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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Andrey Churkin

PhD Program: Engineering Systems

Title of Thesis: Game-theoretical approach to cooperation stability analysis in cross-border power interconnection planning

Supervisor: Professor Janusz Bialek, Skoltech

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Name of the Reviewer: Ross Baldick

I confirm the absence of any conflict of interest CONFIRMED! (Alternatively, Reviewer can formulate a possible conflict)	**Signature:** Ross Baldick **27-09-2020** **Date: DD-MM-YYYY**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

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Reviewer's Report

Reviewers report should contain the following items:

- Brief evaluation of the thesis quality and overall structure of the dissertation.
- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation
- The scientific significance of the results obtained and their compliance with the international level and current state of the art
- The relevance of the obtained results to applications (if applicable)
- The quality of publications

The summary of issues to be addressed before/during the thesis defense

The thesis considers a cooperative game theory approach to modeling cross-border upgrades in electric transmission, combining both a detailed representation of the strategic issues and (within limits) a representation of the technical complexities of transmission expansion. Overall, the thesis is of high quality and appropriately structured, with an elaborate case study demonstrating the derived analysis. I have a number of suggestions and questions, which have been annotated to the PDF of the thesis and will be sent separately. Once these suggestions and questions have been addressed by the candidate, I think that the thesis will provide an excellent discussion of the topic with relevant results and quality publications, and I look forward to the thesis defense.

Provisional Recommendation

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*

Skolkovo Institute of Science and Technology

Comment: stability is commonly used in power systems to refer to stability of dynamical systems modeling electromechanical transients. I appreciate that you added "cooperation" here, but perhaps there is another way to phrase this, eg "analyzing stability of coalitions"

GAME-THEORETIC APPROACH TO COOPERATION STABILITY ANALYSIS IN CROSS-BORDER POWER INTERCONNECTION PLANNING

Doctoral Thesis

by

ANDREY CHURKIN

DOCTORAL PROGRAM IN ENGINEERING SYSTEMS

Supervisor
Professor Janusz Bialek

Co-advisor
Assistant Professor David Pozo

Moscow 2020

I hereby declare that the work presented in this thesis was carried out by myself at Skolkovo Institute of Science and Technology, Moscow, except where due acknowledgement is made, and has not been submitted for any other degree.

Candidate (Andrey Churkin)
Supervisor (Prof. Janusz Bialek)

Abstract

Game-theoretic approach to cooperation stability analysis
in cross-border power interconnection planning

Andrey Churkin

When you see a good move,
look for a better one.
- Emanuel Lasker
World chess champion 1894-1921

Electrical interconnections of neighboring power systems bring a long list of benefits in terms of generation cost savings, CO_2 emissions reduction, flexibility and stability improvements. The common practice of power lines updates identification lies in formulating mathematical optimization models where the objective functions minimize the total cost of power systems or maximize social welfare of electricity market participants. This approach is widely known as Transmission Expansion Planning (TEP). It can provide valuable insights into the optimal design of a system and complement engineering and heuristic plans developed by Power System Operators (PSO). However, common TEP tools become inadequate when applied to international projects of cross-border power interconnections. System operators or governments of neighboring countries may have different views on the TEP problem as well as on their role in energy cooperation. Despite the fact that there exist multiple studies and initiatives to establish regional electricity cooperation, very few projects are currently being realized. Therefore, along with finding the optimal TEP solution, it becomes necessary to share the benefits of cooperation rationally and suggest an investment scheme that would satisfy all the participants.

Comment: not sure what is intended by " power lines updates identification" but perhaps "identifying upgrades of power lines" is intended.

In this thesis, we examined cooperation in cross-border power interconnection projects and dedicated our effort to cover the research gap in costs and benefits allocation mechanisms. Cooperative Game Theory solution concepts were used as the basis for our analysis. The special emphasis was put on the stability of cooperation: we searched for the allocation solutions which have no participants with incentives of breaking an agreement of regional cooperation. We

went beyond state-of-the-art of Cooperative Game Theory applications in power systems and presented the manipulability analysis of allocation rules. We also proposed a novel bilevel TEP model that incorporates Cooperative Game Theory principles into the planning algorithm. The model enables the identification of expansion plans with the desired level of stability of cooperation. Through a series of case studies, we explained the mechanisms of cooperation, interpreted the results of the game-theoretic analysis, and illustrated the usefulness of the developed bilevel TEP approach. Specifically, the original contributions of the thesis are as follows:

I. We demonstrated that cooperation in TEP based on Cooperative Game Theory solution concepts (such as the Shapley value, the Nucleolus, and equal sharing) is prone to manipulations. We analyzed the incentives of players' strategic behavior depending on their positions in electricity trading and discussed the need for developing strategyproof mechanisms of cooperation.

II. We suggested using the coalitional excess theory as the metric of cooperation stability to complement existing ex-post game-theoretic approaches. We then formulated an anticipative bilevel TEP model that incorporates Cooperative Game Theory principles. The proposed approach enables including game-theoretic constraints (such as the Core of the game, the convexity conditions, maximum surpluses among players, etc.) into the planning algorithm. In this manner, it becomes possible to identify expansion plans with a predefined level of stability of cooperation.

III. Moreover, we performed the manipulability analysis of cooperation in TEP under the proposed bilevel planning model. We found that the anticipative bilevel game-theoretic approach could decrease players' incentives to manipulate allocation rules and might be used for developing strategyproof mechanisms of cooperation.

IV. Finally, we considered a real-world case study of potential power interconnections in Northeast Asia. We implemented the Cooperative Game Theory solution concepts and analyzed the stability of cooperation. We also discussed the practical implementation issues, such as the arrangement of investment and payment schemes between countries.

An additional contribution of the thesis is the advanced review of existing research, which we performed using the citation network analysis. We analyzed more than 3 000 related studies from 1996 to 2020, identified the main research communities, and formulated the challenges and limitations of Cooperative Game Theory applications. The citation network analysis justified the novelty of the ideas presented in this work.

Publications

1. A. Churkin, D. Pozo, J. Bialek, N. Korgin, E. Sauma, "Can Cross-Border Transmission Expansion Lead to Fair and Stable Cooperation? Northeast Asia Case Analysis," *Energy Economics*, vol. 84, 2019.
2. A. Churkin, D. Pozo, J. Bialek, N. Korgin, E. Sauma, "Manipulability of Cost and Benefit Allocation in Cross-border Electrical Interconnection Projects," *IEEE PES PowerTech 2019 Conference*, Milan, Italy, Jun. 2019.
3. A. Churkin, J. Bialek, "Analysis of the Prospective Energy Interconnections in Northeast Asia and Development of the Data Portal," *Proceedings of the Joint Conference on Northeast Asia Regional Power Interconnection*, Irkutsk, 29-30 Aug. 2017.

Submitted papers

1. A. Churkin, J. Bialek, D. Pozo, E. Sauma, N. Korgin, "Cooperative Game Theory Applications to Power Systems Expansion Planning," Renewable and Sustainable Energy Reviews.

Presentations

1. A. Churkin, "Breaking the Wall of Energy Cooperation," *Falling Walls Lab*, Berlin, Germany, Nov. 8, 2019.
2. A. Churkin, "Incorporating Cooperative Game Theory Principles into Cross-Border Transmission Expansion Planning Algorithms," *INFORMS Annual Meeting*, Seattle, USA, Oct. 22, 2019.

3. A. Churkin, "Interstate Electrical Interconnection Benefits and Cost Allocation: Northeast Asia Case Analysis," *Asia International Grid Connection Symposium*, 2018, Tokyo, Japan, Jul. 23, 2018.
4. A. Churkin, "Interstate Electrical Interconnection Benefits and Cost Allocation: Northeast Asia Case Analysis," *International Conference on International Cooperation in Energy and Innovations at MGIMO university*, Moscow, Russia, May 2018.
5. A. Churkin, "Analysis of the Prospective Energy Interconnections in Northeast Asia and Development of the Data Portal," *Joint Conference on Northeast Asia Regional Power Interconnection*, Irkutsk, Russia, 29-30 Aug. 2017.

Seminars

1. A. Churkin, "Cooperative Game Theory Applications in Power Systems," *Energy Research Seminars*, Skoltech, Moscow, Feb. 2020.
2. A. Churkin, "Incorporating Cooperative Game Theory Principles into Cross-Border Transmission Expansion Planning Algorithms," *Seminars on Expert Assessment and Data Analysis*, Institute of Control Sciences of Russian Academy of Sciences, Moscow, Oct. 9, 2019.
3. A. Churkin, "Methodology for Costs and Benefits Allocation in Cross-Border Power Interconnection Projects," *Russian CIGRE committee C5,* Market Council, Moscow, Nov. 2, 2018.

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This thesis is the most difficult challenge I have overcome so far. Looking back at the past four years, I see how complicated and surprising life could be. It was not only my time and effort that constituted the successful research but also the fortuitous combination of circumstances and, of course, support of the people I have met during this journey. Even though sometimes I felt weak and lost, at this moment, I am grateful for the opportunities granted to me. And the least I can do is mention the people who guided, supported, and inspired me, which made this work possible.

I was lucky to have two excellent advisors at Skoltech, who had a significant influence on my work and me personally. First of all, Prof. Janusz Bialek and Prof. David Pozo spotted and revealed my potential. They were treating me as a colleague from the very beginning and never made me feel dumb. They directed me to a new topic where we literally did not know where to move on and how to make a novel contribution. I had to study Game Theory from scratch and program the models that we were hardly able to interpret. In the end, most of our ideas worked out. I cannot imagine such progress without the guidance of my advisors, who formed my vision of research. Second, Janusz and David introduced me to the power systems scientific community. They encouraged me to participate in top conferences and events. Thanks to their suggestions and funding support, during the last four years, I traveled more than in all my life before. This gave me a lot of experience and confidence. Not to mention the unique internships in Bangkok and Santiago, which I consider important stages of my life. Moreover, Janusz and David gave me a ton of advice regarding my professional and personal problems. They are still supporting me in building my future scientific career. Thank you, Janusz. Thank you, David.

Two people have to be mentioned next. They are my colleagues and co-authors, Prof. Enzo Sauma and Prof. Nikolay Korgin. Enzo gladly accepted me as an intern at the Energy Research Center of Pontificia Universidad Católica de Chile. During the three-months internship, he arranged weekly meetings and helped me to improve the methodology of the research. Enzo is the one who first suggested the idea of the bilevel expansion planning model, which later became the main contribution of my thesis. Nikolay also got interested in my research and dedicated much time teaching me game-theoretic concepts. He carefully explained to me the possible pitfalls that one may face while implementing them. Nikolay also suggested the idea of manipulability analysis, which became an essential part of my research. I still remember the evenings with Nikolay at the Institute of Control Sciences when we have long emotional discussions of Game Theory. Thank you, Nikolay. Thank you, Enzo.

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My family and friends always supported me in my desire to achieve something new. My parents put much effort into my education. They always wanted their eldest son to have a passion for knowledge. I did not have it at school, which obviously disappointed them. Now I see that it was just a time lag. I have finally found my passion during my graduate degree. I am happy that I was able to master such a complex topic and even contribute to the field. Thank you, mother. Thank you, father. I also thank my sister, Elena, and brother, Kirill, for their help and advice. And, of course, I recognize the assistance of my friends, especially, Maxim, Grisha, and Dmitry. Thanks for bearing with me.

I want to mention my fiancee, Anna, who was the closest person to me during my graduate study. A few lines in the acknowledgments cannot recognize the overall daily support and care that you gave me. You were the first person to listen to my ideas and fears, read my papers and speeches, check my figures and presentations. There is no point in trying to explain my feelings and gratitude here. I hope you were, are, and will be happy with me. We have a lot more adventures ahead.

Finally, let me thank a few significant people that I have met during the last years. My Chinese teacher, Yang Dapeng (杨大鹏), and my piano teacher, Alexander Velikovsky, helped me not to get obsessed with power systems and Game Theory. They showed that there exist many more exciting things in the world that are worth studying. Thank you for sharing your great experience with me. Pablo Altamirano hosted me in Chile. He showed me the country and helped in many things, from power systems research to personal problems. Thank you, Pablo. Cajon El Yeso is the place I would never forget. Prof. Yury Dvorkin met me several times at conferences and events. He appreciated my research and motivated me to work harder. Thank you, Yury.

To my grandfather, Fedotov Vladimir (Федотов Владимир Алексеевич), who was the only electrical engineer in my family, and, therefore, was proud of my achievements more than anyone else.

Table of Contents

List of Abbreviations

AC – Alternating Current

DC – Direct Current

DPRK – the Democratic People's Republic of Korea

EP – Equilibrium Problem

EPEC – Equilibrium Problem with Equilibrium Constraints

GTEP – Generation and Transmission Expansion Planning

HVDC – High Voltage Direct Current

KKT – Karush–Kuhn–Tucker conditions

LCQP – Linearly Constrained Quadratic Programming

LMP – Locational Marginal Price

LP – Linear Programming

MILP – Mixed-Integer Linear Programming

MINLP– Mixed-Integer Nonlinear Programming

MIP – Mixed-Integer Programming

MPEC – Mathematical Problem with Equilibrium Constraints

NLP – Nonlinear Programming

OPF – Optimal Power Flow

PSO – Power System Operator

ROK – the Republic of Korea

SCOPF – Security Constrained Optimal Power Flow

TEP – Transmission Expansion Planning

TUG – Transferable Utility Cooperative Game

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Chapter 1

Introduction

Play the opening like a book,
the middle game like a magician,
and the endgame like a machine
- Rudolf Spielmann
Austrian grandmaster

Modern challenges make our world more interrelated than ever. Many problems require international cooperation in economics, politics, science, and technology. The volume of international trade is steadily growing worldwide (at the average annual pace exceeding 2.5%) along with the gross world product [1]. The energy sector develops even more rapidly, significantly contributing to international trade, which is justified by the growing demand for oil, natural gas, coal, and electricity [2]. Remarkable progress has been achieved in natural gas trade. Pipelines and liquefied natural gas (LNG) infrastructure development allows the United States, Russia, and the Middle East countries to export up to 32% of their gas production. At the same time, China and the European Union became gas net importers with up to 75% share of imports in their gas demand.

Not recently at this pace, I suspect! Probably needs updating to acknowledge COVID effects.

However, international trade in electricity is lagging behind. Except for North America and the European Union, there are very few regions with significant cross-border power interconnections. Electricity exports and imports still make minor contributions to international trading and energy supply mix. We may identify a few main reasons for such a delay in electricity trading:

- Power systems are generally more complicated in operation that oil or gas supply chains. The main difference lies in the inability to store much electric power, which means that power supply must meet the demand at any time. This creates frequency stability issues that must be resolved quickly in order

Comment: note use of word stability here in a different context to title of thesis. This exemplifies why you should make the title more explicit about the notion of stability, and perhaps add something here to more carefully define what you mean by frequency stability.

to avoid power outages. Therefore, the organization of cross-border electricity trading must meet the grid codes of interconnected power systems and guarantee a reliable uninterruptable supply.

- Energy security policies of many countries set preferences for developing generation capacity within a country instead of buying power from neighbors. The timescale of power systems physics and operation poses an additional threat to the energy security of interconnected countries. In the case of a technical failure or political conflict, cross-border power flow can be unilaterally switched off in seconds by a single circuit breaker.
- Transmitting power for long distances via AC lines causes significant power losses and stability issues that make some cross-border interconnection projects impractical. However, current developments in high-voltage direct current (HVDC) transmission systems enable transmitting gigawatts of power for thousands of kilometers with moderate power losses [3]. This technology is believed to make many ambitious power interconnection projects realistic.
- The privatization of electric power systems and the emergence of electricity markets in many countries led to a competitive environment with numerous market participants [4]. Even though considered socially effective, wholesale electricity markets do not possess sufficient political will to promote cross-border interconnection projects. While some market participants (generating companies or consumers) may be interested in electricity trade, others may be not interested, or even be against it. Therefore, competitive market mechanisms may hinder the development of cross-border power interconnections that could influence multiple parties of integrated electricity markets. Under such circumstances, there is a need for international coordinators that would persuade governments, PSOs, and stakeholders in project rationality.
- Finally, it is not always clear which power system (or country) benefits more due to international electricity trade. None of the participants would like to subsidize the others. Therefore, there is a need for fair allocation of cross-border power lines investment costs and benefits of energy cooperation.

This thesis aims to facilitate cross-border power interconnection projects and cover the research gap in costs and benefits allocation mechanisms for international cooperation in electricity trade.

1.1 Background and Motivation

Building new power lines is essential for power system planning [4]. It allows supplying an increasing demand, enables more participants to enter into electricity markets, and makes power system operation more efficient and reliable. The task of deciding on optimal transmission investments is widely known as Transmission Expansion Planning (TEP) [5], [6]. The mathematical formulation of TEP models usually seeks to minimize the overall operating cost of a power system or maximize the welfare of market participants, subject to physical and technical limits, environmental restrictions, and other constraints.

How about increasing access to renewables?

It was shown by numerous projects and studies that optimal power lines planning leads to significant benefits for power systems [7]. Sometimes, the optimization of transmission planning goes along with generation investment. Such approaches bring even more benefits and are known as Generation and Transmission Expansion Planning (GTEP) [8], [9]. Other studies applied stochastic and multi-level programming in order to perform optimal transmission planning under market and regulatory uncertainties [10]–[15]. Great attention has been paid to TEP in the international context. *Lumbreras et al.* [12] performed a stochastic TEP for the European Continental South West region case study considering power interconnections of Portugal, Spain, and France. *Otsuki et al.* [16] evaluated opportunities for power interconnections in Northeast Asia. Significant cost savings and CO_2 emissions reduction were revealed for the scenario of regional cooperation on power interconnections. *Loureiro et al.* [17] suggested a cross-border electricity interconnection investments and trade mechanism where each PSO maximizes social welfare within its territory and applied it to the Iberian electricity market case study. *Konstantelos et al.* [18] and then *Dedecca et al.* [19] estimated the costs and benefits of the North Sea power interconnections. *Figueroa-Acevedo et al.* [20] explored the benefits of increasing transmission capacity between the US Eastern and Western interconnections to access cost-effective renewables. The study demonstrated that the cost of a macrogrid HVDC transmission is outweighed by the generation-related savings.

There exist even more ambitious projects of power interconnections that involve entire continents. The European Union launched the e-Highway2050 project that aims to develop an optimal European transmission expansion plan from 2020 to 2050 [21]. The International Council on Large Electric Systems (CIGRE) recently published a report on global electricity network feasibility study that shows how the whole world may cooperate in TEP to increase the share renewable energy and reduce CO_2 emissions [22]. Similar ideas are promoted by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO) [23] and the Desertec project [24], [25]. The importance of international cooperation in energy is included in the United Nations sustainable development goals [26].

Considering the above-mentioned results, we can summarize that:

- TEP is an important tool that can provide valuable insights into the optimal design of power systems and complement trial and error and engineering plans developed by PSO.
- The development of TEP algorithms remains an actual research direction for several decades. Modern TEP approaches enable formulating complex models that include security constraints, stochastic parameters, decentralized decision making, and other features of power systems operation and control.
- There exist initiatives and ongoing projects on cross-border TEP that involve several countries or regions.

However, there are still many barriers that hinder the development of cross-border power interconnections. The issues of cross-border electricity trade are especially acute in the regions where countries have not established political and economic integration yet. There is, therefore, no regulatory framework nor intergovernmental coordinating entity to break the mutual mistrust and promote cost-effective interconnection projects. To facilitate the cooperation on interconnection projects, the two following interrelated questions must be addressed. What are the possible benefits of electricity trade for interconnected power systems? How the benefits and the investment cost should be shared among the participants?

In this work, we propose a solution framework based on mathematical optimization and Cooperative Game Theory concepts for cross-border TEP analysis and cost-benefits allocation among countries. The object of our research comprises power systems, electricity markets, transmission expansion modeling, and algorithm design. The subject is cost-benefit allocation principles and cooperation mechanisms for cross-border power interconnection projects.

In the following sections, we describe the existing research and state-of-the-art in power systems cost allocation issues and highlight the contributions of the thesis.

1.2 Existing Research

Being complex multi-agent systems with capital intensive equipment, power systems involve multiple allocation problems. The common tasks are transmission access pricing, investment cost allocation, and reserve allocation.

This section provides an overview of allocation issues studies related to power systems. The most relevant works on TEP cost allocation are identified. Then, the citation network analysis is performed on the basis of the selected references. The evolution of the research and the allied research directions are discussed.

1.2.1 Cost Allocation Issues in Power Systems

Transmission network expansion influences multiple electricity market participants. Moreover, the physical nature of power flows, counterflows, and loop flows makes it hard to suggest a unified approach to transmission cost allocation. Over the last decades, numerous studies put effort into developing cost allocation mechanisms.

What about economies of scale in transmission construction?

Gil et al. [27] elaborated on the problem of transmission cost allocation in large networks with interconnected regions or countries. A common approach requires an international operator to gather data about all the transmission elements as well as generation cost functions and demand forecasts. However, as discussed in [27], such a level of data sharing may be impractical for many regions. Therefore, a multiarea decoupled transmission allocation scheme was suggested where each region performs its internal cost allocation while an international operator carries out region-wise allocations. The equivalent bilateral exchange principle was used as a proxy for cost allocation. A thorough review of other network cost allocation methods is presented in [28].

Similar problems arise in setting transmission tariffs and inter-PSO compensations. Uneven utilization of existing and new transmission facilities by market participants, existence of transit flows and loop flows requires the development of reasonable mechanisms for international transmission tariffs and inter-PSO compensations [29]. Common compensation approaches include the Marginal Participation and the Average Participation methods, and the With and Without Transits method [30]. An additional question is the allocation of transmission capacity between energy trade and reserve services. Proper capacity allocation and PSO coordination in reserves sharing could lead to significant savings for interconnected power systems [31], [32]. *Yang et al.* [33] also suggested transmission capacity usage identification. The cost allocation methods were designed taking into account the conditions under which the capacity should be used (capacity used in normal conditions, reserves for contingencies, reserves for future use, and invalid capacity).

definition of transit flow and loop flow?

Building cross-border power lines requires coordination of regulators and mechanisms for cost-benefit allocation. *Gerbaulet and Weber* [34] illustrated how a lack of coordination might lead to non-fair allocations. In such cases, a profit-maximizing merchant investor may make suboptimal investment decisions and take the major part of the welfare gain. *Konstantelos et al.* [18] reported that conventional benefit allocation methods are less suitable for international grids creation. Based on the North Sea grid example, it was shown that highly asymmetric distribution of costs and benefits could lead to potential issues in achieving political consensus between participating countries.

Several studies exploited complementarity modeling [35] in order to formulate interactions between market participants and different transmission planners. For the Iberian electricity market, *Loureiro et al.* [17] presented investments in cross-border power interconnections as a Nash bargaining between the regions. The resulting bilevel model embedded investment cost allocation. It was formulated as a mathematical program with equilibrium constraints (MPEC). *Tohidi and Hesamzadeh* [36] also examined multi-regional transmission planning from the non-cooperative decision-making point of view. The multiple-leaders single-follower game was formulated as a bilevel model where each independent transmission planner minimizes its own cost. The results showed that without proper compensation mechanisms, the non-cooperative transmission planning leads to inefficient results compared to the cooperative solution. Conflicting outcomes in multilateral transmission planning were observed by *Buijs and Belmans* [37]. The interactions between zonal and supranational planners were formulated as a generalized Nash equilibrium in the form of Equilibrium Problem with Equilibrium Constraints (EPEC). As a possible solution, a Pareto-planner was proposed. Such a planner maximizes overall welfare while acknowledges that a solution should be acceptable for each zone. *Kasina and Hobbs* [38] also highlighted the value of transmission planners cooperation. A bilevel EPEC model was composed to represent a game among multiple transmission planners, generators, and consumers. The hierarchical model represented the optimization of planning decisions by independent regional planners (the upper level) subject to generator investments and energy market equilibrium (the lower revel). This noncooperative solution was compared to cooperative centralized optimization. It was shown that equilibrium transmission plans may differ significantly from the optimal ones. A significant value of cooperation was reported, which results from investment in interregional lines. Moreover, it was found that cooperation among transmission planners leads to increased competition among generators from adjoining regions, which in turn leads to more efficient generation investments. *Huppmann and Egerer* [39] composed a three-stage equilibrium model to represent interactions between a spot market, zonal and supranational planners. It was concluded that zonal planners may have incentives to over-invest or intentionally withhold power line upgrades in their jurisdiction to induce a shift of rents towards them.

The above-mentioned works emphasize the need for efficient allocation and compensation mechanisms in international transmission planning. Searching for justified solutions, a number of researchers turned their attention to the Cooperative Game Theory. One of the very first studies on cost-benefit allocation in transmission expansion projects was done back in 1974 by *Gately* [40], who formulated the energy cooperation among states in the Southern Electricity Region of India as a cooperative game with transferable utility. Each power system was modeled as an independent player who might accept the terms of cooperation or refuse the construction of interconnections. Gately analyzed possible scenarios of cooperation and implemented several Cooperative Game Theory solution concepts such as the Shapley value, the Core, and the Kernel. He also introduced an additional concept of "propensity to disrupt" to identify allocation solution areas with mutually acceptable shares of gains.

The new wave of research on Cooperative Game Theory applications in TEP began in the nineteen-nineties and the two-thousands. *Tsukamoto and Iyoda* [41] suggested a Cooperative Game Theory based methodology for allocating transmission fixed costs. The MW-mile method was complemented with the Nucleolus solution concept to avoid conflicting outcomes. *Javier Contreras* dedicated his thesis and the subsequent papers to the coalition formation analysis in TEP [42], [43]. A decentralized coalition formation scheme based on power systems transmission expansion scenarios was considered. The resulting cost allocation was performed using the backward induction and the Bilateral Shapley Value approach. In the following work, Contreras and Wu [44] developed a TEP algorithm using the Kernel solution concept. The decentralized, negotiation-oriented coalition formation algorithm allowed identifying the Kernel-stable cost allocation solutions. Two years later, several studies on TEP algorithms applied Cooperative Game Theory solution concepts. *Tan and Lie* [45] considered transmission cost allocation among power consumers. The Shapley value was utilized as the allocation rule in a centralized manner. *Zolezzi and Rudnick* [46] formulated decisions on building each line in TEP as separate cooperative games. The Shapley value, the Nucleolus, the marginal participation method, and the generalized load-distribution factors method were compared for transmission cost allocation among power consumers. The idea of transmission expansion plan segmentation was further developed in [47]. Independent cooperative games for each of the expansion segments were solved through the Kernel concept. *Stamtsis and Erlich* [48] formulated a cooperative game in pool markets where counterflows may cause transmission capacity savings. The authors argued that the Shapley value is a more preferable solution than the Nucleolus for transmission fixed-cost allocation. In [49], *Ruiz and Contreras* incorporated market participants' influence on TEP decisions into the expansion and cost allocation algorithm. Each consumer and each producer were allocated weights that measure the influence of each firm on the expansion decision. In order to realize a transmission expansion, all the parties have to be satisfied enough with the allocation. Mathematically, the total weight of the firms that favor the expansion must be larger than a known positive parameter. The issues of transmission lines investors incentivization were further discussed in [50].

Admitting the probabilistic nature of power systems and players' behavior, *Bhakar* [51] suggested extending game approaches for network cost allocation. The probability of existence of players, the probability of coalitions existence, and the probability of players joining a coalition in a particular sequence were introduced into the model. The approach may be useful for cooperation stability analysis. However, it requires reasonable assumptions on the probabilistic characteristic functions.

As indicated by many studies, the application of the Shapley value becomes computationally prohibitive for realistic systems with multiple players. Therefore, some authors suggested using the Aumann–Shapley extension that allows finding an allocation solution through a set of linear optimization programs and reduces the computation effort [52], [53].

