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# Cooperative Game Theory Solutions in Regional European Capacity Markets

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## Abstract

*The present paper investigates the use of cooperative game theory and its methods in the emerging landscape of the capacity markets in Europe. In order not to hinder the development of Europe's internal electricity market and to reduce the costs of ensuring the security of supply in electricity, the coordination between the continent's countries is deemed necessary on regional or even European level. Cooperative game theory methods are ideal to support the establishment of such coordination initiatives and then to allocate the savings occurring from this coordination in the most robust and rational way.*

## Keywords

Cooperative game theory; Shapley value, Capacity market; Coordination; Security of supply; Adequacy requirement; Characteristic function

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## I. Introduction

An extensive justification regarding the necessity of well-designed and well-functioning capacity markets, along with well-functioning energy and ancillary services markets is provided in (Joskow, 2008; Stamtsis, G. and Lychnaras, 2015).

In 2015, the European Commission has launched the first sector inquiry on the development of capacity markets in eleven EU member states. The first interim report of this sector inquiry was published in April 2016 (EC, 2016 [1]). The report recognizes that some EU member states have concerns about the security of supply in electricity and whether the energy-only markets can deliver sufficient investment so as to meet the extreme peaks of demand and to provide adequate flexible capacity in the long-term as back-up to the increasing penetration of intermittent renewable energy sources. The European Commission, although generally in favour of energy-only markets, understands that in some cases, capacity markets will have to complete the electricity market design along with the energy markets. However, the interim report identifies substantial problems in the design of some existing capacity mechanisms in these eleven member states.

According to the European Commission, the basic principles that must be met in the design of the capacity markets are the cooperation of the Transmission System Operators (TSOs) in assessing the capacity adequacy on regional level, instead of individually doing so on national level, and cross-border participation of foreign capacity in the capacity market of a certain member state.

ENTSO-E calls national governments, TSOs and regulatory authorities to coordinate on regional level when it comes to the implementation of capacity markets. Regional cooperation is necessary to enable cross-border participation and to define solutions in the event of coincident scarcity events in some of the region's countries (ENTSO-E, 2015 [1]).

Without cooperation on regional level and strictly following the national path in designing and implementing a capacity market, the relevant authorities of a country will surely have a more conservative approach regarding the necessary domestic capacity (generation, demand response, storage) that is needed in order to meet the adequacy targets. Thus, excessive investments may be considered necessary, while in the neighbouring region the already-available capacity could contribute to the security of supply of this country. Over-dimensioning the capacity needs on national level will result in higher costs for the consumers but also in a possible lock-in effect regarding aged and environmentally-harmful capacity which otherwise (in case of regional cooperation) might not be considered, partially or totally, necessary to ensure the targeted security of supply level.

Therefore, TSOs on regional level should work closely to assess the capacity adequacy levels of the region and the individual countries. This work should be

based on commonly=agreed methods, tools and demand/supply scenarios. If the region's national governments, based on the outcome of the TSOs' work, decide to proceed with establishing a capacity market as a means to safeguard the capacity adequacy, then the most efficient way would be to consider the capacity market on the regional level and not to implement numerous national markets.

Of course, this requires an advanced level of regional cooperation between the TSOs, the regulatory authorities and the national governments. Today, such cooperation is probably not the case in many of Europe's regions and some capacity markets are already in design or implementation phase as illustrated in Fig.1 (Hancher, L. *et al.*, 2015). Additionally, there is also the problem of the absence of a common approach in assessing capacity adequacy (EC, 2016 [1]).

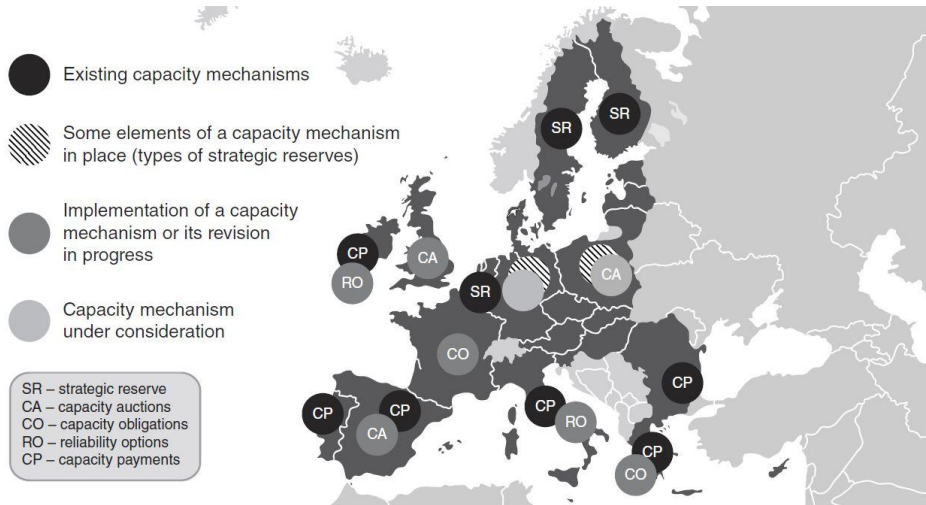
Additionally, there is also the problem of the absence of a common approach in assessing adequacy. The fact that an increasing number of countries apply a similar advanced methodology, based on an hourly LOLE, does not mean the outcomes can now be easily compared with one another (Joskow, 2008).

