

A Cooperative Game Theory Approach to Wind Power Generation Imbalance Cost Allocation

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Abstract - The steady increase in the number of grid-connected wind farms brings to the fore the issue of having to deal with their associated power imbalances. Grid security requires that power imbalances be counteracted by coordinated real-time regulation actions at a cost to be then recovered by the transmission system operator. The current imbalance cost recovery philosophies in many electricity markets give *individual* incentives to producers to keep the system in balance. However, when considering wind producers, this principle breaks down because wind farms generally have little control over their power output. Needless-to-say, this puts wind power at a competitive disadvantage with respect to other fully-controllable generation technologies. This cost recovery principle also neglects the fact that wind farms are most often dispersed over wide geographical areas and are therefore exposed to wide spectra of wind conditions. Empirical evidence shows that this vast variety of operating conditions can *collectively* act to reduce the network-wide power imbalance, albeit in an uncoordinated manner. Recognizing that this “uncoordinated cooperation” is beneficial to the economic efficiency and security of a power system, we develop an imbalance cost allocation method that effectively rewards this cooperation and thus mitigates the competitive disadvantage wind power producers are facing. To that end, we use formal cooperative game theory principles in laying out the foundations of the method. The resulting imbalance cost allocations are shown to be unique, fair and efficient. A case study, based on the Greek electricity market, demonstrates the practical viability of the approach.

Keywords - Cooperative game theory, cost allocation, fairness, power imbalance, spatiotemporal diversity, wind power generation.

1 Introduction

RENEWABLE electricity generation is a key solution to the modern energy and climate challenges. In view of this fact, the impact of wind power variability on the secure and economic operation of power systems becomes an issue of increasing importance. The uncertainty related to wind power forecasting translates into additional system balancing costs, which have been estimated as €1–4/MWh for a wind power penetration up to 20% of the demand [1].

In many European countries, notably in Spain and the United Kingdom, such balancing costs are borne by the wind power producers [2]. While this practice is in accordance with a non-discrimination principle amongst participants in a competitive market, it fails to recognise the

competitive disadvantage of wind power producers with respect to classical hydrothermal units.

Imbalance volumes arise due to the limitations on the accuracy of short-term wind forecasting techniques. In addition, wind power producers have limited means to avoid being out of balance and thus have to bear the associated costs. Under such market arrangements, managing the risk related to the imbalance cost is a crucial part of a wind power producer’s strategy since both the imbalance settlement prices and the forecast errors are exogenous parameters generally beyond its control [3–6].

An additional point for consideration is the *spatial smoothing effect* of the wind power forecast error [7]. As positive and negative forecast errors of many individual wind farms cancel out, the aggregated forecast error of a group of dispersed wind farms may be significantly less than the sum of the individual absolute errors. It follows that, the net balancing cost of a group of dispersed wind farms may be significantly less than the sum of the costs of the respective individual imbalances as well [8].

In view of this effect, an alternative approach is employed in Denmark and Germany where system operators use a single forecast for a large group of wind farms [9]. Nevertheless, the cost of the resulting net imbalance is not paid by the wind power producers but by the system operators [10]. Clearly the fairness of this practice, with respect to the operation of a competitive electricity market, is also questionable.

Integrating the beneficial features of both approaches, this paper introduces an imbalance settlement methodology designed to address the aforementioned fairness considerations and which acknowledges the potential cross-cancellation of imbalances. The settlement process is based on the fact that the imbalance cost associated with wind power is the cost of the aggregated net imbalance of all the wind farms in a power system. This is a cost that should be paid collectively by the wind power producers and not by the system operator (*i.e.* society). In order to allocate this net cost amongst the wind power producers in an equitable manner, we formulate an allocation based on principles from cooperative game theory.

Cooperative game theory has provided the basis for the formulation of a fair and efficient solution in a variety of allocation problems. A method for the allocation of the fixed transmission costs amongst the users of an electricity network was introduced in [11], while [12, 13] addressed the problem of allocating the transmission losses under a pool based electricity market.