Nowadays, Cooperative Game Theory becomes a prominent tool for cross-border power interconnection projects evaluation. *Kristiansen et al.* [54] proposed an international transmission mechanism based on a planning model that considers generation investments as a response to transmission developments and the Shapley value. The results for the North Sea Offshore Grid case study showed the benefits allocation among the countries and possible ways of arranging the side payments (for example, through Power Purchase Agreements). *De Moura et al.* [55] analyzed the perspectives of power systems integration processes between Brazil and its South American neighboring countries. The Shapley value was used for players' bargaining power estimation and cost allocation.

A brief review of the existing research shows that Cooperative Game Theory applications in transmission expansion cost allocation form a distinct interdisciplinary direction. Even though the first work appeared more than forty years ago, the topic is not depleted yet. Moreover, the research evolves over time.

The game-theoretic models become more reasonable and complex, and the case studies – more realistic. There is ongoing work on finding new ways of implementing Cooperative Game Theory in power systems.

In the next sections, we further investigate state-of-art in TEP cost allocations and formulate the contributions of the thesis.

1.2.2 Citation Network Analysis

The citation network analysis is a powerful literature review tool that allows visualizing existing studies and their relationship as a directed graph. The graph layout algorithms and modularity algorithms enable identification of the community structure and the most relevant references. In this section, we perform a citation network analysis for the existing research in TEP cost allocation methods.

Our network is built chronologically: we identify the relevant papers which have a significant citation history (we denote them as generation #0); then, we collect the references that cited the initial ones (generation #1) and the papers that cited those references (generation #2). The citation relationship among the references presents the evolution of the topic and the allied research directions. We have selected the following works as the pivot points of the citation network:

- G0-1: (77 citations) Y. Tsukamoto and I. Iyoda, "Allocation of fixed transmission cost to wheeling transactions by cooperative game theory," IEEE Trans. Power Syst., vol. 11, no. 2, 1996, [41];
- G0-2: (97 citations) J. Contreras and F. F. Wu, "Coalition formation in transmission expansion planning," IEEE Trans. Power Syst., vol. 14, no. 3, 1999, [43];
- G0-3: (132 citations) J. M. Zolezzi and H. Rudnick, "Transmission cost allocation by cooperative games and coalition formation," IEEE Trans. Power Syst., vol. 17, no. 4, 2002, [46].

These works extensively applied Cooperative Game Theory solution concepts to the TEP cost allocation issues[1]. They form the first generation of references in our network and therefore are denoted “G0-...”. The first generation of citations “G1-...” contains 245 unique papers. And the second generation “G2-...” comprises 3690 articles. Thus, the entire citation network has 3938 nodes (papers) and 5332 edges (citations). We used the Scopus citation database and Gephi software [56] to collect and visualize the references. The review was actual for February 2020.

To further analyze the citation network, we exploited graph layout algorithms that allow spatial mapping of interconnected groups of nodes, namely “ForceAtlas2” [57] and “Yifan Hu Proportional” [58]. The community structure was retrieved by the modularity algorithm [59]. Twenty distinct communities have been identified in the network. For convenience, we set the nodes’ sizes proportional to the number of citations. Therefore, it may be easily detected which studies eventually attracted more attention of the communities. The largest node of our network (G1-128) has 772 citations and represents the work by *McArthur et al.* [60] on multi-agent systems for power engineering applications.

The overview of the entire network is depicted in Figure 1.1. The identified communities are highlighted in corresponding colors. It can be noticed that the structure of the network resembles clouds of papers in the communities. Each cloud has distinguished features that allow identifying its research direction. We identified the three main directions and, therefore, split the network into three sectors. The central cloud of the network is formed around the selected pivot papers G0-1, G0-2, and G0-3. These works are not distant from each other, that is a good sign for our research. The consequent communities form a highly interrelated sector with a focus on cost and benefit allocation issues in power systems and Cooperative Game Theory applications. The bottom (blue-green) cloud of papers contains the mentioned work G1-128 by *McArthur et al.* [60] and as well as many other studies on multi-agent approach to power systems. The papers of this sector have not many connections with the remaining network, which signifies that this research

[1] We avoid including the initial work by *Gately* [40] in the citation network to keep focused on the topic. The reasoning is that the work has a too long and wide citation history. It has been cited by many game-theoretic and applied studies that are not relevant to TEP cost allocation problems.

direction has not much in common with the Game Theory applications and cost allocation issues. Finally, the upper cloud of papers can be characterized as studies that involve transmission expansion algorithms. One of the most significant nodes of this sector, G1-149, represents the review of publications and TEP models by *Latorre et al.* [5]. This paper connects to numerous works in the sector and contributes to forming the distinct TEP communities of the network.

To provide more details on the mentioned research directions and identify additional relevant papers, we describe each of the three sectors separately below. For convenience, we list the considered references (nodes) of the citation network in Table 1.1. An interactive version of the citation networks is available at http://materials.andreychurkin.ru/network2/. As discussed, the upper and the lower sectors reveal the aligned research directions. The central sector contains the most relevant works to the current thesis and, therefore, will be examined especially accurately.

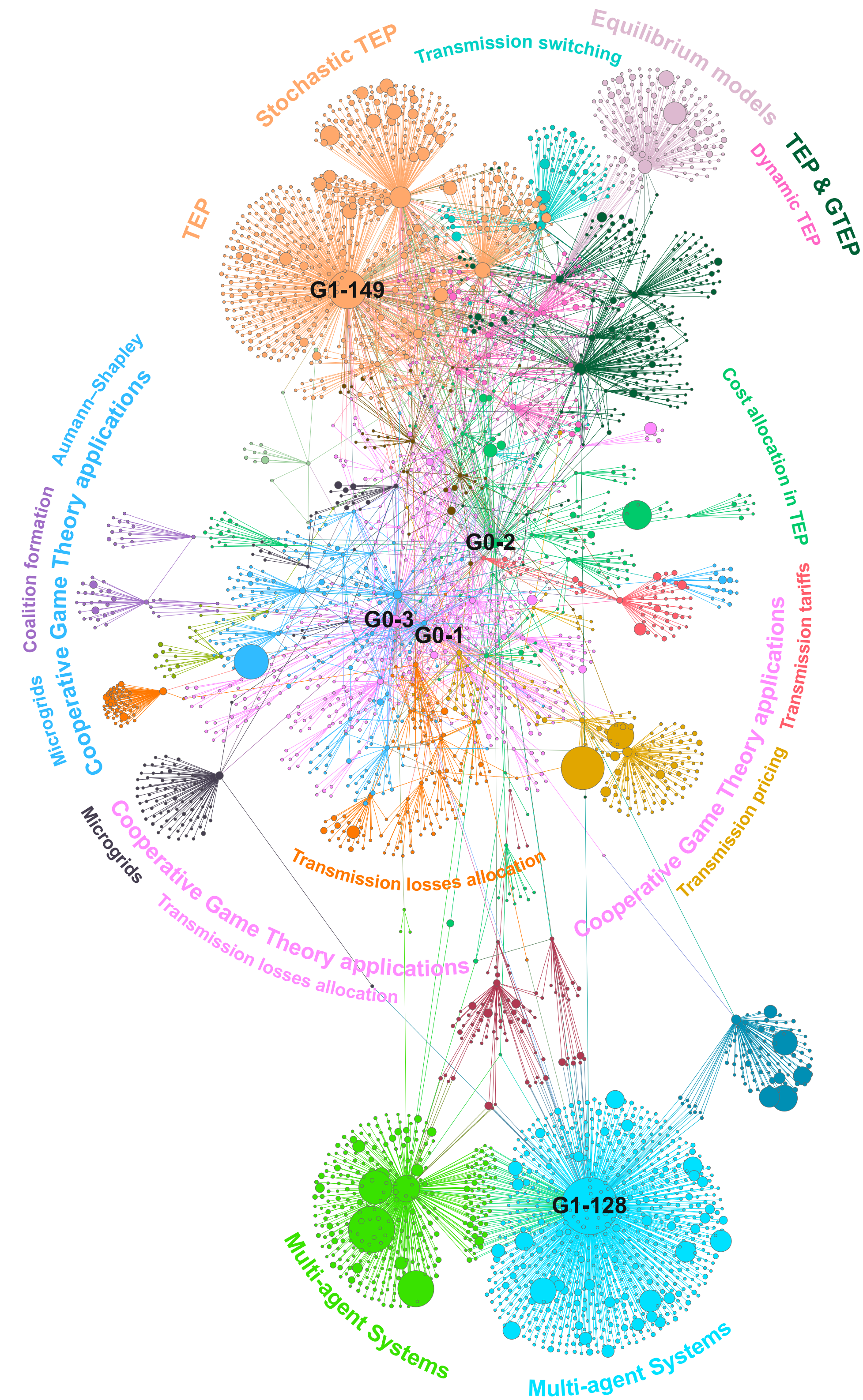

Figure 1.1: Citation network overview.

1.2.2.1 Multi-agent Systems

The bottom sector of the citation network (Figure 1.2) comprises the studies which use multi-agent approaches for power systems. Such approaches consider systems with multiple interacting intelligent agents who make independent decisions and follow a beneficial strategy. The goal of multi-agent systems studies is to develop the design of such systems and suggest operation and control algorithms. The multi-agent approaches have been successfully applied in a broad range of engineering problems such as modeling of cooperation and coordination, distributed optimization, distributed control, multi-agent learning. The formulations of multi-agent systems overlap with game-theoretic models in terms of interaction assumptions and areas of application. We, therefore, review the main ideas of this research direction.

One of the most influential works here is the mentioned review of multi-agent systems concepts, approaches, and technical challenges by *McArthur et al.*, G1-128 [60]. The review resonated with the community and was cited by numerous studies that form the blue cloud around G1-128. Many works in the community implement multi-agent concepts for microgrids operation and distributed control systems. *Bidram et al.* [61] proposed a secondary voltage control of microgrids based on the distributed cooperative control of multi-agent systems (G2-1821). Similar works on distributed control techniques in microgrids are represented by nodes G2-1703 [62], G2-1845 [63], and G2-1971 [64]. Several studies in this community used Game Theory to model microgrid market operation (G2-1449 [65], G2-1644 [66]).

The left green community is formed around the node G1-154 that is the study by *Nagata and Sasaki* [67] on a multi-agent approach to power system restoration. The surrounding nodes mainly represent the studies on distribution networks and microgrids control and protection management based on the multi-agent systems approach.

At the top of the sector, we see several stretched communities (highlighted red and greed) that link the sector with the remaining citation network. The nodes such as G1-156 [68] represent the works on multi-agent systems for energy management and distributed control.

Finally, there is a separate dark-blue community to the right that is formed around the work G1-130 by *Ilic* [69], who discussed the challenges of transition from hierarchical to open access power systems, particularly in design, monitoring and control. The connected papers also put effort into solving problems of power systems operation and control. Some of them rely on multi-agent system design principles.

Through the above review, we see that the communities in the bottom sector form a distinct research direction that can be classified as multi-agent systems. The authors of the communities use the multi-agent approaches to address the issues of power systems design, operation and control. Even though not many studies in the sector used Cooperative Game Theory or considered cost allocation issues, it is still useful to analyze the methods of this aligned research direction.

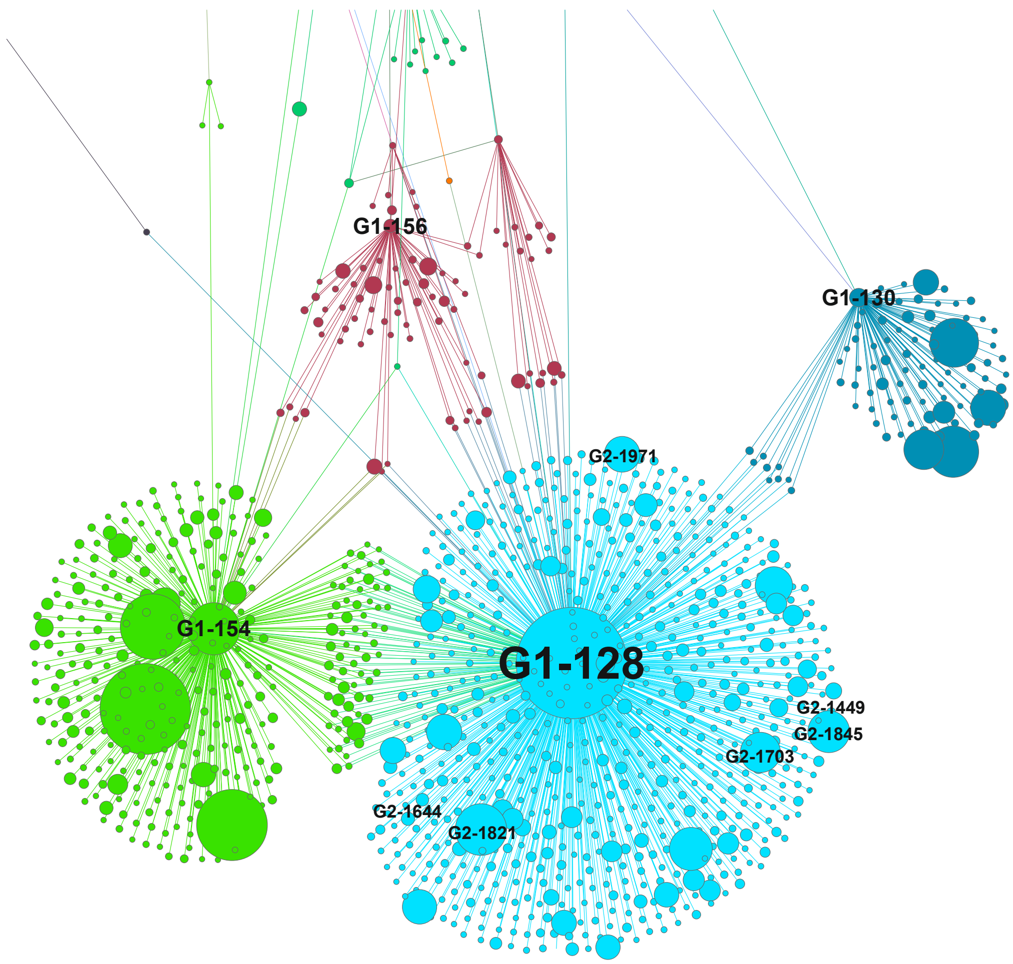

Figure 1.2: The bottom sector: multi-agent systems.

1.2.2.2 Expansion Planning

Another important sector of the citation network (Figure 1.3) comprises the communities that address planning issues in power systems. One of the largest communities (highlighted in peach color) is formed over the nodes G1-149 [5], G1-136 [6], G1-123 [70], and G1-150 [71]. The node G1-149 represents the mentioned review by *Latorre et al.* [5]. This work classified publications and TEP models and found a broad response within the network. Another review of TEP algorithms by *Lee et al.* [6] also tightly interrelates with the main papers of the community and is depicted as G1-136. *De la Torre et al.* [70] presented a MILP for long-term TEP in a competitive pool-based electricity market (node G1-123). To estimate the expansion effect on the generators, demands, and the power system as a whole, the authors proposed using a set of metrics based on changes in surpluses. In the related study G1-150, *Fang and Hill* [71] not only elaborated on TEP models for competitive electricity markets but also considered uncertainty in power-flow patterns.

The related peach-colored nodes represent the studies on different features of TEP problems. *Zhang et al.* [72] proposed a multi-stage MILP algorithm that embeds N-1 security-constrained verification into the TEP framework (node G2-2600). Linearization of power losses and generation cost functions was used to make the problem tractable. *Sauma and Oren* [73] presented a concept of proactive transmission planning (node G2-2738). In their framework, the competitive interaction among generation firms was taken into account. The decisions of generation capacity investments and production were affected by the transmission investments and the congestion management protocols. The interaction was formulated mathematically by means of equilibrium problems (EP). Node G2-2688 is the work by *Maghouli et al.* [74], where the authors proposed a multi-objective TEP framework for deregulated power systems. Investment cost, reliability, and congestion cost were included in the objective function. The optimal solutions were found using a fuzzy decision making analysis.

Summarizing the above references, we can state that the driving force for research in this community is power system restructuring and deregulation (sometimes called unbundling or liberalization). Most of the papers around node G1-149 [5] justify their results by the need for a new TEP framework in the deregulated and competitive environment. The main tools exploited include MILP models, multi-stage programming, equilibrium models, and multi-objective optimization.

A slightly different focus can be observed in the articles surrounding node G1-150 [71]. The authors in this community make efforts to solve TEP problems under uncertainties. The main tools applied are scenarios sampling methods and stochastic programming. *Yu et al.* [75] proposed a chance-constrained TEP formulation to consider uncertainties in wind turbines generation (G2-2841). The probabilistic DC power flow calculations were performed to include the effects of the uncertainties in transmission planning schemes. Several nodes represent the works on robust TEP algorithms. For example, in G2-2809, *Jabr* [76] presented a robust optimization approach for TEP under uncertainties of renewable generation and load. The budget of uncertainty was included in the model formulation and the Benders decomposition was used to solve the MILP problem iteratively.

The nearby turquoise blue community is formed around node G1-111. In this work, *Khodaei et al.* [77] proposed embedding transmission switching in TEP algorithms. Is was demonstrated that transmission switching could add flexibility to expansion plans and reduce the total planning cost. The TEP model was decomposed into a master problem and subproblems, where the master problem performs transmission and generation investments, and the subproblems apply transmission switching to relieve power flow violations and calculate the optimal dispatch. Many of the related studies elaborate on transmission topology control and transmission switching effects on power systems reliability and power markets operation.

The dark-green community to the right contains the studies that combined both generation and transmission expansion planning. Some of the works discussed expansion planning in a multi-regional context where two or more transmission planners make independent decisions. The proposed frameworks are based on multi-level optimization, MILP, and equilibrium models. Node G1-104 stands for the work by *Pozo et al.* [78], who proposed a three-level static MILP model for generation and transmission expansion planning. A pool-based market equilibrium was represented by the lower-level model. Then, the intermediate level introduced generation capacity expansion as the Nash equilibrium problem. Finally, the upper-level contained a TEP formulation with anticipation of the decisions of the other levels. Many of the related works follow the same logic when formulating multi-level TEP models. The nearby node G1-102 is another work by *Pozo et al.* [79] where the anticipative TEP algorithm was illustrated. It was also shown how the non-cooperative nature of the model produces a range of equilibrium solutions. A transmission planner, therefore, should decide on considering the optimistic or pessimistic outcomes. In G1-105, *Munoz et al.* [80] analyzed the impact of wind power generation on long-term TEP. The model incorporated the variability of wind resources and its influence on system security and reserve market. The loss of load expectation constraint was used to guarantee a minimum system security level.

Several works in the community, such as G1-107 and G1-93, considered multi-regional TEP problems. In G1-107, *Khodaei et al.* [81] proposed coordination of long-term and short-term expansion planning. The multi-area expansion planning problem was decomposed into a planning problem and annual reliability subproblems which verify the reliability conditions for transmission plans and impose additional constraints if needed. In G1-93, *Tohidi and Hesamzadeh* [36] formulated TEP with multiple cost-minimizing transmission planners. The non-cooperative solutions were found using the worst-case Nash equilibrium concept. It was shown that without proper compensation mechanisms, the non-cooperative transmission planning is inefficient compared to the cooperative solution.

The lavender-colored community at the top of the sector features studies on finding equilibrium solutions in electricity markets. The reference node G1-145 represents the work by *Contreras et al.* [82], who suggested a numerical method for finding Nash-Cournot equilibrium in electricity markets. The equilibrium problem was transformed into an optimization problem. Then, a relaxation algorithm of the optimum response function was utilized to find the equilibrium in a finite number of iterations. In the nearby node G2-2359, *Pozo and Contreras* [83] enhanced the method and analyzed multiple Nash equilibria in pool-based markets. The stochastic EPEC model allowed addressing multi-period strategic bidding problems with a stochastic demand forecast. Most of the related studies follow the same path and develop Nash equilibrium based solutions for electricity markets.

The last expansion planning community contains the pink-colored nodes in the center of the sector. These studies focus on TEP algorithms application and have much in common with the surrounding communities. As a distinct feature, we may highlight the works on dynamic multi-stage TEP problems. In G1-109, *Aguado et al.* [84] formulated a MILP model of dynamic TEP that explicitly considers a multi-year planning horizon. The authors introduced several efficiency metrics to analyze the TEP effect on generators and demands. The realistic Spanish power system case study was considered with a ten-year planning horizon. Since multi-stage TEP problems usually involve large-scale optimization models, multiple authors relied on metaheuristic algorithms in solving them. For example, in G1-96, *Kamyab et al.* [85] considered the N-1 reliability criterion in multi-stage TEP and used particle swarm optimization method to solve the large-scale non-linear combinatorial problem.

The references mentioned in this section show that the development and application of TEP algorithms is an important research direction that gains increasing attention in the last two decades. The existing methods mainly rely on mathematical programming. However, deregulation in power systems and the emergence of electricity markets pose new problems for expansion planning. Therefore, classical mathematical programming methods are being augmented with game-theoretic models.

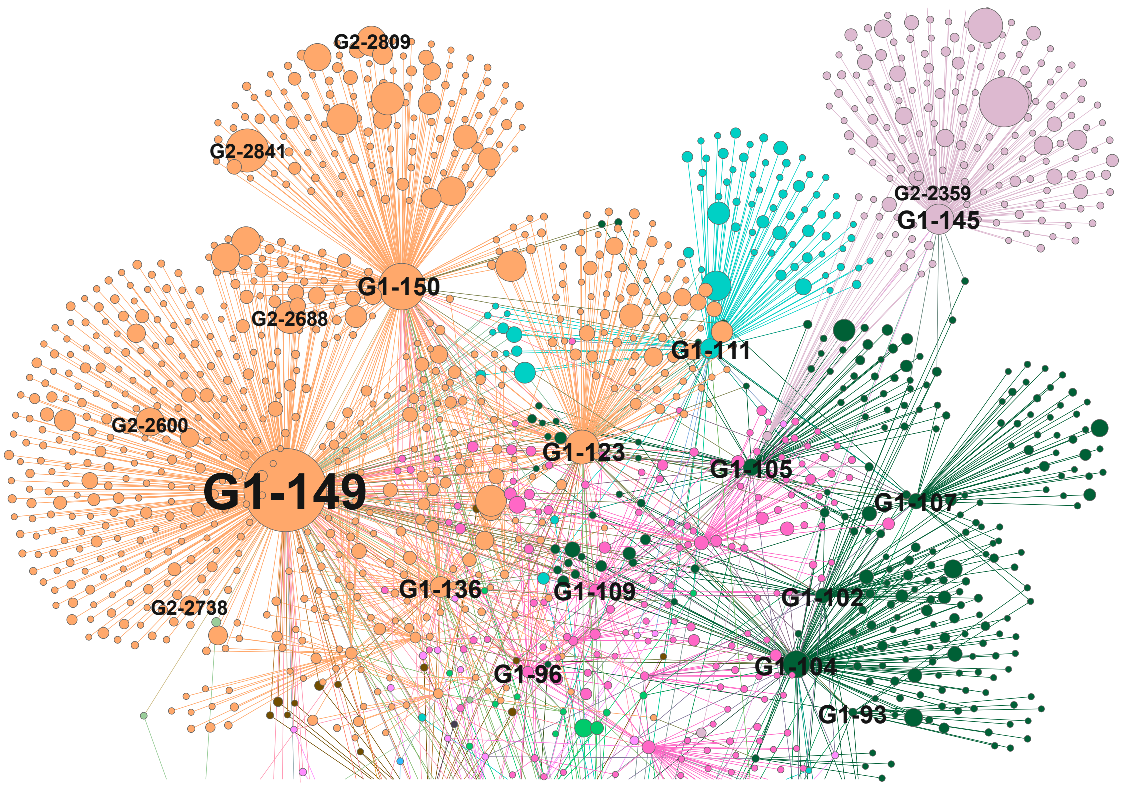

Figure 1.3: The upper sector: expansion planning.

1.2.2.3 Cooperative Game Theory Applications in Power Systems

The central sector of the citation network (Figure 1.4) contains the three pivot papers: G0-1 [41], G0-2 [43], and G0-3 [46]. It is characterized by extensive use of Cooperative Game Theory for solving cost and benefit allocation problems in power systems. Below, we examine the notable contributions of the communities involved and complement our review of existing research with more actual references.

The largest community (highlighted in pink) was formed around the works by *Tsukamoto and Iyoda* [41] (node G0-1) and by *Zolezzi and Rudnick* [46] (node G-03). The surrounding papers adopted and developed the ideas of cooperative game formulation in power systems. Some of the works focus on transmission cost allocation issues, while others found different applications such as allocation of power losses. Interestingly enough, most of the papers in the community did not notice or cite the second pivot paper by *Contreras and Wu* [43] (node G0-2). The possible reasoning is that Contreras and Wu had a shift towards coalitional formation in their work. Less attention was paid to applications of existing Cooperative Game Theory solution concepts. Thus, the community better acknowledged the works G0-1 and G0-3.

Node G1-32 to the right represents the review of cooperative games and cost allocation problems by *Fiestras-Janeiro et al.* [86]. The authors considered possible applications of transferable utility cooperative games in transportation, natural resources, and power industry. The review summarizes the main ideas of cost allocation solution concepts in power systems and refers to other papers in the community. Node G1-61 is the previously mentioned work by *Stamtsis and Erlich* [48] on Cooperative Game Theory applications in power system fixed-cost allocation. The authors illustrated how collective network usage leads to cost savings. The Shapley value and the Nucleolus solution concepts were used for cost allocation. Node G1-37 stands for the above-discussed study by *Bhakar et al.* [51], who introduced a probabilistic Cooperative Game Theory approach to network cost allocation. The probabilistic extension of the allocation solutions could be useful for the case studies where it is possible to evaluate the probabilities of coalitions formation.

A different application of the Cooperative Game Theory solution concepts can be found in G2-143, where *Dabbagh and Sheikh-El-Eslami* [87] considered allocation of virtual power plant's profit among its distributed energy resources. It this framework, distributed generators cooperated in the day-ahead and balancing markets to reach the desired risk-aversion level. The payoffs to the generators were calculated based on the Shapley value and the Nucleolus.

In G1-35, *Rao et al.* [88] compared existing approaches for transmission usage cost allocation. The authors suggested a min-max fair power flow tracing approach and argued that it might be superior to the Cooperative Game Theory solution concepts, marginal participation method, "with and without transit", and other methods.

Several studies applied Cooperative Game Theory solution concepts to allocate power losses. For example, in G1-185, *Sharma and Abhyankar* [89] suggested power losses allocation in radial distribution systems according to the Shapley value. A sequential Shapley value method was proposed to reduce the computational burden when allocating the losses among distributed generators and loads.

At the top of the community, we see the mentioned works by *Evans et al.* [47] (node G1-66) and by *Ruiz and Contreras* [49] (node G1-51). In G1-66, a transmission expansion cost assignment model was proposed that considers independent cooperative games for each expansion segment. The Kernel solution concept was used to find individual cost allocations. The resulting solution summed up the individual allocations for each expansion segment. In G1-51, an allocation scheme was presented that considers market participants' incentives to support an expansion plan. In the model, each prosumer and each producer were assigned voting weights that reflect the level of firms' influence on transmission expansion decisions. Thus, it becomes necessary to suggest a vector of payments in such a way that the total sum of votes on an expansion plan would be higher than some positive parameter. Otherwise, market participants would not agree on network expansion. Node G1-86 represents the work by *Csercsik* [90], who analyzed the effects of cooperation, asymmetric information, and market regulations on the profit of generator companies. A transferable utility game framework was used for profit estimation.