Nevertheless, we think that the current national plans for capacity markets should be designed and implemented in such a way that, in the first place, they should at least be open for cross-border participation and that their design should allow their regional integration at a later stage.

The present paper considers the case where regional cooperation and coordination is available as an option, illustrates the benefits of this approach and provides quantitative solutions for allocating these benefits among the countries of a region. For that purpose, we take advantage of the methods and solutions provided by the cooperative game theory.

## **II. Cooperative game theory**

While game theory, being a study of multi-person decision problems, aims to describe the behaviour of different participants (players) in a certain situation (game), the cooperative game theory rather investigates the allocation of benefits resulting from the possible cooperation, within the framework of a certain game, between the different players (Peleg and Sudhölter, 2007; Lui, 2008; Stamtsis, 2003).



**Fig. 1 Capacity mechanisms in Europe, 2015**

Source: Hancher, L. *et al.*, 2015

### A. Terminology of cooperative game theory

The set of players participating in a cooperative game is denoted

$$N = \{1, 2, \dots, n\} \quad (1)$$

In a cooperative game, it is possible that a coalition  $S$  may emerge between some or all the players. Of course, it holds

$$S \subset N \quad (2)$$

The aim of the players participating in a coalition  $S$  is to maximize the payoff to the coalition's participants and then allocate this payoff among the individual players of this coalition. We call characteristic function  $v(S)$ , of a certain cooperative game, the function that assigns to each coalition  $S$  the maximum payoff that this coalition can ensure by itself. Which coalitions are more likely to form depends on the distribution of the coalition's payoff between the players. Some players may try to attract other players in their coalition by promising them a higher payoff. Of course, the players will have the willingness to accept only reasonable payoffs. The set of the reasonable payoffs in a cooperative game

are called imputations. Any vector  $y$  which represents payoffs to the players of a cooperative game will be characterized as imputation if the following two conditions hold:

$$\sum_{i=1}^n y_i = v(N) \quad (3)$$

$$y_i \geq v(i) \quad (4)$$

The condition in (3) is called global rationality and requires the sum of the reasonable payoffs to be equal to the payoff that the grand coalition  $N$  (consisting of all players) can guarantee by itself. The condition in (4) calls for individual rationality and illustrates that any player will not accept a payoff lower to what he can ensure by acting alone.

### *B. The Shapley Value*

Once the cooperative game, the players, and the characteristic function are defined, there are numerous methods that have been proposed in order to allocate the resulting surplus. The present paper focuses on the use of the Shapley Value in the game of regional capacity markets (Shapley, 1953).

The Shapley Value has already been proposed as a solution to cooperative games during the earlier period of the theory's development. In contrast to other methods which aim to identify which payoffs will most likely persist during the negotiating phase of the game, the Shapley Value provides a quantitative answer to the following question: what should a single player expect from the game before it starts? Thus, the Shapley Value is a rather *ex-ante* approach to the game. As the capacity markets in Europe are in an early development stage, we have chosen to use the Shapley Value in this paper precisely in order to provide an *ex-ante* assessment of the benefits that regional cooperation could bring to the individual countries that plan or are currently implementing such mechanisms. Moreover, the Shapley Value's calculation is more transparent in comparison to other cooperative game theory methods as the core or the nucleolus. In that stage of the capacity markets' development, the balance between robustness and transparency is expected to be rather in favour of the latter.

The three main properties of the Shapley Value are Symmetry, Efficiency and Additivity. (Shapley, 1953) proved that the only function that satisfies all these three conditions is the following:

$$\varphi_i(v) = \sum_{S, i \notin S} \frac{(n_S - 1)!(n - n_S)!}{n!} (v(S) - v(S - \{i\})) \quad (5)$$

Where,  $\varphi_i(v)$  the Shapley Value assigned to player  $i$ .

