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Can cross-border transmission expansion lead to fair and stable cooperation? Northeast Asia case analysis

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ABSTRACT

In this paper, we present a framework for analyzing cross-border power interconnection projects based on Cooperative Game Theory. Compared to existing studies, we not only quantify the benefits of interconnections and suggest cost-benefit allocation techniques, but also analyze the stability of the allocations, which is a crucial aspect in regions where coordination and mutual trust between countries have not been built yet. We apply our framework to the Northeast Asia where six countries (China, Russia, Mongolia, South Korea, North Korea, and Japan) are suggested for cross-border transmission expansion planning cooperation. Cost-benefits allocation of the interconnections is analyzed according to the marginal contribution of each country to the grand coalition and the minimal dissatisfaction of each coalition that ensures the stability of the solution. Accordingly, Game Theory concepts (the Shapley value and the Nucleolus) are used in our analysis. Moreover, we employ the Core concept to further analyze the stability of the allocation solution and present a visualization of the feasible space formed by all stable allocations. We found out that the grand coalition (i.e., the scenario where all countries agree on the cooperation) is the optimal and stable coalition, with $7.1 billion total savings per year. We also suggested a scheme of investment allocation and payments between the Northeast Asian countries in order to ensure that the proposed interconnections are plausible in practice.

1. Introduction

Interconnection of power systems brings similar benefits as global economic cooperation. If a country can produce power in a cheaper way than its neighbors, there may be an opportunity for power export. However, there are many factors influencing this potential exchange. Naturally, economic benefits are one of them. The stability of cooperation is also a key factor for ensuring the practical feasibility of the interconnections. This is crucial in case of several countries cooperating (e.g., Northeast Asian or South American countries), where mutual trust has not necessarily been strongly built in the past.

Any cooperation must be economically efficient to take place, even though some participants may eventually incur losses. Additionally, power interconnections bring technical advantages such as reliability, production efficiency, and controllability of power supply, which are especially important under a massive renewable-energy integration (Bailey et al., 2014; Munoz et al., 2014; Spyrou et al., 2017).

The importance of international energy cooperation is included in United Nations sustainable development goals: "*By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology*" (UN, 2018). China, being one of the most proactive countries in power systems development, is also highlighting the importance of cross-border interconnections through the Global Energy Interconnection Initiative, which is proposed and analyzed by the Chinese Grid Company and Global Energy Interconnection Development and Cooperation Organization (GEIDCO) (Pai et al., 2017). In Europe, the European Network of Transmission System Operators for Electricity (ENTSO-E) was established to coordinate more than 40 regional transmission system operators (ENTSO-E, 2018a), delivering power from one country to another according to economic signals. New scenarios of interconnection were studied (Aigner et al., 2012; Ciupuliga and Cuppen, 2013; Lumbreras et al., 2017; Sabolić, 2017),

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motivated by the need for planning and construction of new cross-border interconnections to meet the demand growth.

International power cooperation has been helped by development of high voltage and ultra-high voltage direct current technologies (HVDC) that enable transferring power of the order of gigawatts, for thousands of kilometers (Bahrman and Johnson, 2007). There are numerous advantages of HVDC lines in comparison to traditional alternating current power lines. The major advantage of HVDC technology is the reduced level of power losses that is a key factor for long-distance lines. Considering a hypothetical 750-mile overhead line with 3 GW capacity, power losses at its full load would reach 5–7% in the case of AC lines (depending on the voltage level and the technology) and 3–6% in the case of HVDC lines (Bahrman and Johnson, 2007). Considering cable lines, the difference between AC and HVDC power losses would be even greater. HVDC cable losses can be about half of the AC cable losses, and additionally, HVDC cables avoid reactive power compensation problems. The economic break-even distance of HVDC lines comparing to the AC ones is about 500 km. Thus, current cross-border power interconnection projects would most likely be implemented with HVDC technology. The second advantage is controllability of HVDC interconnections that makes it possible to set power transfers at required levels while power flows in AC lines must obey Kirchhoff laws and are therefore a function of transmission network parameters and the overall generation/demand pattern. Controllability of HVDC flows is important for operation of power markets and energy exchanges. In addition, one potential disadvantage of AC interconnections is related to the reliability issue. AC synchronization may sometimes influence the interconnected countries in a negative way (ENTSO-E, 2018b) while HVDC lines allow systems to exchange power while not being synchronized. With all these advantages, HVDC becomes a practical technology that makes power cross-border interconnection projects realistic.

The current status of power market integration between countries varies widely. Europe has a history of cooperation and mutual trust. On the other hand, Asia and South America have a history of mistrust and lack of stability. These differences among regions explain why many countries are not electrically connected with their neighbors yet, even though power interconnections could be beneficial. Moreover, bilateral contracts of electricity trade prevail in existing cross-border interconnection practice. This approach is far from the establishment of international power markets.

Numerous studies, technical and economic analyzes of cross-border interconnections have been performed in the past. Otsuki et al. (2016) studied the aggregated economic effects of the Northeast Asian power market creation. This analysis was based only on the comparison of the power system cost in two scenarios: non-interconnection (each country develops its own expansion plan within the borders), and fully coordinated plan (all countries in the region cooperate to optimally invest in cross-border interconnections). The difference between these costs showed benefits that the entire region could obtain in an aggregated manner. Other studies focused on technical performance and the accuracy of the optimization models. Roughly speaking, the optimization of cross-border power interconnections can be mathematically formulated as the classical transmission expansion planning (TEP) problem (Kirschen and Strbac, 2004). Lumbreras et al. (2017) proposed a TEP problem in a stochastic optimization context, accounting for the uncertainty caused by significant renewable energy sources. Other authors modeled different features of the problem, such as simultaneous co-optimization of generation and transmission capacity (Baringo and Baringo, 2018), placement of new control technologies (such as thyristor-controlled series compensators) (Ziaee et al., 2017), accounting for correlation between stochastic parameters, and applying robust optimization techniques and multi-level programming (Moreira et al., 2017). Those studies used different optimization techniques and models to answer the key questions: what power lines should be built; what capacity they should have; and what would be the costs and benefits for the interconnected region.

Contrary to the classic TEP, cost-benefit allocation problem has attracted less attention, especially within the framework of cross-border power interconnections. Gil et al. (2005) investigated interregional compensations that guaranteed cost recovery of investments. Some studies used Cooperative Game Theory in order to split costs and benefits of cooperation among market participants, usually generators and consumers. Stamtsis and Erlich (2004) used the Shapley value concept to examine the problem of network fixed-cost allocation among the power market participants. The key idea behind the work was that cooperative usage of a network creates counter flows that relieves power line congestion, allowing cheaper power supply. Tan and Lie (2002) discussed drawbacks of transmission cost charging methods (MW-mile and postage-stamp methods) and suggest the Shapley value as a tool for transmission services cost allocation. A similar idea was suggested by (Junqueira et al., 2007; Molina et al., 2013) who investigated the Aumann-Shapley concept. Ruiz and Contreras (2007) analyzed transmission expansion cost allocation from the investor's point of view. In their approach, the increase in social welfare caused by a new transmission line is allocated according to the Shapley value. Yang et al. (2016) suggested dividing the transmission capacity of a line into four components: capacity used in normal conditions, capacity reserved for contingencies, capacity reserved for future use, and invalid capacity, using different cost allocation approaches.

Cost allocation between power systems is complex since usually there is neither a centralized coordinating entity nor a regulatory framework. Each country has its own bargaining power and can easily veto a project of cross-border interconnection. Hence, it is necessary to allocate cost and benefits as fair as possible in order to persuade countries to cooperate. Kristiansen et al. (2018) recently examined the cost allocation issue in the North Sea offshore grid using the Shapley value, but without a thorough allocation stability analysis. The authors simply checked that the Shapley value is within the Core of the game, ensuring that the TEP solution is stable. Such an analysis does not allow getting insights into the shape of the stability region of the cross-border interconnection solutions (i.e., the Core). In this study, we analyze the structure of the Core and compare the allocation results by the Shapley value with the Nucleolus allocation technique that gives an insight into the stability of the cooperation.

As noted above, each country involved in the cross-border power interconnection possesses the power for independently and unilaterally supporting the initiative of power interconnection with neighbors, as well as the power to partially or completely veto the interconnection. In this context, new projects of interconnections can be analyzed from the Cooperative Game Theory point of view where every country is represented as an independent player (Peters, 2015). Cooperative Game Theory has been widely used in the context of international/interstate cooperation. Such rules, as the Shapley value, allow for not only allocating benefits/savings in a fair way, but also estimating the bargaining power of the parties. Hubert and Ikonnikova (2011), and then Nagayama and Horita (2014), used the Shapley value concept to analyze countries' bargaining power in the Eurasian gas supply system. He et al. (2018) exploited the same concept to allocate savings due to CO_2 emissions abatement among mainland China regions. In this paper, we focus on different allocation rules used in cooperative Game Theory and apply them to international power cooperation. In particular, we are interested not only in the analysis of fairness for cost and benefit allocation, but also in the stability analysis of the coalitions. The fairness of allocations is ensured by the Shapley value, which condenses the axiomatic definition of fairness in the cost allocation problem (Shapley, 1953). However, the allocation result from the Shapley value may be not stable. Some players may have incentives to deviate from the grand coalition (where all players do cooperate). Stability is an important aspect to consider in the cross-border interconnection models for the regions such as South America and Northeast Asia where trust among neighboring countries is not built yet. Thus, we extend the analysis to also focus on the stability of the coalitions. We introduce the concept of the Core

(Peters, 2015), defined as the set of cost-benefit allocations such that every player has the incentives to remain in the grand coalition. In some cases, the Core can contain a single allocation point or even be empty. This means that it would be theoretically impossible to persuade all players to stay in the grand coalition. In order to analyze the stability of the coalitions, we also exploit the Nucleolus concept (Peters, 2015). The Nucleolus represents a unique cost-benefit allocation for every player such that it minimizes the dissatisfaction of the coalitions. As a stable allocation point, the Nucleolus always belongs to the Core whenever the latter is not an empty set.

In summary, there is still a lack of comprehensive research on cross-border power interconnections for regions not politically integrated, i.e. without a centralized planning and coordination. There is a need to incentivize countries to be electrically interconnected by explicitly showing the benefits that could be obtained and the costs that should be paid. Accordingly, the main contributions of this paper are threefold:

- Formulation of a technical and economic methodological framework for cross-border power projects analysis that involves optimal transmission expansion and cost-benefits allocation among countries;
- Description of a stability analysis of the cost-benefit allocation, with a visualization of the feasible solutions using Cooperative Game Theory;
- Application of the methodological framework to the Northeast Asia case study, determining the optimal investment allocation scheme and payments among the countries that ensure the stability of cooperation.

The rest of the paper is organized as follows. In Section 2, we consider a simple case of cooperation between two power systems. We explicitly quantify cost and benefits of the interconnections and provide a background of cost-benefit allocation techniques in Section 3. Section 4 introduces the mathematical formulation of the TEP problem. In Section 5, we present a case of cross-border power interconnection in Northeast Asia that comprises power systems of six countries. The results and discussion of cost-benefits allocation techniques and issues regarding international energy cooperation are presented in Section 6. Finally, Section 7 concludes the paper.

2. Illustrative two-system case of cross-border power interconnections

Before analyzing complex models of cross-border power interconnection projects, we examine an illustrative case of two power systems initially not connected. The case is adopted from (Kirschen and Strbac, 2004), where market prices in the systems differ significantly and an interconnection with limited capacity allows power exchange, coupling both markets (Fig. 1). The initial data (supply functions and technical limits) is provided in Table 1, where λ_i is the market price in system i, and p_i is the produced power. We assume power markets with perfect competition, but our analysis is equally applicable to countries with traditional monopolistic vertically-integrated utilities.

The supply functions are assumed to be linear. They are represented with bold solid lines in Fig. 1. Power demand is considered perfectly inelastic in each power system (vertical lines). It can be observed that the clearing electricity price and demand in power system B are significantly higher than the ones in power system A. Thus, the construction of a transmission line will lead to power export of electricity from power system A towards power system B. In Table 2, we provide the results of the main market indicators before and after the interconnection.[1] Red areas in Fig. 1 denote the cost incurred by generating companies. Blue areas stand for social welfare, which equals to the generating companies' surplus in the case of inelastic power demand. The sum of both areas equals to the total payment made by consumers in a market. It is worth mentioning that we did not include consumer surplus in our analysis. In order to do this, it would be necessary to set the maximum price that consumers would be willing to pay. Some studies suggest using the value of loss load (VoLL) as a reference point of measuring consumer surplus when considering inelastic demand (Kristiansen et al., 2018).