We should also mention our recent work [91] on cross-border power interconnection project analysis. This paper is represented by node G2-263. It introduces the main ideas of the thesis and shows how Cooperative Game Theory solution concepts can be implemented in real-world case studies. Therefore, the citation network analysis confirms that our research contributes to the Cooperative Game Theory applications in power systems and is a part of the significant community formed around G0-1 and G0-3.

The second-largest community of the sector is presented by the blue colored nodes. These studies also focus on Cooperative Game Theory solution concepts applications to power systems allocation issues. Notably, many of the works in the community exploited the Aumann-Shapley value, which is an extension of the Shapley value solution concept to infinite games. The two central blue nodes G1-234 and G1-200 represent the earlier mentioned studies on transmission network cost allocation by *Junqueira et al.* [52] and by *Molina et al.* [53]. In G1-234, the authors introduced an Aumann–Shapley approach for transmission cost allocation and compared it with existing pricing mechanisms such as the Average

Participation Factors (APF) method and the long Run Marginal Costs (LRMC) scheme. It was illustrated that the "infinitesimal agents" idea behind the Aumann–Shapley approach allows avoiding the computational feasibility issues of the original Shapley value concept and eliminates the dependence on the size of the agents. The approach was tested on the Brazilian network case study, for which the transmission tariffs distribution was estimated. The authors of G1-200 agree with the disadvantages of the Shapley value's combinatorial nature and suggest a similar method based on circuit theory and the Aumann-Shapley value. The proposed method considers active are reactive power flows and allows identifying transmission cost allocation among generators and consumers.

In G2-3618, *Molina et al.* [92] used a similar Aumann-Shapley approach to power losses allocation. The model included both active and reactive losses and allowed allocating them among generators and loads. It was illustrated that because of the counter-flows, some participants may have negative allocations and should be therefore subsidized. Many of the related studies at the bottom of the blue community elaborate on transmission losses allocation methods.

Srinivasan et al. [93] formulated strategic bidding and cooperation strategies for consumers in power markets (node G2-193). It was shown that because of the network's physical constraints, consumers might be able to influence the market by cooperating with each other. The coevolutionary algorithm was used for market modeling under deterministic and stochastic conditions. The values of the coalitions were defined by Cooperative Game Theory concepts.

Cooperation can take a multi-level form. This happens when groups of players cooperate, or there is a hierarchical structure (subordination) between them. Thus, there is a need to consider both the upper-level cooperation and the allocation of value within groups. To this end, node G2-3430 is a recent work by *Petrosyan and Sedakov* [94], who proposed an allocation procedure for two-level cooperation in network games.

The left side of the blue community contains papers with a focus on Cooperative Game Theory applications in smart grids and microgrids. The large node G2-3541 is the review of game-theoretic methods for smart grids by *Saad et al.* [95]. The authors argue that emerging technologies in communications and control make it possible to apply Non-cooperative and Cooperative Game Theory techniques to address the challenges in smart grids. The neighboring node G1-11 represents the work by *Du et al.* [96], who studied the potential advantages of cooperation among multiple microgrids with distributed energy resources. In this framework, cooperating microgrids could be dispatched in a centralized manner to reach a reduction in operating cost. The Nucleolus solution concept was used for cost allocation. To overcome the computational issues, authors suggested finding the Nucleolus via Benders decomposition.

Another elegant application of the Aumann-Shapley concept can be found in G1-225, where *Faria et al.* [97] examined the allocation of firm energy rights among hydropower plants. It was shown that synergy benefits could happen in coordinated firm energy production compared to the separate operation of hydro plants. Such situations are usual for plants located in a cascade (in the same river basin). The authors compared several methods for firm energy rights allocation and argued that the Aumann-Shapley approach provides the most reasonable results. Several cases of river cascades in Brazil were analyzed to reveal the dependence of firm energy rights allocation on the reservoirs of upstream and downstream power plants. A somewhat similar idea was proposed by *Kristiansen et al.* [98] for power system flexibility analysis (node G1-82). It was discussed that flexibility providers such as fast-ramping gas turbines or demand-side management are needed to accommodate a significant amount of variable renewable energy sources. Thus, it is necessary to include the flexibility providers in GTEP models. The authors suggested evaluating all possible scenarios of expansion planning and ranking spatially distributed flexibility providers according to the Shapley value. The effects of renewables share levels on operating costs, CO_2 emissions reduction, and marginal system value of the flexibility providers were illustrated based on the North Sea Offshore Grid case study.

The neighboring nodes G1-188, G1-189 are the papers by *Banez-Chicharro et al.* [99], [100] on transmission expansion projects benefits estimation using the Aumann-Shapley approach. In G1-188, the authors formulated a cooperative game to allocate the benefits of an expansion plan to individual expansion projects. The Aumann-Shapley approach was compared to the existing project evaluation schemes such as “take out one at a time” and “put in one at a time”. It was shown that project importance ranking by the Aumann-Shapley value might lead to higher net benefits while satisfying consistency and fairness properties. In G1-189, the authors exploited the similar Aumann-Shapley approach to address the issue of transmission expansion projects benefits allocation among the users of transmission networks.

The distant blue nodes to the right represent a group of studies on demand-side management. The reference node G1-89 is the work by *Haring et al.* [101], who compared centralized and decentralized contract designs for demand response programs. The authors formulated the decentralized contract proposal scheme as a heuristic process based on Q-learning. Consumer's incentives to join the coalitions were expressed by means of Cooperative Game Theory. It was found that the level of demand response exploitation depends on information accuracy and coalition formation costs.

We should also mention the citations of the second pivot paper G0-2 by *Contreras and Wu* [43]. As discussed above, few of the game-theoretic works in the pink community did refer to G0-2. Instead, the paper drew much more attention from the expansion planning communities at the top of the network. Many of the key works in TEP and GTEP, such as G1-104 [78], G1-111 [77], G1-123 [70], G1-149 [5], and G1-150 [71], referred to the Contreras' initial paper as one of the first studies on coalition formation and Cooperative Game Theory application in power systems. Nonetheless, no significant community was formed around G0-2. The surrounding green colored nodes split into different research directions. Several works elaborate on TEP and allocation issues. In G1-55, *Hu et al.* [102] applied Cooperative Game Theory for allocating generators start-up costs among power consumers. A multiperiod unit commitment problem was formulated to identify the optimal dispatch of generating units. Then, the estimated start-up and no-load costs were allocated by the Nucleolus and the Shapley value solution concepts. In this manner, the proposed framework allowed the unbundling of fixed and variable operating costs. In G1-38, *Xie et al.* [103] presented an emission-constrained generation scheduling model in which the trading of emission allowance was optimized. The resulting cost reduction was allocated among generators according to the Shapley value. A couple of neighboring nodes represent the contribution of N. Voropai's research group to TEP modeling, coordination and allocation methods. In G1-138, *Voropai and Ivanova* [104] formulated a game-theoretic approach for the cooperation of power supply companies in expansion planning. The authors examined different criteria of cooperation and used the Shapley value for benefits allocation. Other green nodes represent not relevant topics (such as radio resource allocation problems) and therefore are not considered in the review.

Lastly, we briefly describe the minor communities of the central sector. The light brown group of nodes to the right comprises the studies on transmission management and pricing mechanisms. In G1-74, *Marangon Lima and de Oliveira* [105] discussed the long-term effect of transmission pricing on generation and transmission expansion planning. The adjoint node G2-550 is the review of the transmission management methods in deregulated power systems by *Christie et al.* [106]. Most of the related works focused on transmission pricing, wheeling of power, and congestion management.

The issues of transmission tariffs and charges are also addressed by the works in the light red colored community. In G1-220, *Olmos and Perez-Arriaga* [107] proposed a transmission charges method based on average participation factors and argued that it might complement the existing LMP approach. Another discussion of tariff design methodologies in distribution networks was presented by *Rodrıguez Ortega et al.* [108] in node G1-122. There is still an ongoing interest in transmission network tariffs research. Modern studies suggest using more sophisticated approaches such as multi-level and equilibrium modeling. In the recent study G2-3566, *Grimm et al.* [109] analyzed subsidization schemes effect on locational choices of generation investment in electricity markets. Regionally differentiated network fees were introduced in the model as a component of payment by generators. It was found that the proposed scheme influences investment and decommissioning decisions and might lead to welfare gains.

The orange community below features the studies on transmission loss allocation. In G1-124, *Lima et al.* [110] analyzed loss allocation to generators and demands using Cooperative Game Theory principles. Equivalent bilateral exchanges were considered as independent players of the game. The related studies further elaborate on loss allocation methods using multidisciplinary approaches. For example, *Dev Choudhury and Goswami* [111] suggested combining Cooperative Game Theory and artificial neural networks for solving transmission loss allocation problems (node G1-205). The authors considered bilateral contracts in electricity markets and argued that loss allocation by the Shapley value might be intractable for real power systems. Thus, an artificial neural network was trained on a large amount of generated sample cases and then tested on IEEE 14 and 30 bus systems.

In the minor black community to the left, we find it necessary to highlight the contribution by K. N. Hasan to Cooperative Game Theory applications in power systems. In G1-97, *Hasan et al.* [112] considered TEP for renewables integration in remote areas of the Australian grid. Such location-constrained projects require building long capital intensive interconnections. Under the existing transmission pricing mechanisms, the transmission fee for the newly built renewable generation could be unreasonably high. The authors discussed the issues in transmission pricing policies and suggested using the Shapley value for transmission cost allocation among market participants. In G1-179, *Hasan et al.* [113] presented a unique Cooperative Game Theory application to power system stability analysis. The authors formulated small uncertain disturbances as players of the cooperative game and used several allocation concepts to rank the most influential parameters. It was shown that the suggested game-theoretic probabilistic power system analysis tool might be superior to common sensitivity analysis methods.

A small dark brown colored community at the top of the sector also features Cooperative Game Theory applications in electricity markets and TEP. Node G1-116 is the earlier mentioned work by *Contreras et al.* [50], who suggested an incentive-based mechanism for transmission investment. A decentralized investment model was suggested considering each investor as an independent player. Then, the rewarding procedure iteratively evaluated possible welfare gains and allocated them among the investors using the Shapley value. The expansion plan was considered settled once all the investors decided on the rationality of their TEP projects (no more investors were willing to build more transmission assets). In the linked node G2-1066, *Lo Prete and Hobbs* [114] examined incentives for market participants to cooperate in microgrid forming. A Cooperative Game Theory framework was used to quantify cost and benefit allocation among the market participants. It was reported that market failure could lead to the misalignment between the social and private objectives and inefficient scale and types of microgrid installations.

The far-left purple community has very few connections with the remaining citation network (only with G0-2 and G0-3 directly) and represents the studies on coalition formation. In G1-129, *An et al.* [115] proposed dynamic coalition formation algorithms and referred to the work by Contreras (node G0-2) as an example of coalition formation analysis in TEP. The neighboring purple nodes refer to Zolezzi's work G0-3 and feature overlapping issues in coalition formation. For example, in G1-219, *Zhang et al.* [116] used particle swarm optimization to identify overlapping coalitions formation in multiple project tasks (situations where a player can participate in several coalitions simultaneously).

At this point, we have reviewed most of the existing relevant studies on Cooperative Game Theory applications in power systems. We found that the topic significantly evolved since the initial works G0-1 [41], G0-2 [43], and G0-3 [46]. The allocation concepts have been applied from a variety of angles, and the models complexified considerably. The identified applications can be classified into essential and specific approaches. The essential approaches involve the straightforward modeling of player interactions in power markets and in expansion planning projects. We include the following applications here:

- Allocation of costs (usually operating) or benefits (cost savings or welfare gains) among the power market participants (generators and demands) [86], [90], [93];
- Allocation of transmission costs among the market participants (development of new transmission pricing mechanisms) [48], [52], [53], [88], [105];
- Solving the mentioned allocation issues as a part of TEP or GTEP [47], [49], [50], [99], [100], [104], [112];
- Identification of beneficiaries in expansion projects [100] and ranking projects within an expansion plan [99];
- Multi-regional expansion planning (usually, cross-border power interconnection projects) [54], [55], [91];
- Cooperation among microgrids [95], [96], [114];
- Allocation of benefits within virtual power plants [87].

Other approaches suggest unique ways of the cooperative game formulation. Sometimes, these formulations are not straightforward (for example, players of a game can hardly be called players in the usual sense). We mention the following specific applications:

- Allocation of power losses (instead of the total cost, the allocation of losses among the agents, sometimes, among bilateral contracts) [89], [92], [110], [111];
- Using probabilistic game approaches for cost allocation (requires additional data on probabilities of coalitions) [51];
- Allocation of firm-energy rights or emission allowances [97];
- Ranking of flexible generation projects to accommodate renewable energy sources [98];
- Cost allocation in unit commitment (for example, mechanisms for start-up costs allocation) [102], [103];
- Power system stability analysis (contingency ranking based on Cooperative Game Theory principles) [113].

Our work falls into the directions of the multi-regional expansion planning and transmission cost allocation. In the following sections, we will summarize the citation network analysis and highlight the contributions of the thesis.

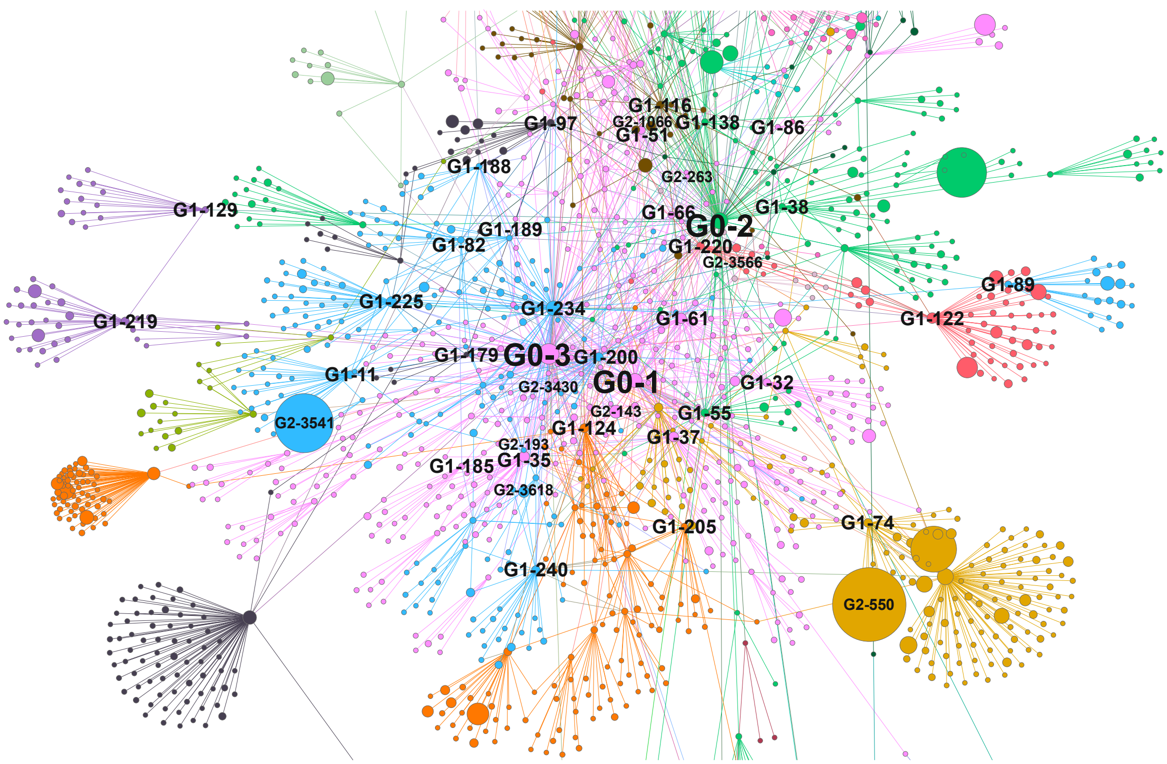

Figure 1.4: The central sector: Cooperative Game Theory applications in power systems.

1.2.2.4 Opportunities, Challenges, and Limitations of Cooperative Game Theory Applications in TEP

Additionally, the review of existing studies allowed us to identify the main challenges and limitations of Cooperative Game Theory applications in power systems, which we discuss in this section. First, we consider it important to discuss the applicability of the Cooperative Game Theory solution concepts.

Applicability

Cooperative Game Theory provides a rich theoretical background for the analysis of cooperation in power systems. Existing concepts enable identifying reasonable allocation solutions while satisfying some desired properties of cooperation. It is not surprising that many authors reported on the successful implementation of the solution concepts and suggested using them as the basis for cooperation mechanisms in power systems.

In most of the covered applications, Cooperative Game Theory provides intuitive results with explicit incentives for participants of cooperation and regulatory or coordinating entities. In [49], *Ruiz and Contreras* suggested using Cooperative Game Theory in transmission assets investment schemes and argued that such schemes would give market participants incentives to support an expansion plan. *Faria et al.* [97] examined the allocation of firm-energy rights among hydro plants in Brazil. The authors considered several allocation methods and recommended using the Aumann–Shapley since “it is robust in relation to small variations of a plant’s size and computationally efficient, besides originates from an intuitive methodology (Shapley value)”. *Banez-Chicharro et al.* [99] used the Aumann-Shapley value for estimating the benefits of transmission expansion projects. Having compared several methods, the authors concluded that “the proposed methodology provides regulatory authorities with the most relevant information for the identification of high-priority expansion projects”.

Many authors mentioned that the identification of agents (players) and formulation of cooperative games is straightforward and clear. Moreover, the solution concepts adequately consider the key parameters of cooperation in power systems such as topology, electrical distance, usage of the network, etc. In [89], *Sharma and Abhyankar* used the Shapley value for power loss allocation in radial distribution systems. The authors mentioned that the proposed game-theoretic approach could be superior to existing methods since "it is easy to understand and implement", "it considers the size and location of loads and distributed generations", "it is based on individual network usages", and "it recovers the total amount of losses". *Junqueira et al.* [52] developed an open access transmission tariff scheme based on the Aumann-Shapley value. It was demonstrated that the proposed approach "presents desirable characteristics in terms of economic coherence and isonomy". It was also found that the Aumann-Shapley approach captures the physics of power systems (the fact that power demands are mainly supplied by local generators, if any), while other methods require setting the economic slack bus and may provide unreasonable results.

The discussed studies show that Cooperative Game Theory can be applied to power systems' allocation problems. The solution concepts could be valuable in analyzing projects with multiple participants or used as the basis for mechanisms of cooperation. For instance, in [95], *Saad et al.* reviewed game-theoretic methods for smart grids and concluded, "Clearly, cooperative games could become a foundation for introducing local energy exchange between microgrids in future smart grid systems. This local energy exchange could constitute one of the main steps towards the vision of an autonomous microgrid network." We, therefore, expect more studies and applications of Cooperative Game Theory to appear in the near future.

Now we proceed to the challenges and limitations.

Scalability

One of the most challenging limitations of Cooperative Game Theory is the scalability of the solution concepts. Most of the covered studies considered a moderate number of players in the cooperative game formulations, which is two - six participants of a project. It was reported that the implementation of the solution concepts for realistic systems with more players would be computationally infeasible. Indeed, the number of scenarios to consider (coalitions) grows exponentially with the number of players. The number of possible orderings in the Shapley value grows factorially. In [97], *Faria et al.* examined the Brazilian power system, which has around one hundred hydro plants. It is practically not possible to estimate the Shapley value for such a high number of players. The authors also mentioned the computational efficiency of the Core of the game, "the major difficulty in the calculation of the Core in realistic situations is the exponential increase of the Core constraints with the number of plants: a system with ten plants would have 1 000 constraints, and the modeling of 40 plants would require about one trillion constraints."

Under such circumstances, several studies exploited the Aumann-Shapley value, which provides an analytical solution to allocation problems where each agent could be divided into infinitesimal parts. This solution has a decreased computational burden and can be applied to cooperative games with dozens and hundreds of players. Additionally, many authors praised the isonomy of the Aumann-Shapley value. This property makes the allocation solution irrelevant to the size or capacity of the players since only infinitesimal shares of their capacities are considered. Studies as [43] and [89] proposed using the allocation rules in a sequential manner, which also allows decreasing the computational complexity.

Certainly, there is a need for developing new cooperative game formulations that would enable accounting for more players. Such formulations might include decomposition techniques and approximations of the allocation rules, coalitional structure, etc. Applications of machine learning techniques in the field could be rather promising, as demonstrated by *Dev Choudhury and Goswami* [111].

In addition, we feel it important to mention that cooperative games with a high number of players may provide hardly-interpretable results. It might be problematic to understand why and how certain players affect others. Moreover, such formulations imply that numerous participants, sometimes irrelevant to each other, agree on joining the grand coalition, which might not be the case in practice. In such cases, it would make sense to consider several separate cooperative games with a moderate number of players.

Nonconvex cooperative games

The discussed concepts, such as the Shapley value and the Nucleolus, are guaranteed to provide rational solutions only for the class of convex games. However, technical limitations of power systems (topology of interconnections, maximum capacity of lines and generators) could lead to nonconvex cooperative games. In such cases, marginal contribution by certain players to subcoalitions could be higher than to the grand coalition. As an extreme example of this violation, the Core of the game could become an empty set. Other examples include cooperative games with the Core that could be rather small in volume or be very distant from some players. Even the Shapley value could fall out of the Core, which signifies that contribution by some players is underestimated in the grand coalition. The decreased volume of the Core indicates issues with the stability of cooperation. The point is that there are not many rational allocation solutions to consider. Under some changes in data provided by the players, the Core could become an empty set, and the cooperation would no longer be rational for the players.

Repetition

Even though some of the authors formally verified that their models lead to convex cooperative games, there is no proof that the entire class of proposed games in convex. That is, under specific changes in parameters, the mechanisms of cooperation would fail. For example, in [91], we considered a transmission expansion case with six players and hybrid topology of interconnections. We found that the cooperative game over the optimal expansion plan is nonconvex. We then tuned the parameters of the system and were able to identify cooperative games with an empty Core.

Definitely, arranging cooperation over nonconvex games could be a practical issue since solution concepts might fail to provide rational results. In the light of this, there is a need for producing proofs of convexity for cooperative game formulations in power systems. Alternatively, it is necessary to identify the weak points of cooperation and parameters that may cause nonconvexity. The development of algorithms and mechanisms that avoid nonconvex cooperative games would be highly useful for practical applications.

Coalition formation and other assumptions

Cooperative Game Theory introduces several assumptions that might not hold in power systems. The main assumption is that the grand coalition will form. In reality, players, say generating companies, investors, or independent PSOs, might not be necessarily obliged to join the coalitions. In this case, they might refuse to join the grand coalition if it is not incentive compatible for them.

Therefore, to correctly implement the Cooperative Game Theory solution concepts, there is a need to establish a coordinating entity and protocols of cooperation.

Moreover, Cooperative Game Theory considers the coalitions of players as equally possible. In [41], *Tsukamoto and Iyoda* compared the coalitions with player's cards in the negotiation process. They mention that "the subcoalition is never actually realized, but is presented as a basis of an assertion in the negotiation". Such logic could be controversial for some applications. In practice, it might be necessary to add corrections to the coalition formation assumptions. For example, *Bhakar et al.* [51] suggested modeling the probability of the existence of players, the probability of the existence of coalitions, and the probability of players joining a particular coalition.

Choosing an appropriate single-valued solution concept is also a disputable task. Many authors mentioned that the definition of the fairness of a solution concept is controversial. Therefore, it is not clear whether the Shapley value is an adequate solution for certain problems or not. The Nucleolus is also open to criticism, as discussed in Section 3.2.3. Set solution concepts as the Core definitely make sense for the analysis of cooperation. However, the Core, if nonempty, provides a variety of solutions, which may not be useful in practical applications.

Some authors mentioned the transferable utility assumption as a crucial one. The point is that in practice, it may not be possible to fully represent the worth of cooperation in transferable units, say monetarily. Moreover, the outcome of cooperation could be multi-valued. For example, electricity trade could lead to cost reduction, CO_2 emissions reduction, and an increase in power losses.

Comment: all of these items: cost reduction, CO_2 reduction, and losses are commensurable (at least given a carbon price), so I do not think they are a fundamental problem. A more fundamental problem would be presented by attributes that are incommensurable. Do you have an example of incommensurable attributes?

In this regard, the future research trajectory could focus on the relaxation of the mentioned assumptions. It is also worth developing the mechanisms of cooperation that would enable cooperation in power systems while keeping the Cooperative Game Theory assumptions actual. Additionally, we want to mention that current Cooperative Game Theory applications consider static problems, where a single snapshot of a system and proposed cooperation (usually at the planning stage) is analyzed. However, it is worth addressing the dynamic nature of cooperation. For example, in the first stage, players may cooperate in planning and building assets. Then, several stages of operation follow. During the operation, some players may change their initially declared strategy or refuse cooperation at all.

Ex-post game-theoretic analysis

Comment: a good topical example of this is Nordstream

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Existing works on Cooperative Game Theory applications in power systems exploit the solution concepts in an ex-post manner. The common approach is first to solve a model for all possible scenarios of cooperation (coalitions) and formulate the characteristic function. Then, the solution concepts are used to allocate the value of cooperation. This approach enables analyzing the optimal plan (calculated in a centralized manner), estimating the stability of cooperation and the bargaining power of players.

However, some players may have additional expectations or requirements on their minimal share of benefits or levels of usefulness in the coalition. A coordinating entity may also want to reach a cooperation with a desired level of stability. Therefore, a more promising approach would be incorporating Cooperative Game Theory principles into planning and operation algorithms. Such an approach would enable identification of decisions in an anticipating manner to obtain a cooperative game with desired properties. The inclusion of Cooperative Game Theory principles into the existing planning and operating models can provide additional insights into the structure of cooperation, as we will demonstrate in Chapter 5. Moreover, it would allow a coordinating entity to produce a "menu" of possible decisions and modify the coalitions if needed. We consider the idea of the anticipating application of Cooperative Game Theory highly promising for establishing cooperation in TEP.

Incomplete information and manipulability of allocation rules

Another crucial assumption of Cooperative Game Theory is that cooperation happens under perfect information: parameters of the power system and each player are known to other players and the coordinating entity. In [47], *Evans et al.* used the Kernel for transmission expansion cost allocation and mentioned that "the coalition creation in the Kernel requires perfect information between the agents that will form the coalition". In reality, it may be hard to collect accurate information from several independent participants. Moreover, players may have incentives to misreport their data and manipulate the allocation rule. *Evans et al.* continued, "If that information is not perfect (information asymmetry), the assignment will be biased. Information becomes a competitive advantage within an environment of cooperation." In Chapter 4, we elaborate on this issue and demonstrate how the Cooperative Game Theory solution concepts can be unilaterally manipulated by players. We then discuss the ways of preventing such manipulations and the need for strategyproof mechanisms of cooperation.

We would like to highlight that many of the covered studies used rather simple models in simulating power systems and interactions among players. The reasoning lies in the nature of cooperative games modeling: the models have to be solved multiple times for all possible coalitions, which increases the computational burden. Therefore, a possible extension to existing studies could be the complexification of game-theoretic models (for example, detailed AC modeling of power systems, formulating stochastic optimization models), which may reveal additional insights.

Summing up the section, we see that there exist several obstacles to Cooperative Game Theory application in power systems. Most of the challenges are related to game-theoretic assumptions that might not hold in practical cases. Nonetheless, significant progress has been achieved in developing algorithms and mechanisms based on Cooperative Game Theory solution concepts. We believe that future studies would overcome the mentioned obstacles and enable consistent application of Cooperative Game Theory in power systems.

