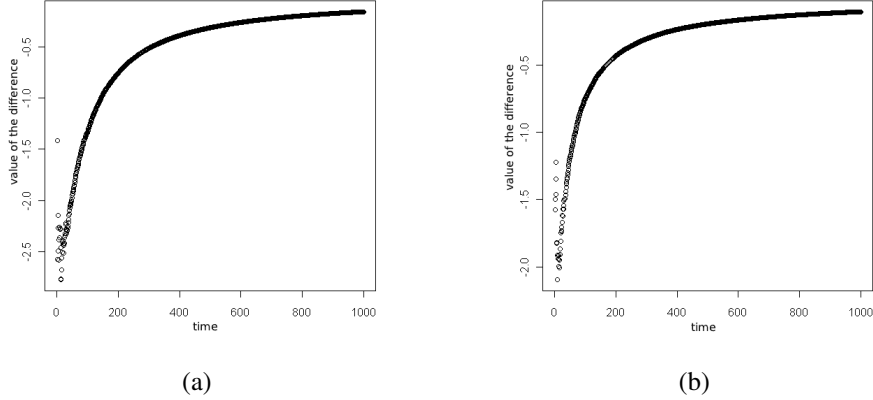


Figure 3: Difference between the best achievable cumulative regret and the one obtained with the internal regret minimization algorithm in (a) and with the external regret minimization algorithm in (b) for the grand coalition of service providers.

probabilistic structure. This extraordinarily general demand and supply structure allows to take into account exogenous events. As a result, it is more robust to extreme events and appears as particularly well suited to model quite erratic processes such as renewable energy production. We prove that the producers set their prices to avoid the penalties that the capacity market regulator threatens to apply in case where the providers' orders were not entirely satisfied. All the risk is then reported on the intermediaries. Additionally, we prove that these latter can minimize their regret by sharing information and coordinating their forecasts. These theoretical results are illustrated on a toy network: we observe that the rates of convergence under collaborative learning through a grand coalition, where the providers share their information and coordinate their forecasts, is higher than under decentralized learning, using regret minimization as performance criterion.

The Sido-Poignant report [28] highlighted the alarming growth of the peaks of consumption. The electrical network will no longer be able to meet the totality of the consumer demand during peaks of consumption. The market does not seem to remunerate efficiently the investments in the capacity. The principle of a capacity market is to provide the guarantee that the electrical system has the capacity to meet the consumer demand either by forcing the providers to provide the guarantee that they have enough capacity to meet their own consumer demand or by implementing a feedback mechanism where the regulator activates its own capacity in case of negative energy balances. Which economic incentives should be implemented to generate enough investments in the right capacities, i.e., according to the energy mix minimizing environmental and budget objectives, and at the right places? In this article, the regulators penalizes the producers who cannot meet the provider demand. The penalties are paid to the regulator who compensates the negative energy balances by activating its capacity. It might be interesting to design mechanisms giving the agents incentives to participate

in the market and avoiding speculations, like capacity retention or on the contrary over-investment in capacity. Such behaviors create artificial market power and substantial price rises.

Appendix

Proof of Proposition 2

By definition of provider s_i 's loss and thanks to Equation (15), we have:

$$\begin{aligned} l_i(f(t), \nu(t)) &= \pi_i^0(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \right) \\ &+ \frac{L(i)}{\tilde{\gamma}_i} \frac{n-1}{\delta} \sum_{k=1, \dots, K} f_i(\nu_k^e, t) + \gamma_i \left(\nu_i^s(t) - \frac{f_i(\nu_i^s, t) + \gamma_i}{2} \right) \\ &- \sum_{k=1, \dots, K} \frac{f_i(\nu_k^e, t) L(i)}{\sum_{j=1, \dots, n} f_j(\nu_k^e, t) L(j)} \nu_k^e(t) \end{aligned}$$