Actually, for any player  $i$ , the Shapley Value is the sum of the contributions (expressed as increases of the characteristic function) this player brings to each coalition that includes this player. The fraction in (5) illustrates the probability that in coalition  $S$ , the  $n_S - 1$  players first participate, then player  $i$  and then the  $n - n_S$  players.

### III. The game in capacity markets

Initially, cooperative game theory methods have been proposed in the electricity markets as tools to provide robust solutions for the allocation of the transmission system's fixed costs (Tsukamoto and Iyoda, 1996; Stamtsis and Erlich, 2004). Since then, such methods have also been proposed for, inter alia, allocation of unit's start-up costs and inter TSOs compensation (Hu et al., 2006; Dietrich, Olmos and Perez-Arriaga, 2008). Apart from these cases, the cooperative game theory has been applied in a wide range of cost allocation problems (Fiestras-Janeiro, Garcia-Jurado, and Mosquera, 2011).

In the emerging landscape of the capacity markets, each country in order to deal with capacity adequacy shall ensure reliable and available capacity in the forthcoming years equal to the forecasted peak demand (by the local TSO) plus a safety margin -- e.g. 5%. ENTSO-E's most recent adequacy forecast provides a dataset for the individual European countries load forecast (ENTSO-E, 2015 [2]). In this paper, we use the forecast referring to 2020, as we believe a 3-4 year lead-in period is needed when it comes to capacity markets (i.e. in order to ensure adequate capacity for 2020, the capacity market should perform auctions or other market-based tools in 2016). Table 1 summarizes the forecasted peak demand regarding four Southern European countries in 2020. We have chosen these countries for two main reasons. The first is that almost all of them (as can be seen in Fig. 1) have experience with capacity markets. Even Croatia has announced a capacity tender, as explained in *EC, 2016 [1]*, to meet future demand. The second reason is the regional aspect of a possible coalition between these countries. The figures are the sum of the forecasted load at a reference time-point plus the margin against seasonal peak load.

**Table 1 Peak demand forecast and adequacy requirement for Southern European countries in 2020**

Country	Peak demand (MW)	Adequacy requirement (MW)
Italy (IT)	54.850	57.593
Greece (EL)	10.400	10.920
Croatia (HR)	3.530	3.707
Spain (ES)	46.000	48.300

Source: ENTSO-E, 2015 [2]

Each country could either put effort to safeguard the necessary capacity to meet the adequacy requirement through a national path or choose to cooperate with the neighbouring countries by establishing coalitions that would target a regional achievement of capacity adequacy. The incentive to form a coalition is that each country could take advantage of the capacity located in the neighbouring country to serve the peak demand at its time of scarcity. Of course, this incentive is limited by the transfer capacity of the interconnection between the two countries. Another limitation could be simultaneous scarcity events in the two countries (i.e. peak demand occurs at the same time). For simplicity reasons, this paper assumes that peak demand occurs at different times in each country.

Table 2 provides the available transfer capacities between these four countries in Southern Europe. Figures have been derived by the ENTSO-E's NTC matrix for 2010/2011 (ENTSO-E, 2015 [3]). Where there is direct interconnection between the two countries, the corresponding figure was used. Where there is no direct connection, the transfer capacity represents the capacity of the shortest and more likely path (applying also some derating factors to take into consideration possible events due to the intervention of TSOs that do not participate in the coalition). E.g. the path Spain-France-Italy was chosen in the case of the coalition  $S=\{ES, IT\}$ .

**Table 2 Available Transfer Capacity (MW)**

From/To	Italy (IT)	Greece (EL)	Croatia (HR)	Spain (ES)
Italy (IT)	-	160	500	900
Greece (EL)	160	-	200	130
Croatia (HR)	500	300	-	400
Spain (ES)	500	130	400	-

Source: ENTSO-E, 2010

Thus, if Greece forms a coalition with Italy (which means the two TSOs will establish a common framework for capacity market-safeguarding availability of generation capacity - and ensure the availability of the interconnection in case of a scarcity event in one of the two countries) then it just needs to ensure 10.420 MW of local capacity. Similarly, Italy should ensure 57.093 MW of local capacity. In total, the coalition {IT, EL} should ensure 1.000 MW less of generation/demand response/storage capacity to meet the adequacy requirements in the two countries in comparison to the situation where the two countries take national measures in security of supply issues.