1.2.2.5 Bibliometrics and Summaries

The citation network analysis revealed the structure of the existing research and allowed us to locate the most relevant works in the field. We found out that our thesis contributes to the major community (the pink-colored group of nodes around G0-1 [41] and G0-3 [46]) and is, therefore, a part of the ongoing research on Cooperative Game Theory applications in power systems.

In this section, we provide more details on the identified research directions and highlight the relevance of our work. First, to ease the navigation through the presented analysis, we list the references used in the citation network in Table 1.1.

Table 1.1: References in the citation network analysis.

Network ID	Paper	Reference
	Bottom sector: multi-agent systems	
G1-128	S. D. J. McArthur *et al.*, "Multi-agent systems for power engineering applications - Part I: Concepts, approaches, and technical challenges," *IEEE Trans. Power Syst.*, vol. 22, no. 4, 2007	[60]
G2-1821	A. Bidram, A. Davoudi, F. L. Lewis, and J. M. Guerrero, "Distributed cooperative secondary control of microgrids using feedback linearization," *IEEE Trans. Power Syst.*, vol. 28, no. 3, 2013	[61]
G2-1703	M. Yazdanian and A. Mehrizi-Sani, "Distributed control techniques in microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 6, 2014	[62]
G2-1845	H. S. V. S. Kumar Nunna and S. Doolla, "Multiagent-based distributed-energy-resource management for intelligent microgrids," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, 2013	[63]
G2-1971	T. Logenthiran, D. Srinivasan, and A. M. Khambadkone, "Multi-agent system for energy resource scheduling of integrated microgrids in a distributed system," *Electr. Power Syst. Res.*, vol. 81, no. 1, 2011	[64]
G2-1449	C. S. Karavas, K. Arvanitis, and G. Papadakis, "A game theory approach to multi-agent decentralized energy management of autonomous polygeneration microgrids," *Energies*, vol. 10, 2017	[65]

G2-1644	M. H. Cintuglu, H. Martin, and O. A. Mohammed, "Real-time implementation of multiagent-based game theory reverse auction model for microgrid market operation," *IEEE Trans. Smart Grid*, vol. 6, no. 2, 2015	[66]
G1-154	T. Nagata and H. Sasaki, "A multi-agent approach to power system restoration," *IEEE Trans. Power Syst.*, vol. 17, no. 2, 2002	[67]
G1-156	L. M. Tolbert, H. Qi, and F. Z. Peng, "Scalable multi-agent system for real-time electric power management," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, 2001	[68]
G1-130	M. D. Ilic, "From hierarchical to open access electric power systems," *Proc. IEEE*, vol. 95, no. 5, 2007	[69]

Upper sector: expansion planning

G1-149	G. Latorre, R. Darío Cruz, J. M. Areiza, and A. Villegas, "Classification of publications and models on transmission expansion planning," *IEEE Trans. Power Syst.*, vol. 18, no. 2, 2003	[5]
G1-136	C. W. Lee, S. K. K. Ng, J. Zhong, and F. F. Wu, "Transmission expansion planning from past to future," in *2006 IEEE PES Power Systems Conference and Exposition, PSCE 2006 - Proceedings*, 2006	[6]
G1-123	S. de la Torre, A. J. Conejo, and J. Contreras, "Transmission expansion planning in electricity markets," *IEEE Trans. Power Syst.*, vol. 23, no. 1, 2008	[70]
G1-150	R. Fang and D. J. Hill, "A new strategy for transmission expansion in competitive electricity markets," *IEEE Trans. Power Syst.*, vol. 18, no. 1, 2003	[71]

G2-2600 H. Zhang, V. Vittal, G. T. Heydt, and J. Quintero, "A mixed-integer linear programming approach for multi-stage security-constrained transmission expansion planning," *IEEE Trans. Power Syst.*, vol. 27, no. 2, 2012 [72]

G2-2738 E. E. Sauma and S. S. Oren, "Proactive planning and valuation of transmission investments in restructured electricity markets," *J. Regul. Econ.*, vol. 30, 2006 [73]

G2-2688 P. Maghouli, S. H. Hosseini, M. O. Buygi, and M. Shahidehpour, "A multi-objective framework for transmission expansion planning in deregulated environments," *IEEE Trans. Power Syst.*, vol. 24, no. 2, 2009 [74]

G2-2841 H. Yu, C. Y. Chung, K. P. Wong, and J. H. Zhang, "A chance constrained transmission network expansion planning method with consideration of load and wind farm uncertainties," *IEEE Trans. Power Syst.*, vol. 24, no. 3, 2009 [75]

G2-2809 R. A. Jabr, "Robust transmission network expansion planning with uncertain renewable generation and loads," *IEEE Trans. Power Syst.*, vol. 28, no. 4, 2013 [76]

G1-111 A. Khodaei, M. Shahidehpour, and S. Kamalinia, "Transmission switching in expansion planning," *IEEE Trans. Power Syst.*, vol. 25, no. 3, 2010 [77]

G1-104 D. Pozo, E. E. Sauma, and J. Contreras, "A three-level static MILP model for generation and transmission expansion planning," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 202–210, 2013 [78]

G1-102 D. Pozo, J. Contreras, and E. Sauma, "If you build it, he will come: Anticipative power transmission planning," *Energy Econ.*, vol. 36, 2013 [79]

G1-105 C. Muñoz, E. Sauma, J. Contreras, J. Aguado, and S. De La Torre, "Impact of high wind power penetration on transmission network expansion planning," *IET Gener. Transm. Distrib.*, vol. 6, no. 12, 2012 [80]

G1-107	A. Khodaei, M. Shahidehpour, L. Wu, and Z. Li, "Coordination of short-term operation constraints in multi-area expansion planning," *IEEE Trans. Power Syst.*, vol. 27, no. 4, 2012	[81]
G1-93	Y. Tohidi and M. R. Hesamzadeh, "Multi-regional transmission planning as a non-cooperative decision-making," *IEEE Trans. Power Syst.*, vol. 29, no. 6, 2014	[36]
G1-145	J. Contreras, M. Klusch, and J. B. Krawczyk, "Numerical Solutions to Nash-Cournot Equilibria in Coupled Constraint Electricity Markets," *IEEE Trans. Power Syst.*, vol. 19, no. 1, 2004	[82]
G2-2359	D. Pozo and J. Contreras, "Finding multiple Nash equilibria in pool-based markets: A stochastic EPEC approach," *IEEE Trans. Power Syst.*, vol. 26, no. 3, 2011	[83]
G1-109	J. A. Aguado, S. De La Torre, J. Contreras, A. J. Conejo, and A. Martínez, "Market-driven dynamic transmission expansion planning," *Electr. Power Syst. Res.*, vol. 2, no. 1, 2012	[84]
G1-96	G. R. Kamyab, M. Fotuhi-Firuzabad, and M. Rashidinejad, "A PSO based approach for multi-stage transmission expansion planning in electricity markets," *Int. J. Electr. Power Energy Syst.*, vol. 54, 2014	[85]
	Central sector: Cooperative Game Theory applications in power systems	
G1-32	M. G. Fiestras-Janeiro, I. García-Jurado, and M. A. Mosquera, "Cooperative games and cost allocation problems," *TOP*, vol. 19, 2011	[86]
G1-61	G. C. Stamtsis and I. Erlich, "Use of cooperative game theory in power system fixed-cost allocation," *IEE Proc. - Gener. Transm. Distrib.*, vol. 151, no. 3, pp. 401–406, 2004	[48]

G1-37	R. Bhakar, V. S. Sriram, N. P. Padhy, and H. O. Gupta, “Probabilistic game approaches for network cost allocation,” *IEEE Trans. Power Syst.*, vol. 25, no. 1, 2010	[51]
G2-143	S. R. Dabbagh and M. K. Sheikh-El-Eslami, “Risk-based profit allocation to DERs integrated with a virtual power plant using cooperative Game theory,” *Electr. Power Syst. Res.*, vol. 121, 2015	[87]
G1-35	M. S. S. Rao, S. A. Soman, P. Chitkara, R. K. Gajbhiye, N. Hemachandra, and B. L. Menezes, “Min-max fair power flow tracing for transmission system usage cost allocation: A large system perspective,” *IEEE Trans. Power Syst.*, vol. 25, no. 3, 2010	[88]
G1-185	S. Sharma and A. R. Abhyankar, “Loss allocation of radial distribution system using Shapley value: A sequential approach,” *Int. J. Electr. Power Energy Syst.*, vol. 88, 2017	[89]
G1-66	F. Evans, J. M. Zolezzi, and H. Rudnick, “Cost assignment model for electrical transmission system expansion: An approach through the kernel theory,” *IEEE Trans. Power Syst.*, vol. 18, no. 2, 2003	[47]
G1-51	P. A. Ruiz and J. Contreras, “An effective transmission network expansion cost allocation based on game theory,” *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 136–144, 2007	[49]
G1-86	D. Csercsik, “Competition and Cooperation in a Bidding Model of Electrical Energy Trade,” *Networks Spat. Econ.*, vol. 16, 2016	[90]
G2-263	A. Churkin, D. Pozo, J. Bialek, N. Korgin, and E. Sauma, “Can cross-border transmission expansion lead to fair and stable cooperation? Northeast Asia case analysis,” *Energy Econ.*, vol. 84, 2019	[91]

G1-234	M. Junqueira, L. C. da Costa, L. A. Barroso, G. C. Oliveira, L. M. Thomé, and M. V. Pereira, “An Aumann-Shapley approach to allocate transmission service cost among network users in electricity markets,” *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1532–1546, 2007	[52]
G1-200	Y. P. Molina, O. R. Saavedra, and H. Amaris, “Transmission network cost allocation based on circuit theory and the Aumann-Shapley method,” *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4568–4577, 2013	[53]
G2-3618	Y. P. Molina, R. B. Prada, and O. R. Saavedra, “Complex losses allocation to generators and loads based on circuit theory and aumann-shapley method,” *IEEE Trans. Power Syst.*, vol. 25, no. 4, 2010	[92]
G2-193	D. Srinivasan, L. T. Trung, and C. Singh, “Bidding and Cooperation Strategies for Electricity Buyers in Power Markets,” *IEEE Syst. J.*, vol. 10, no. 2, 2016	[93]
G2-3430	L. Petrosyan and A. Sedakov, “Two-level cooperation in network games,” *Lect. Notes Inst. Comput. Sci. Soc. Telecommun. Eng. LNICST*, vol. 277, 2019	[94]
G2-3541	W. Saad, Z. Han, H. V. Poor, and T. Başar, “Game-theoretic methods for the smart grid: An overview of microgrid systems, demand-side management, and smart grid communications,” *IEEE Signal Process. Mag.*, vol. 29, no. 5, 2012	[95]
G1-11	Y. Du *et al.*, “A cooperative game approach for coordinating multi-microgrid operation within distribution systems,” *Appl. Energy*, vol. 222, 2018	[96]
G1-225	E. Faria, L. A. Barroso, R. Kelman, S. Granville, and M. V. Pereira, “Allocation of firm-energy rights among hydro plants: An Aumann-Shapley approach,” *IEEE Trans. Power Syst.*, vol. 24, no. 2, 2009	[97]

G1-82	M. Kristiansen, M. Korpås, and H. G. Svendsen, "A generic framework for power system flexibility analysis using cooperative game theory," *Appl. Energy*, vol. 212, 2018	[98]
G1-188	F. Banez-Chicharro, L. Olmos, A. Ramos, and J. M. Latorre, "Estimating the benefits of transmission expansion projects: An Aumann-Shapley approach," *Energy*, vol. 118, 2017	[99]
G1-189	F. Banez-Chicharro, L. Olmos, A. Ramos, and J. M. Latorre, "Beneficiaries of transmission expansion projects of an expansion plan: An Aumann-Shapley approach," *Appl. Energy*, vol. 195, 2017	[100]
G1-89	T. W. Haring, J. L. Mathieu, and G. Andersson, "Comparing Centralized and Decentralized Contract Design Enabling Direct Load Control for Reserves," *IEEE Trans. Power Syst.*, vol. 31, no. 3, 2016	[101]
G1-55	Z. Hu, L. Chen, D. Gan, and D. Chattopadhyay, "Allocation of unit start-up costs using cooperative game theory," *IEEE Trans. Power Syst.*, vol. 21, no. 2, 2006	[102]
G1-38	J. Xie, X. Wei, Y. Lu, and D. Gan, "Emission-constrained optimal generation scheduling incorporating equity principles," *IET Gener. Transm. Distrib.*, vol. 4, no. 2, 2010	[103]
G1-138	N. I. Voropai and E. Y. Ivanova, "Shapley game for expansion planning of generating companies at many non-coincident criteria," *IEEE Trans. Power Syst.*, vol. 21, no. 4, 2006	[104]
G1-74	J. W. Marangon Lima and E. J. De Oliveira, "The long-term impact of transmission pricing," *IEEE Trans. Power Syst.*, vol. 13, no. 4, 1998	[105]
G2-550	R. D. Christie, B. F. Wollenberg, and I. Wangensteen, "Transmission management in the deregulated environment," *Proc. IEEE*, vol. 88, no. 2, 2000	[106]

G1-220	L. Olmos and I. J. Pérez-Arriaga, "A comprehensive approach for computation and implementation of efficient electricity transmission network charges," *Energy Policy*, vol. 37, no. 12, 2009	[107]
G1-122	M. P. Rodríguez Ortega, J. I. Pérez-Arriaga, J. R. Abbad, and J. P. González, "Distribution network tariffs: A closed question?," *Energy Policy*, vol. 36, no. 5, 2008	[108]
G2-3566	V. Grimm, B. Rückel, C. Sölch, and G. Zöttl, "Regionally differentiated network fees to affect incentives for generation investment," *Energy*, vol. 177, 2019	[109]
G1-124	D. A. Lima, J. Contreras, and A. Padilha-Feltrin, "A cooperative game theory analysis for transmission loss allocation," *Electr. Power Syst. Res.*, vol. 78, no. 2, 2008	[110]
G1-205	N. B. Dev Choudhury and S. K. Goswami, "Transmission loss allocation using combined game theory and artificial neural network," *Int. J. Electr. Power Energy Syst.*, vol. 43, no. 1, 2012	[111]
G1-97	K. N. Hasan, T. K. Saha, D. Chattopadhyay, and M. Eghbal, "Benefit-based expansion cost allocation for large scale remote renewable power integration into the Australian grid," *Appl. Energy*, vol. 113, 2014	[112]
G1-179	K. N. Hasan, R. Preece, and J. Milanović, "Application of game theoretic approaches for identification of critical parameters affecting power system small-disturbance stability," *Int. J. Electr. Power Energy Syst.*, vol. 97, 2018	[113]
G1-116	J. Contreras, G. Gross, J. M. Arroyo, and J. I. Muñoz, "An incentive-based mechanism for transmission asset investment," *Decis. Support Syst.*, vol. 47, no. 1, 2009	[50]
G2-1066	C. Lo Prete and B. F. Hobbs, "A cooperative game theoretic analysis of incentives for microgrids in regulated electricity markets," *Appl. Energy*, vol. 169, 2016	[114]

G1-129	B. An, Z. Shen, C. Miao, and D. Cheng, "Algorithms for transitive dependence-based coalition formation," *IEEE Trans. Ind. Informatics*, vol. 3, no. 3, 2007	[115]
G1-219	G. Zhang, J. Jiang, Z. Su, M. Qi, and H. Fang, "Searching for overlapping coalitions in multiple virtual organizations," *Inf. Sci. (Ny).*, vol. 180, no. 17, 2010	[116]

To analyze the evolution of the research, we collected data on the annual number of publications included in the citation network. A total of 3938 works were considered in the period from 1996 till the first quarter of 2020. Figure 1.5 shows the cumulative number of publications per year. The resulting curve resembles exponential growth. Thus, we may conclude, while acknowledging the limited selection of papers in the citation network, that the topic evolves and gains more attention from the power systems research community. We also plot the three identified research directions separately. At first glance, it seems that the sectors are almost balanced in the number of publications and the development pace.

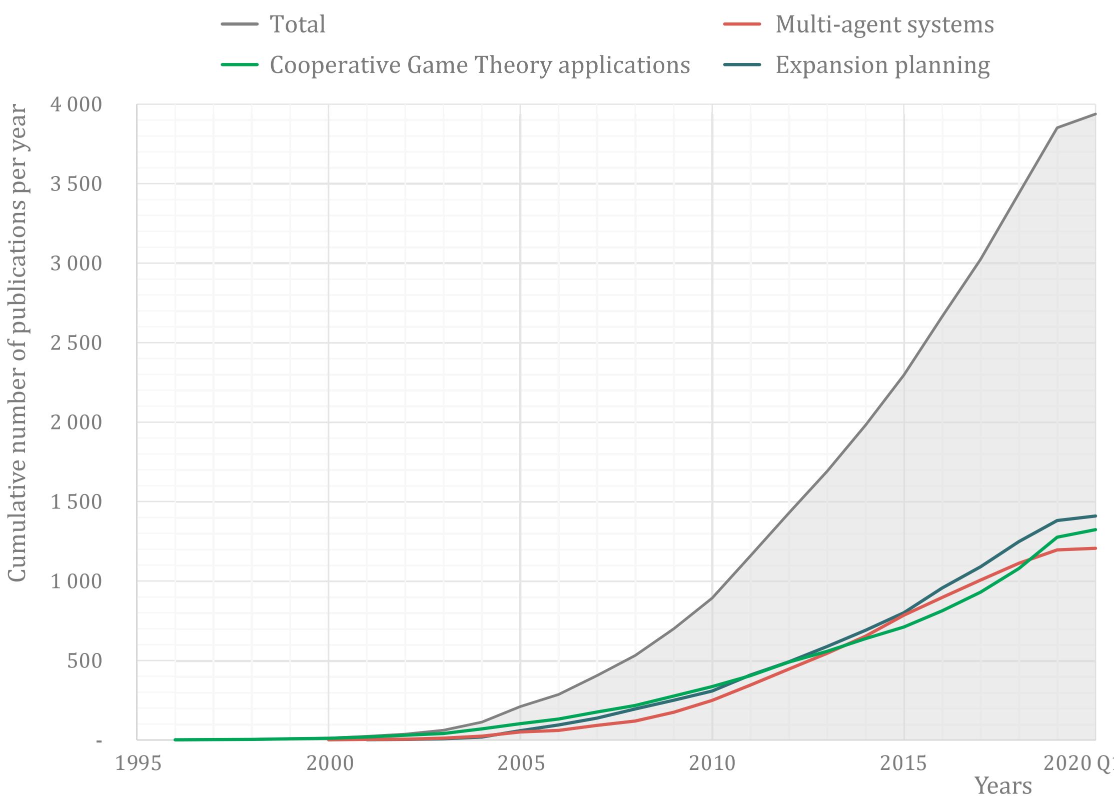


Figure 1.5: Analysis of the publications evolution:
the cumulative number of published works.

In Figure 1.6, we plot the annual changes in the number of published works. It is seen that between 2010 and 2018, Cooperative Game Theory applications in power systems were gaining less attention than expansion planning and multi-agent systems. But, since 2015, there emerged a clear upward trend in the research on

Cooperative Game Theory applications. As a result, in 2019 and the first quarter of 2020, Cooperative Game Theory applications covered in our citation network surpass the aligned research directions in the number of new publications. We see the following possible reasoning for the upward trend. While being useful for finding optimal (for example, least-cost) decisions, classical expansion planning approaches are not able to address the modern issues of deregulated power systems. There is a need for novel methods applicable to the multi-agent environment. To solve the cooperation and cost allocation issues, more scientists turn attention to Cooperative Game Theory and other multidisciplinary approaches. We hereby conclude that our work contributes to the highly relevant and developing research direction.

Comment: I am not sure I agree with this. In the US, for example, RTOs seem to have taken over the role of transmission planning from their constituent transmission owners. This means that classical approaches are possibly now more applicable in deregulated power systems because there is a single planner. Of course, individual owners might choose to not cooperate!

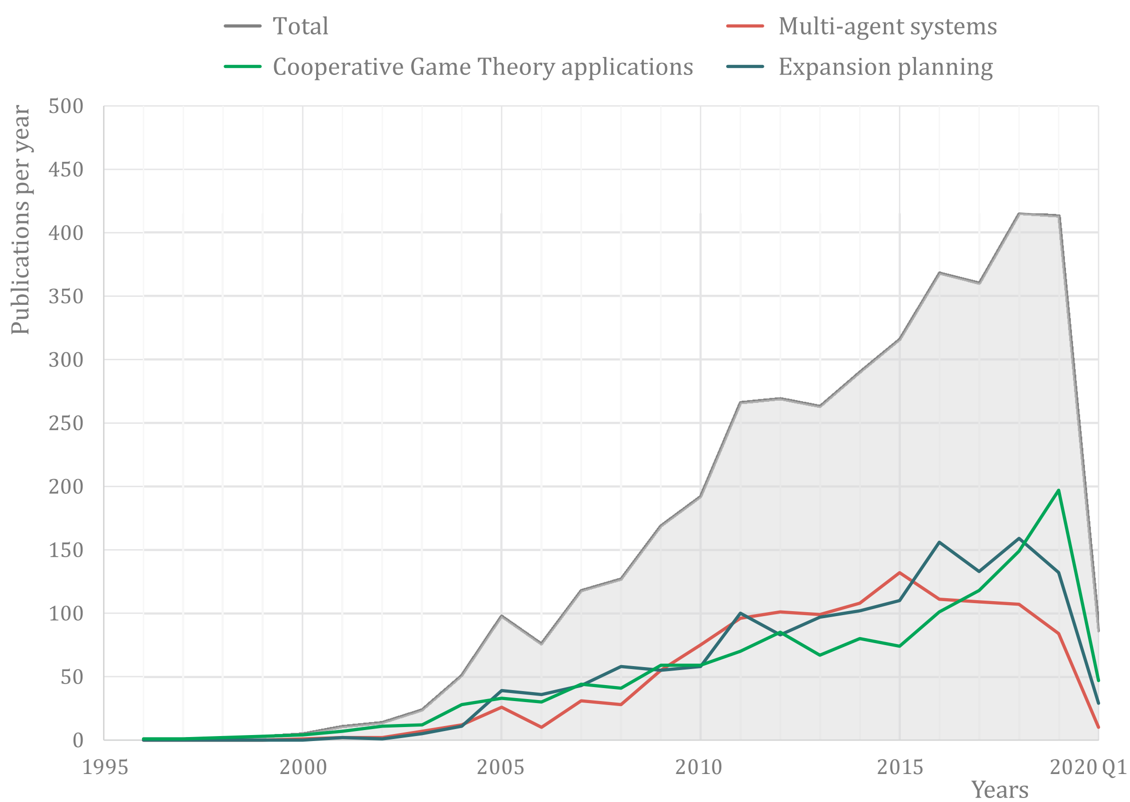


Figure 1.6: Analysis of the publications evolution: annual changes in the number of published works.

At the end of the analysis, we discuss the most significant contributions by the authors and the most influential journals considered in the citation network.

Figure 1.7 presents a list of the authors with the highest number of publications covered by the citation network. The chart is headed by R. Romero, who significantly contributed to TEP algorithms, MIP and metaheuristic methods for power systems. Even though not mentioned directly in the analysis, Romero is a co-author of multiple papers in the expansion planning sector, especially around node G1-150 [71]. Next, we should mention the contribution by J. Contreras, who is the author of one of the earliest papers on Cooperative Game Theory applications in power systems, G0-2 [43]. In the subsequent studies, Contreras focused on expansion planning issues and made a significant contribution to TEP algorithms and power market analysis methods. He actively used MIP [70], multi-level optimization [78], [79], equilibrium models [82], [83], and Cooperative Game Theory solution concepts [49], [50], [110]. E. Sauma also elaborated on TEP and GTEP problems and has published a number of works in the expansion planning sector, mainly in the dark-green community around G1-104 [78], G1-102 [79], G1-105 [80]. Another influential author in the expansion planning research is M. J. Rider, who focused on TEP with security constraints and uncertain parameters. He is a co-author of many works in the peach-colored community around nodes G1-149 [5] and G1-150 [71]. Other notable authors in the expansion planning research are M. R. Hesamzadeh, M. Rashidinejad, Z.-Y. Dong, M. Shahidehpour, J. Choi, B. F. Hobbs, D. Pozo, H. Cheng, A. J. Conejo.

Stephen McArthur is the author of the influential work G1-128 [60]. He found numerous applications of the multi-agent systems in power engineering and published multiple papers in the bottom sector of the citation network. C. Rehtanz also used multi-agent systems approach for power system planning and control. He contributed to multiple works located around node G1-128 [60] and G1-154 [67]. Moreover, he is a co-author of several TEP papers related to G1-149 [5], in particular, studies on FACTS devices investment. D. Srinivasan wrote several highly cited papers on multi-agent system applications, mostly in microgrids G2-1971 [64]. Srinivasan also contributed to analysis of cooperative behavior and bidding strategies in power markets G2-193 [93]. Other notable authors in the multi-agent systems research direction are P. H. Nguyen, A. Monti, T. Nagata, F. Ponci, W. L. Kling, S. Lehnhoff.

In the central sector of the network we should mention H. Rudnick, who has published one of the pioneer works G0-3 [46] on Cooperative Game Theory solutions to transmission cost allocation. In the next decades, Rudnick continued studying cooperation and coordination issues in power systems and contributed to many works in expansion planning research and Game Theory applications. F. Li published multiple works on transmission pricing mechanisms. Most of these works are located in the light brown community near node G1-74 [105]. F. Wen is a co-author of a number of papers on transmission fixed costs allocation methods and transmission tariffs. N. P. Padhy contributed to transmission cost allocation methods. Padhy is a co-author of several works related to G1-74 [105] and the mentioned paper on probabilistic game-theoretic approach G1-37 [51]. L. Olmos studied transmission expansion issues related to cost and benefit allocation, transmission pricing, and compensation mechanisms. He is the author of several papers in the central blue colored community. In the mentioned works G1-188 [99] and G1-189 [100], Olmos implemented an Aumann-Shapley approach for benefits allocation in transmission expansion projects.

We see that a number of authors have put effort into solving cost allocation issues in power systems. Several of them relied on Cooperative Game Theory solution concepts and followed a similar path as we do in this thesis. We can state that our work is closely related to the contributions by J. Contreras, H. Rudnick, L. Olmos, and other authors discussed in the citation network analysis.