It is seen that, once the power systems are interconnected, both the generation cost and the generation surplus of power system B decrease, from Cb to Cb' and from Sb to Sb', respectively. On the contrary, both the generation cost and the generation surplus of power system A increase by Ca' and Sa'+ Sa'', respectively. It should be noted that generators at system A get additional cost Ca' due to the need of 400 MW extra generation. However, generation surplus of system A increases not only due to the export component Sa'', but also because its own consumers have to buy electricity at a new higher price and pay the surplus Sa'. The overall benefit of the interconnection is caused by the significant reduction of the generation cost in power system B (area Cb'').

At first glance it seems that the results of market interconnection are outstanding: total consumers' payment was decreased by 14% and the price in power market B dropped significantly. However, it turns out that some market participants are not satisfied with the interconnection decision. Consumers in power system A used to buy energy for 15 $/MWh, and now they are compelled to pay more. The surplus of generating companies in system B has decreased dramatically, even more than the increase in generators A benefits. Thus, certain market participants might not support the initiative of interconnection. The question that arises is whether it possible to find a benefit allocation that is profitable for all the parties. We suggest in this paper that the Cooperative Game Theory provides an appropriate analytical framework to analyze those problems and in the next section we apply a few allocation tools for that purpose.

3. Cooperative Game Theory applied to cross-border power interconnections

In our setting, some power systems or countries intend to cooperate in order to get mutual benefits. Next, we present the definitions of the Shapley value, the Nucleolus and the Core for cooperative games in the context of cross-border power interconnections.

Before examining the allocation techniques, it is important to state what type of utility function we are going to consider. There are two equivalent approaches to allocation problems: allocation of benefits or allocation of costs. In the former approach, the value to be allocated is a benefit, surplus or a certain gain, while in the latter approach the allocated value is related to the cost reduction due to the cooperation. Avoided costs, cost savings or cost reductions can be interpreted as benefits obtained from the coalition in the case of cross-border interconnection. Hereinafter, we consider costs allocation and formulate utility functions in terms of costs. References to benefits in the subsequent sections come from cost reductions when two or more players cooperate.

3.1. The Shapley value

The solution concept known as Shapley value is widely used in economic and technical problems due to its properties and unique distribution of utility among players. Several studies (Junqueira et al., 2007; Kristiansen et al., 2018; Molina et al., 2013; Ruiz and Contreras, 2007; Stamtsis and Erlich, 2004; Tan and Lie, 2002) have applied this concept to transmission network cost allocation. The essence of this allocation rule is to estimate the marginal contribution that each player makes to a coalition. Since players are not under the same conditions, they contribute to the total benefit differently, and thus, possess different bargaining power. A fair distribution of costs and benefits should be

[1] Power losses are not included in the calculations for simplicity reasons. The inclusion of losses makes power transfers less significant and reduces the amount of energy exported. However, this simplification does not alter the economic principles of system interconnections used here.

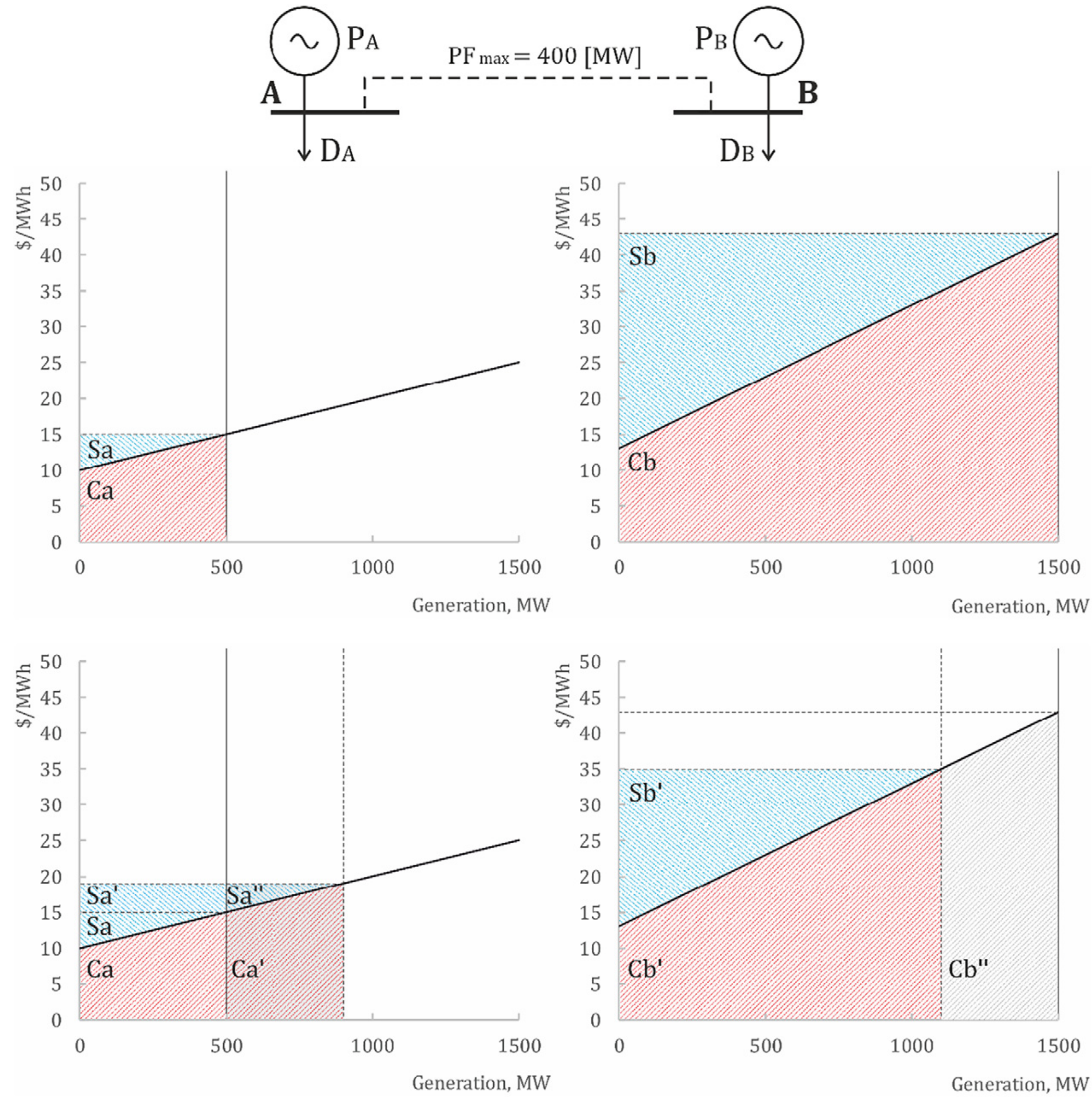


Fig. 1. (a) Stylized model of the two power systems and their potential interconnection; (b) power markets clearing before interconnection; (c) power markets clearing after interconnection.

done according to players' bargaining power. The final value x_i allocated to player i can be calculated by the Shapley value formula:

$$x_i = \sum_S \left[\frac{(|S|-1)!(|N|-|S|)!}{|N|!} \cdot [\upsilon(S \cup \{i\}) - \upsilon(S)] \right] \tag{1}$$

The total number of players is described by $|N|$, and $|S|$ stands for the number of players in a coalition S. The utility function of a coalition S is represented by $\upsilon(S)$. Please note that the term utility function in the context of this study means the total cost in a certain scenario. Mathematically, it is a result of the TEP formulation (8)–(15) described in the following section. In the two-system example, by $\upsilon(S)$ we imply a sum of the generation costs of both systems. The term $[\upsilon(S \cup \{i\}) - \upsilon(S)]$ shows the incremental contribution that player i can make to

Table 1
The two-system case study data.

Parameter	System A	System B
Supply function [$/MWh]	$\lambda_A = 10 + 0.01 \cdot p_A$	$\lambda_B = 13 + 0.02 \cdot p_B$
Power demand [MW]	500	1500

Table 2
Power markets analysis before and after the interconnection.

	Separate markets No interconnection	Markets interconnected via 400 MW line
Market price [$/MWh]	$\lambda_A = 15$	$\lambda'_A = 19$
	$\lambda_B = 43$	$\lambda'_B = 35$
Generation cost [$/h]	$C_A = 6\,250$	$C_A + C'_A = 13\,050$
	$C_B = 42\,000$	$C'_B = 26400$
	Total = 48 250	Total = 39 450
Generation surplus [$/h]	$S_A = 1\,250$	$S_A + S'_A + S''_A = 4\,050$
	$S_B = 22\,500$	$S'_B = 12\,100$
	Total = 23 750	Total = 16 150
Consumers' payment [$/h]	$P_A = 7\,500$	$P'_A = 9\,500$
	$P_B = 64\,500$	$P'_B = 52\,500$
	Total = 72 000	Total = 62 000

the coalition S. In order to calculate allocation to a certain player, it is needed to analyze all possible coalitions that can happen in the game and sum up marginal contributions of the player to them.

In the simple example from the previous section, we can see that only two scenarios are possible: countries agree or disagree on building the interconnection. Thus, value allocation to each player calculated by Eq. (1) consist of two components: marginal contribution to the coalition of one and marginal contribution to the coalition of two. However, we should first select the utility function. Shapley value is just a tool that distributes gain of the cooperation among players. The result of the distribution highly depends on the utility function formulation. We suppose that the utility function can be formed on the basis of three criteria: total generation cost, generation surplus, and consumer's payments. The allocations are different for each criterion. Following the two-system illustrative example presented before, we have calculated the Shapley values for each criterion and presented them in Table 3.

Among the three criteria mentioned above for defining the utility function in computing the Shapley value, we select the total generation cost as the proxy for the cost-benefit allocation. We believe this criterion is more appropriate than the others. The main argument supporting generation cost as a proxy for the utility function definition is its consistency with the approach selected for the expansion planning. That is the case in this paper where we are using transmission expansion model for optimal selection of new power lines updates based on cost minimization criteria. Conversely, arguments disregarding other proxies are the next. Firstly, it is possible to have negative surplus gains after coalition. In fact, the two-system illustrative case results in a negative generation surplus (see Table 3). However, when consumer surplus is included, the total change in generation and consumer benefits may be positive. Secondly, the customer payments resulting from the electric market wholesale equilibrium are lower than the final cost of the electricity for customers due to the taxes, complimentary services, externalities, etc., that are charged to the customers. These extra payments could be very different country by country. Wholesale customer payments would not be enough to clearly determine gains from cooperation at the customer side. Therefore, hereinafter we will use generation cost as a proxy for defining the utility function of a cooperative game.

It can be observed that most of the savings occur in power system B, which makes it in favor of the coalition. However, in order to persuade power system A to cooperate, there is a need to arrange a payment that would cover generation cost and provide benefits for cooperation. The amount of the payment equals the difference between the values after interconnection and the Shapley values. In each of the performed calculations, the efficiency condition (global rationality condition) can be verified: the sum of the Shapley values equals the total value being distributed.

The presented illustrative case reveals the features and problems of cost and benefits allocation when two power systems are going to be interconnected. Unlike the illustrative case, real-world projects of power interconnection require significant investment. This investment changes the allocation result when added to the utility function. Cross-border interconnection projects become especially complicated when there are three or more countries involved. In such cases, the bargaining power of the players may be different. Allocation of benefits becomes unequal as well, which may leave some parties unsatisfied. The issues of allocation stability are analyzed in the next sub-sections.

Table 3
Comparison of the allocation techniques for the two-system example.