The remainder of this paper is organized as follows: Section 2 introduces the main principles of cooperative

game theory, based on which a model of the cooperation of the wind power producers reducing their aggregated imbalance is formulated in Section 3. Section presents the imbalance cost allocation process, which is analysed through theoretical examples in Section 5. The application of the proposed allocation method on a realistic case study is simulated in Section 6. In the final section, conclusions are summarized.

2 Cooperative Game Theory

Game theory [14] studies situations in which various agents compete through decision making with the purpose of maximising their payoffs from a certain activity. The characteristic function of every game is a function that determines the payoff of every player in the game according to certain criteria. In cooperative games, the players can attempt to increase their payoffs by forming a coalition.

In such a case, the characteristic function of the game would determine the common payoff of the coalition rather than the payoff of each individual player. In the event that the characteristic function of the game is super additive the players have the potential to benefit from participating in a coalition. Super additivity, expressed through inequalities (1) and (2) for a cooperative game with N players and characteristic function $u(\cdot)$, enforces that the joint payoff of the coalition cannot be less than the sum of the players' individual payoffs for every subset of players $S \subseteq N$.

$$u(S) \geq \sum_{i \in S} u(i) \quad \forall S \subseteq N \quad (1)$$

$$u(S) + u(T) \leq u(S \cup T) \quad \forall S, T \subset N; S \cap T = \emptyset \quad (2)$$

2.1 The Shapley Value

Super additivity in cooperative games begs a question regarding the allocation of the common gains amongst the members of a coalition. Consideration should be given to the fact that the extent of the various players' contribution to the common achievement is not equal. An allocation principle based on the philosophy of egalitarianism has been introduced by Shapley in his seminal work [15]. The Shapley allocation assigns a nonzero value to all the members of the coalition that contribute to the coalition's gain. This value is indicative of the extent of each player's contribution to the common achievement. The *Shapley value* can lead to a unique, efficient and symmetric allocations [16].

Let us consider $n \in N$ players participating in a cooperative game. The Shapley value of each player $i \in N$, denoted by $\phi_i(N)$, is the average marginal contribution of that player in all the possible player coalitions. Considering every possible subset $S \subseteq N$ as a coalition, the Shapley values can be calculated by assessing the marginal contribution of player i for each coalition S it participates in, $\mu(S, i)$ defined in (3), which is averaged out considering the probability that player i joins each coalition $S \subseteq N$ as shown in (4).

$$\mu(S, i) = u(S \cup \{i\}) - u(S) \quad \forall i, S \subseteq N \quad (3)$$

$$\phi_i(N) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|! (n - |S| - 1)!}{n!} \cdot \mu(S, i) \quad (4)$$

3 Wind Power Generation Imbalance Cooperative Game

Wind power producers have limited control on the sign or the magnitude of their forecast errors. Nevertheless, they have the potential to cooperate naturally as negative and positive individual forecast errors may cancel out. The value of this uncoordinated cooperation is the reduction in the net system cost of wind power unpredictability with respect to the aggregated cost of the producers' individual imbalances. As the way to achieve this reduction is by settling the imbalance volumes of wind power producers collectively and not individually (*i.e.* there is potential gain from cooperation), the process can be modelled through a cooperative game.

3.1 Characteristic Function

The outcome of the game should be determined by evaluating the sum of the wind power producers absolute imbalances in contrast to their aggregated absolute imbalance. In the event that the former is greater than the latter the outcome of the game leads to a win. Clearly the value of this win should reflect the magnitude of the achieved net imbalance reduction. In this spirit, we propose the following characteristic function:

$$u(S) = \begin{cases} 1 - \frac{|\sum_{i \in S} w_i|}{\sum_{i \in N} |w_i|} & \text{if } \sum_{i \in S} |w_i| > |\sum_{i \in S} w_i| \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

where w_i is the measured imbalance volume of producer i . This function assigns a value that not only indicates whether or not the natural cooperation reduces the system's net imbalance; it also recognizes the extent of this cooperation between the group of wind power producers. Through (5), a greater reduction in the net system imbalance would be rewarded through a greater payoff. We note that this characteristic function is not super additive as condition (2) may not hold when the balance condition of an existing coalition (S , say) is made worse by joining one or several producers (T) whose imbalance sign already matches that of the coalition.