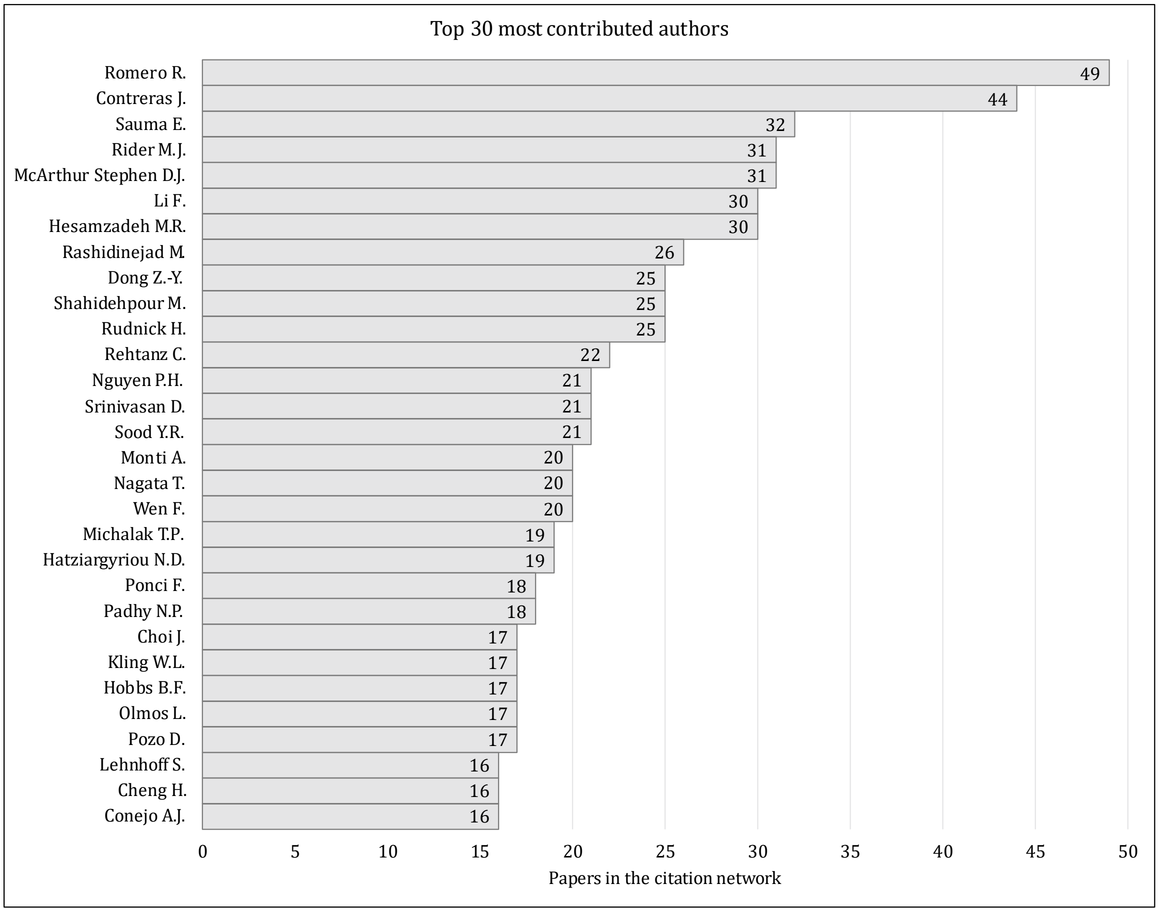


Figure 1.7: Analysis of publications evolution: most contributed authors.

We also show the list of the most influential journals of the citation network in Figure 1.8. There is a significant shift in the number of publications towards the IEEE Transactions on Power Systems journal. The reasoning lies in the computational aspects of power system modeling. There is a need to use advanced computational techniques and analytical methods for power systems planning, operations and control. Many authors in the citation network work on developing new algorithms for power market mechanisms, stability control, TEP and GTEP, and therefore prefer to publish in the journal with engineering and mathematical audience. Other journals in the list not only focus on power systems modeling and algorithms development but also case study applications, energy economics and policies. We may conclude that our work contributes to a multidisciplinary research direction that is covered by the most influential scientific journals in the field of energy and power systems.

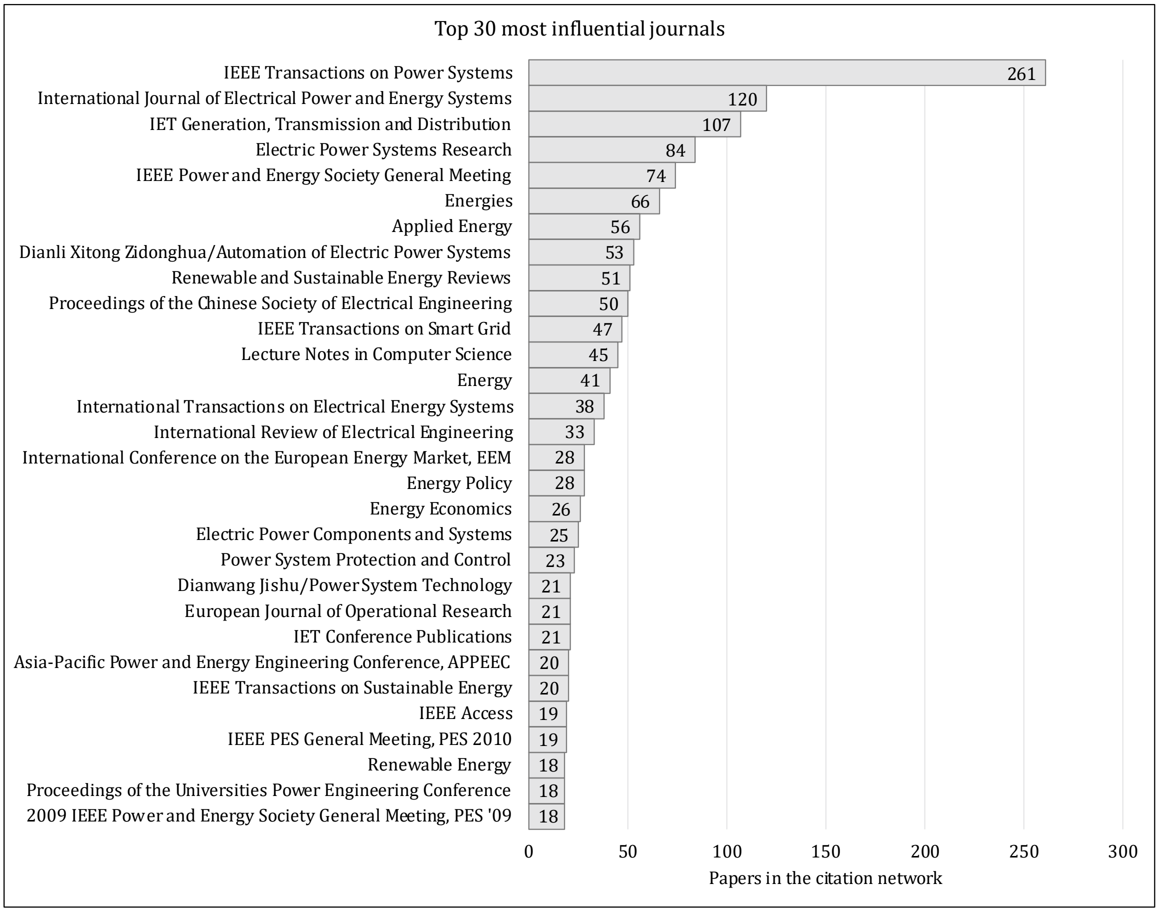


Figure 1.8: Analysis of publications evolution: most influential journals.

Finally, we consider it important to present a keyword analysis of the papers covered in the citation network to distinguish the main indicators of the research. Each node of the citation network (paper) has been split into several nodes (related keywords). Then we merged the repeating keywords and launched the modularity algorithm [59] to highlight the research directions based on those keywords. The initial keyword network contained more than 7 000 unique words and 90 000 links between them, which is impossible to display. Therefore, we removed most of the keywords and kept only the frequent ones (that are mentioned in more than ten papers). The Fruchterman-Reingold graph drawing algorithm [117] was used to locate the remaining keywords. The resulting scheme presented in Figure 1.9 turned out to be highly intuitive.

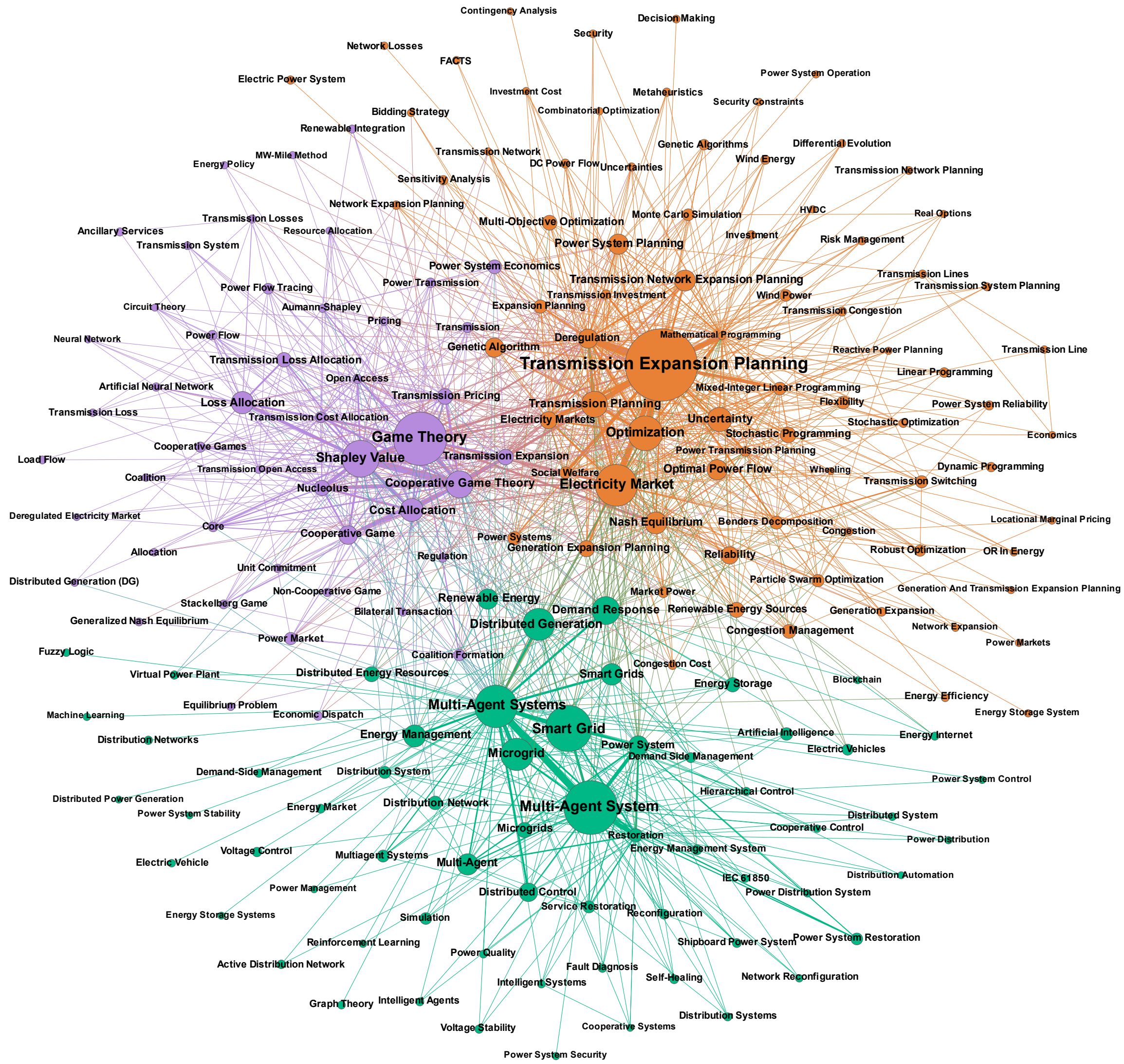


Figure 1.9: Keyword analysis.

The keyword analysis confirms our classification of the research directions. Indeed, the considered studies can be grouped into game-theoretic works, research on expansion planning, and multi-agent systems application. We also used the identified keywords to look for the missing contributions and justify the novelty of our research. We found that no attempt has been made to analyze the manipulability of the allocation mechanisms and incorporate Cooperative Game Theory into TEP algorithms. This thesis elaborates on these issues and makes novel contributions, which we describe in the following section.

1.3 Original Contributions

In this thesis, we focus on cost allocation issues that arise in cross-border power interconnection projects when several independent PSOs cooperate in international transmission planning. We use Cooperative Game Theory solution concepts as the basis for our analysis. Special emphasis is placed on the stability of cooperation and applicability of the solution concepts to real-world case studies. We formulate a cooperative game among PSOs based on TEP model and analyze possible payoffs that would lead to stable cooperation where no one of the participants would have incentives to break the agreement on building cross-border power interconnections. Our approach is close to the works on transmission cost allocation [41], [43], [46], [47], [48], [49], [50], [54], [99], [100] mentioned in the citation network analysis. However, we went beyond and further investigated the stability of cooperation in cross-border power interconnection projects. We performed the manipulability analysis of cost allocation rules and discussed the need for developing strategyproof mechanisms of cooperation. We also introduced the novel bilevel TEP approach that incorporates Cooperative Game Theory principles into the planning algorithm and enables the identification of transmission plans with a predefined level of cooperation stability. To the best of our knowledge, such ideas have never been implemented in power systems research.

Specifically, the original contributions of the thesis are as follows:

I. We demonstrated that cooperation in TEP based on Cooperative Game Theory solution concepts (such as the Shapley value, the Nucleolus, and equal sharing) is prone to manipulations. We analyzed the incentives of players' strategic behavior depending on their positions in electricity trading and discussed the need for developing strategyproof mechanisms of cooperation.

II. We suggested using the coalitional excess theory as the metric of cooperation stability to complement existing ex-post game-theoretic approaches. We then formulated an anticipative bilevel TEP model that incorporates Cooperative Game Theory principles. The proposed approach enables including game-theoretic constraints (such as the Core of the game, the convexity conditions, maximum surpluses among players, etc.) into the planning algorithm. In this manner, it becomes possible to identify expansion plans with a predefined level of stability of cooperation.

III. Moreover, we performed the manipulability analysis of cooperation in TEP under the proposed bilevel planning model. We found that the anticipative bilevel game-theoretic approach could decrease players' incentives to manipulate allocation rules and might be used for developing strategyproof mechanisms of cooperation.

IV. Finally, we considered a real-world case study of potential power interconnections in Northeast Asia. We implemented the Cooperative Game Theory solution concepts and analyzed the stability of cooperation. We also discussed the practical implementation issues, such as the arrangement of investment and payment schemes between countries.

Could you indicate which chapters involve which contributions? From my reading, most of chapters 2 to 4 is background and stylized examples, and it is only in chapter 5 that you begin to make a seriously original theoretical contribution. It would be helpful to point the read to what is background and what is fundamentally new.

An additional contribution of the thesis is the comprehensive review of Cooperative Game Theory applications in power systems. The citation network analysis performed in Chapter 1 allowed us to identify the main research communities, formulate the challenges and limitations of Cooperative Game Theory solution concepts, and justify the novelty of the ideas presented in this work.

Chapter 2

Transmission Expansion Planning Formulation

The stock market and the gridiron and the battlefield aren't as tidy as the chessboard, but in all of them, a single, simple rule holds true: make good decisions and you'll succeed; make bad ones and you'll fail.

- Garry Kasparov
World chess champion 1985-1993

Making decisions on power lines updates has a deep impact on the overall power system's effectiveness and stability. Thus, TEP has been a subject of research since the middle of the last century. The common planning tasks include the minimization of operating and investment costs or the maximization of social welfare. One of the earliest studies on mathematical programming applications in power systems planning was done by *Massê and Gibrat* [118], who formulated a linear programming model for optimizing decisions of investment in power plants. Since then, the optimization models substantially complexified to account features of modern power systems. However, the main TEP principle remains the same: supply the forecasted power demand as economically as possible, while satisfying reliability constraints. In this section, we classify the main approaches used in existing TEP research. Then, we introduce the TEP and market integration model that will be used as a basis for cooperative games formulation in the subsequent sections.

As discussed in the citation network analysis section, expansion planning in power systems is a distinct developing research direction which comprises thousands of publications. To classify the TEP approaches, we identified the following comprehensive reviews and surveys published in the last two decades: [5], [6], [7], [119]. These works highlight the main achievements in TEP models and solution methods and point out the remaining issues and challenges. The classification is presented as a diagram in Figure 2.1. The red-orange color palette indicates the complexity of a model or method.

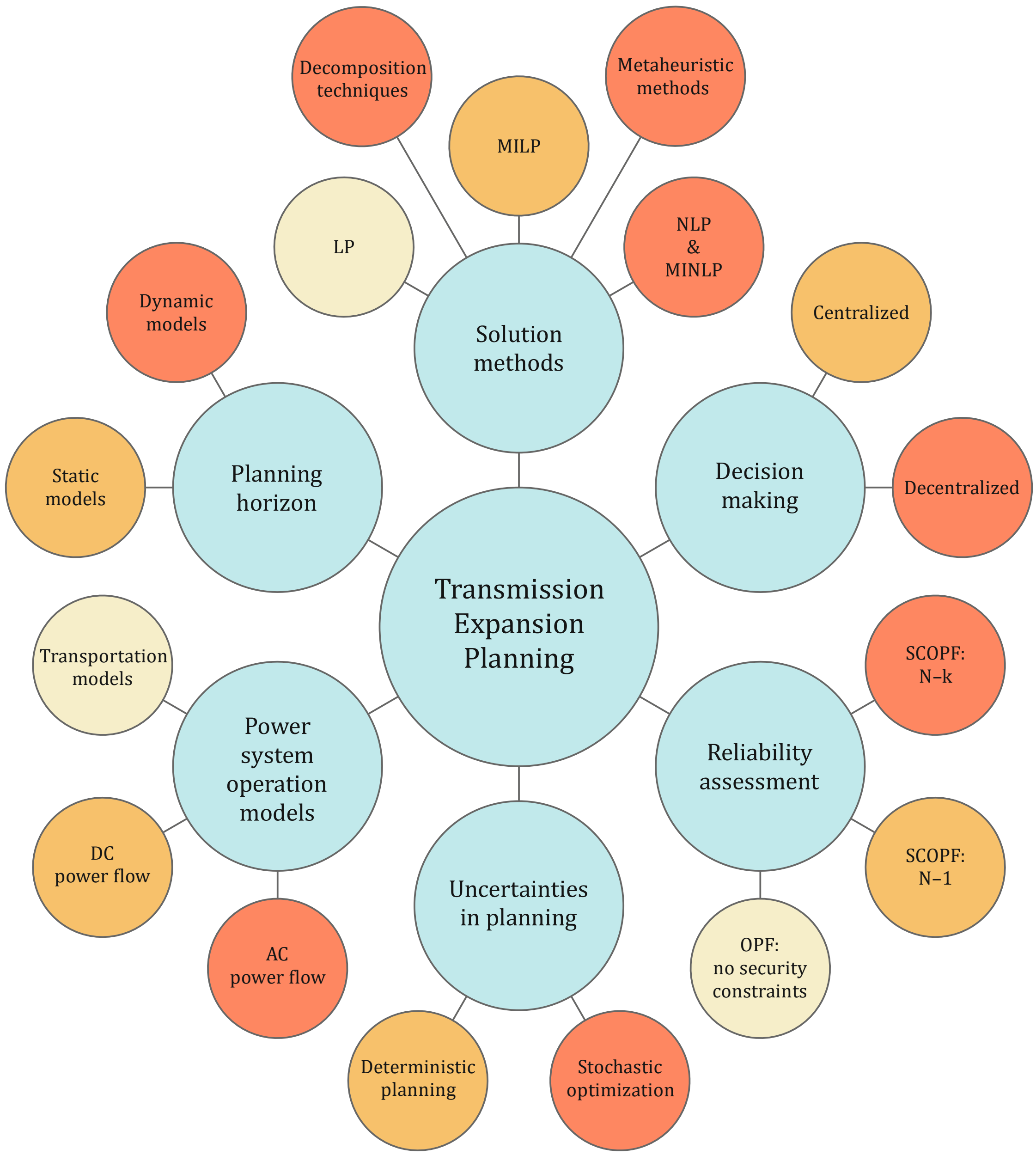


Figure 2.1: Classification of TEP approaches

First, we should mention the treatment of the planning horizon and decision dynamics in the models. A majority of TEP studies consider static planning formulation (a single snapshot of a power system in the future where investment decisions should be made). Such models allow evaluating the effectiveness of expansion projects while keeping computational complexity moderate. Dynamic models usually involve several time horizons (sequential static models) and enable revisiting expansion decisions and fitting them closer to reality. The downsides of this approach are the increased computational burden and loss of clarity due to the investment decisions stretched in time.

Another important aspect of TEP models is the level of detail of power systems representation. The simplest models take into account only the energy conservation law and transmission constraints. Even though such models correspond to transportation problems, they are still useful in providing insights into the effectiveness of TEP decisions. The direct current (DC) power flow models incorporate a linearized version of Kirchhoff's laws. These models omit reactive power flows, power losses, and changes in voltage magnitudes. However, they found an extensive application being a compromise between detailed modeling and computational issues. The alternating current (AC) models fully incorporate Kirchhoff's laws and enable evaluation of voltage stability and power losses. However, the nonlinearity of this formulation poses significant problems that force researchers to use relaxation techniques and equivalent convex formulations [120].

The choice of the power system operation model, formulation of the objective function, and additional constraints predefine selection of the solution methods. Classical models imply linear programming (LP) and simplex-based methods. More complex models require applying nonlinear programming (NLP). Some models represent the discrete nature of investment decisions and include binary or integer variables. The inclusion of binary variables can also be a result of complementarity modeling of electricity markets [35]. Such models require much greater computational efforts and are usually treated using mixed-integer programming (MIP). Algorithms like "branch-and-bound" (B&B) are capable of solving linear MIP problems (MILP) with thousands of binary variables. However, large-scale nonlinear MIP problems (MINLP) are generally hard to solve. In such cases, there is a need for using decomposition techniques or metaheuristic algorithms.

Several major changes in TEP approaches have been caused by current trends in power systems operation, namely, power systems deregulation and large-scale integration of renewable energy sources. Treatment of the deregulation and electricity market considerations can be split into centralized and decentralized decision making. The classical centralized approach implies that all expansion and operation decisions are taken unilaterally by a PSO or a central planner. The optimization model can be formulated in a straightforward way to find the least-cost solution. However, modeling modern power systems with a competitive environment and multiple independent investors requires using more sophisticated decentralized models. The integration of renewables raises concerns over including uncertainties in TEP models. Thus, in recent years, classical deterministic TEP models are being complemented with stochastic optimization methods.

Finally, TEP models have different reliability considerations. Classical studies performed optimal power flow (OPF) calculations to find the least-cost solution subject to transmission constraints. More advanced approaches involve contingency analysis and the "N-1" criterion, which means that a transmission plan must be resilient against any possible contingency. This approach is widely known as security constrained optimal power flow (SCOPF) [121]. Inclusion of more than one of the possible contingencies at the same time, the "N-k" criterion, leads to highly complex combinatorial optimization problems.

The mentioned models can be additionally complexified by incorporating additional control variables such as FACTS devices and energy storage. However, our interest lies in Cooperative Game Theory applications in TEP cost allocation. Thus, we avoid using complex expansion models to provide clear insights into possible allocation solutions. We consider TEP as a static, deterministic, centralized, linear programming model. The exact mathematical formulation is given in the following sections.

2.1 Electricity Market Integration

Constructing a line between power systems allows electricity trading among the interconnected power markets. In our setting, we consider a centralizer (pool-based) trading over a newly built asset. Thus, PSOs determine market clearing prices and evaluate optimal power flows from systems with lower prices towards systems with higher prices, subject to transmission constraints. To illustrate the benefits of cross-border power interconnections, we introduce a two-system case of electricity market integration adopted from [4]. In this case, two power systems with different linear supply functions consider building a transmission line with a maximum capacity of 400 MW, thus, integrating the electricity markets. The supply functions and demands of the systems are listed in Table 2.1.

Table 2.1: The two-system case study data.

Parameter	System A	System B
Supply function ($/MWh)	$\lambda_A = 10 + 0.01p_A$	$\lambda_B = 13 + 0.02p_B$
Power demand (MW)	500	1 500

System B has a higher supply cost function and power demand. Therefore, it should have a higher market clearing price than System A and would be a power importer. We visualize the supply functions and market clearing prices of the systems before and after the interconnection in Figure 2.2. It is supposed that demand functions (vertical solid lines) are perfectly inelastic in both power systems. The intersection of the supply and demand functions indicate the market clearing prices. Indeed, without the interconnection, System B has an electricity price of 43 $/MWh, whereas System A price is 15 $/MWh. For simplicity reasons, we suppose in this two-system example, that the power line can be built for free (with zero investment cost). We also do not consider power losses in our framework. The inclusion of losses makes power transfer less efficient and reduces the amount of energy exported. Such simplifications do not alter the economic principles of electricity market integration discussed in this section. Under such conditions, it would be optimal to transfer as much cheaper power from System A to System B as possible, until both systems start operating as a single market with equal clearing prices $\lambda_A = \lambda_B$. However, because of the transmission constraints, only 400 MW of power would be transferred. System A would increase its generation up to 900 MW, while System B would produce only 1100 MW.

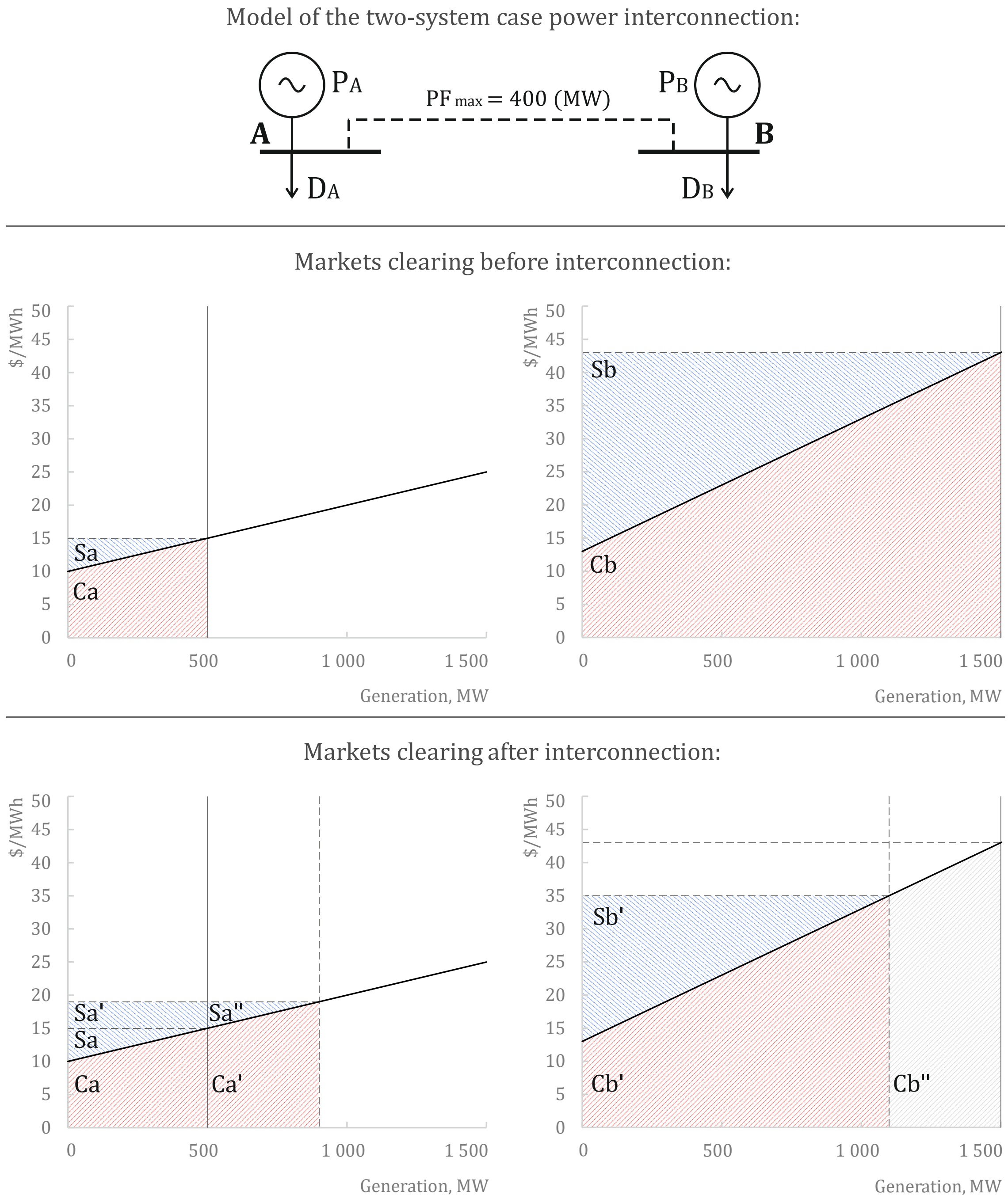


Figure 2.2: Electricity market integration for the two-system case.