	System A	System B
Consumers' payment before interconnection [$/h]	$P_A = 7\,500$	$P_B = 64\,500$
Consumers' payment after interconnection [$/h]	$P'_A = 9\,500$	$P'_B = 52\,500$
Shapley value calculated on the basis of consumer's payments [$/h]	$P_A^{Sh\ P} = 2\,500$	$P_B^{Sh\ P} = 59\,500$
Generation cost before interconnection [$/h]	$C_A = 6\,250$	$C_B = 42\,000$
Generation cost after interconnection [$/h]	$C_A + C'_A = 13\,050$	$C'_B = 26\,400$
Shapley value calculated on the basis of generation cost [$/h]	$C_A^{Sh\ C} = 1\,850$	$C_B^{Sh\ C} = 37\,600$
Generation surplus before interconnection [$/h]	$S_A = 1\,250$	$S_B = 22\,500$
Generation surplus after interconnection [$/h]	$S_A + S'_A + S''_A = 4\,050$	$S'_B = 12\,100$
Shapley value calculated on the basis of generation surplus [$/h]	$S_A^{Sh\ SW} = -2\,550$	$S_B^{Sh\ SW} = 18\,700$

3.2. The core and the nucleolus

Cost allocation of a coalition among the set of players N should not only be fair, but also stable. This is particularly important in cross-border power interconnections among several countries. In terms of cooperative games, stability implies allocations that satisfy all players. That is, no one would like to deviate from the grand coalition. The set of all stable allocations is called the Core of a game (Stamtsis and Erlich, 2004). Mathematically this can be described via coalitional rationality condition (2a) and global rationality condition (2b):

$$\sum_{i \in S} x_i \le v(S)\,,\ \forall S \subset N \tag{2a}$$

$$\sum_{i \in N} x_i = v(N) \tag{2b}$$

The left-hand side of Eq. (2a) is the total cost allocated to a group of participants S when the grand coalition is formed, and the right-hand side is the cost when the participants form a sub-coalition S just among themselves. Thus, the first condition (2a) states that, for each possible coalition S, the sum of allocated costs x_i for every player i that belongs to the coalition S must be less than the cost for this particular coalition $v(S)$. In other words, the sum of allocated costs obtained from the grand coalition N is always lower than in all other possible coalitions. Condition (2b) enforces equality of the total value of the grand coalition and the sum of all cost allocation to the players, i.e. it is not possible to allocate more cost than obtained from the grand coalition. Unfortunately, there is no guarantee that the Core is not an empty set for every game. There could be cases with no allocation solution that makes the coalition stable. In the previous two-system example, there are just two possible scenarios: the systems do interconnect or decide to pay for electricity as it is. Thus, the grand coalition consists of two players and is much more effective than keeping systems separate. All the players can be satisfied with a variety of feasible solutions (allocations). Therefore, the Core of the game is not empty in this case.

Despite the nice properties of the Shapley value, its solution does not always belong to the Core. Therefore, other allocation techniques with a unique solution are of a great interest. One of such single point solution concepts is the Nucleolus. The advantage of using the Nucleolus is that it always lies in the Core. Computation of the Nucleolus is based on excess or “satisfaction” of being in a coalition (3).

$$e(S) = v(S) - \sum_{i \in S} x_i \tag{3}$$

The excess of a coalition $e(S)$ shows the difference between the value obtained by the coalition itself $v(S)$ and the sum of each member's allocation from the grand coalition. The larger is the excess $e(S)$ the more satisfied are players from the coalition S for being in the grand coalition. Their overall cost is less when they are in the grand coalition. In this context, the excess represents the extra cost to pay for the coalition S with regard to the cost allocated in the grand coalition.

The Nucleolus is defined as the optimal cost allocation, x_i, that minimizes dissatisfaction of the most dissatisfied coalition (4).

$$\min_{x_i} \max_{S} -e(S) \tag{4}$$

The inner problem in Eq. (4) selects the coalition S with the maximum dissatisfaction (minimum excess). The outer problem, optimally selects the allocations, x_i, in order to minimize the maximum dissatisfaction. The inner problem can be replaced by $\varepsilon = \max_{S}[\sum_{i\in S}x_i - \upsilon(S)]$. Thus, problem (4) is equivalent to the Linear Programming (LP) problem:

$$\min_{x_i} \varepsilon \tag{5}$$

s.t.:

$$\varepsilon \ge \sum_{i\in S}x_i - \upsilon(S) \qquad \forall S\subset N \tag{6}$$

$$\sum_{i\in N}x_i = \upsilon(N) \tag{7}$$

The max operator has been replaced by the set of constraints (6). Eq. (7) ensures that the total cost is allocated among all players. By solving Eqs. (5)–(7) we obtain an allocation that minimizes the dissatisfaction of the most dissatisfied coalition, that is with the lowest excess. However, this may be not the Nucleolus if the problem (5)–(7) has multiple solutions. In this case, we need to fix the minimized dissatisfaction of the coalition from the previous LP and similarly minimize the dissatisfaction of the second most dissatisfied coalition. After solving the second LP, if no unique solution exists, we need to create a third problem and so on so forth. By consequently solving the LP problems we finally obtain the unique and stable allocation, the Nucleolus. Note that, if the initial problem in Eqs. (5)–(7) has a single solution, there is no need for iterative adjusting the allocations. We refer to (Durga, 2016; Guajardo and Jörnsten, 2015) for the more detailed description of the Nucleolus solution process.

In the two-system example, the allocations calculated by the Shapley value and the Nucleolus are exactly the same. This is a feature of two-player games where both sides can split the benefits equally. It can be verified that according to the Shapley allocation, both countries get the same savings, 4400 [$/h], that is the difference between the initial generation cost and the cost allocation after the interconnection. However, the more players participate in the game, the more unequal allocations may appear due to differences of players' relation to coalitions and topology of a network. This feature is analyzed in the following sections.

Finally, it is worth remarking the different purposes of the Shapley value and the Nucleolus. They are modeling completely different ideologies of allocation, as the former is treated as utilitarian while the later one is egalitarian. Thus, the Shapley allocation tends to be a fair distribution that analyzes marginal contribution (utilities) of the players to all possible coalitions, while the purpose of the Nucleolus is to satisfy all players in the grand coalition starting with the most dissatisfied coalition.

4. Cross-border power interconnection problem formulation

Investment planning in cross-border power lines, by its nature, is a transmission expansion problem (TEP) that has been thoroughly examined in (Alguacil et al., 2003; Baringo and Baringo, 2018; García-Bertrand and Mínguez, 2017; Li et al., 2016; Lumbreras et al., 2017; Moreira et al., 2017; Saberi et al., 2017; Spyrou et al., 2017; Ziaee et al., 2017) with various solution methods. In this study, we do not introduce a new TEP solution algorithm. Instead, we exploit a simple TEP model as a tool for optimal decision-making about new transmission lines updates. This allows us to focus on allocation issues while not interfering with the main insights and results obtained for the analysis. Thus, we use a static linear TEP formulation. It is worth saying that simultaneous co-optimization of generation and transmission expansion plans leads to greater benefits of cross-border interconnection (Pozo et al., 2013). However, we do not consider generation expansion in this problem because it would be difficult to coordinate generation expansion among countries. In general, generation expansion constitutes an independent and unilateral exercise for each country that is aligned with their energy roadmaps and environmental commitments. At this stage, we use the TEP only in order to trace the results of cost allocation.

First, we estimate a set of nodes that represent power systems $\mathcal{N} = \{1, \ldots, N\}$. Every country/state could be represented by one or more nodes. The set of candidate lines is denoted by $\mathcal{L} = \{1, \ldots, L\}$. Each candidate line is assigned a binary parameter y_l that equals one if the decision to build a line is made and zero otherwise. Actual power flow through an existing or candidate line l is depicted by f_l and maximum line capacity by F_l. An annualized net preset costs of investment, CI_l, depends on final line capacity, F_l, in case the line is built ($y_l = 1$). Each node possesses a generation mix represented by several types of generation technologies $\mathcal{T} = \{1, \ldots, T\}$. An operational year is divided into several seasons $\mathcal{S} = \{1, \ldots, S\}$, each season is representing h_s hours. At each season inelastic power demand $D_{n,s}$ is given for every node. The resulting optimization problem can be formulated as follows as a mixed-integer linear program (MILP):

$$\min_{y,f,p,F} \pi_{\mathcal{G}} + \pi_{\mathcal{L}} \tag{8}$$

s.t.:

$$\pi_{\mathcal{G}} = \sum_{s\in\mathcal{S}} h_s \cdot \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} p_{n,t,s} \cdot C_{n,t,s} \tag{9}$$

$$\pi_{\mathcal{L}} = \sum_{l\in\mathcal{L}} F_l \cdot CI_l + y_l \cdot CF_l \tag{10}$$

$$\sum_{t\in\mathcal{T}} p_{n,t,s} + \sum_{l\in\mathcal{L}} B_{n,l} \cdot f_{l,s} = D_{n,s} \qquad \forall n, s \tag{11}$$

$$0 \le p_{n,t,s} \le P^{max}_{n,t} \qquad \forall n, t, s \tag{12}$$

$$-F_l \le f_{l,s} \le F_l \qquad \forall l, s \tag{13}$$

$$y_l \cdot F^{min}_l \le F_l \le y_l \cdot F^{max}_l \qquad \forall l \tag{14}$$

$$y_l \in \{0, 1\} \qquad \forall l \tag{15}$$

The objective function, (8), consists of the annualized net present value of the generation cost, $\pi_{\mathcal{G}}$, and the transmission expansion investment cost, $\pi_{\mathcal{L}}$. The first component, (9), multiplies the actual output of each generation technology by its corresponding variable generation cost. Investment cost in power lines, (10), has two cost terms: the first term is related to the variable investment cost, CI_l, proportional to the line capacity F_l, and the second term refers to the fixed cost, CF_l, incurred to create the line interconnection. Eq. (11) corresponds to the power balance constraint, where $B_{n,l}$ is the node-line incidence matrix. Inequality (12) imposes restrictions on the generators output. In Eq. (13), actual power flows are set to be below the transmission line capacities. The transmission capacity for new lines ranges from minimum, F^{min}_l, and maximum, F^{max}_l, capacity, if the line is built, as imposed in Eq. (14). Binary variable y_l represents the nature of the investment decisions of new line corridors, as imposed in Eq. (15). Thus, the optimization problem described in Eqs. (8)–(15) leads to an optimal solution in terms of generation costs and transmission investment costs.

It should be noted that we do not specify Kirchhoff's voltage law in our model. This is made according to the assumption that most of the long-distance power lines would be constructed on the basis of HVDC technologies. Therefore, we formulate our optimization problem as a transportation problem with transferable utilities.

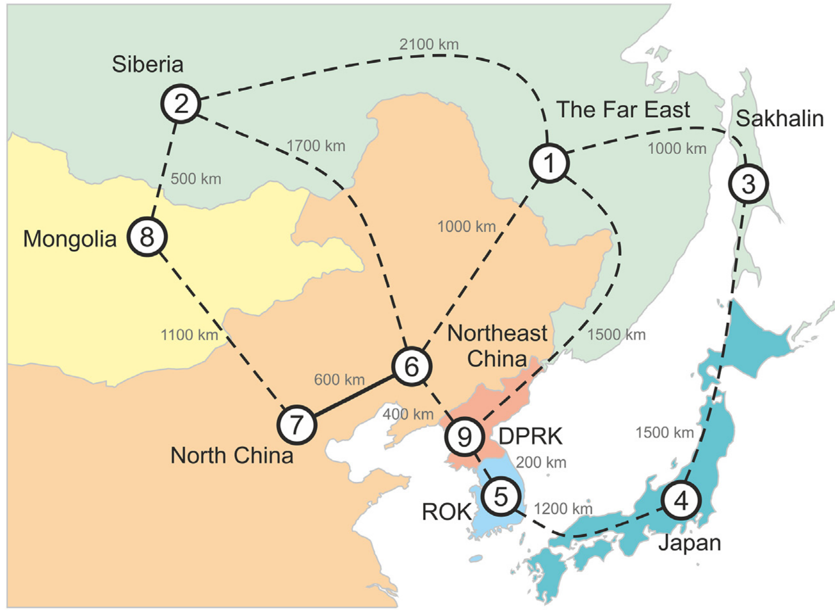


Fig. 2. Scheme of potential cross-border power interconnections in Northeast Asia.

5. Case study: Northeast Asia grid

Potential cross-border power interconnections in Northeast Asia have been studied since the beginning of the last decade. Various interconnection initiatives comprised power systems of China, Russia, the Republic of Korea (ROK), the Democratic People's Republic of Korea (DPRK), Japan and Mongolia. Not to describe the entire historical background of this initiative, we refer to (Churkin and Bialek, 2017; Liu et al., 2016; Voropai et al., 2019) for more details. Nonetheless, it is worth remarking that the significant differences in the economics and the power systems of the involved countries make cross-border interconnections challenging in the region. While electricity prices and generation mixes vary widely over the power systems, very few power interconnections have been built in Northeast Asia. The opportunity for international energy trade in the region was examined in studies like (Khamisov et al., 2005; Otsuki et al., 2016).