3.2 Shapley Allocation

The Shapley values of this game should reflect the extent of each producer's contribution to the reduction of the net system imbalance. Producers that are assigned with higher Shapley values would be the ones that contribute most to the reduction of the aggregated imbalance and thus should be rewarded by receiving the greatest share of the common benefit (*i.e.* the reduced balancing cost). We must note that only a positive Shapley value indicates that a player is contributing to the common achievement of

a coalition. A zero Shapley value suggests that a player's contribution is ineffectual. Furthermore a negative Shapley value indicates that a player's contribution is detrimental to the coalition's common goal.

4 Imbalance Cost Allocation Process

The process of allocating the aggregated imbalance cost follows the Shapley values of the wind power producers' cooperative game. Producers with nonpositive Shapley values effectively do not contribute to reduce the net wind power imbalance; hence, they should be asked to settle their individual imbalance at the market price (π_{IM}) independently. That is, for all producers $i \in N$ with $\phi_i(N) \leq 0$

$$C_w(i) = \pi_{IM} \cdot w_i. \quad (6)$$

As a reward for their cooperation producers with positive Shapley values should share the difference between the net wind power imbalance cost and the amount of money collected from the producers with nonpositive Shapley values

$$\hat{C}_w = \pi_{IM} \cdot \sum_{i \in N} w_i - \sum_{i \in N: \phi_i(N) \leq 0} C_w(i) \quad (7)$$

If this amount of money is positive, cooperative producers will be sharing the residual cost. As the players with the greatest Shapley value have contributed the most to the imbalance reduction, the allocation of this cost should be made in inverse proportion to their Shapley values through (8) and (9). Alternatively, in the event that the residual amount of money is negative, the system operator will have collected more money than the cost of the wind power imbalance. In such a case cooperative producers should be rewarded for their contribution by sharing the excess charges in proportion to the Shapley values through (10) and (11). Those allocation principles translate mathematically into:

- If $\hat{C}_w > 0$ and $\forall i \neq j \in N : \phi_i(N), \phi_j(N) > 0$

$$\alpha_i = \frac{\phi_j(N)}{\phi_i(N)} \cdot \alpha_j \quad (8)$$

$$\sum_{i \in N: \phi_i(N) > 0} \alpha_i = 1 \quad (9)$$

- If $\hat{C}_w < 0$ and $\forall i \neq j \in N : \phi_i(N), \phi_j(N) > 0$

$$\alpha_i = \frac{\phi_i(N)}{\phi_j(N)} \cdot \alpha_j \quad (10)$$

$$\sum_{i \in N: \phi_i(N) > 0} \alpha_i = 1 \quad (11)$$

In both cases the cost allocation coefficients distribute the residual wind power imbalance cost amongst the cooperative producers as

$$C_w(i) = \alpha_i \cdot \hat{C}_w \quad \forall i \in N : \phi_i(N) > 0 \quad (12)$$

We note in closing that the above allocation principles lead to a *unique* balancing cost allocation since (8) and (9) (or equally (10) and (11)) define full-rank square systems of linear equations.

4.1 Allocation Algorithm

The process of settling the wind power producers imbalance costs through the proposed methodology materializes through the following algorithm

Step 1: Evaluate the characteristic function (5) for each producer $i \in N$.

Step 2: If $u(N) = 0$

Step 2.1: Settle the imbalance of every producer according to (6).

Step 2.2: Continue to Step 8.

Step 3: Calculate the Shapley values through (3) and (4).

Step 4: Settle the imbalance of every producer with a nonpositive Shapley value according to (6).

Step 5: Calculate the residual wind power imbalance cost through (7).

Step 6: If $\hat{C}_w > 0$

Step 6.1: Calculate the imbalance allocation coefficients through (8) and (9).

Step 6.2: Allocate the residual imbalance cost according to (12).

Step 6.3: Continue to Step 8.

Step 7: If $\hat{C}_w < 0$

Step 7.1: Calculate the reward allocation coefficients through (10) and (11).

Step 7.2: Allocate the residual reward according to (12).

Step 7.3: Continue to Step 8.