To estimate the effects of market integration, we introduce the following indicators. Red areas in Figure 2.2 represent the costs incurred by generating companies in the systems. Blue areas stand for generation surplus and are formed as the difference between the clearing prices and generation cost functions. The sum of both areas equals to the total payment made by consumers. It is worth mentioning that we do not include consumer surplus in our analysis. To do this, it would be necessary to set the maximum price that consumers would be willing to pay. Studies as [54] suggest using the value of loss load (VoLL) as a reference for measuring consumer surplus when considering inelastic demand. The sum of consumer and generation surpluses is often referred to as social (total, economic) welfare. We present the changes in power markets' indicators before and after the interconnection in Table 2.2.

Table 2.2: Power markets analysis before and after the interconnection.

	Separate markets, no interconnection	Markets interconnected via 400 MW line
Market price (\$/MWh)	$\lambda_A = 15$ $\lambda_B = 43$	$\lambda'_A = 19$ $\lambda'_B = 35$
Generation cost (\$/h)	$C_A = 6\,250$ $C_B = 42\,000$ Total = 48 250	$C_A + C'_A = 13\,050$ $C'_B = 26\,400$ Total = 39 450
Generation surplus (\$/h)	$S_A = 1\,250$ $S_B = 22\,500$ Total = 23 750	$S_A + S'_A + S''_A = 4\,050$ $S'_B = 12\,100$ Total = 16 150
Consumers' payment (\$/h)	$P_A = 7\,500$ $P_B = 64\,500$ Total = 72 000	$P'_A = 9\,500$ $P'_B = 52\,500$ Total = 62 000

The performed analysis shows that market participants are affected by the interconnection in different ways. Generating companies in System B have to produce less power. Both their cost and surplus decrease from Cb to Cb' and from Sb to Sb' respectively. However, consumers in System B appreciate the power export since they have a significant decline in payment. A reverse situation happens in System A, where generation cost increases by Ca', and surplus - by Sa'+Sa''. But, the consumers in System A have to pay more after the interconnection and, therefore, should be against the market integration. Ie unless there is some compensation for them.

Comment: I know that this is a first introductory example, but it would be useful to also explore a two-period model where the direction of flow is different in each period. This represents eg seasonal diversity and can result in net benefits to consumers in both places.

Despite the discrepancies in market participants' interests, the project can be estimated as beneficial because of the significant reduction in total generation cost. In the following sections, we give a mathematical formulation of TEP and discuss the applicability of Cooperative Game Theory solution concepts for different electricity market indicators.

2.2 Mathematical Optimization Framework

To provide clear insights into Cooperative Game Theory applications, we avoid using complex models and rely on the classical cost-based transmission planning that can be formulated by means of mathematical programming [122]. First, we define a set of nodes that represent power systems $\mathcal{N} = \{1, \dots, N\}$. Every system (or country/state) could be represented by one or several nodes. The set of candidate lines is denoted by $\mathcal{L} = \{1, \dots, L\}$. Actual power flow through line l is depicted by f_l, and maximum line capacity by F_l^{max}. The transmission cost of a line depends on its selected capacity, F_l, and net present costs of investment, CI_l. Inelastic power demand at each node is given by D_n. The "sc" subscript indicates the scenario under consideration. It will be recalled in the next sections to distinguish values for different coalitions. For the long-term planning cases, we will additionally introduce time periods (representative hours and seasons) into the model. The resulting optimization problem is formulated as the following linear programming model:

Why no binary decision variables for build/not build?
Why no economies of scale in transmission construction?
Why no admittances?
Why no contingency cases?
I realize that there is some discussion of this below, but the simplifications should at least be briefly acknowledged up front.

$$\min_{p_{n,sc}, f_{l,sc}, F_{l,sc}} \sum_{n \in \mathcal{N}} CG_n(p_{n,sc}) \cdot + \sum_{l \in \mathcal{L}} F_{l,sc} \cdot CI_l \tag{2.1}$$

s.t.:

$$p_{n,sc} + \sum_{l \in \mathcal{L}} B_{n,l} \cdot f_{l,sc} = D_n \qquad \forall\, n, sc \tag{2.2}$$

$$0 \le p_{n,sc} \le P_n^{max} \qquad \forall\, n, sc \tag{2.3}$$

$$-F_{l,sc} \le f_{l,sc} \le F_{l,sc} \qquad \forall\, l, sc \tag{2.4}$$

$$F_{l,sc} \le F_l^{max} \qquad \forall\, l, sc \tag{2.5}$$

The total generation and investment costs are minimized in the objective function (2.1), where CG_n represents generators' cost functions (the integrals of the supply functions). Nodal power balance constraints are imposed by (2.2), where $B_{n,l}$ is the incidence matrix that contains topology of interconnections. Generators' outputs and power flows are limited by (2.3) and (2.4) respectively. Equation (2.5) restricts the power lines' capacities. In this formulation, we neglected reactive power, lines' admittances, voltage magnitudes and angles. Thus, our model is equivalent to a linear transportation problem [122] where power demand should be supplied at the lowest possible cost. In the two-system case study and the following cases, we consider that proposed interconnections will be realized using HVDC technology. Therefore, the assumptions of our TEP model (such as the omission of the Kirchhoff's voltage law) will be reasonable for analysis of cooperation. Nevertheless, it is worth mentioning that the ideas behind our work may be applied to TEP models of any degree of complexity.

Usually, generators' cost functions are represented as cost bids, i.e., discrete constant values. In such cases, market clearing is based on a supply step-function [123], and TEP formulation (2.1)-(2.5), indeed, corresponds to a linear programming model. However, in the two-system case study, electricity markets are represented by continuous linear supply functions listed in Table 2.1. Therefore, generation costs in (2.1) are given by the integrals of the supply functions (red areas in Figure 2.2). TEP becomes a nonlinear optimization problem. In this case, a linearly constrained quadratic programming model (LCQP). To give more details on the expansion planning principles, we visualize the solution of the nonlinear TEP formulation in Figure 2.3. The feasible region is restricted by the power balance equations (2.2) and, therefore, is represented by the linear space (colored triangular comprising linear combinations of p_A and p_B). Point "1" notes the solution with no transmission capacity (separate markets operation): both generators must supply local demands, and the solution space is described by the single point. When power interconnection with a capacity of up to 400 MW is possible, the feasible region contains infinitely many solutions. However, only point "2" is the optimal one. To prove this, we plot a series of optimization levels as colored curves corresponding to different values of the objective function (2.1). In order to decrease the cost, the solution should be moved according to the negative of the gradient, as shown by the arrows. The solution at point "2" reaches the lowest possible objective function and, therefore, is optimal under current transmission constraints. Without constraints, it would be possible to reach an even lower cost at point “3” where feasible space is tangent to the optimization level. In this case, market clearing prices at both markets would be equal, and the objective function could not be further improved by building additional capacity. It is important to mention that we considered a zero investment cost in this example. Thus, the gradient of the objective function does not have a third term related to the line’s capacity. This, however, is not true in realistic case studies, where complete market integration may not be optimal in terms of cost minimization.

The two-system example introduced in this section interprets the main ideas and assumptions of the market integration and TEP model. Transmission lines should be built up to the economically justified capacities to allow exporting power from nodes with lower electricity prices to nodes with higher prices, thus, reaching the maximum reduction in operating and investment costs. This straightforward model lies in the core of our work and will be used in the next sections for formulating cooperative games in TEP as well as developing more complex models.

2.3 Discussion of HVDC and AC Transmission Systems

We have already mentioned in the previous sections that recent advances in HVDC technology make it a promising tool for long-distance transmission. Many of the covered studies on TEP and cross-border power interconnections, including our work, consider HVDC lines as the option for establishing economic and stable electricity trade among power systems. However, for the sake of completeness, in this section, we provide a discussion of HVDC and AC transmission technologies and justify the assumptions of our TEP model.

Not to overload the discussion with the technologies’ background, for technical details, we refer to the HVDC systems overview by *Bahrman and Johnson* [3] and the ABB’s report [124]. An excellent review of HVDC studies was made by *Alassi et al.* in [125]. The issues of stability and control in HVDC and AC systems were thoroughly addressed in [126]–[128]. Most of the relevant studies acknowledge HVDC as a superior technology over AC systems for long-distance transmission.

We, therefore, want to open our discussion by listing the main advantages of HVDC systems. We identified the following points relevant to the development of cross-border power interconnections:

- The cost of HVDC systems is lower than AC whenever a long-distance transmission is required. HVDC systems have fewer conductors (no need in three phases), do not carry the reactive component of current, and experience no skin-effect. The economic break-even distance of HVDC lines compared to AC lines, depending on the technology, varies at about 500 km. Many projects of cross-border power interconnections suggest building lines for hundreds and thousands of kilometers. Thus, HVDC transmission becomes the only cost-effective option.

  should be rephrased.
- HVDC systems have a reduced level of power losses compared to AC lines, which allows transmitting more power for long-distance. In a hypothetical 1200-km 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 [3]. 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. Moreover, AC cables have capacity limits for long-distance transmission due to high reactive charging current. Although charging currents can be compensated by intermediate shunt compensation for underground cables, it is not practical to do so for submarine cables. HVDC cables do not have reactive power compensation problems and, therefore, remain the only viable option for long-distance submarine transmission.
- The major advantage of HVDC technology is controllability and flexibility of power systems. Power flow through an HVDC line can be rapidly changed by the connected converter stations. There is no dependence on the phase angle or the properties of the line, which increases the controllability of the system. Thus, HVDC interconnections make it possible to transfer a required amount of power according to economic signals or security reasons. On the contrary, power flows in AC lines obey Kirchhoff's laws and cannot be easily controlled. The power flow controllability is important for cross-border

electricity trading, where a predefined amount of energy should be transmitted.

- HVDC allows power transmission between unsynchronized AC transmission systems. Electricity trade through an asynchronous interconnection leads to mutual benefits while providing a buffer between the interconnected systems. In this regard, HVDC transmissions can be considered more reliable than power systems synchronization via AC lines, which could propagate frequency deviations [129].

The above advantages of HVDC technology justify its increasingly significant role in TEP and long-distance transmission. There is a rise in the number of projects where HVDC lines are built to strengthen existing interregional interconnections (creating a backbone of power system) or develop cross-border power interconnections. It is worth mentioning the progress in the HVDC application achieved by China. Chinese State Grid Corporation operates a dozen ultrahigh-voltage DC lines and has an ambitious plan to build the world's biggest supergrid [130]. A comprehensive overview of the HVDC market evolution can be found in [125]. It was estimated that by 2022, there would be more than 250 projects of HVDC interconnections (both commissioned and announced) with a total transmission capacity of more than 400 GW. The largest number of projects is recorded in Asia (mainly in China) and Europe.

Nevertheless, HVDC transmission systems suffer from a series of drawbacks:

- HVDC transmission requires conversion equipment at converter stations. This equipment is relatively expensive (especially in projects with small transmission distances). Moreover, it causes additional power losses and reduces the overall reliability of a transmission system. The complexity and high cost of converter stations are considered as the obstacles to HVDC technology application.
- HVDC systems are less standardized and harder to operate than AC systems. It is especially hard to operate complex multi-terminal systems, where coordination of several converter stations is required. Localization and

clearing of HVDC faults are also problematic. There is ongoing research on HVDC systems coordination and protection.

- There exist stability issues of AC power systems connected to HVDC grids [126]. HVDC interconnection affects reactive power and voltage control in several nodes of an AC grid. The problems become especially acute in weak AC systems connected to powerful HVDC lines [128]. Moreover, some converter stations consume reactive power and, therefore, require reactive power support from an AC grid. This reactive power dependence makes the overall system more vulnerable to voltage drops and power outages.

Comparing the mentioned features of HVDC transmission, we may conclude that HVDC technology has great potential for cross-border power interconnection projects. The cost-effectiveness and controllability outweigh the issues of grids operation and control. Moreover, the technology evolves: new converters and DC breakers appear; novel coordination and protection mechanisms are being implemented. We, therefore, believe that it is reasonable to assume that future projects of cross-border power interconnections would be realized based on HVDC transmission.

This assumption allows us to legitimately apply the TEP model (2.1)-(2.5). In all case studies of this work, we consider the asynchronous interconnection of AC power systems via HVDC lines. Such interconnections enable control of power flows according to economic signals. We, therefore, omit the Kirchhoff's voltage law and use the linear TEP model to estimate the possible benefits of cross-border electricity trade and analyze the stability of cooperation.

2.4 Summary and Conclusions

TEP is an essential tool that enables economic planning and operation of power systems. The common practice of power lines updates identification lies in formulating mathematical optimization models that minimize the total cost of power systems or maximize the social welfare of electricity market participants. In this section, we classified existing approaches to TEP and reviewed the state-of-the-art. Significant progress has been achieved in developing expansion planning algorithms. Modern TEP approaches enable formulating complex models that include security constraints, stochastic parameters, decentralized decision making, and other features of power systems operation and control.

However, in this work, we focus on the game-theoretic framework for cost allocation in TEP and stability analysis of cooperation on cross-border power interconnection projects. Thus, we avoid using complex expansion planning models to provide clear insights into possible allocation solutions. We formulated TEP as a static, deterministic, centralized, linear programming model. We discussed the assumptions of expansion planning and demonstrated its relation to electricity market integration. The TEP model described in this section will be used throughout the work as the basis for cooperative games formulation and subsequent game-theoretic analysis.

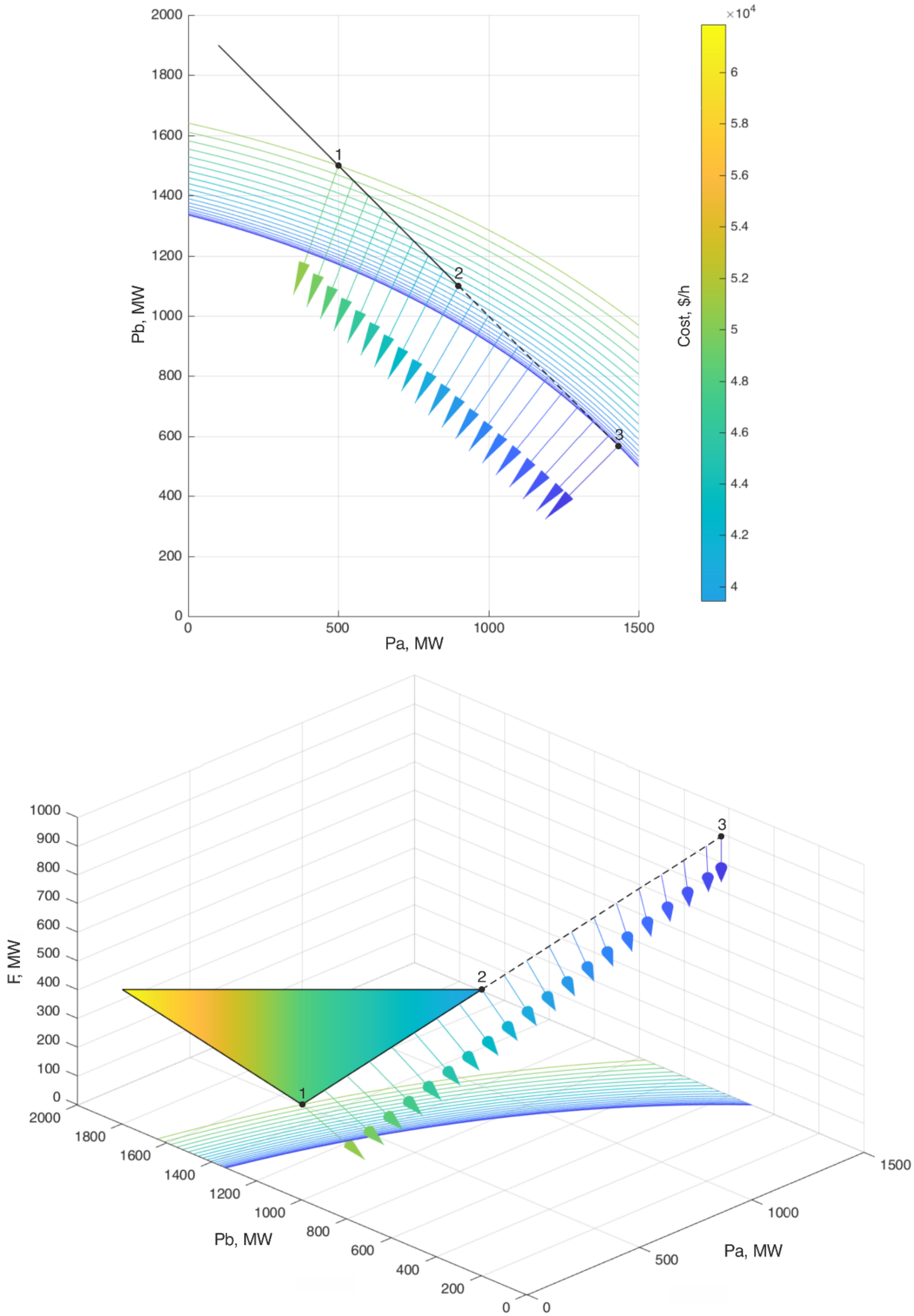


Figure 2.3: Visualization of the LCQP model for the two-system case TEP.

Chapter 3

Mathematical Background of Cooperative Game Theory

In my games I have sometimes found a combination intuitively simply feeling that it must be there. Yet I was not able to translate my thought processes into normal human language.

- Mikhail Tal

World chess champion 1960-1961

Game Theory provides a rich background for mathematical modeling of strategic interaction among rational decision-makers. Depending on the interaction assumptions, it is important to distinguish noncooperative and cooperative game formulations. The main assumption in the noncooperative games is that each player acts fully independently. Neither preventing correlation of actions nor any kind of recommendations are binding for the players. The noncooperative formulation usually represents competition among players that can be analyzed using equilibria-based solution concepts. In power systems research, noncooperative games are widely used for the estimation of possible electricity market equilibria [35], [82], [83], [131] and modeling outcomes of competitive investment decisions [38], [39], [73], [78], [79], [132]. In this thesis, we use an opposite approach and formulate cooperative games (also called coalitional games) to model situations where players conclude binding agreements to reach mutual benefits. In such games, the key questions to address are: what coalitions will form, and what should be the payoffs to the participants? We focus on cooperative games with transferable utilities, where benefits generated by cooperation may be easily distributed and shared among the players. Transferable utility games (TUG) have been formulated for allocation issues in power systems in [40], [41], [43], [46] and other studies covered in the citation network analysis. However, the Cooperative Game Theory principles discussed in this section are universal and are being successfully applied in numerous areas. In [86], *Fiestras-Janeiro et al.* reviewed Cooperative Game Theory applications in transportation, natural resources, and power industry. A relevant work was done by *Lozano et al.* [133], who analyzed horizontal cooperation (between two or more actual or potential competitors) for shipping companies using Cooperative Game Theory solution concepts. The authors found that significant cost savings give players incentives to form large coalitions and supposed that these results may be extended to a broader class of transportation problems.

In this section, we present the mathematical formulation for cooperative games with transferable utility, introduce the main properties and solution concepts, which will be later combined with the TEP model to analyze projects of cross-border energy cooperation. While describing cooperative games, we rely on the mentioned papers on Cooperative Game Theory applications and the book by *Maschler et al.* [134], which provides a comprehensive introduction to Game Theory.

3.1 Definition and Properties of Cooperative Games

Comment: this section is very confusing. I think you have cost and value muddled in the definitions. Please fix this!

In our setting, several power systems agree on building lines for electricity market integration to reach mutual benefits in the form of cost savings. The savings can be expressed in monetary units and then allocated among the participants. Thus, the strategic interaction over an interconnection project can be described by the following TUG formulation.

Definition 3.1 A cooperative game with transferable utility specifies a value for every possible coalition by setting a pair $(N; v)$ such that:

- $N = \{1, 2, \ldots, n\}$ is a finite set of players (agents who are potential users of the project). A subset of N is called a coalition. The largest possible coalition containing all players is called the grand coalition. The collection of all the coalitions is denoted by 2^N. A partition of the set of players, N, is called a coalitional structure, B. It is a collection of disjoint and nonempty sets whose union is N.

- $v : 2^N \to \mathbb{R}$ is a function associating every coalition S with a real number $v(S)$, satisfying $v(\emptyset) = 0$. This function is called the characteristic (also coalitional or utility) function of the game.

so, to be clear, v represents vlue and bigger v is better, right?....but this seems to contradict much of the discussion below.

The objective of the cooperative game formulation is to suggest a reasonable solution for allocating the value of the grand coalition, $v(N)$, among the agents in N. At this point, it is important to highlight the interpretation of the characteristic function. If a value $v(S)$ associated with a coalition S represents some profit or gain that players obtain together, then a cooperative game is called a profit (or value) game. However, in this work, we are interested in cost games, where players act together to decrease the costs that their coalitions should pay. Therefore, in the following definitions, we imply that the characteristic function is formulated in terms of costs.

Now, we introduce several important properties of cooperative games that will be useful for analyzing the merits and applicability of the solution concepts.

Definition 3.2 A cooperative game $(N; v)$ is called superadditive if for any pair of disjoint coalitions S and T holds:

$$v(S \cup T) \leq v(S) + v(T) \tag{3.1}$$

....but this says that the merger is less desirable than the sum of the individual utilities. Did you intend \geq rather than \leq ?

Superadditivity implies that every two disjoint coalitions ($S \cap T = \emptyset$) that choose to merge can obtain at least what they could obtain if they instead were working separately. We visualize this property of cooperative games in Figure 3.1. Coalitions S and T are represented by the two disjoint ellipses, which signifies that they do not have any players or coalitions in common. The grand coalition is depicted by the large ellipse N. Equation (3.1) states that there is some synergy of cooperation among S and T. Thus, the union $S \cup T$ can get an equal or lower cost than the two separate coalitions. Superadditivity is a useful property that reveals a "positive pressure" to form the grand coalition N and serves as a justification for solution concepts implementation.

Unitil here, discussion was about value; here you discuss minimizing costs. So, is cost equal to minus v ? Please clarify.

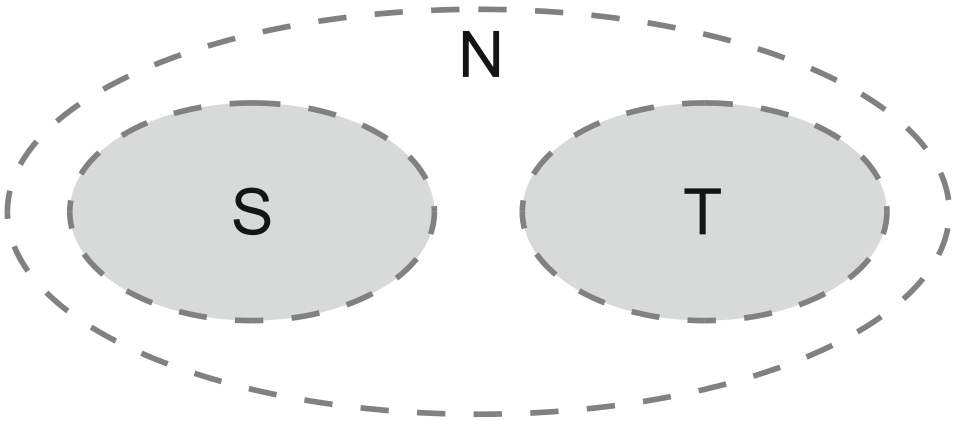


Figure 3.1: Example of disjoint coalitions in a superadditive cooperative game.

However, the superadditivity condition is not strong enough since it considers only disjoint coalitions. The following definition introduces the class of convex games where similar restrictions hold for every pair of coalitions.

Definition 3.3 A cooperative game $(N; v)$ is called convex if for every pair of coalitions S and T holds:

$$v(S \cup T) + v(S \cap T) \leq v(S) + v(T) \tag{3.2}$$

Here talking about cost. Is cost equal to v or minus v?

The above definition states that two coalitions that have some players in common should obtain together less or equal cost than the two separate coalitions minus the cost of their intersection. We present an example of intersecting coalitions in Figure 3.2. It follows that every convex game is superadditive. Thus, the set of convex games is a subset of the superadditive games. We are interested in the convexity property since it characterizes games where players have clear incentives for forming large coalitions. It is worth mentioning that in cost games, the property of superadditivity is sometimes referred to as subadditivity, and convex games are called concave. However, we find it more common to use terms superadditive and convex for describing the synergy properties of cooperation. The same terms are also used by *Maschler et al.* in [134].

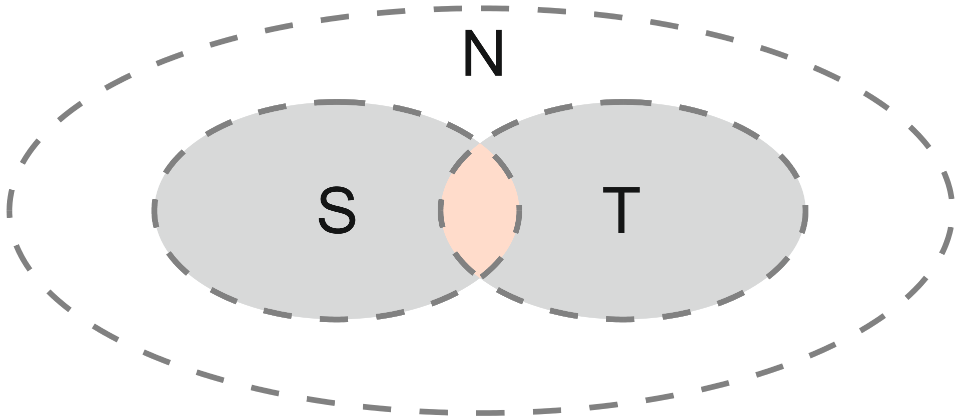


Figure 3.2: Example of intersecting coalitions in a convex cooperative game.

Equation (3.2) may not always be convenient for verifying game convexity based on intersecting coalitions. Therefore, we present the following equivalent formulation, which depends on players' marginal contributions.

Definition 3.4 In a convex game, the following equivalent formulation of convexity holds for every $S \subseteq T \subseteq N$ and every player $i \in N \backslash T$:

$$v(S \cup \{i\}) - v(S) \geq v(T \cup \{i\}) - v(T) \tag{3.3}$$

The equivalent formulation considers cases where coalition S is a subset of T, as shown in Figure 3.3. Equation (3.3) states that the game is convex if and only if the marginal contribution of any fixed player i to coalition S increases as more players join the coalition. In our cost game formulation, the contributions are the differences in costs before and after cooperation. Convex cooperative games have a "snowballing" effect where large coalitions become more beneficial for players.

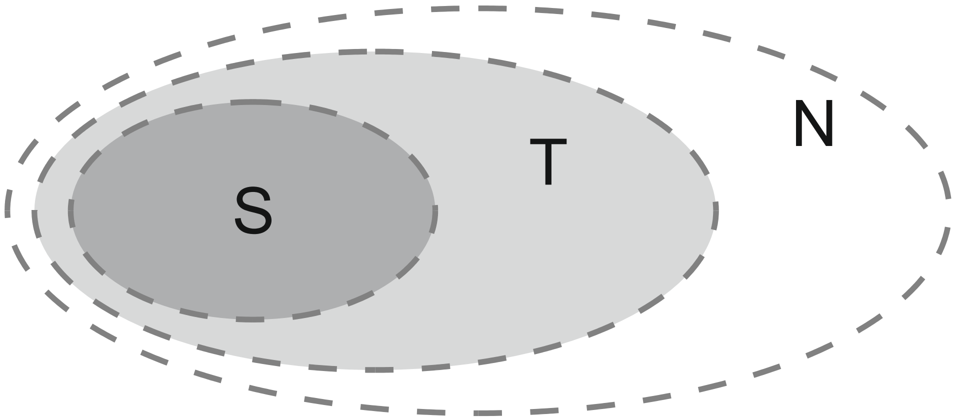


Figure 3.3: Example of coalition subsets in a convex cooperative game.