The results of existing studies show possible annual benefits that all the countries can obtain by being interconnected. The order of magnitude of these benefits – billions of US dollars per year and gigawatts of installed capacity reduction. However, the issue of cost and benefit allocation was not addressed in those studies. It is crucial to quantify the benefits that could be obtained by each country and understand how the investment costs in HVDC cross-border power lines should be divided among the participants. In order to analyze this issue, we study the following case based on realistic data and apply the Game Theory allocation techniques described in the previous sections.

We consider the target year 2035 as the period where different interconnection scenarios could take place. The rationale for such long-term planning lies in the economic and political efforts needed to persuade countries for regional power cooperation. Therefore, we model the Northeast Asian power systems of the future and estimate benefits of possible interconnections. Data collection was performed in May 2018 on the basis of International Energy Agency World Energy Outlook (IEA, 2018) and local technical reports and documents, such as Chinese electric power yearbook (China Electric Power Press, 2017), reports of the Institutes of Energy Economics (Japan) (The Institute of Energy Economics, 2018), long-term energy supply and demand outlook (Japan) (Japanese ministry of Economy Trade and Industry, 2015), and the basic plan for long-term electricity supply and demand (ROK)

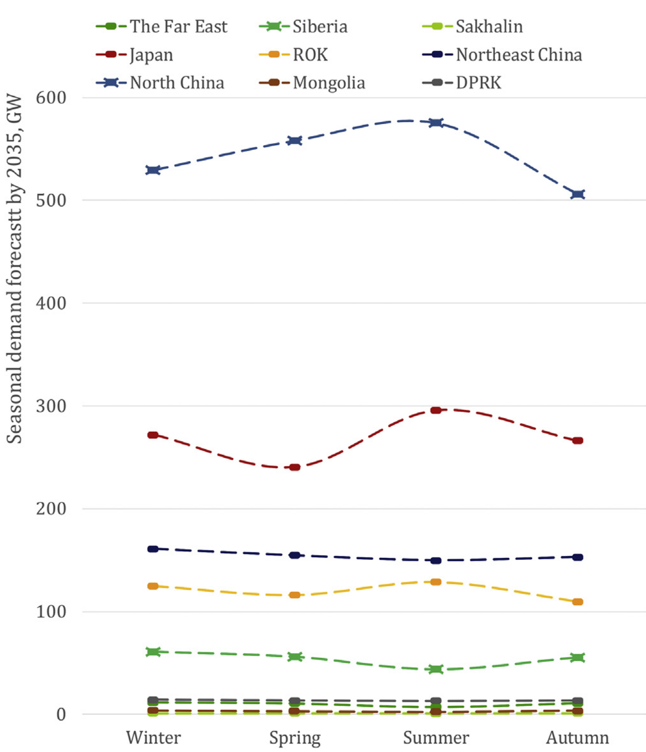


Fig. 3. Seasonal demand curves forecast.

Table 4
Generation mix forecast.

	Installed capacity by generation type, GW						
	Nuclear	Coal	Gas	Oil	Hydro	Wind	PV
The Far East	–	4.18	5.01	–	5.87	0.004	0.003
Siberia	2.50	31.73	3.64	–	28.61	0.30	0.10
Sakhalin	–	0.36	0.89	0.03	–	0.12	–
Japan	32.00	41.00	92.00	5.00	55.00	13.00	78.00
ROK	38.33	43.29	33.77	1.09	4.70	8.06	16.57
Northeast China	14.80	103.60	7.40	–	33.30	29.60	11.10
North China	48.00	336.00	24.00	–	108.00	96.00	36.00
Mongolia	–	3.38	–	–	0.72	0.45	0.20
DPRK	–	1.14	5.86	1.57	7.71	0.57	0.71

Table 5
The levelized cost of electricity assumptions.

	Levelized cost of electricity by generation type, $/kWh						
	Nuclear	Coal	Gas	Oil	Hydro	Wind	PV
The Far East	–	0.050	0.060	–	0.032	0.071	0.089
Siberia	0.027	0.050	0.060	–	0.032	0.071	0.089
Sakhalin	–	0.050	0.070	0.150	–	0.075	–
Japan	0.079	0.116	0.141	0.261	0.099	0.090	0.108
ROK	0.051	0.084	0.126	0.220	0.103	0.112	0.102
Northeast China	0.066	0.064	0.117	–	0.055	0.063	0.086
North China	0.066	0.064	0.117	–	0.055	0.063	0.086
Mongolia	–	0.075	–	–	0.060	0.095	0.100
DPRK	–	0.060	0.120	0.250	0.100	0.120	0.130

(The South Korean Ministry of Trade Industry and Energy, 2017). The proposed scheme of cross-border interconnections is presented in Fig. 2. It is based on the schemes used in the studies (Khamisov et al., 2005; Otsuki et al., 2016) and own judgment of the authors. Only the interconnection between North and Northeast Chinese power systems is considered existing. Other interconnections (dashed lines) in Fig. 2 have not been built. Their construction is under consideration in our model.[2]

The forecast of the seasonal changes in demand is presented in Fig. 3. There is a wide difference in power consumption among the countries. Fig. 3 suggests that China, Japan, and ROK are the main countries that would influence regimes and prices of the future cross-border power interconnections system. We rely on generation expansion plans made at the national level of each country (Table 4) and do not perform generation capacity optimization. Cost assumptions for different types of generators are listed in Table 5. We consider the levelized cost of electricity as the indicator for our long-term planning task. The rationale for this assumption is that, even though power market operations are usually performed on the basis of marginal costs, long-term planning decisions require considering investment decisions, cost recovery, the strategic value of water and renewables.

The power supply in each country can be represented by an arrangement of generators' costs in ascending order. In the current work, we assume that demand curves in each country are perfectly inelastic. We extend the diversity of the generation costs by splitting the blocks of each technology into several blocks with costs ranging from −5% to 5% of the nominal cost values from Table 5. All supply generation curves in the region are represented in a single plot (Fig. 4).

As it can be seen from Fig. 4, the cost and capacity of generation in Northeast Asia vary significantly. This creates an opportunity for power exchange that could replace expensive generation with more affordable and/or clean energy sources. We consider the interconnection scheme presented in Fig. 2. To assess the effectiveness of creating the cross-border power lines, we use the annualized cost of transmission investment expressed in per unit of capacity, in a similar manner as (Otsuki et al., 2016). A 25-year investment return period is considered with a 10% interest rate. Annualized net present costs of transmission lines are presented in Table 6. We impose technical limits of cross-border power lines capacity equal to 5 GW per corridor between countries. This limit is set due to energy security issues and technological and political aspects that would exist in the considered period.

6. Results and discussion

The optimization problem formulated in Eqs. (8)–(15) for the case-study of Northeast Asia contains 1908 continuous and 11 integer variables. It was solved using the Gurobi solver v7.5.2 under JuMP v0.18.1 in Julia v0.6.1 programming language. In order to illustrate the benefits of cross-border power interconnections in the region and power flow directions, we present the comparison of two scenarios in Fig. 5: no cooperation (no cross-border power lines can be built) and complete cooperation (all power lines suggested can be constructed). The two-headed arrows in Fig. 5 depict reversible power flows that change their direction depending on seasons. The detailed information on power flows, market prices, generation cost, and investment costs can be found in Table 7. When no interconnections are allowed, there just two power flows between the systems: from Northeast China towards North China and from the Far East towards Sakhalin. The line 1–3 is newly constructed (does not exist until 2035) with optimal capacity 595 MW and annualized investment of 26.79 million of US dollars per year.

In the scenario of complete energy cooperation, it is optimal to build all candidate power lines except line 2–6. This line turns out to be too long and expensive. Besides, there is no need for the additional loop between Russia and China. The general direction of the power flows is from Russia, Mongolia, and China towards the Korean peninsula and Japan. Thus, the cheapest energy flows towards the markets with the highest prices, as expected. The power export leads to market price changes. Importers such as Japan experience a decrease in prices while exporters experience an increase in the price of electricity. Nevertheless, with an annual investment cost of 2.99 billion dollars per year, it is possible to get total savings of 7.1 billion dollars per year, i.e. a cost reduction. Having this benefit due to the interconnections, there is a need to organize money transfers and compensations in order to make all the participants satisfied. Moreover, it is necessary to determine shares of investment that each country should cover.

As discussed in Section 3, cost allocation tools from the Cooperative Game Theory can address this issue. In order to apply these tools, we consider all possible scenarios of cooperation. In the case of 6 countries (players), there are 63 possible scenarios associated with all possible coalitions between countries. For each scenario, we run our TEP model and optimize the power capacities of the lines. Thus, the optimized objective value (8) is used to compose a utility function for the cooperative game analysis. The coalitions of each scenario are presented in Fig. 6. If two neighboring countries are in a coalition, a cross-border power line can be built. Otherwise, there is no way to build any lines if countries do not agree on them (e.g., as in Coalition #1). Coalition #6, or the so-called grand coalition, is indeed the least-cost configuration in the region. It is worth mentioning that the allocation approach used in this paper slightly differs from the one used by Kristiansen et al. (2018). Instead of considering each cross-border line as a decision variable, we count the decisions of joining coalitions with other countries. This implies that if a country does not join a coalition, no power-lines with its neighbors can be built.

6.1. The Shapley value and the nucleolus of the Northeast Asia energy cooperation

Even though the grand coalition turns out to be the most effective one, there is a need to persuade countries to join it. The problem is that certain countries may perform their own calculations and observe that the grand coalition is not the most suitable for them. For example, Russia and Japan may form their own sub-coalition (#18 in Fig. 6). The power export “Siberia – The Far East – Sakhalin – Japan” of 5 GW, in this case, would allow getting cost reduction up to 2.06 billion dollars per year that can be split in half among the two countries. In order to prevent such deviations, each country should be allocated more savings than it can get in any possible sub-coalition. This condition is the Core of the game. In Table 8 we show the results of allocation on the basis of the Shapley value and the Nucleolus. We also verified whether the Shapley value and the Nucleolus belong to the Core or not by checking criteria (2a) and (2b) for each coalition scenario, i.e., 63 times. As we

[2] We want to highlight that the proposed scheme of interconnections is not a fictional or pure-academic exercise. Possible routes of interconnection have been the subject of political discussions over the last decade. The initiatives of cross-border electrical interconnection are often referred to as the “Asian Super Grid” in the media.

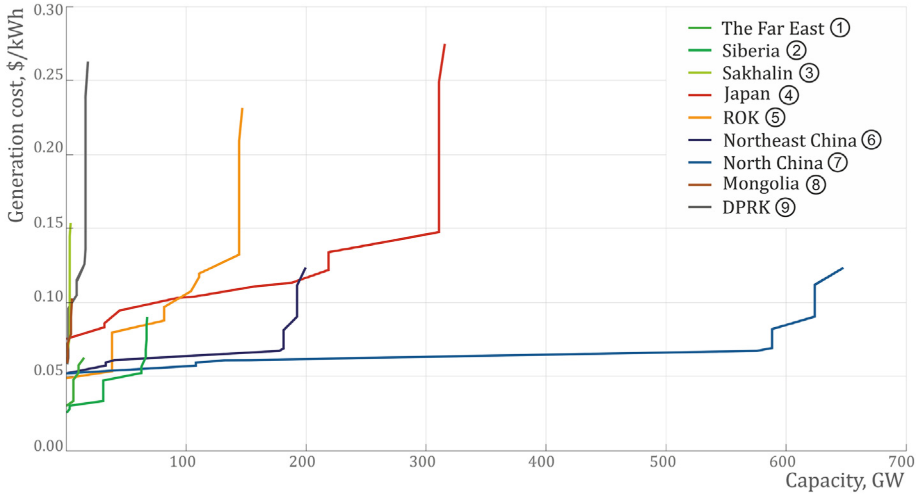


Fig. 4. Northeast Asia power supply functions forecast.

stated before, benefits here are represented by the avoided cost (cost savings).

As mentioned before, the objective function (8) was used to compose the utility function for allocation analysis. Thus, the result of allocation shows how much of the total generation cost and total investment cost can be allocated to a country. The comparison with the similar values in case of no cooperation reveals the benefits that each country may get out of collaboration. We separately consider investment costs and generation costs allocation in the following sections.