Step 8: End

5 Illustrative Examples

To demonstrate the philosophy of the allocation method we will consider some illustrative basic examples. These are specifically designed to emphasise on the properties of the proposed allocation process.

5.1 Example 1

The first example refers to a group of 5 wind power producers. Table 1 lists the amount of imbalance (in per unit) introduced by each producer. For the sake of simplicity it is assumed that a single price of $\pi_{IM} = \pounds 10$ per unit is used to settle positive and negative imbalances. According to this price, the third column of Table 1 presents the imbalance charges when each producer faces the cost of its individual absolute imbalance ($C_w^{abs}(i)$). We note that the total cost the wind producers would be asked to pay is significantly greater ($\pounds 195$) than the cost of the net system imbalance ($\pounds 25$).

i	w_i (per unit)	$C_w^{abs}(i)$ (£)	$C_w(i)$ (£)	$\frac{C_w(i)}{C_w^{abs}(i)}$
1	11	110	0.758	0.007
2	-1	10	9.04	0.904
3	-3	30	4.345	0.145
4	-2	20	5.868	0.293
5	-2.5	25	4.989	0.200
N	-2.5	195	25	0.128

Table 1: Example 1, producer Imbalances and Cost Allocations

Let us now examine the imbalance charges resulting from the proposed allocation method ($C_w(i)$, in the fourth column of Table 1). As expected, the total charges paid by wind power producers are equal to the cost of their aggregated imbalance. Furthermore, every producer realizes a reduction in its imbalance cost. In order to comment on the fairness of the allocation we need to compare the imbalance costs faced by the 5 producers. Producer 1 introduces the greatest amount of absolute imbalance but would be asked to pay the smallest share of the cost (3.03%). At the same time, producer 2 would be called to pay the greatest share of the cost (36.16%) whilst introducing the smallest absolute imbalance value. Even though this result appears to be counterintuitive it is the fair solution to this allocation problem.

We recall that the decisive factor should be the contribution of each producer to the group's net imbalance, as this is the only actual cost a system operator needs to recover. As Table 2 indicates, the large positive imbalance of producer 1 counteracts the negative imbalance of all the remaining producers. As this contribution results in the greatest reduction in the aggregated imbalance, this producer is rewarded through the largest Shapley value which translates into the lowest cost allocation coefficient, $\alpha_1 = 0.030$.

i	$ w_N - w_{N \setminus \{i\}} $ (per unit)	$\phi_i(N)$	α_i
1	-6	0.568	0.030
2	-1	0.047	0.362
3	-3	0.099	0.174
4	-2	0.073	0.235
5	-2.5	0.085	0.200
N	-17	0.872	1

Table 2: Example 1, producer Contributions' Comparison

Producer 2 not only failed to counteract the negative imbalance introduced by producers 3–5, but also contributed the least against the positive imbalance of producer 1. For these reasons, it would be asked to pay the greatest share of the net cost. In a similar manner, producer 3 has the greatest Shapley value, amongst the producers with negative imbalances. Even though the absolute imbalance it introduced was greater than that of 2, 4 and 5, it is rewarded for being the one that counteracted the most the imbalance of producer 1. We should also stress out the efficiency of the proposed allocation. The net imbalance of the group is equal to -2.5 while the sum of the absolute imbalances equals 19.5. Through the characteristic function of the cooperative game (5) the value of this coalition is equal to 0.872. As Table 2 confirms, the Shapley values add up to this value, which represents the total gain of their cooperation.

We should note that repeating this allocation exercise, but this time with a different producer ordering, would not alter the final results of the process. This is indicative of the uniqueness character of the Shapley value which translates to the proposed cost allocation process. This feature is highly desirable from a regulatory point of view as it essentially entails that the system operator treats all wind producers anonymously.