Having defined cooperative games and their properties, we are ready to pose the main question studied in Cooperative Game Theory: what coalitions will form in a cooperative game, and how to divide the cost of a coalition among its members? Numerous solution concepts have been developed to allocate coalition cost among the players in the most reasonable way. In the next sections, we describe the main solution concepts that will be further used in the thesis for cross-border TEP cost allocation.

3.2 Solution Concepts

Comment: on page 91/211, you referred to v(N) as the value of the grand coalition, not the cost. Please fix these inconsistencies!!!

The main assumption in Cooperative Game Theory solution concepts is that the grand coalition N will be formed. The task is then to suggest a payoff vector x to allocate the cost of the grand coalition, $v(N)$, to its participants. Before introducing the solution concepts, it is worth discussing their features and desired properties.

First, it is necessary to distinguish single-valued (point) and set solution concepts.

Definition 3.5 A solution concept is called a point solution of a cooperative game $(N; v)$ if the set of possible payoffs, $x(N; v)$, contains only one element.

Comment: is x a vector or a set? I do not understand what you mean by x(N;v)

Single-valued solution concepts provide unique answers to cost allocation problems, and, therefore, are of particular interest for practical applications. On the contrary, set solution concepts define a set of possible allocation solutions, which is useful for further analysis of cooperation. We should also notice that there exist games with an empty vector of possible payoffs, $x(N;v) = \emptyset$. It is obvious, that is such cases, players will not agree on forming the grand coalition.

Next, we define the desired properties of solution concepts. These properties impose the following restrictions on the payoff vector x.

Definition 3.6 A vector $x \in \mathbb{R}^N$ is called efficient for a cooperative game $(N;v)$ if:

$$\sum_{i \in N} x_i = v(N) \tag{3.4}$$

In words, the payoff vector exactly splits the total value among the players. Players cannot divide more or less value than they obtain in the grand coalition.

Definition 3.7 A vector $x \in \mathbb{R}^N$ is called individually rational if for every player $i \in N$:

$$x_i \leq v(i) \tag{3.5}$$

This condition means that no player obtains a higher cost than what he could get on his own. In our analysis, we are interested in the set of possible allocation solutions satisfying equations (3.4) and (3.5), which is the set of imputations.

Definition 3.8 Let $(N;v)$ be a cooperative game, and let B be a coalitional structure, that is a partitioning of the set of players N. Then, the set of all possible payoff vectors $x \in \mathbb{R}^N$ that are efficient and individually rational for the coalitional structure B is called the set of imputations $X(N;v)$.

Efficiency and individual rationality are essential properties that allow estimating the possibility of cooperation in a particular game. However, they do not fully represent the rationality constraints imposed by the coalitional structure of a game. Therefore, we need to define the coalitional rationality.

Definition 3.9 An imputation $x \in X(N; v)$ is called coalitionally rational if for every coalition $S \subseteq N$:

$$\sum_{i \in S} x_i \leq v(S) \tag{3.6}$$

This definition states that every coalition has to be awarded less or equal cost than it had on its own before cooperation. It is an essential property exploited in numerous solution concepts.

3.2.1 The Core

Having described the rationality properties of allocation solutions, we are now ready to define one of the main solution concepts in Cooperative Game Theory, the Core of the game.

Definition 3.10 The Core of a cooperative game $C(N; v)$ is the collection of all coalitionally rational imputations.

Thus, the allocation solutions within the Core must satisfy conditions (3.4), (3.5), and (3.6). The Core is the intersection of a finite number of half-spaces, which means that it is a convex compact set.

The Core is often referred to as a concept for evaluating the stability of cooperation since every solution within it should satisfy all the players. A logical question arises: in which cases the Core is not an empty set? The necessary and sufficient conditions for the nonemptiness of the Core of a cooperative game were proved in the Bondareva–Shapley theorem [135], which is based on the balanced collections of coalitions. However, this theorem is not useful for verifying the nonemptiness of the Core in practical cases. Therefore, we omit its formulation and proof in our work. Instead, we introduce the following theorems that are of particular interest in our analysis of cooperation on cross-border interconnection projects.

Theorem 3.1 The Core of a market game is nonempty [136].

There exist several thoroughly studied classes of cooperative games, among which market games hold a valuable place. Such games naturally arise from an exchange economy where a set of producers trades commodities. The producers have different production functions and try to maximize their benefits. According to the theorem, if the production functions are continuous and concave, the resulting market game is guaranteed to have a nonempty Core. We will later refer to the class of market games while analyzing cooperative games in TEP.

Theorem 3.2 The Core of a convex game is nonempty (the proof may be found in [134]).

As discussed earlier, in convex games players have clear incentives for forming large coalitions. Additionally, the class of convex games has a remarkable feature that interrelates the Core of a game with players' marginal contributions. To explain this relation, one would suggest an imputation rule where players receive marginal contributions that they provide to a coalition when joining it in ordering π. There exist multiple possible orderings leading to different imputations w^{π}. To describe the set of such imputations, we introduce the following definition.

Definition 3.11 The convex hull of the imputations $\{w^{\pi}\colon \pi\ is\ a\ permutation\ of\ N\}$ is called the Weber set of the cooperative game $(N; v)$.

The Weber set is a polytope over the maximum contributions of players to possible coalitions. The remarkable property of convex games is that the Core always contains the Weber set. Thus, convexity is indeed the desired property of cooperative games that guarantees the formation of the grand coalition and the nonemptiness of the Core.

The mentioned theorems provide us a tool for cooperative games analysis. If we are able to prove that our case study can be formulated as a market or convex cooperative game, then we are assured that it is possible to reach stable cooperation where the grand coalition N will be formed, and all the players will be satisfied with the payoff vector x.

3.2.2 The Shapley Value

In this section, we introduce the Shapley value, which is one of the two most important single-valued solution concepts for cooperative games. It assigns a unique payoff vector x with several desired solution properties based on players' marginal contributions to possible coalitions. We have already discussed the efficiency and the rationality properties of allocation solutions in Section 3.2. Before defining the Shapley value formula, it is useful to describe the following desired properties.

Definition 3.12 Players i and j are symmetric players in a cooperative game $(N; v)$ if for every coalition $S \subseteq N \backslash \{i, j\}$:

$$v(S \cup \{i\}) = v(S \cup \{j\}) \tag{3.7}$$

Definition 3.13 A solution concept satisfies the symmetry property if for every cooperative game $(N; v)$ and every pair of symmetric players i and j in the game:

$$x_i(N; v) - v(i) = x_j(N; v) - v(j) \tag{3.8}$$

Symmetry is an essential property that implies equal treatment for players who give the same marginal contribution to every coalition. This property requires a solution concept to be independent of the names and order of the players.

Definition 3.14 A player i is called a null player in a game $(N; v)$, if for every coalition $S \subseteq N$, it holds:

$$v(S) = v(S \cup \{j\}) \tag{3.9}$$

Definition 3.15 A solution concept satisfies the null player property if for every coalitional game $(N; v)$ and every null player i in the game:

$$x_i(N; v) = v(i) \tag{3.10}$$

A null player contributes nothing to any coalition he could join. Thus, the desired property of solution concepts is to allocate no benefits (cost savings) to such players.

Finally, we mention the additivity property that concerns several games with the same set of players. For example, a set of players N may participate in the two cooperative games $(N; v)$ and $(N; \omega)$. The additivity property states that each player must receive a sum of payoffs from the independent games played simultaneously.

Definition 3.16 A solution concept satisfies the additivity property if for every pair of cooperative games $(N; v)$ and $(N; \omega)$:

$$x_i(N; v + \omega) = x_i(N; v) + x_i(N; \omega) \tag{3.11}$$

Now we are ready to define the Shapley value, which is the unique solution concept satisfying the efficiency, symmetry, null player, and additivity properties. The explicit Shapley value formula is given by the following equation.

Definition 3.17 The Shapley value is the solution concept Sh defined as follows:

$$Sh_i(N; v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(|N| - |S| - 1)!}{|N|!} \big(v(S \cup \{i\}) - v(S)\big) \tag{3.12}$$

The above equation is a linear function of the worths of the various coalitions, where $|N|$ is the total number of players in a game, and $|S|$ is the number of players in coalition S, which is a subset of N. The number of different ways that the players in S can be ordered is $|S|!$, and the number of different ways that the remaining players in $N \setminus (S \cup \{i\})$ can be ordered is $(|N| - |S| - 1)!$. It follows that the number of permutations in the ordering of joining the coalition S is

$|S|!\,(|N| - |S| - 1)!$, and the number of all possible orderings in joining all possible coalitions in $|N|!$. Thus, the payoff x_i to player i is a weighted sum of its marginal contributions $v(S \cup \{i\}) - v(S)$ to coalitions he could join.

The Shapley value is a popular allocation tool that is often referred to as a fair solution concept because of the mentioned properties. It is frequently used in economic studies not only for cost allocation but also for estimating the bargaining power of players. For example, the Shapley value is used in the Shapley–Shubik power index [137] to measure the power of members in a decision-making process. Unfortunately, there is no guarantee that the Shapley value would be within the Core of a game and, therefore, be a rational solution. Only convex cooperative games have this property, as stated by the following theorem.

Theorem 3.3 If $(N; v)$ is a convex game, then the Shapley value is in the Core of the game (the proof may be found in [134]).

Once again, we see the merits of convex cooperative games. Not only they have the nonempty Core, but also it is guaranteed that the Shapley value is a part of it. As we will show in the following sections, many practical cases of cooperation cannot be formulated as convex cooperative games. Therefore, the Shapley value should be used with caution not to violate the rationality constraints.

3.2.3 Coalitional Excess Theory: the Nucleolus and the Kernel

Several important solution concepts are based on the coalitional excess theory, which involves the following additional metric.

Definition 3.18 For every imputation $x \in \mathbb{R}^N$ and every coalition $S \subseteq N$, the excess of the coalition is defined as:

$$e(S; x) \coloneqq v(S) - \sum_{i \in S} x_i \tag{3.13}$$

For cost games[2], the excess is a measure of how satisfied a coalition is with the imputation $x(N; v)$. The larger the excess of S, the more satisfied coalition S is. The Nucleolus, a solution concept first introduced by *Schmeidler* [138], suggests searching for an allocation that maximizes the excess of the most dissatisfied coalitions. To formally define the Nucleolus, we need to compose a vector, θ, that computes the excesses of all the coalitions at x and arranges them in increasing order: $\theta(x) = (e(S_1; x), e(S_2; x), \dots, e(S_{2^n}; x))$, where $e(S_1; x) \leq e(S_2; x) \leq \cdots \leq e(S_{2^n}; x)$. This vector is needed to perform a lexicographical comparison with other possible vectors of excesses. We say that vector $a = (a_1, a_2, \dots, a_m)$ is lexicographically greater than another vector $b = (b_1, b_2, \dots, b_m)$ if either $a = b$ or there exists $h \in \{1, \dots, m\}$ such that $a_h \geq b_h$ and $a_i = b_i \; \forall i < h$. We annotate this lexicographical comparison as $a \gtrsim b$. Now we are ready to define the Nucleolus, the imputation x which lexicographically maximizes[3] the excess vector, θ, for all possible imputations $\bar{x}$.

Definition 3.19 Let $(N; v)$ be a cooperative game and let $K \in \mathbb{R}^N$ be a set of possible imputations. The Nucleolus of the game $(N; v)$ relative to K is the solution concept $\mathcal{N}$ defined as follows:

$$\mathcal{N}(N; v; K) = \{x \in K : \; \theta(x) \gtrsim \theta(\bar{x}), \qquad \forall \bar{x} \in K\} \tag{3.14}$$

To find the Nucleolus of a cooperative game, it is necessary to solve a series of linear programming models. We refer to the paper by *Guajardo and Jörnsten* [139], who presented an algorithm for computing the Nucleolus and discussed common mistakes that appear in its applications. The first linear program in the sequence maximizes the excess of the most dissatisfied coalition and can be formulated as follows.

Comment: you have not explicitly defined value versus cost games! This is part of the reason why your section 3.1 is so confusing!!!

---

[2] Note that for value games, the formulation of excess (3.13) shows how dissatisfied the members of S are with the vector x. If the excess is positive, the members of S are not satisfied with x, because they could form S together, obtain $v(S)$, and then divide that sum in such a way that each member of S receives more than he receives under x. In our work, we formulate cost games, for which excess of a coalition means the opposite.

[3] For value games, the Nucleolus lexicographically minimizes the excess vector arranged in decreasing order.

$$\max_{x} \varepsilon \tag{3.15}$$

$$\text{s.t.} \quad \varepsilon + \sum_{j \in S} x_j \leq v(S) \qquad \forall S \subset N, S \neq \emptyset \tag{3.16}$$

$$\sum_{j \in N} x_j = v(N) \tag{3.17}$$

$$\varepsilon \in \mathbb{R}, x_j \in \mathbb{R}, \forall j \in N \tag{3.18}$$

The objective function (3.15) maximizes the value ε, which is constrained by the excesses of all possible coalitions in (3.16). Thus, (3.15) and (3.16) together provide that ε is exactly equal to the minimum excess. Constraint (3.17) refers to the efficiency property (3.4). Constraint (3.18) states the nature of the variables. The solution to (3.15)-(3.18) may not necessarily be unique. It may occur that more than one allocations x lead to the optimal objective value. Moreover, formulation (3.15)-(3.18) provides an allocation that maximizes the lowest excess, but not necessarily the second or the subsequent lower excesses. To find the unique solution, the Nucleolus, it is necessary to solve a series of k linear programs formulated as follows.

$$\max_{x} \varepsilon_k \tag{3.19}$$

$$\text{s.t.} \quad \varepsilon_k + \sum_{j \in S} x_j \leq v(S) \qquad \forall S \subset N: S \notin \mathcal{F}_k \tag{3.20}$$

$$\varepsilon_i + \sum_{j \in S} x_j = v(S) \qquad \forall\, S \in F_i \qquad i \in \{1, \dots, k-1\} \tag{3.21}$$

$$\sum_{j \in N} x_j = v(N) \tag{3.22}$$

$$\varepsilon_k \in \mathbb{R}, x_j \in \mathbb{R}, \forall j \in N \tag{3.23}$$

Similarly to (3.15) and (3.16), the objective function (3.19) and constraints (3.20) provide that the minimum excess of the k^{th} program is maximized. Constraints (3.21) consider the results obtained in the previous linear programs and state that the excess of coalitions in the set F_i must be equal to the optimal objective value ε_i of i^{th} program. The set $\mathcal{F}_k$ then is the union of all the coalitions for which the excess has already been fixed in previous linear programs of the sequence. Constraints (3.22) and (3.23) state conditions for the efficiency and nature of the variables, respectively. The model (3.19)-(3.23) should be solved k times unless the unique allocation solution is obtained. The definition of F_i sets between the iterations can be done by means of dual linear programming, as it was shown in [139]. The payoff vector at the last interaction is the unique single-valued solution $\mathcal{N}(N;v)$, the Nucleolus of a cooperative game. The above procedure shows that the Nucleolus lexicographically maximizes the excess vector for all possible imputations.

The Nucleolus solution concept is widely used for solving allocation issues, particularly bankruptcy problems. The merit of this concept lies in the following properties.

Theorem 3.4 If the Core of a cooperative game $(N;v)$ for the coalitional structure B is nonempty, then the Nucleolus for B is in the Core (the proof may be found in [134]).

This remarkable property of the Nucleolus makes it a universal tool for solving allocation issues: whenever it is possible to prove that the Core of a game is not empty, the Nucleolus can be used to find a solution within the Core. Moreover, the Nucleolus satisfies the efficiency, symmetry, and null player properties.

Theorem 3.5 Let $(N;v)$ be a cooperative game with coalitional structure B, and let i and j be symmetric players who are the members of the same coalition in B. Then the Nucleolus satisfies the symmetry property (the proof may be found in [134]):

$$\mathcal{N}_i(N;v;B) - v(i) = \mathcal{N}_j(N;v;B) - v(j) \tag{3.24}$$

Theorem 3.6 Let $i \in N$ be a null player in a cooperative game $(N; v)$. Then the Nucleolus satisfies the null player property (the proof may be found in [134]):

$$\mathcal{N}_i(N; v) = v(i) \tag{3.25}$$

It may seem that the Nucleolus is the absolute best choice of the solution concept since it not only satisfies almost all of the desired properties that the Shapley value does (efficiency, symmetry, null player) but also reduces the dissatisfaction of the most dissatisfied coalitions and guarantees the stability of cooperation. However, the implementation of the Nucleolus is still open to criticism. The idea of allocating more savings to the most dissatisfied coalition is questionable. The point is that more dissatisfied coalitions may have fewer players than the less dissatisfied ones. Thus, it may be not fair to create an allocation mechanism that cares most about a few of the players. In this regard, the Nucleolus is classified as an egalitarian concept, while the Shapley value considers the contribution of players and is, therefore, a utilitarian concept.

Lastly, we define the Kernel, the solution concept first introduced by *Davis and Maschler* [140]. The Kernel is based on a similar excess metric that is called the maximum surplus of player i over player j.

Definition 3.20 For any cooperative game $(N; v)$ and any distinct pair of players $i, j \in N$, $i \neq j$ the maximum surplus of player i over player j with respect to the imputation $x(N; v)$ is defined by:

$$s_{ij}(x) \coloneqq \min_{S \in \mathcal{G}_{ij}} e(S; x) \text{ where } \mathcal{G}_{ij} \coloneqq \{S \mid i \in S, j \notin S\} \tag{3.26}$$

It is again important to note that we consider cost games. Thus, the maximum surplus $s_{ij}(x)$ describes the minimal cost that player i can get without cooperating with player j. In other words, this is the maximum amount player i can gain (or the minimum amount he may lose) if withdrawing from the grand coalition without the consent of player j and joining a coalition that does not include j.

Because of its nature, the maximum surplus of player i over player j is often called a bilateral threat. Thus, if $s_{ij}(x)$ is lower than $s_{ji}(x)$, we can say that player

i outweighs player j. The idea of the Kernel is to equalize all bilateral threats and reach a multi-bilateral bargaining equilibrium.

Definition 3.21 The set of imputations $X(N;v)$ that balances the maximum surpluses for each distinct pair of players is called the Kernel of the game $(N;v)$ and is defined by:

$$\mathcal{K}(N;v) \coloneqq \{x \in X(N;v) \mid s_{ij}(x) = s_{ji}(x) \;\; \forall\, i,j \in N,\; i \neq j\} \tag{3.27}$$

As follows from the definition, the Kernel is a set solution concept. Not only the Kernel interprets a bargaining process among players, it also has some valuable properties. It is important to mention that the Kernel always contains the Nucleolus. Moreover, it was proven by *Maschler et al.* [141] that for the class of convex games, the Kernel and the Nucleolus coincide.

Unfortunately, there is no straightforward way of computing the Kernel. In [142], *Meinhardt* suggested an algorithm for computing the Kernel through a series of linear programs based on the bisection property of the Kernel elements. In this work, we rely on the complementarity modeling and find an element of the Kernel as a solution to the equilibrium problem. We simultaneously solve several interrelated optimization problems, each of which defines the surplus among a pair of players.

$$\max_{x} s_{ij} \tag{3.28}$$

$$\text{s.t.} \quad s_{ij} \leq v(S) - \sum_{k \in S} x_k \qquad \forall S \subset N\colon\; i \in S, j \notin S \tag{3.29}$$

$$\sum_{k \in S} x_k \leq v(S) \qquad \forall k \in S \tag{3.30}$$

$$\sum_{k \in N} x_k = v(N) \qquad \forall k \in N \tag{3.31}$$

The above model seeks for the maximum bilateral surplus (3.28) restricted by the excesses of coalitions to which player i belongs, and player j does not (3.29). Conditions (3.30) and (3.31) refer to the coalitional rationality and efficiency properties (3.5), (3.4), and, therefore, define the Core of the game. Observe that

(3.28)-(3.31) is an LP model. To find an element of the Kernel solution, we jointly solve model (3.28)-(3.31) for all maximum surpluses via necessary and sufficient optimality conditions, Karush–Kuhn–Tucker (KKT) conditions, and setting the bilateral equality of the surpluses:

$$s_{ij} = s_{ji} \qquad \forall\, i, j \in N,\ \ i \neq j \tag{3.32}$$

This formulation allows us to find a single element of the Kernel, which is the Nucleolus. However, in this work, we will use the Kernel solution concept not only for computing cost allocation but also for developing novel TEP algorithms that embed the coalitional excess theory for suggesting transmission plans with enhanced cooperation stability.

The remaining part of this chapter shows how the discussed solution concepts can be implemented in TEP cost allocation case studies.

3.3 Transmission Cost Allocation Examples

To further investigate the applicability of the Cooperative Game Theory solution concepts, we present the results of TEP cost allocation for the two illustrative case studies.

3.3.1 The Two-System Case Study

First, we analyze the simplest possible case where two power systems (players) cooperate on building a cross-border line. We have already introduced this case in Chapter 2. The effects of the electricity market integration are presented in Figure 2.2, and the expansion planning model is defined by equations (2.1)-(2.5). The changes in consumers' payments, generation costs and surpluses are listed in Table 2.2. Based on these metrics, it is possible to formulate cooperative games and find the allocation solutions. However, the space of imputations for two-player games has very few dimensions. There is no need to compute the Shapley value, the Nucleolus, and the Kernel since all of these solutions will coincide with the single imputation, which is called the standard solution of the game.

Theorem 3.7 Let $(N; v)$ be a two-player cooperative game. Then the standard solution of this game is defined by:

$$(x_i, x_j) = \left(\frac{v(i,j) + v(i) - v(j)}{2}, \frac{v(i,j) - v(i) + v(j)}{2}\right) \tag{3.33}$$

The standard solution of a two-player game divides the gain (or cost savings) of cooperation into halves among the players. In [42], [43], *Contreras* called this approach bilateral Shapley value and used it for transmission cost allocation among coalitions in a sequential manner. Based on the results presented in Table 2.2, we computed several allocation solutions using different values in the characteristic function of the game: consumers' payment, generation cost, and generation surplus. The changes in these parameters caused by the market integration and the allocation solutions are given in Table 3.1.

Table 3.1: Allocation solutions for the two-system case.

Parameter	System A	System B
Consumers' payment before interconnection (\$/h)	$P_A = 7\,500$	$P_B = 64\,500$
Consumers' payment after interconnection (\$/h)	$P'_A = 9\,500$	$P'_B = 52\,500$
The allocation solution (\$/h)	$P_A^x = 2\,500$	$P_B^x = 59\,500$
Generation cost before interconnection (\$/h)	$C_A = 6\,250$	$C_B = 42\,000$
Generation cost after interconnection (\$/h)	$C_A + C'_A = 13\,050$	$C'_B = 26\,400$
The allocation solution (\$/h)	$C_A^x = 1\,850$	$C_B^x = 37\,600$
Generation surplus before interconnection (\$/h)	$S_A = 1\,250$	$S_B = 22\,500$
Generation surplus after interconnection (\$/h)	$S_A + S'_A + S''_A = 4\,050$	$S'_B = 12\,100$
The allocation solution (\$/h)	$S_A^x = -2\,550$	$S_B^x = 18\,700$

The obtained solutions make it possible to suggest the shares of investment in the power line and estimate the amount of payment from power importer (System B) to power exporter (System A). It is seen that for each of the parameters, the difference caused by the interconnection was equally split among the systems, which in this case have equal bargaining power. The question arises, which criterion of cooperation is more appropriate than the others? We believe that for consistency with the TEP approach, allocation based on the costs is the preferable one. Moreover, we want to avoid situations where some players may be allocated negative values, as it happens for the generation surplus allocation in the two-system case study. Thus, in the subsequent cases, we use generation cost for formulating characteristic function of cooperative games.

How does this relate to a traditional "split savings" rule in inter-utility trade?

Cooperation on TEP projects becomes far more complicated once there are three or more independent power systems (players). We address such cooperative games in the following case study.

3.3.2 The Three-System Case Study

To visualize the set of imputations, the Core of the game, and differences in the solution concepts, we introduce the case study where three independent power systems negotiate on building cross-border power lines. We use the same electricity market integration assumptions and TEP model (2.1)-(2.5) as in the two-system case to estimate the effect of the power interconnections. The data on power systems' supply functions and demands is given in Table 3.2. The scheme of power interconnections is depicted in Figure 3.4. It is assumed that the three possible power lines with the maximum capacity of 100 MW each and investment cost 10 \$/MWh are a subject of the transmission expansion discussion.

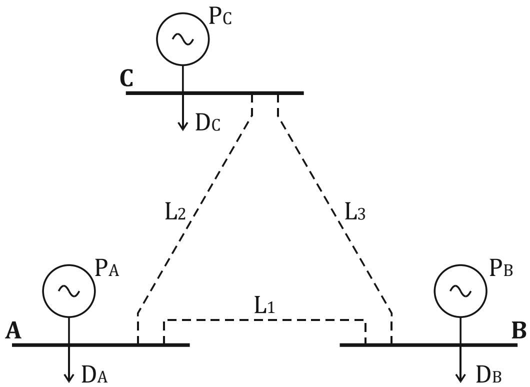


Figure 3.4: Model of the three-system case power interconnections.

Table 3.2: The three-system case study data.

Parameter	System A	System B	System C
Supply function (\$/MWh)	$\lambda_A = 10 + 0.01p_A$	$\lambda_B = 13 + 0.03p_B$	$\lambda_C = 12 + 0.025p_C$
Power demand (MW)	500	1 500	1 000

The cost of the separate operation for Systems A, B, and C is 6 250, 53 250, and 24 500 \$/h, respectively. The TEP model (2.1)-(2.5) was solved several times for all possible scenarios of cooperation (coalitions of players). Parameters of the optimal solutions are listed in Table 3.3. The grand coalition, {A,B,C}, leads to the highest possible cost savings of 4 800 \$/h. Systems A and B act as power exporter and importer, respectively, while C turns out to be a transfer system.

Kind of obvious from the costs!

Table 3.3: Scenarios of cooperation for the three-system case.

Parameter	Scenarios / coalitions of players				
	{A},{B}, or {C}	{A,B}	{A,B,C}	{A,C}	{B,C}
p_A (MW)	500	600	700	600	500
p_B (MW)	1 500	1 400	1 300	1 500	1 400
p_C (MW)	1 000	1 000	1 000	900	1 100
F_{AB} (MW)	—	100	100	—	—
F_{AC} (MW)	—	—	100	100	—
F_{CB} (MW)	—	—	100	—	100
λ_A ($/MWh)	15	16	17	16	15
λ_B ($/MWh)	58	55	52	58	55
λ_C ($/MWh)	37	37	37	34.5	39.5
Generation cost ($/h)	84 000	79 900	76 200	81 975	82 175
Investment cost ($/h)	—	1 000	3 000	1 000	1 000
Total cost ($/h)	84 000	80 900	79 200	82 975	83 175

But how stable is this cooperation? And how should the systems allocate the cost savings and share the investment in the cross-border power lines? To address these questions, we formulated the cooperative game with the cost-based characteristic function of coalitions and implemented the discussed solution concepts. Table 3.4 shows the obtained solutions indicating the allocation of both costs and savings among the systems. Note that for three-player games, the Kernel contains only a single element that coincides with the Nucleolus. We also computed the equal sharing solution, which is a straightforward approach of splitting the savings equally among the participants.