According to the results of the total cost allocation, it is possible to assure that each country may be compensated highly enough to stay in the grand coalition. The Core of the game is nonempty. This means that the development of cross-border power interconnections in Asia is economically feasible and stable, at least theoretically. However, one can observe that benefits that countries can claim differ significantly (Fig. 7). This happens due to differences in the countries' bargaining power, which, in its turn, is explained by the topology of the cross-border system and the power market conditions. For instance, DPRK possesses a significant bargaining power since it is on the way towards ROK and Japan and, thus, can veto this power export direction. Regarding this, China can consider the construction of undersea cables to ROK and decrease the bargaining power of DPRK.

It is seen that not only shares of benefits differ significantly, but also solutions on the basis of Shapley value and the Nucleolus do not coincide. As discussed in Section 3, the Shapley value allocates values to players in a fair way analyzing marginal contributions of each player to possible coalitions. The Nucleolus, on the other hand, suggests the stable solution that is guaranteed to belong to the Core (when the Core is not empty). In this case-study, both the Shapley value allocation and the Nucleolus belong to the Core. Therefore, allocation by the Shapley value can be used as a solution in this case since it allocates benefits among countries more evenly.

However, there is no guarantee that the Shapley value would remain in the Core under certain data permutations. It has been proven that the Shapley value belongs to the Core only in the case of convex cooperative games (the proof may be found, for example, in (Michael et al., 2013)). The convexity implies that the marginal contribution of any fixed player i, or of any fixed set of players, to coalition S rises as more players join S:

$$v(S\cup\{i\})-v(S)\leq v(T\cup\{i\})-v(T) \qquad \forall S\subseteq T\subseteq N,\ \forall i\in N \tag{16}$$

Unfortunately, the Northeast Asia cooperation case turn out to be a non-convex game when formulated in terms of cost allocation. To prove this, we present a counterexample. We compute the marginal contributions of Russia to all possible coalitions that it may participate. Values are shown in Fig. 8.

The objective function of the cooperation (8) reduces by 4.4 $ bln per year when Russia joins the grand coalition. However, an even greater reduction of 4.5 $ bln per year occurs when Russia joins the sub-coalition Russia-Japan-ROK-Mongolia-DPRK (excluding China). Also, the contribution to the coalition Russia-Japan-DPRK (4.03 $ bln) is higher than to the coalition Russia-China-Japan-DPRK (3.53 $ bln). Here are just a few counterexamples of decreasing marginal contribution to the coalitions with a larger number of participants that shows that convexity definition (16) does not hold. The considered cooperative game is not convex. Therefore, the Nucleolus solution can be useful for the following two reasons: first, as a benchmark of the stable cost allocation; second, as a feasible solution when the Shapley value allocation is outside of the Core.

Table 6
Annualized transmission cost assumptions.

Direction		Length [km]	Annualized cost [$/kW/year]
2-1	Siberia – The Far East	2100	84
2-8	Siberia – Mongolia	500	20
2-6	Siberia – North China	1700	68
1-3	The Far East - Sakhalin	1000	45
1-6	The Far East – North China	1000	40
1-9	The Far East – DPRK	1500	60
3-4	Sakhalin – Japan	1500	256
8-7	Mongolia – North China	1100	44
6-7	Northeast China – North China	600	0
6-9	Northeast China – DPRK	400	16
9-5	DPRK – ROK	200	8
5-4	ROK – Japan	1200	88

6.2. Transmission lines investment allocation and scheme of the money flows

The allocations presented in the previous section indicate a way of sharing the total generation cost and the total investment cost among the countries. The allocation techniques captured the countries' contributions and suggested fair and stable solutions. However, two more questions are needed to be addressed. First, it is necessary to suggest an investment mechanism to fund cross-border power lines. Countries should understand what amount of money they are going to invest and in which power lines.

The fair allocation ratios obtained by the Shapley value may be used as a solution. It reveals how much of the total investment cost countries should invest. However, it does not indicate how to allocate investment

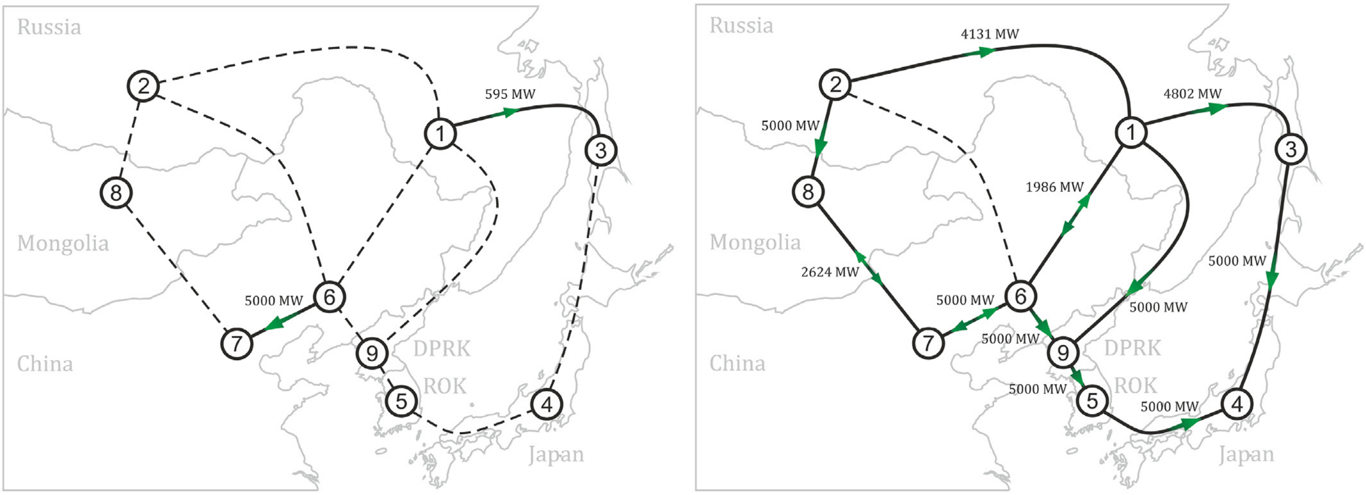


Fig. 5. Optimal transmission capacities and power flow directions in case of no cross-border interconnections (left) and in case of cooperation (right).

of every single line among the participants. It is challenging to evaluate the contribution made by each line to the overall cost reduction. Moreover, in order to allocate the investment cost of the line, it is necessary to estimate how different coalitions of countries influence TEP decisions. There are scenarios of cooperation where the capacity of some lines decreases once more players join the coalition. For example, line 2–6 "Siberia - North China" is built up to the maximum 5 GW capacity in scenario of Russian-Chinese cooperation. However, in other coalitions, when there exists power export through Mongolia, line 2–6 is not built at all. In such cases, Cooperative Game Theory allocation techniques may provide results that are hardly interpretable in practice.

Therefore, we keep the allocation ratios obtained by the Shapley value and distribute the investment cost of the lines based on the two following principles: a power line should be close to the territory of a country that takes a share of the line's investment; a country should benefit from the power export through a line that it is investing in.

Table 7
Comparison of the scenarios of non-cooperation and cooperation.

		Non-cooperation (no cross-border lines can be built)				Cooperation (all the suggested lines can be built)			
Total generation cost [million $/year]		756 949.72				746 846.86			
Annualized investment cost [million $/year]		26.79				2 998.05			
	Line	Seasons				Seasons			
		Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Power flows [MW]	2-1	–	–	–	–	4131	4131	4131	4131
	2-8	–	–	–	–	1414	5000	5000	5000
	2-6	–	–	–	–	–	–	–	–
	1-3	596	596	486	596	4680	4802	4802	4802
	1-6	–	–	–	–	-1987	-1078	1987	-1423
	1-9	–	–	–	–	5000	5000	5000	5000
	3-4	–	–	–	–	5000	5000	5000	5000
	8-7	–	–	–	–	-1466	2624	2624	2336
	6-7	4760	5000	5000	4400	-2227	5000	5000	467
	6-9	–	–	–	–	5000	5000	5000	5000
	9-5	–	–	–	–	5000	5000	5000	5000
	5-4	–	–	–	–	5000	5000	5000	5000
	Node	Seasons				Seasons			
		Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Market prices [$/MWh]	1	59.7	58.5	49.5	58.8	78.8	66.8	62.4	66.5
	2	52.3	51.5	49.8	51.5	66.8	60.9	51.0	60.0
	3	67.6	58.5	49.5	66.9	78.8	72.8	70.4	73.1
	4	142.1	137.1	145.6	141.4	140.7	135.7	144.2	139.9
	5	125.4	121.6	126.6	115.5	125.4	121.6	126.6	115.5
	6	66.8	66.5	66.5	66.5	66.8	66.8	66.5	66.5
	7	66.8	67.1	67.4	66.5	66.8	67.1	67.4	66.5
	8	78.0	76.5	75.0	77.3	66.8	61.5	51.0	66.5
	9	124.2	123.0	121.8	122.4	114.6	104.5	104.0	104.5

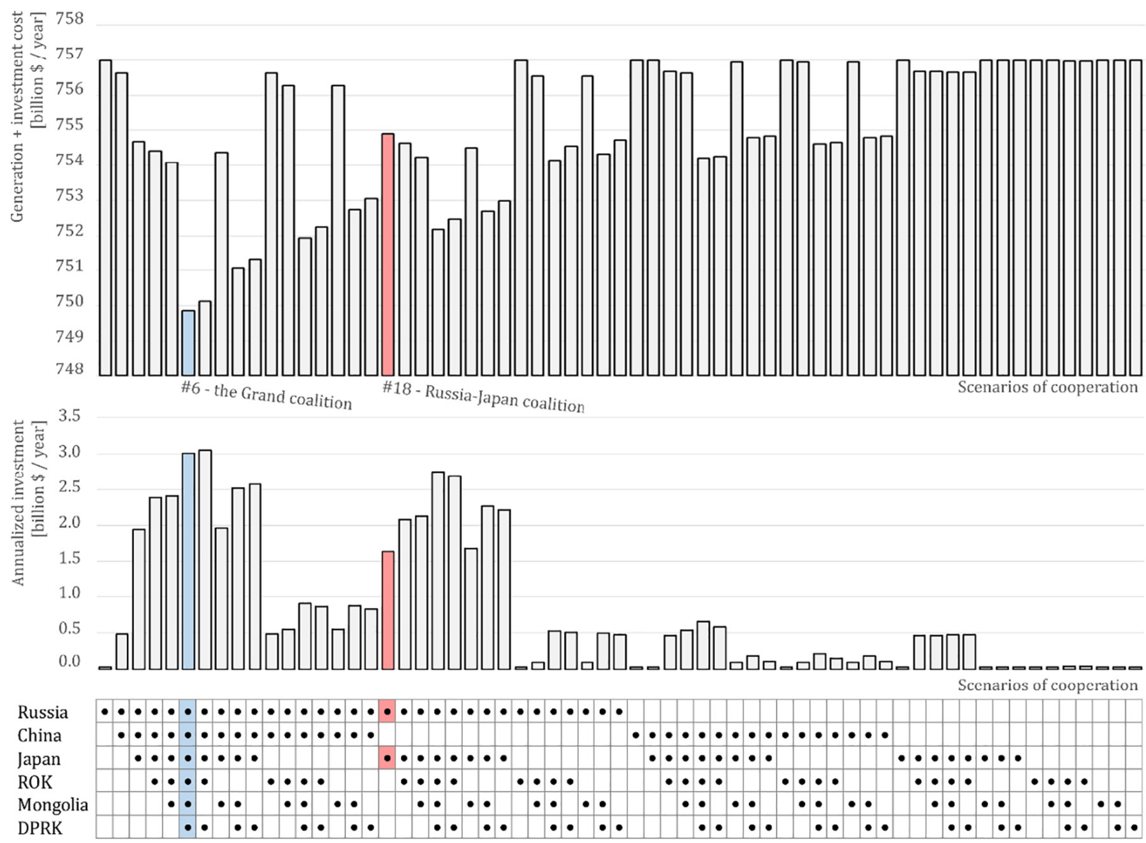


Fig. 6. Generation cost and annualized investment costs of possible coalitions: (top) annualized total cost and investment cost per coalition scenario; (mid) annualized investment cost per coalition scenario; (bottom) member countries of each coalition scenario.