5.2 Example 2

The next simple example, summarized in Table 3, refers to four wind producers and is designed to illustrate what happens negative Shapley values arise in the allocation process. Once again the single imbalance settlement price is assumed to be £10 per unit. By examining Table 3, we note that the imbalances of producers 2 and 3 are of opposing sign and almost equal magnitude. While these imbalances would practically cancel out, producers 1 and 4 introduce greater amounts of positive imbalance.

i	w_i (per unit)	$\phi_i(N)$	$C_w^{abs}(i)$ (£)	$C_w(i)$ (£)	$\frac{C_w(i)}{C_w^{abs}(i)}$
1	5	-0.066	50	50	1
2	-2	0.342	20	-1.772	-0.013
3	1.8	0.044	18	-0.228	-0.089
4	7	-0.117	70	70	1
N	11.8	0.203	158	118	0.74

Table 3: Example 2 Summary

Producers 1 and 4 would increase significantly the net imbalance in every possible coalition they would join. This detrimental effect is reflected through their corresponding Shapley values, which are negative. According to the proposed imbalance settlement method, they would have to settle their individual imbalances at the market price. Following this process the residual net imbalance cost would be

$$\hat{C}_w = 10 \cdot 11.8 - 10 \cdot (5 + 7) = -2$$

As this amount is negative, the system operator would have already recovered the cost of the net wind power imbalance, and would reward producers 2 and 3 by refunding them the excess charges in proportion to their Shapley values. Since producer 2 counteracted the imbalance, of all the remaining producers, it collects the greatest share of the reward (£1.772), while producer 3 realizes some benefit as well (£0.228).

6 Realistic Case Study

This section presents the application of the proposed cost allocation technique on a realistic case study. The data for the formulation of this case study were kindly supplied by the *Greek Regulatory Authority for Energy*. We would like to clarify that the scope of this case study is not to examine the conditions in this market. The aim of this case study is to assess the applicability of the proposed allocation technique and comment on the method's behaviour.

6.1 Market Environment

The hourly imbalance settlement of the electricity market with several wind power producers has been simulated for a complete day. The electricity market modelled consists of 16 power producers, whose wind farm portfolios are presented in Appendix A. These producers own a total of 43 wind farms situated in 9 separate geographical areas. The hourly average yearly production of each wind farm has been employed as the respective hourly generation forecast. Using these forecasts, imbalance volumes have been simulated based on the statistical analysis of the wind power prediction errors introduced in [8]. According to this study, the probability density function of wind power prediction errors follows a beta distribution and can be uniquely defined through the normalized predicted power output and the prediction error standard deviation. To represent the spatial smoothing effect, it was assumed that sites located in the same geographical area share a common prediction error standard deviation. This assumption is justified through studies confirming that the correlation of the prediction standard deviation reduces as the size of a geographical area increases [7].

The yearly average value of the hourly price in the Greek electricity market has been used as the single price at which positive and negative imbalances are settled. It is considered that each producer participates in the market with the total energy that his portfolio of wind farms produces. Consequently, every producer has to settle the aggregated imbalance of its portfolio of wind farms. Figure 1 presents the assumed hourly imbalance settlement price along with the absolute hourly aggregated imbalance of the wind producers and the sum of their absolute imbalances. As the former is always greater than the latter, this simulated case study is appropriate to analyze the performance of the proposed cost allocation method.

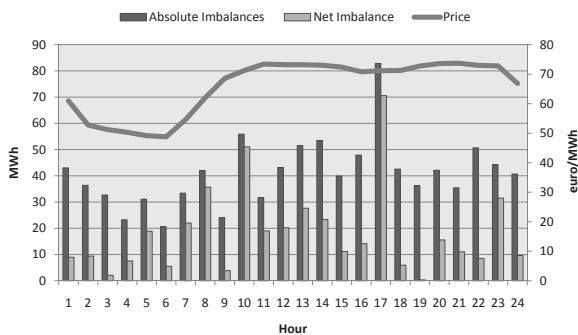


Figure 1: Imbalance Cost Allocation Case Study

6.2 Cooperative Game Theory Application

According to the formulation introduced in Section 3 a cooperative game has been formulated for each settlement period. Figure 2 summarizes the data on the hourly absolute imbalance of each producer. We recall that producer portfolios vary significantly in terms of number of sites, installed capacity and geographical dispersion. Such differences are reflected through their absolute imbalance values. The initial intuition is that producers with the biggest values of installed capacity, notably producers 1

and 5, should have the biggest impact on the net generation imbalance as they have the biggest values of average absolute imbalance.