For $l = 1, \dots, K + 1$, the l -th component of vector $y \in \mathcal{X}_s \times \mathcal{X}_e^K$ will be denoted: $y(l)$. If we let:

$$\begin{aligned} l_i^{(1)}(y, \nu(t)) &= \pi_i^0(t) - \frac{y(1) + \gamma_i}{2} \left(\nu_i^s(t) - \frac{y(1) + \gamma_i}{2} \right) \\ &+ \frac{L(i)}{\tilde{\gamma}_i} \frac{n-1}{\delta} \sum_{k=1, \dots, K} y(k+1) + \gamma_i \left(\nu_i^s(t) - \frac{y(1) + \gamma_i}{2} \right) \end{aligned}$$

and

$$\begin{aligned} l_i^{(2)}\left((d_{ij}^k(t))_{j,k}, \nu(t)\right) &= -\gamma_i L(i) \sum_{k=1, \dots, K} \nu_k^e(t) \left[\sum_{j=1, \dots, n} L(j) \left(1 \right. \right. \\ &\left. \left. - \frac{d_{ij}^k(t)}{\min\{\mathcal{X}_e\}} \mathbf{1}_{d_{ij}^k(t) \leq 0} - \frac{d_{ij}^k(t)}{\max\{\mathcal{X}_e\}} \mathbf{1}_{d_{ij}^k(t) \geq 0} \right) \right]^{-1} \end{aligned}$$

Using the fact that we are in energy shortage in the sense of Inequality (14) and that $\min\{\mathcal{X}_e\} \leq f_i(\nu_k^e, t) \leq \max\{\mathcal{X}_e\}$, $\forall k = 1, \dots, K$, we can check easily that provider s_i 's loss function can be upper-bounded by $l_i^{(1)}(f_i(t), \nu(t)) + l_i^{(2)}\left((d_{ij}^k(t))_{j,k}, \nu(t)\right)$. It is the sum of two functions: the first one depending only on s_i 's forecasts, and the second one depending only on his disagreement with the other providers' forecasts. \square

Proof of Lemma 4

Suppose that provider s_i plays according to a Hannan consistent strategy according to his loss upper bound i.e., $l_i^{(1)}(f_i(t), \nu(t)) + l_i^{(2)}((d_{ij}^k)_{j,k}(t), \nu(t))$. This means that:

$$\begin{aligned} & \limsup_{T \rightarrow +\infty} \frac{1}{T} \left[\sum_{t=1}^T l_i^{(1)}(f_i(t), \nu(t)) + \sum_{t=1}^T l_i^{(2)}((d_{ij}^k(t))_{j,k}, \nu(t)) \right. \\ & \left. - \min_{y \in \mathcal{X}_s \times \mathcal{X}_e^K} \left(\sum_{t=1}^T l_i^{(1)}(y, \nu(t)) + \sum_{t=1}^T l_i^{(2)}((d_{ij}^k(y, t))_{j,k}, \nu(t)) \right) \right] \leq 0 \quad (19) \end{aligned}$$

where $d_{ij}^k(y, t)$ contains the disagreement between provider s_i and all the other providers when s_i makes the prediction y at time period t without any change in the predictions of the other providers.

In Section 4, we have introduced lower and upper bounds on the disagreements between provider s_i and the other providers about the forecasts of the energy productions $\underline{D}_{ss}(i)$ and $\overline{D}_{ss}(i)$. According to Corollary 3, $l_i^{(2)}(\cdot)$ being increasing in $d_{ij}^k(t)$, it is possible to provide lower and upper bounds for the function by evaluating it in $\underline{D}_{ss}(i)$ and $\overline{D}_{ss}(i)$ respectively. The lower bound is:

$$b_l(i, t) = -\frac{\gamma_i L(i)}{g(\underline{D}_{ss}(i))} \sum_{k=1, \dots, K} \nu_k^e(t)$$

Whereas, the upper bound takes the form:

$$b_u(i, t) = -\frac{\gamma_i L(i)}{g(\overline{D}_{ss}(i))} \sum_{k=1, \dots, K} \nu_k^e(t)$$