The investment allocation scheme is shown in Fig. 9, where diameters of the pie charts are set proportional to the annualized investment costs of the lines. It is worth mentioning that this is not the only possible solution. Other allocation schemes may be suggested. We leave that for further research. However, even the presented allocation shed light on the features of cooperation. First of all, it is seen that investment cost shares do not correspond to the territories of the countries. This means that some participants have to invest abroad according to the fair cost allocation. For instance, Russian share of investment does not cover all the lines within its territory. Therefore, Russia may invest only in lines 1–3 and 3–4 that are used for Russian-Japanese power export. Investment in other lines connected to Russia such as 2–1, 1–6, 1–9 should be covered by China and DPRK. This can be interpreted in the following way: China and DPRK turn out to be so interested in creating the grand coalition that they should invest in the lines for power export from Russia. Japan has the most expensive interconnections because of the high undersea power cables cost. The fair investment cost allocation implies that Japan should cover only a share of the undersea cables cost and, therefore, should not invest abroad.

The second important aspect of cross-border power interconnection projects is the arrangement of money transfers between the countries. The money transfers must be organized in a way that each participant's generation and investment cost will be exactly as allocated by the Shapley value (Table 8). As an example, we show the following calculations of compensation that should be paid to Russia. Before joining the coalition, the generation cost of the considered Russian power systems reached 22.46 billion $ per year. In the grand coalition, Russia mainly acts as power exporter, transferring about 75 TWh per year to its neighbors. The generation and investment cost of Russia grows up to 30.06 billion $ per year in this scenario. According to the Shapley value allocation, Russian generation and investment cost should equal 20.21 billion $ per year. Thus, it is necessary to organize money transfers towards

Table 8
Cost-benefit allocation among the countries.

	Russia	China	Japan	ROK	Mongolia	DPRK
Generation cost + investment cost of the countries in case of no cooperation [billion $/year]	22.46	378.51	256.26	85.69	1.90	12.14
Allocation of the costs according to the Shapley value [billion $/year]	20.21	377.37	255.19	85.28	1.74	10.05
Benefits of participation according to the Shapley value [billion $/year]	2.25	1.13	1.07	0.41	0.16	2.08
Allocation belongs to the Core			Yes			
Allocation of the costs according to the Nucleolus [billion $/year]	20.74	377.79	254.91	85.09	1.78	9.53
Benefits of participation according to the Nucleolus [billion $/year]	1.72	0.72	1.35	0.60	0.12	2.60
Allocation belongs to the Core			Yes by definition			

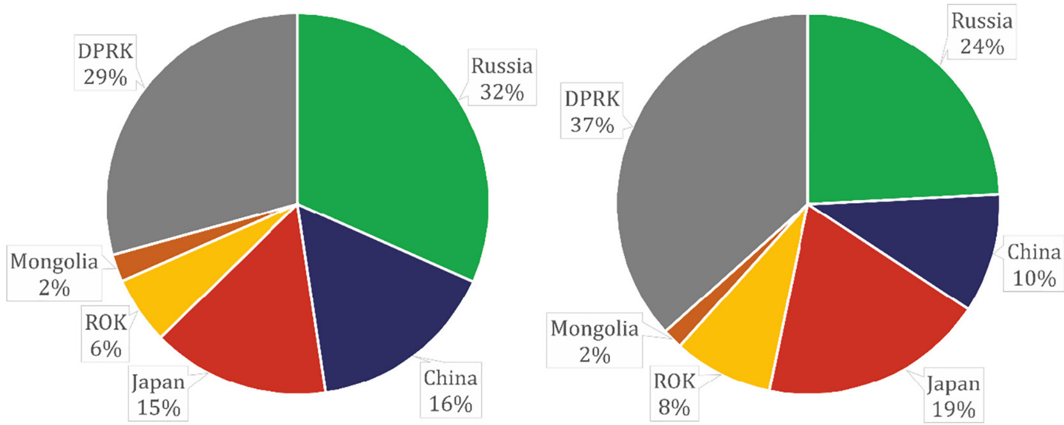


Fig. 7. Benefits allocation among the countries according to the Shapley value (a) and to the Nucleolus (b).

Russia to compensate 30.06–20.21 = 9.85 billion $ per year. Japan, on the contrary, is a power importer and must pay the other countries. We illustrate the money flows between the countries in Fig. 10.

As in the previous case of investment cost allocation, there is no unique solution for setting money transfers between the countries. The Northeast Asia case study topology allows numerous combinations of the money flows that lead to the desired cost allocation. Ideally, if money flow can be settled between countries in advance, it would make possible to sign long-term bilateral contracts that respect the cost allocation solution without the need of an international coordinator that collects and redistributes costs and benefits.

In order to suggest a meaningful solution, we have proposed an optimization problem that minimizes the sum of all bilateral money transfers while satisfying certain rules. Bilateral money transfers should result in a bilateral contract between countries that physically interchange power. Bilateral contract prices are obtained as a solution of the problem. Results for the bilateral contract prices are presented in Fig. 10 for the case of total money flow minimization. The average nodal prices of exporters and importers are listed at the top and bottom of each contract. We found that imposing contract prices constraints (the price should not exceed the price at an importer's node and should not be lower than at exporter's node) makes the problem infeasible. For example, in the presented solution, the contract prices for power exports "Russia-Mongolia" and "Mongolia-China" contradict the nodal pricing theory. Namely, exporters sell energy at prices lower than their marginal costs. This example reveals that bilateral contracts may not assure the fair cost allocation suggested by the Shapley value. There is a need for developing new mechanisms for international power trading. Another way of dealing with the issues described in this section is the development of an international coordinator that would be in charge of collecting and distributing money among the participants.

6.3. Sensitivity analysis

In this sub-section, we analyze the sensitivity of the solution obtained in terms of its stability. There are two ways of verifying the stability of the solution. First, we need to analyze the stability of the benefit estimation. In order to do this, we varied total power demand of the systems from −20% up to +5% and found possible benefits of energy

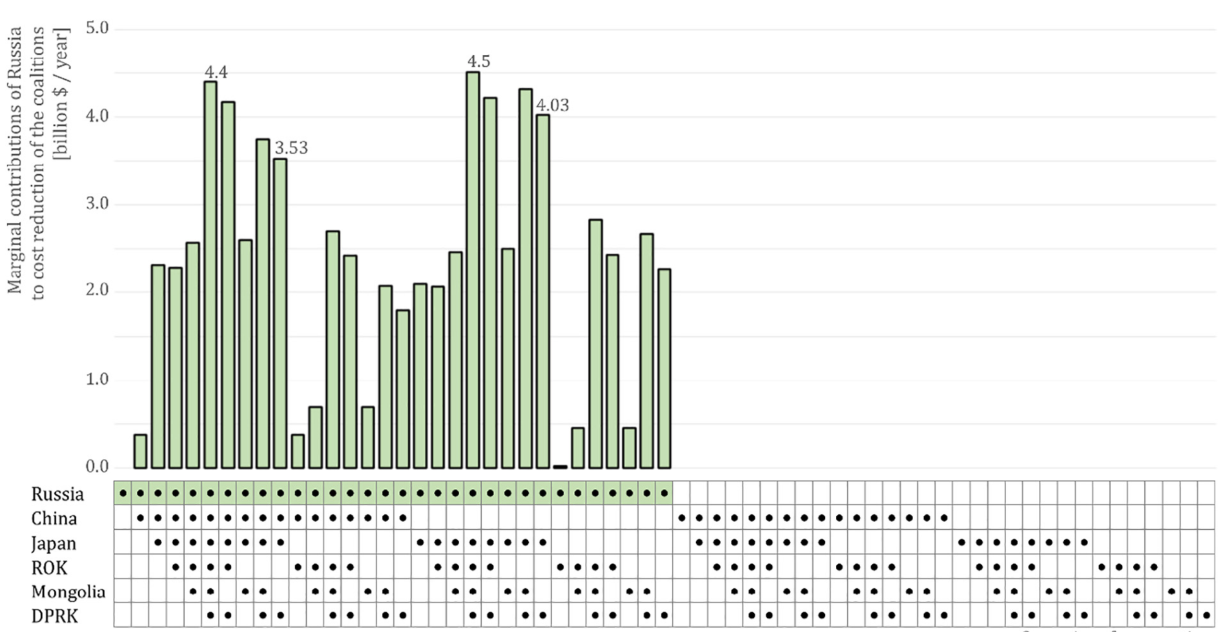


Fig. 8. Marginal contributions of Russia to the coalitions that it may participate.

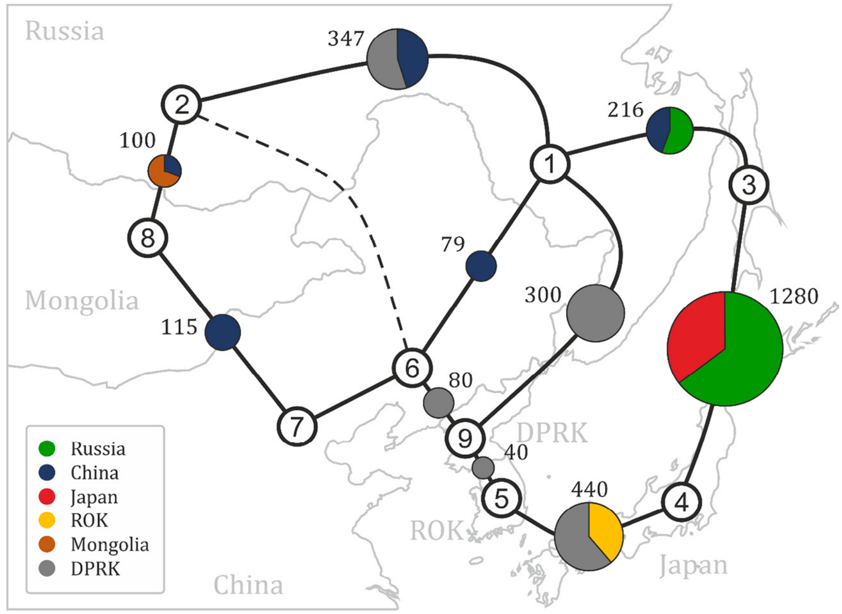


Fig. 9. Power lines investment allocation scheme, millions of US dollars per year.

cooperation. This sensitivity analysis is presented in Fig. 11. The deviations of the total benefits and investment cost are not significant around the point of our forecast. Further increase in demand leads to a rather sharp growth of the benefits, whereas investment does not change significantly. However, analysis of the deviations exceeding +5% leads to infeasible solutions (power balance equation is not fulfilled in certain nodes). When the demand forecast is decreased benefits of interconnection do not change significantly until the level −5%. Further decrease of the demand leads to a decrease in total benefits and makes the project less effective. We also performed a sensitivity analysis when the availability of renewable energy resources varies (Fig. 11). When the share of renewable energy increases, the benefits of the interconnections are slightly reduced. The reasoning is that the integration of renewables decreases generation cost and the price difference between power exporters and importers, that makes interconnection projects less profitable. However, the slope of this curve is rather low. We can state that our solution is stable and would not deviate significantly depending on demand and renewable generation forecast.

6.4. Coalitional stability: The Core of the game

Another sensitivity issue is the analysis of cost-benefit allocation stability. As it was explained before, stability of a certain allocation can be verified by the Core of a game. Even though we have found that the Core of our case-study is not empty and the allocation solutions (the Shapley value and the Nucleolus) belong to it, it is insightful to check the size and the shape of the Core in order to see if there is a "reserve" of feasible allocation solutions. This means that under certain data permutation it will be still possible to organize the grand coalition.