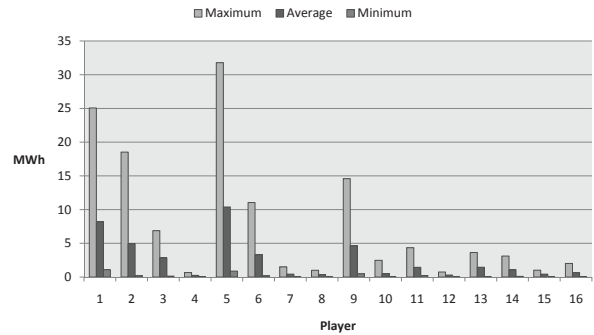


Figure 2: Producer Absolute Imbalance Data

Figure 3 presents a synopsis of the hourly Shapley values for the 16 wind power producers. As expected, producers 1 and 5 have the largest impact on the aggregated net imbalance. These producers have, on average, a negative Shapley value which indicates that the amount of imbalance they introduce is usually detrimental to the reduction of the group's net imbalance. Nevertheless, we should not neglect that having a big impact can also result in a considerable positive effect if the imbalances are in a direction opposite to the that of the system. This can be identified by comparing the maximum Shapley values of all the producers. As we can see the greatest values also belong to producers 1 and 5. The remaining producers have positive average Shapley values indicating that they contribute on average at reducing the net imbalance. Still their ability to counteract the imbalance of the large producers is limited by their small capacities. The fact that their maximum Shapley values are, in absolute terms, smaller than the minimum Shapley values of the large producers confirms that their individual contributions are weak against the large producer's potential detrimental effects.

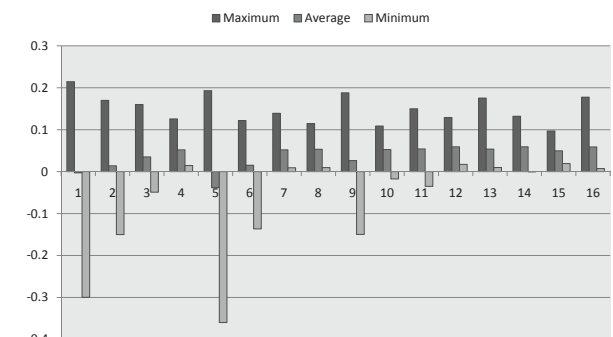


Figure 3: Shapley Values Summary

6.3 Cost Allocation

Taking into account the analysis of the producer's Shapley values, we examine the resulting allocation of the daily imbalance cost. As Figure 4 indicates, the allocation of the daily cost is in complete accordance with the conclusions on the outcome of the hourly cooperative games. The producers which were identified as mostly responsible for the net aggregated imbalance are asked to pay greater

portions while those that have a smaller effect only face a limited share of the cost. On the other hand, those producers that assisted in balancing the system through appropriate imbalance signs and volumes are rewarded by collecting a revenue in accordance to the extent of their contribution.

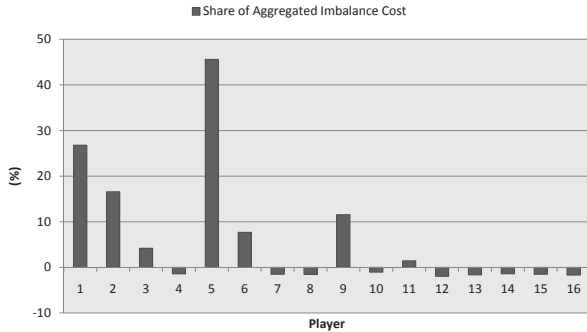


Figure 4: Net Imbalance Cost Allocation

Since the significance of the differences in the installed capacities is apparent, we should make conclusions on the fairness of the resulting cost allocation by expressing the costs per MW of installed capacity. Figure 5 compares these relative costs to the producers' individual imbalance costs. This comparison demonstrates clearly the philosophy of the proposed allocation method.