We now define the characteristic function of the cooperative game in the capacity market as follows:

$$v(S) = \sum_{i=1}^n AR_i - AR_S \quad (6)$$

Where AR is the capacity needed to meet the adequacy requirement

Table 3 illustrates the calculations for the adequacy requirements and the value of the characteristic function for all the possible coalitions that can be formed among these four countries.

**Table 3 Adequacy requirement and characteristic function values (MW)**

Coalition	Adequacy Requirement	v(S)
{IT}	57.593	0
{EL}	10.920	0
{HR}	3.707	0
{ES}	48.300	0
{IT,EL}	67.513	1.000
{IT,HR}	60.979	320
{IT,ES}	104.493	1.400
{EL,HR}	14.127	500
{EL,ES}	58.420	800
{HR,ES}	51.747	260
{IT,EL,HR}	70.399	1.820
{IT,EL,ES}	113.613	3.200
{IT,HR,ES}	107.619	1.980
{EL,HR,ES}	61.367	1.560
{IT,EL,HR,ES}	116.239	4.280

One can observe that a possible coalition of all four countries could result in essential savings of 4.280 MW less capacity needed so as to deal with a peak-



demand situation in any of the four countries. Under the framework of the current European Commission Guidelines for state aid in energy and environment (EC, 2014), there are only two capacity mechanisms that have been approved as compatible with these Guidelines: the permanent UK market (2014) and the Greek transitory mechanism (2016). We use the most recent Greek mechanism (EC, 2016 [2]) to disclose the value of those savings. In this mechanism, each MW of flexible capacity (i.e. gas-fired and hydro units) is rewarded with 45.000 Euro/MW-year. Since gas-fired units seem to be the most efficient conventional units, in order to cope with future capacity demands, we may attribute to the saving occurred in our cooperative game this specific value. Thus, the total savings (in terms of Euro) are **192,6 million Euro/year**. This is a considerable figure which can provide a strong signal for regional cooperation regarding the design, the establishment and the operation of the capacity markets.

We now use the Shapley value method so as to provide the interested countries with an ex-ante indication of what they could achieve by forming the grand regional coalition. Table 4 illustrates the savings assigned to each country according to that method.

**Table 4 Savings assigned to each country using the Shapley Value**

Country	$\phi_i(v)$ (MW)	$\phi_i(v)$ (million Euro)
Italy	1.360	61,20
Greece	1.150	51,75
Croatia	540	24,30
Spain	1.230	55,35
Total	4.280	192,60

One can observe that the Shapley Value in this game holds the condition of the global rationality (it assigns the total of the savings to the players) as well as the condition of the individual rationality (each player has positive savings which are higher than the zero savings achieved by the one-player coalitions).

Another observation is that the Shapley Value, as an incentive to the individual countries to form the grand coalition, assigned to each country prevails over any other payoff that a country could guarantee by forming a coalition with just a subgroup of the other players. For example, if Greece wanted to only convince Italy and Spain to form a coalition {IT, EL, ES} then the payoff to that coalition is 3.200 MW. Assuming that Italy and Spain would not accept an allocation lower than the Shapley Value assigned to them, only 610 MW remain as payoff for Greece. This is much less than the 1.150 MW that

Greece is assigned by the Shapley Value. Thus, Greece would have no intention to pursue the formation of that coalition instead of forming the grand coalition by including Croatia as well.

#### **IV. Conclusions**

The present paper investigates the use of the cooperative game theory in the design and establishment of regional capacity markets in Europe. Currently, a number of countries plan or are already implementing such markets as complimentary to the energy markets in order to safeguard a desired level of security of supply.

Regional coordination can result in substantial savings regarding the total necessary capacity that should be available in a region in order to meet the most extreme load situations of any region's country. In order for this to happen, close and systematic cooperation of the TSOs and the regulatory authorities of the region's countries is an absolute prerequisite. Moreover, the national governments should accept that security of supply is better served on regional (or even European) level than on national level. This is a large change from the traditional attitude of the national governments when it comes to energy policy. But exactly this paradigm shift is one of the most important targets of the mega-project of the Energy Union.

The cooperative game theory can provide robust and efficient tools in order to support the formation of regional capacity markets. Future work will focus on the investigation of methods like the core and the nucleolus in this cooperative game. Of course, apart from the engineering work, a lot of research is needed in the elaboration of energy policy procedures and tools which will enable and realize the cooperation of governments, regulatory authorities and TSOs on regional level.

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