The Core of the Northeast Asia energy cooperation game is a 6-dimensional polyhedron defined by (2). Unfortunately, we need five-

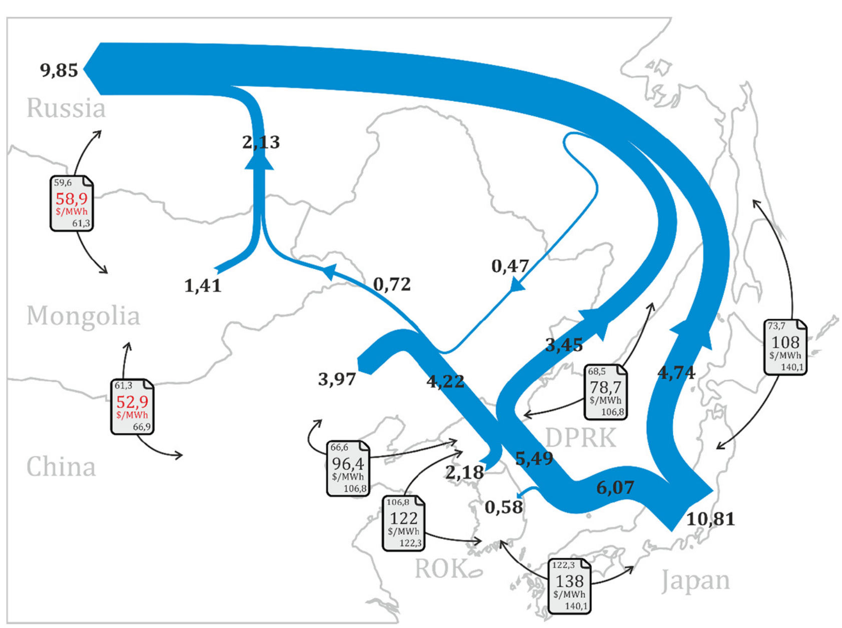
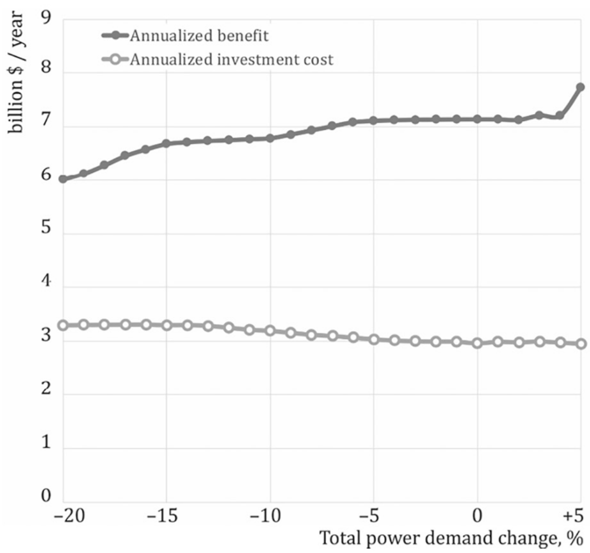


Fig. 10. Scheme of the money flows between the countries according to the Shapley allocation (in billions of US dollars per year) and bilateral contracts prices (US dollars per MWh).



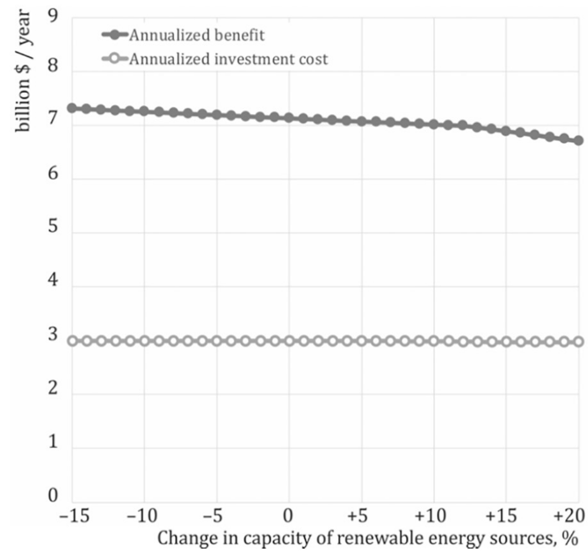


Fig. 11. Sensitivity analysis of annualized benefits and investment cost depending on power demand forecast (left) and renewable energy capacity (right).

dimensional space, using barycentric coordinates,[3] to show the Core of our six-player case-study. We decided to fix allocation of the two players with the lowest share of benefits and lowest bargaining power at the Shapley value point. The remaining part of the game can be presented as a tetrahedron of benefits allocation with the area inside – the Core of the game. Thus, the figure obtained is the projection of the six-player game Core into the four-player game that can be represented in the three-dimensional space. As mentioned in the previous sections, we allocate the costs among the countries. The benefits come from cost reduction in each country after cooperation. The Core for our case study is plotted in Fig. 12 by using the toolbox TUGlab for Matlab (Calvo and Rodriguez, 2006).

The four players with the highest bargaining power are placed at the vertices of the tetrahedron: Russia (R), China (C), Japan (J), and DPRK (K). Each of these points (vertices) means that the corresponding player gets all the benefits of cooperation (keep in mind that a share of the total benefits is already allocated between Mongolia and ROK, and is fixed). It is obvious that a solution where all the benefits are allocated to a single player is neither realistic nor stable. The volume determined by the grey planes is the Core of the game. Each facet of the polyhedron is associated with a scenario defined in Eq. (2a). By analyzing all the scenarios and coalitions we were able to plot the area of the Core. There are some points in the core that touch the opposite plane of the tetrahedron for each player. This means that there are some stable theoretical allocations in which some players would accept no benefit allocation.

A single snapshot of the Core that we present is not enough to make a thorough analysis. Nevertheless, it is possible to draw several important conclusions. First, the volume of the Core is considerably large, so the set of stable cost allocations solutions is significant. Moreover, we can see that the Core is closer to the DPRK than to any other player. Japan and China are more remote from the Core than Russia and DPRK. This agrees with the obtained results in terms of the bargaining power and the possible shares of benefits of each country.

The Core visualization in Fig. 12 allows examining its shape in different projections. For example, the parallelepiped shape of the Core can be interpreted in the Russia-Japan-DPRK projection. It is seen that DPRK cannot get the utmost share of benefits because there is a possibility of power export from Russia to Japan. Without this interconnection, DPRK would become the main player of the game with dominating bargaining power.

Finally, we have shown the Shapley value (S) and the Nucleolus (N) of the game. We see that the Shapley value is not far away from the Nucleolus and is remote enough from the facets of the Core. We conclude that under the studied conditions, benefits allocation according to the Shapley value is stable and will remain stable with moderate input data permutations in our model.

6.5. Information accuracy and data manipulability

One of the major drawbacks of the suggested framework is that Cooperative Game Theory solution highly relies on information accuracy. We assumed cooperation with perfect information about generation cost functions. It would not be easy in reality to aggregate information about each generator cost function in every country. In order to achieve such a level of cooperation, it would be necessary to establish a centralized coordinating entity similar to the ENTSO-E in Europe.

Moreover, the allocation techniques used are not free of manipulations. Once the players know the allocation rule, they may misreport information to get more benefits. For example, a power exporter may submit a higher generation cost function than a real one. By doing so, he not only gets a share of total savings but also hides some benefits from other participants since no one else knows that the submitted cost function is not true. Energy importers may also act accordingly, pretending that their cost function is lower than it is. Such manipulations can be harmful for the overall cooperation, especially at the planning stage. We launched a series of simulations changing cost functions of each participating country. The results show that even though there exist beneficial directions of manipulation for each of the countries, none of the manipulation strategies keeps totals savings at the optimum level. In other words, as soon as one of the strategies is applied, the total benefit from cooperation may be reduced. The following picture (Fig. 13) shows an illustrative hypothetical situation where Japan claims to have a cost function not higher than the South Korean one.

Under the new conditions, there would be no point in building ROK-Japan cable interconnection. The Republic of Korea would change its role from transferring country to a pure power importer. Total savings of the cooperation would decrease by 0.418 $ billions per year compared to the optimal interconnection scheme. However, Japan would increase its benefits from 1.07 to 1.55 $ billions per year. The reasoning behind such strategic behavior is the following: it should be more profitable for Japan to refuse the plan of building two power lines (ROK-Japan,

[3] In the barycentric coordinate system, values associated with each of the players are placed as masses at vertices of a geometric figure. In a 3-player game, the figure becomes a triangle and can be depicted in a two-dimensional space. The figure with 4 vertices becomes a three-dimensional tetrahedron. The center of mass is the point where the total value is equally distributed among the players. The farther the allocation point is from a certain vertex, the lower the share of benefits the corresponding player gets.

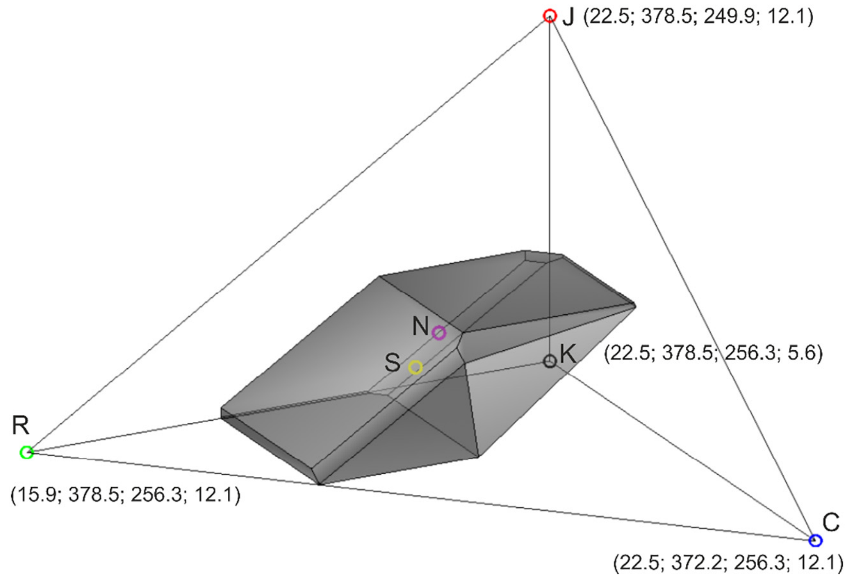


Fig. 12. The Core, the Shapley value and the Nucleolus of the Northeast Asia energy cooperation: the values represent the costs (of Russian, Chinese, Japanese, and DPRK's power systems accordingly) in billions of US dollars per year.

Sakhalin-Japan – 10 GW in total) in favor of building the only power line to Russia that would allow buying electricity at a much lower price.

Unfortunately, the strategic behavior of the participants may lead to sub-optimal equilibrium solutions, or cooperation without forming the grand coalition. There is a need for developing new mechanisms to ensure stable cooperation free of manipulations. We leave this issue for further research.

7. Conclusions

Existing studies of cross-border power interconnections demonstrate potential benefits of cooperation, which can be estimated in generation cost decrease, changes in electricity prices, and decrease in consumer's payment. Construction of cross-border grids that cover the entire regions with multiple countries has been proved to be even more efficient. However, the analysis of the cross-border power interconnection projects cannot be complete without cost-benefits allocation among the countries. It is necessary to estimate what contribution could be made by each country and how it should be rewarded in case of building cross-border interconnections.

In this paper, we have shown how allocation concepts of Cooperative Game Theory can be applied to cross-border power interconnection projects. On the basis of a fair benefits allocation, it becomes possible to suggest allocations of investment costs and a scheme of the money flows among countries. However, a weak point of cross-border power interconnection projects is allocation stability, which implies an analysis of feasible allocation points where all countries are satisfied with being in the grand coalition. In the case study of Northeast Asia, we have not only proved that there exist feasible allocations, but also analyzed the size and shape of the stable allocation region. This allows us to claim that the creation of cross-border power interconnections in Northeast Asia is economically possible. There should be enough resources to compensate all countries and persuade them to participate in the energy cooperation.

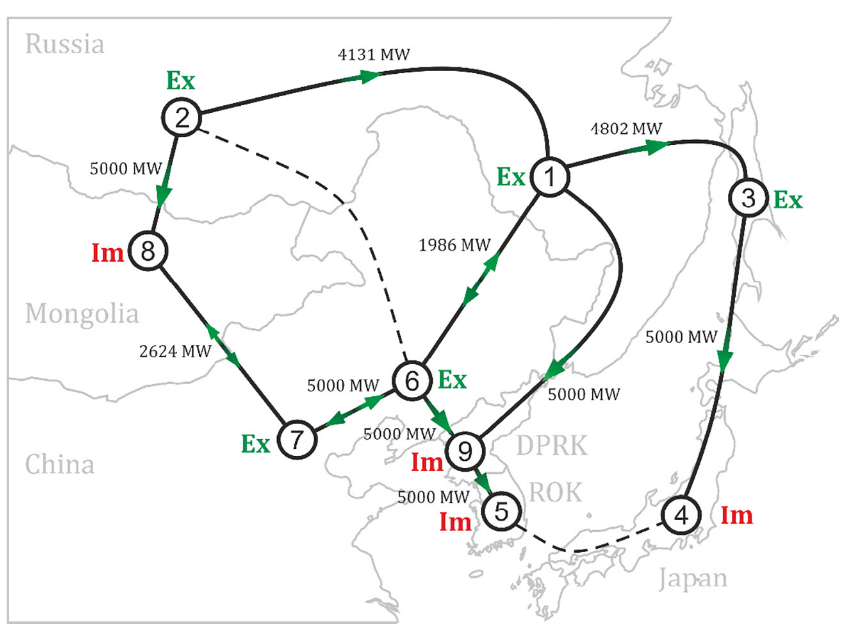


Fig. 13. The sub-optimal scheme of cross-border electrical interconnections in Northeast Asia driven by Japanese strategic behavior ("Ex" and "Im" label power exporters and importers).