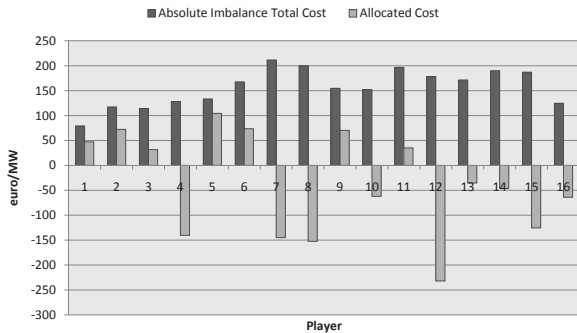


Figure 5: Costs per MW of Installed Capacity

The reduced aggregated imbalance is a result of the cooperation of all the producers and so every producer is assigned a cost smaller than the cost of its individual absolute imbalance. Amongst the producers that face a cost, those that contributed least have to pay greater shares of their individual costs. Similarly, producers which were most beneficial to the reduction of the imbalance either pay smaller shares of shares of their imbalance costs or even collect some money back. While wind power producers realize this benefit, the amount of money collected by the system operator is sufficient to balance their aggregated imbalance.

6.4 Discussion

This section presented a simulated case study with the purpose of assessing the performance of the proposed allocation technique in a realistic market setting. While conclusions on the properties of the solution have already been drawn, we should also address the issue regarding the applicability of the method. The presented algorithm has been implemented in MATLAB 7.0.1. We note that

the capabilities of this language have set a limit on the calculation of the Shapley values to a 19-power producer cooperative game (because of the limitations associated with the calculation of $n!$ and the number of possible coalitions to consider). Nevertheless, in most European electricity markets typically there are fewer large independent wind power producers than that. Moreover, investigations into the asymptotic behaviour of the $|S|!(n - |S| - 1)!/n!$ term in (4) as well as exploring the conditions under which coalitions with ineffectual significance can be neglected outright in the calculation could assist also in reducing the required computational power.

7 Conclusions

This paper introduced an imbalance settlement methodology for wind power producers. Wind power unpredictability is natural and cannot be eliminated completely. This unpredictability puts wind power producers in a disadvantageous position with respect to their competitors in the electricity market. The proposed settlement method works towards alleviating this competitive disadvantage by acknowledging that geographical dispersion can reduce the correlation of wind forecast errors. On this basis wind power producers as a group should settle their imbalance collectively and not individually. This paper established that such a process provides wind power producers with an opportunity to realize a significant benefit without undermining the technical and financial interests of the system operator. The system operator is ensured to collect the appropriate compensation for balancing the wind power producers' aggregated deviation.

To distribute the potential common benefit impartially an allocation based on cooperative game theory has been introduced. Theoretical examples validated the efficiency, the uniqueness and most importantly the fairness of the resulting solution. We must note that while the characteristic function employed has been proven to possess those desired features as well as rewarding balancing cost minimisation. Exploring alternative characteristic functions is an issue for further research with the potential of enhancing the method's performance.

Finally, the application on a realistic case study has not only identified the extent of the potential benefits to the wind power producers, but it also established the applicability of the allocation process. While further work would be required to be required to address the issue related the maximum admissible number of wind power producers, this is not a major hurdle to adopting the introduced cost allocation technique by the industry.

Acknowledgment

The authors wish to thank Dr. Michael Caramanis and Prof. Prodromos Efthimioglou, formerly with the Greek Regulatory Authority for Energy, for providing the information about the Greek electricity market used in this paper.

Appendix A

Table 4 summarizes the data¹ on the portfolios of the wind power producers participating in the market simulation of Section 6.

Producer	Installed Capacity (MW)	Sites	Area
1	170	8	1
		2	2
2	67.6	3	1
		1	3
3	39.2	1	1
		3	2
4	3	2	1
		4	1
5	128.7	1	4
		2	5
		1	6
6	30.8	1	2
		1	3
7	3.1	2	7
8	3	1	3
		1	1
9	48.4	1	2
		1	8
10	5	1	1
11	12	1	1
12	2.5	1	1
13	13.6	1	9
14	9	1	1
15	3.6	1	1
16	7.8	1	1

Table 4: Wind Power Producers' Portfolios

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¹For a detailed version of the data we refer the reader to <http://tinyurl.com/33heg6q>.