If Inequality (19) is checked, then the following inequality holds:

$$\begin{aligned} & \limsup_{T \rightarrow +\infty} \frac{1}{T} \left[\sum_{t=1}^T l_i^{(1)}(f_i(t), \nu(t)) + \sum_{t=1}^T b_l(i, t) - \min_{y \in \mathcal{X}_s \times \mathcal{X}_e^K} \left(\sum_{t=1}^T l_i^{(1)}(y, \nu(t)) \right. \right. \\ & \left. \left. - \sum_{t=1}^T b_u(i, t) \right) \right] \leq 0 \end{aligned}$$

This last inequality provides an upper bound for the external regret associated with provider s_i 's partial loss. □

Proof of Theorem 5

With the proposed expression of ψ , the upper bound of the external regret evaluated in provider s_i 's partial loss becomes:

$$\begin{aligned} & \limsup_{T \rightarrow +\infty} \frac{1}{T} \left[\sum_{t=1}^T l_i^{(1)}(f_i(t), \nu(t)) - \min_{y_i \in \mathcal{X}} \sum_{t=1}^T l_i^{(1)}(y_i, \nu(t)) \right] \\ & \leq \frac{1}{T} \psi(\underline{D}_{ss}(i), \overline{D}_{ss}(i)) \sum_{t=1}^T \sum_{k=1, \dots, K} \nu_k^e(t) \end{aligned} \quad (20)$$

Summing Inequality (20) over all $i = 1, \dots, n$, the external regret evaluated in the sum of the providers' partial losses, becomes:

$$\begin{aligned} & \limsup_{T \rightarrow +\infty} \frac{1}{T} \left[\sum_{t=1}^T \tilde{l}_g(f(t), \nu(t)) - \min_{f(\cdot)} \sum_{t=1}^T \tilde{l}_g(f(\cdot), \nu(t)) \right] \\ & \leq \frac{1}{T} \sum_{i=1, \dots, n} \psi(\underline{D}_{ss}(i), \overline{D}_{ss}(i)) \sum_{t=1}^T \sum_{k=1, \dots, K} \nu_k^e(t) \end{aligned}$$

In addition:

$$\min_{f(\cdot)} \frac{1}{T} \sum_{t=1}^T \tilde{l}_g(f(\cdot), \nu(t)) = \min_{\otimes_{i=1, \dots, n} d(f_i) \in F_s^n} \frac{1}{T} \sum_{t=1}^T \tilde{l}_g^E(\otimes_{i=1, \dots, n} d(f_i), \nu(t))$$

where \tilde{l}_g^E represents the expectation of function \tilde{l}_g .

We assume that each service provider makes his forecasts independently of the other service providers. Then $\tilde{l}_g^E(\cdot, \nu(t))$ is linear in $\otimes_{i=1, \dots, n} d(f_i)$. As a result, its minimum over the simplex of probability vectors is reached in one of the corners of the simplex.

Let: $d_T(z) = \frac{1}{T} \sum_{t=1}^T \mathbf{1}_{\{\nu(t)=z\}}$ be the marginal empirical frequency of play evaluated in prediction $z \in \mathcal{X}_s^n \times \mathcal{X}_e^K$.

Then:

$$\begin{aligned} & \min_{\otimes_{i=1, \dots, n} d(f_i) \in F_s^n} \frac{1}{T} \sum_{t=1}^T \tilde{l}_g^E(\otimes_i d(f_i), \nu(t)) \\ & = \min_{\otimes_{i=1, \dots, n} d(f_i) \in F_s^n} \sum_{z \in \mathcal{X}_s^n \times \mathcal{X}_e^K} d_T(z) \tilde{l}_g^E(\otimes_i d(f_i), z) \\ & = \min_{\otimes_{i=1, \dots, n} d(f_i) \in F_s^n} \tilde{l}_g^E(\otimes_{i=1, \dots, n} d(f_i), d_T(\cdot)) \\ & \leq \underbrace{\max_{d(\nu) \in F_m} \min_{\otimes_{i=1, \dots, n} d(f_i) \in F_s^n} \tilde{l}_g^E(\otimes_{i=1, \dots, n} d(f_i), d(\nu))}_{\hat{V}_g} \end{aligned}$$

□

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