As future work, we see the following challenges that may be further investigated. Cross-border interconnection could be studied along with demand response programs and other policy implications that could cause a need of cross-subsidies. Such policies can be treated as externalities or be included in the cooperation game, for example, as additional decisions. Another research direction is accounting for other sources of uncertainty (such as gas prices and renewable generation) in cross-border interconnection planning. Optimal generation capacity investment response could be an important aspect to consider when analyzing interconnection projects. In addition, the methodology proposed may be applied to a more detailed representation or each system. That is, each power system can be presented as hundreds of nodes and generators. Finally, it would be interesting to explore how results change when considering an integrated gas-electricity expansion planning process.

Answering the question posed in the title of the paper, we would say that fair and stable cooperation in cross-border transmission expansion projects is possible, at least theoretically. However, the new approaches need to be developed in order to implement a fair investment cost allocation and money transfers among the participants. As shown in this work, the creation of regional international coordinators of transmission expansion planning and energy trading would be highly useful for cross-border power interconnection projects like the Asian Super Grid.

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References

Aigner, T., Jaehnert, S., Doorman, G.L., Gjengedal, T., 2012. The effect of large-scale wind power on system balancing in Northern Europe. IEEE Trans. Sustain. Energy 3, 751–759. https://doi.org/10.1109/TSTE.2012.2203157.
Alguacil, N., Motto, A.L., Conejo, A.J., 2003. Transmission expansion planning: a mixed-integer LP approach. IEEE Trans. Power Syst. 18, 1070–1077. https://doi.org/10.1109/TPWRS.2003.814891.
Bahrman, M.P., Johnson, B.K., 2007. The ABCs of HVDC transmission technologies. IEEE Power Energy Mag. 5, 32–44. https://doi.org/10.1109/MPAE.2007.329194.
Bailey, M., Brownlee, B., Moyer, K., Zhang, H., 2014. Planing for energy futures: the WECC interconnection-wide transmission expansion experience, in: 2014 IEEE PES General Meeting | Conference & Exposition. https://doi.org/10.1109/PESGM.2014.6939920.
Baringo, L., Baringo, A., 2018. A stochastic adaptive robust optimization approach for the generation and transmission expansion planning. IEEE Trans. Power Syst. 33, 792–802. https://doi.org/10.1109/TPWRS.2017.2713486.
Calvo, M.A.M., Rodriguez, E.S., 2006. TUGlab: A Cooperative Game Theory Toolbox.
China Electric Power Press, 2017. China Electric Power Yearbook.
Churkin, A., Bialek, J., 2017. Analysis of the prospective energy interconnections in Northeast Asia and development of the data portal, in: 10th International Conference on Asian Energy Cooperation.
Ciupuliga, A.R., Cuppen, E., 2013. The role of dialogue in fostering acceptance of transmission lines: the case of a France-Spain interconnection project. Energy Policy 60, 224–233. https://doi.org/10.1016/j.enpol.2013.05.028.
Durga, M.V., 2016. An efficient algorithm for solving nucleolus of cooperative TU games using MATLAB. Int. J. Innov. Res. Dev. 5.
ENTSO-E, 2018a. Market Committee [WWW Document]. URL. https://www.entsoe.eu/about/market/.
ENTSO-E, 2018b. [Press Release] Continuing Frequency Deviation in the Continental European Power System Originating in Serbia/Kosovo: Political Solution Urgently Needed in Addition to Technical [WWW Document]. URL. https://www.entsoe.eu/news/2018/03/06/press-release-continuing-frequency-deviation-in-the-continental-european-power-system-originating-in-serbia-kosovo-political-solution-urgently-needed-in-addition-to-technical/.
García-Bertrand, R., Mínguez, R., 2017. Dynamic robust transmission expansion planning. IEEE Trans. Power Syst. 32, 2618–2628. https://doi.org/10.1109/TPWRS.2016.2629266.
Gil, H.A., Galiana, F.D., Conejo, A.J., 2005. Multiarea transmission network cost allocation. IEEE Trans. Power Syst. 20, 1293–1301. https://doi.org/10.1109/TPWRS.2005.851951.
Guajardo, M., Jörnsten, K., 2015. Common mistakes in computing the nucleolus. Eur. J. Oper. Res. 241, 931–935. https://doi.org/10.1016/j.ejor.2014.10.037.
He, W., Yang, Y., Wang, Z., Zhu, J., 2018. Estimation and allocation of cost savings from collaborative CO2 abatement in China. Energy Econ. 72, 62–74. https://doi.org/10.1016/j.eneco.2018.03.025.
Hubert, F., Ikonnikova, S., 2011. Investment options and bargaining power: the eurasian supply chain for natural gas. J. Ind. Econ. 59, 85–116. https://doi.org/10.1111/j.1467-6451.2011.00447.x.
IEA, 2018. World Energy Outlook.
Japanese ministry of Economy Trade and Industry, 2015. Long-term Energy Supply and Demand Outlook.
Junqueira, M., da Costa, L.C., Barroso, L.A., Oliveira, G.C., Thomé, L.M., Pereira, M.V., 2007. An Aumann-Shapley approach to allocate transmission service cost among network users in electricity markets. IEEE Trans. Power Syst. 22, 1532–1546. https://doi.org/10.1109/TPWRS.2007.907133.
Khamisov, O.V., Kostenko, P.V., Podkovalnikov, S.V., 2005. Modeling of potential interstate electricity markets in Northeast Asia, in: IEEE Russia Power Tech. https://doi.org/10.1109/PTC.2005.4524776.
Kirschen, D., Strbac, G., 2004. Fundamentals of Power System Economics. https://doi.org/10.1002/0470020598.
Kristiansen, M., Muñoz, F.D., Oren, S., Korpås, M., 2018. A mechanism for allocating benefits and costs from transmission interconnections under cooperation: a case study of the North Sea offshore grid. Energy J. 39. https://doi.org/10.5547/01956574.39.6.mkri.
Li, J., Li, Z., Liu, F., Ye, H., Zhang, X., Mei, S., Chang, N., 2016. Robust coordinated transmission and generation expansion planning considering ramping requirements and construction periods. IEEE Trans. Power Syst. 33, 268–280. https://doi.org/10.1109/TPWRS.2017.2687318.
Liu, Z., Chen, G., Guan, X., Wang, Q., He, W., 2016. A concept discussion on Northeast Asia power grid interconnection. CSEE J. Power Energy Syst. 2, 87–93.
Lumbreras, S., Ramos, A., Banez-Chicharro, F., 2017. Optimal transmission network expansion planning in real-sized power systems with high renewable penetration. Electr. Power Syst. Res. 149, 76–88. https://doi.org/10.1016/j.epsr.2017.04.020.
Michael, M., Eilon, S., Shmuel, Z., 2013. Game Theory. Cambridge University Press.
Molina, Y.P., Saavedra, O.R., Amaris, H., 2013. Transmission network cost allocation based on circuit theory and the Aumann-Shapley method. IEEE Trans. Power Syst. 28, 4568–4577. https://doi.org/10.1109/TPWRS.2013.2278296.
Moreira, A., Pozo, D., Street, A., Sauma, E., 2017. Reliable renewable generation and transmission expansion planning: co-optimizing system's resources for meeting renewable targets. IEEE Trans. Power Syst. 32, 3246–3257. https://doi.org/10.1109/TPWRS.2016.2631450.
Munoz, F.D., Hobbs, B.F., Ho, J.L., Kasina, S., 2014. An engineering-economic approach to transmission planning under market and regulatory uncertainties: WECC case study. IEEE Trans. Power Syst. 29, 307–317. https://doi.org/10.1109/TPWRS.2013.2279654.
Nagayama, D., Horita, M., 2014. A network game analysis of strategic interactions in the international trade of Russian natural gas through Ukraine and Belarus. Energy Econ. 43, 89–101. https://doi.org/10.1016/j.eneco.2014.02.010.
Otsuki, T., Mohd Isa, A.B., Samuelson, R.D., 2016. Electric power grid interconnections in Northeast Asia: a quantitative analysis of opportunities and challenges. Energy Policy 89, 311–329. https://doi.org/10.1016/j.enpol.2015.11.021.
Pai, L., Yuehui, H., Weisheng, W., Zhang, L., Li, S., Luca, B., 2017. Optimization of continental power exchange under the framework of global energy interconnection, in: IEEE Conference on Energy Internet and Energy System Integration.
Peters, H., 2015. Game Theory: A Multi-leveled Approach. Springer. https://doi.org/10.1017/CBO9781107415324.004.
Pozo, D., Sauma, E.E., Contreras, J., 2013. A three-level static MILP model for generation and transmission expansion planning. IEEE Trans. Power Syst. 28, 202–210. https://doi.org/10.1109/TPWRS.2012.2204073.
Ruiz, P.A., Contreras, J., 2007. An effective transmission network expansion cost allocation based on game theory. IEEE Trans. Power Syst. 22, 136–144. https://doi.org/10.1109/TPWRS.2006.888987.
Saberi, H., Monsef, H., Amraee, T., 2017. Probabilistic congestion driven network expansion planning using point estimate technique. IET Gener. Transm. Distrib. 11, 4202–4211. https://doi.org/10.1049/iet-gtd.2016.2065.
Sabolić, D., 2017. On economic inefficiency of European inter-TSO compensation mechanism. Energy Policy 110, 548–558. https://doi.org/10.1016/j.enpol.2017.08.047.
Shapley, L.S., 1953. A Value for n-person Games (Contrib. to Theory Games).
Spyrou, E., Ho, J.L., Hobbs, B.F., Johnson, R.M., McCalley, J.D., 2017. What are the benefits of co-optimizing transmission and generation investment? Eastern Interconnection Case Study. IEEE Trans. Power Syst. 32, 4265–4277. https://doi.org/10.1109/TPWRS.2017.2660249.
Stamtsis, G.C., Erlich, I., 2004. Use of cooperative game theory in power system fixed-cost allocation. IEE Proc. - Gener. Transm. Distrib. 151, 401–406. https://doi.org/10.1049/ip-gtd:20040156.
Tan, X., Lie, T.T., 2002. Application of the Shapley value on transmission cost allocation in the competitive power market environment. IEE Proc. - Gener. Transm. Distrib. 149, 15–20. https://doi.org/10.1049/ip-gtd:20020005.
The Institute of Energy Economics, 2018. No Title [WWW Document]. URL. https://eneken.ieej.or.jp/en/report_list.php.
The South Korean Ministry of Trade Industry and Energy, 2017. 8th Basic Plan for Electricity Supply and Demand.
UN, 2018. Sustainable Development Goals [WWW Document]. URL. https://www.un.org/sustainabledevelopment/energy/.
Voropai, N., Podkovalnikov, S., Chudinova, L., Letova, K., 2019. Development of electric power cooperation in Northeast Asia. Glob. Energy Interconnect. 2. https://doi.org/10.14171/j.2096-5117.gei.2019.01.001.
Yang, Z., Zhong, H., Xia, Q., Kang, C., Chen, T., Li, Y., 2016. A structural transmission cost allocation scheme based on capacity usage identification. IEEE Trans. Power Syst. 31, 2876–2884. https://doi.org/10.1109/TPWRS.2015.2464108.
Ziaee, O., Alizadeh Mousavi, O., Choobineh, F., 2017. Co-optimization of transmission expansion planning and TCSC placement considering the correlation between wind and demand scenarios. IEEE Trans. Power Syst. 33, 206–215. https://doi.org/10.1109/TPWRS.2017.2690969.