Table 3.4: Allocation solutions for the three-system case.

Solution concept	Allocation of costs (savings) ($/h)		
	System A	System B	System C
The Shapley value	4 237.5 (2 012.5)	51 337.5 (1 912.5)	23 625 (875)
The Nucleolus and the Kernel	4 187.5 (2 062.5)	51 362.5 (1 887.5)	23 650 (850)
Equal sharing	4 650 (1 600)	51 650 (1 600)	22 900 (1 600)

The obtained allocations reveal the usefulness and the bargaining power of the players. For example, both the Nucleolus and the Shapley value agree that System C is the less important player. It is therefore allocated fewer savings than Systems A and B. Indeed, System C has a medium market price and is neither a power exporter nor importer. Thus, without System C, other players are still able to yield significant cost savings.

To analyze the stability of cooperation, we impose the coalitional rationality conditions (3.6) and examine the Core of the game. We visualize the set of imputations, the Core, and the obtained allocation solutions using the barycentric coordinate system, as shown in Figure 3.5. The vertices A, B, and C represent the solution points where the corresponding systems get the maximum cost savings, i.e., the minimum possible cost. For example, System A is allocated 100% of the total savings at point A. Its cost decreases from 6 250 to 1 450 $/h. The farther solution moves from the A point, the fewer savings are allocated to the system. In the extreme case, solutions that lie on the line BC imply that System A is allocated zero savings – its cost does not change after the interconnection. The equal sharing point lies right at the center of mass of the ABC triangle. The set of coalitionally rational imputations is depicted by the grey polytope, the Core of the game. We see that all of the considered solutions meet the rationality conditions and, therefore, are feasible for the current case study. We should also mention that not only System C is allocated fewer savings by the Nucleolus and the Shapley value, but also it is far more distant from the Core's borders than other players. This fact signifies that System C has less space for bargaining in negotiations on the project.

To provide more insights about the allocation solutions, we implemented an additional concept that measures players' *propensity to disrupt*. The concept was introduced by *Gately* [40], who considered player's incentives of breaking an agreement and suggested limiting the ratio of how much other players would lose if player i refuses to cooperate to how much player i would lose himself.

Definition 3.22 Let $(N; v)$ be a cooperative game, and let $x(N; v)$ be the imputation. Then, the propensity of player i to disrupt the cooperation is defined by:

$$d_i(N; v; x) = \frac{v(N \backslash \{i\}) - \sum_{j \neq i} x_j}{v(\{i\}) - x_i} \quad \forall i, j \in N \tag{3.34}$$

The interpretation of this concept is highly intuitive. If a player does not receive any share of savings, its propensity to disrupt is infinite. Contrariwise, a player who gets most of the savings could have zero or even negative propensity to disrupt the agreement. It is worth mentioning that the initial formulation by Gately included gains of cooperation. We modified the formulation to suit our cost game and considered the difference between the cost of coalitions and cost imputations of players. In an extreme case, if one player gets most of the savings, other players would receive more savings in a subcoalition rather than in the grand coalition. Thus, the numerator of (3.34) would be a negative value. The player with most of the savings would have a negative propensity to disrupt. Note that in our setting, we consider superadditive games and impose the coalitional rationality conditions (3.6) on the imputation. Therefore, such extreme cases become infeasible.

It is required to define a limit on the maximum propensity for the players to implement the concept. In our case, we consider the imputations limited by the propensities equal to one and two. The corresponding regions are shown by the dashed purple triangles in Figure 3.5. The decrease in the limit makes the regions shrink towards the solution where all the players have equal propensities to disrupt, the Gately point of the cooperative game. In our case study, the solutions by the Shapley value and the Nucleolus are within the region where players' propensity to disrupt is less than one. We, therefore, might conclude that both of these solutions are reasonable for allocating the savings and sharing the investment cost of the TEP project.

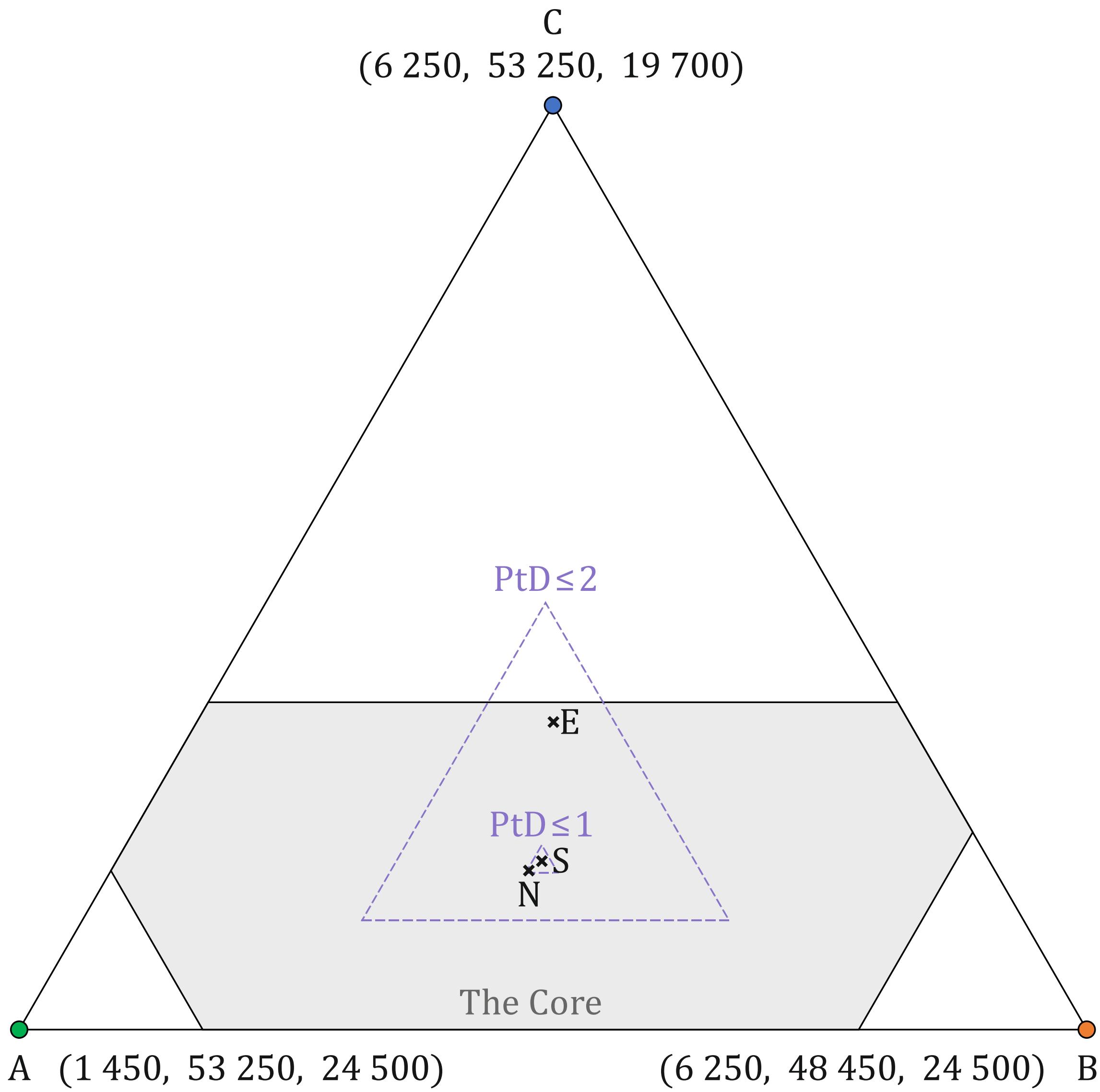


Figure 3.5: The set of imputations and the Core of the cooperative game for the three-system case. The values represent the corresponding costs for (A, B, C) in \$/h. The allocation solutions are denoted as follows: S - the Shapley value, N - the Nucleolus (coincides with the Kernel), E - equal sharing point, PtD - regions constrained by players' propensity to disrupt.

We should also discuss the properties of the formulated cooperative game. First, it is important to notice that we solved the cost minimization problem (2.1)-(2.5) for every coalition. Thus, it is guaranteed that the characteristic function cannot increase when more players join a coalition. It follows that our game satisfies condition (3.1) and is superadditive. To verify the convexity property of the game, we can check condition (3.3) for all possible contributions of players to the coalitions. The three-player cooperative game has not many contributions to consider. We list them in Table 3.5.

Table 3.5: Cooperative game convexity verification for the three-system case.

Marginal contributions of players to coalitions ($/h)		
Player:	Coalition:	Contribution:
A	{A,B}	-3 100
A	{A,C}	-1 025
A	{A,B,C}	-3 975
B	{A,B}	-3 100
B	{B,C}	-825
B	{A,B,C}	-3 775
C	{A,C}	-1 025
C	{B,C}	-825
C	{A,B,C}	-1 700

For cost games, the marginal contributions of players to the coalitions result in a cost reduction. For consistency, we display the contributions as negative values. It is seen that the players bring higher cost reduction when joining larger coalitions. Thus, the cooperative game satisfies condition (3.3) and is convex. As discussed in this chapter, convexity is one of the most desired properties of cooperative games. It guarantees the nonemptiness of the Core and the rationality of the allocation solutions. Additionally, one may verify using Figure 3.5 that the Shapley value of a convex game is the center of gravity of the Core. However, the convexity of cooperative games in TEP projects depends on the parameters of the systems and topology of the interconnections. As we will show later, some transmission expansion plans may cause the nonconvexity or even situations where the Shapley value falls out of the Core.

Finally, we estimate the maximum surpluses among players defined by (3.26) for the obtained allocation solutions (imputations). The values showed in Table 3.6 represent the bilateral threats for every distinct pair of players. For cost games, a threat of leaving the grand coalition and joining a subcoalition implies an increase in cost for the threatening player. Thus, the threats are displayed as positive values that reveal the interdependence of players.

Table 3.6: Analysis of the bilateral threats for the three-system case.

$s_{ij}(x)$ - the maximum surplus of player i over player j with respect to the imputation $x(N;v)$, in \$/h				
The imputation defined by:	i/j	A	B	C
the Shapley value (4 237.5; 51 337.5; 23 625)	A	—	1 862.5	825
	B	1 912.5	—	825
	C	875	875	—
the Nucleolus and the Kernel (4 187.5; 51 362.5; 23 650)	A	—	1 887.5	850
	B	1 887.5	—	850
	C	850	850	—
the equal sharing (4 650; 51 650; 22 900)	A	—	1 600	100
	B	1 600	—	100
	C	1 600	1 600	—

The bilateral threats analysis shows that Systems A and B highly depend on cooperation with each other. A threat of leaving the coalition results in significant losses for both systems. The consequences of threatening System C are much lower, which again confirms that this system has less influence on the project and less bargaining power. It may also be verified that the Nucleolus is the only solution that equalizes all bilateral threats among the players.

At this stage, we have considered the implementation of the main Cooperative Game Theory solution concepts for TEP cost allocation. In the next should this be chapters?

sections, we will focus on the stability of cooperation and present a way of incorporating the Cooperative Game Theory principles into planning algorithms.

3.4 Summary and Conclusions

Cooperative Game theory provides a rich theoretical background for the analysis of projects where participants can make collective actions to obtain mutual benefits. In this chapter, we defined cooperative games and examined their properties. Then we introduced several important solution concepts and discussed their features. We also covered the coalitional excess theory and paid especial attention to the maximum surplus among players. The maximum surplus (also called bilateral threat) is an important parameter that allows us to identify the usefulness and interdependence of players. We will use it in Chapter 5 as the metric of cooperation stability to develop a proactive game-theoretic TEP approach.

Using the two-system and three-system cases, we demonstrated the application of the discussed solution concepts to cost allocation in TEP. We considered several parameters of cooperation and, for consistency with the TEP approach, decided to formulate cooperative games in terms of costs. The two-system case study led to a trivial allocation solution, which is called the standard solution of a cooperative game. However, for the three-system case, we implemented several solution concepts and observed differences in the players' bargaining power. The inequality of players' positions (caused by their cost functions and the topology of interconnections) could undermine the stability of cooperation and hinder the development of cross-border TEP projects. We will revisit the three-system case study in Chapter 5 to further discuss the stability issues.

The Cooperative Game Theory solution concepts presented in this chapter constitute our main tool for modeling and analyzing cooperation on cross-border power interconnection projects. In the following chapters, we will address the issues of Cooperative Game Theory application related to incomplete information, manipulability of allocation rules, and ex-post game-theoretic analysis. Finally, we will examine a real-world case study of potential power interconnections in Northeast Asia.

Chapter 4

Strategic Behavior and Manipulability of Allocation Mechanisms

One bad move nullifies forty good ones
- I. A. Horowitz
American grandmaster

The discussed solution concepts enable allocating the cost of a TEP project among power systems while satisfying desired properties, such as efficiency, individual and coalitional rationality. However, the allocation mechanisms based on Cooperative Game Theory has several rough assumptions, which limit their potential applicability in real-world projects. First, it is assumed that cooperation happens under perfect information, i.e., the information on power demands and cost functions is available to all players (as well as to regulatory or coordinating entities, if any). Moreover, it is supposed that players reveal their true values of power demand and cost functions. Unfortunately, the information may be only partially accessible, and self-interested participants may not respond truthfully. The strategic behavior of such players would lead to manipulations of the allocation mechanism, which eventually degrade the overall efficiency of cooperation.

Second, Cooperative Game Theory solution concepts are commonly used in an ex-post manner. The optimization of planning decisions is separated from the allocation mechanisms, which require only a characteristic function as an input. Such an approach allocates the value of cooperation over the optimal expansion plan. However, it is unable to identify suboptimal plans where additional requirements of players are satisfied, and a desirable level of stability is guaranteed.

In this chapter, we discuss the manipulability issues of allocation mechanisms and their influence on cross-border expansion planning. Then, in Chapter 5, we will introduce a bilevel TEP model that incorporates Cooperative Game Theory principles and allows identifying suboptimal solutions with a predefined level of cooperation stability. We will also discuss how the proposed model can be used for developing strategyproof allocation mechanisms where players would have incentives to reveal their private information truthfully.

4.1 Background of Algorithmic Game Theory and Algorithmic Mechanism Design

The idea that an allocation mechanism could be manipulated by players because of their personal interest has been formulated in the last century and thoroughly studied in Game Theory and economics. The concept of strategyproofness was introduced to describe games where a dominant (optimal) strategy for every player is to reveal his private information [143]. Several decision rules were proved to be strategyproof. For example, the majority voting system implies that players submit their votes truthfully to select the desired decision among alternatives. There exists no strategy to manipulate the decision rule by misreporting the players' preferences. The system is, therefore, strategyproof. Other examples of strategyproof mechanisms include the second-price auction (Vickrey auction) and the Vickrey-Clarke-Groves (VCG) mechanism [143]. Unfortunately, it was discovered that most of the allocation rules are not strategyproof: revealing private information is not a dominant strategy for every player in a cooperative game. The notable contribution was made by *Thomson* [144], [145], [146], who investigated how unilateral misrepresentation of information affects the allocation of value under different mechanisms. It was demonstrated that if more than one player attempt to manipulate, the resulting cooperative game transforms into a manipulation game, which outcomes can be analyzed by calculating the equilibrium allocation solutions. Unfortunately, such manipulations not only affect the allocation of value among players but also degrade the overall efficiency of cooperation. This effect of players' selfish behavior is often referred to as the price of anarchy or performance degradation.

To better understand the interactions among players in a strategic environment and develop strategyproof mechanisms, the new fields of study emerged at the intersection of Game Theory, economics, and computer science: Algorithmic Game Theory and Algorithmic Mechanism Design. While the former area focuses on implementing existing algorithms and analyzing game properties (equilibria solutions, the price of anarchy, best-response dynamics), the latter designs games with desired game-theoretic and algorithmic properties. It is worth mentioning the contribution by *Nisan* [147], [143], who studied algorithms for self-interested participants and introduced the term Algorithmic Mechanism Design. The essence of the designed mechanisms is to ensure that a reasonable social choice would be achieved if all participants (called agents) act rationally in a game-theoretic sense. Algorithmic Mechanism Design has been implemented in various studies, which include auctions, markets, routing games, resource allocation, network formation games, and scheduling problems. In [148], *Grosu and Chronopoulos* presented an Algorithmic Mechanism Design for load balancing in distributed systems. A computational grid with selfish agents (computers) was considered, where each agent was supposed to misreport information on its processing rate to get additional payment. The authors proved that the optimal allocation algorithm can be used with the truthful payment scheme and analyzed performance degradation and fairness index under the proposed mechanism.

However, to the best of the author's knowledge, no work has been done to implement manipulability analysis and Algorithmic Mechanism Design in power systems research and transmission expansion planning. To complement the developed approach of cross-border expansion planning and cost allocation, we illustrate the nature of possible manipulations and discuss ways of preventing them.

4.2 The Two-System Case Study - Manipulability Analysis

To give a clear insight into the manipulation incentives of players in TEP projects, we start our analysis with the two-system case study first introduced in Chapter 2. The detailed information on power systems' data and the integration of the electricity markets is given in Tables 2.1, 2.2 and Figure 2.2. The possible allocation solutions are presented in Table 3.1. As discussed earlier, two-player games have not many allocation solutions to choose from. Both the Shapley value and the Nucleolus coincide at the single imputation, which is called the standard solution of the game. This solution splits the worth of cooperation in halves among the players, as defined in (3.33). In this section, we suppose that the two power systems will use the standard solution of the game as a cost allocation rule for the TEP project.

The question therefore is, what happens if one of the systems (or both of them) behave strategically and declare its supply cost function untruthfully? We visualize such manipulations in Figure 4.1, where purple dashed lines depict the declared functions that deviate from the true functions represented by the solid black lines. With no manipulations, the systems achieve a cost reduction from Ca+Cb to Ca+Ca'+Cb' (which is equivalent to Cb''-Ca') and share it equally using the allocation rule. This procedure allows estimating the payment from System B to System A that compensates for the increase in generation cost and provides the share of the total savings.

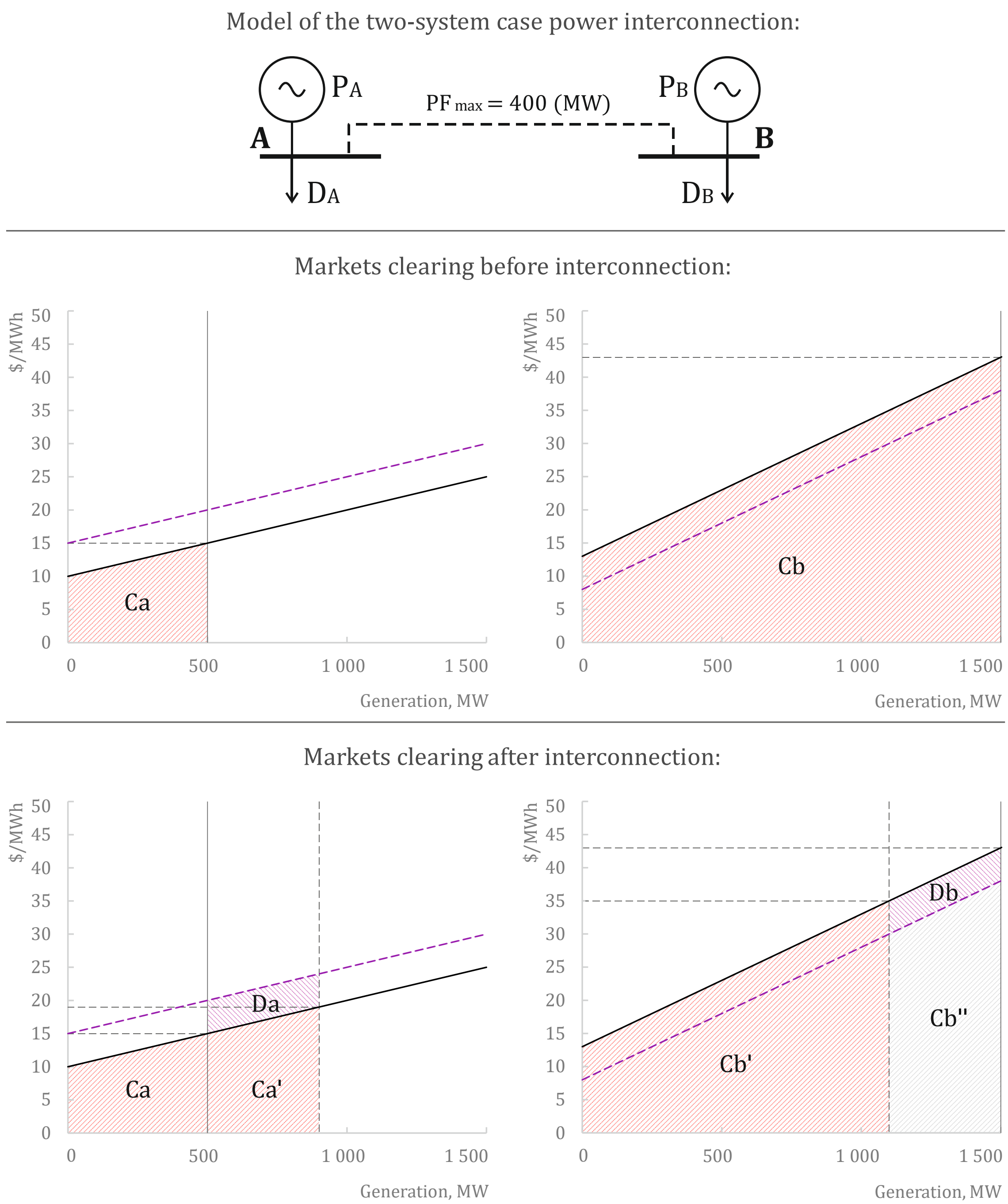
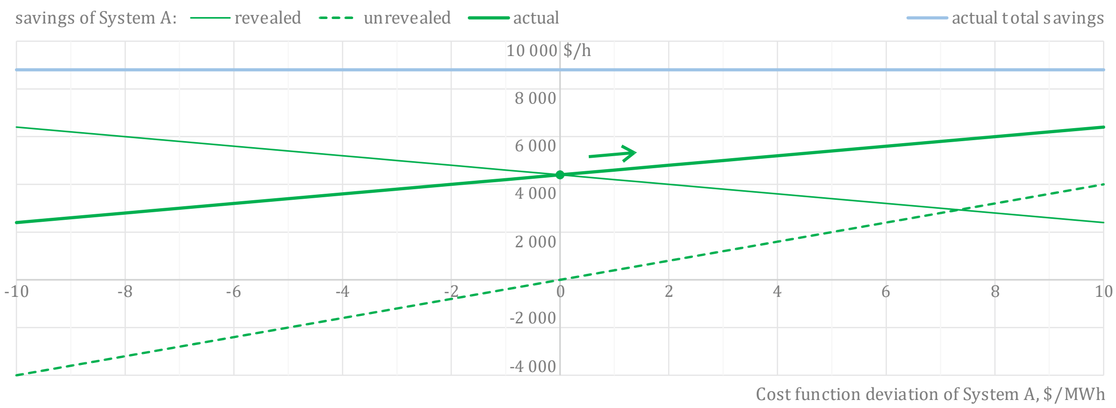


Figure 4.1: Supply function manipulations in the two-system case.

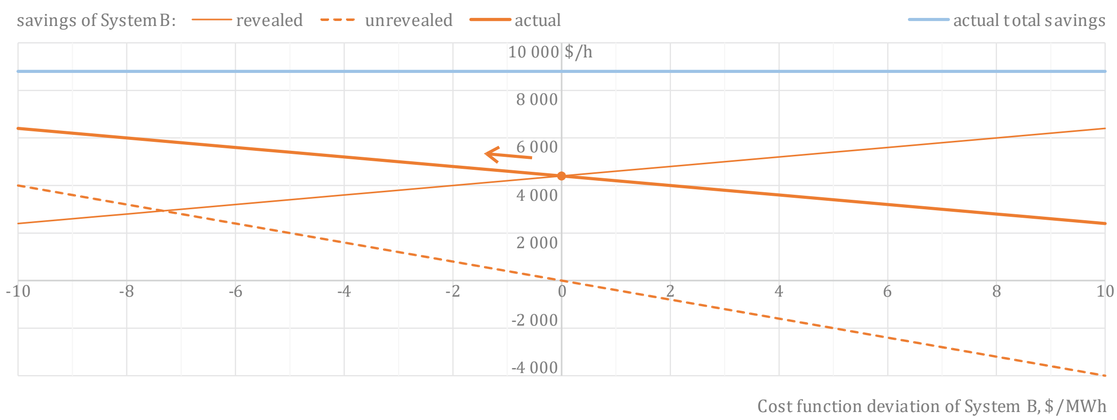
However, being a power exporter, System A may declare a higher cost function when agreeing to participate in the project and follow the allocation rule. In this case, the true benefits of System A would contain the two components.

First, it would be allocated a share of the total savings estimated according to the revealed information. We call this component the revealed savings since all the participants are aware of this value. When increasing the declared cost function, System A decreases the total revealed savings and makes the project seem less efficient. Fewer savings become shared among the players. But, System A has the second component, which we call internal or unrevealed savings. This is the difference between the declared and true costs of the exported power. We illustrate the unrevealed savings as purple area, Da, in Figure 4.1. Thus, while physically exporting the same amount of power, System A may shift the distribution of savings because of the significant increase in the unrevealed component. As a power importer, System B has the opposite incentives to manipulate the allocation rule. It may declare a lower cost function and pay less for the imported power because of the unrevealed savings, Db.

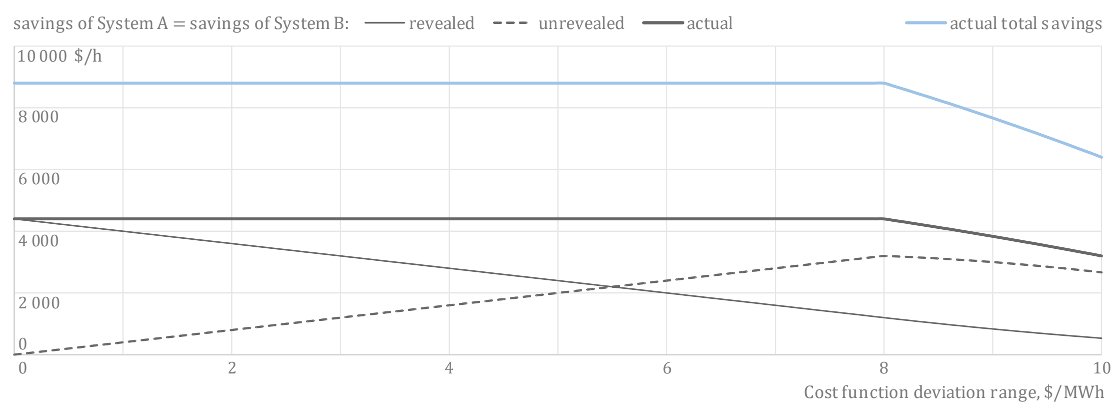
Based on the TEP model (2.1)-(2.5) and the standard allocation solution (3.33), we carried out a series of simulations for the two-system case assuming that one or both of the players behave strategically by misreporting the information on their cost functions. For simplicity, we consider deviations in the constant parts of the functions presented in Table 2.1 in the range of ± 10 \$/MWh. The influence of the manipulations on the allocation of savings is visualized in Figure 4.2.



a)



b)



c)

Figure 4.2: The effect of the cost function manipulations on savings allocation in the two-system case: a) unilateral manipulation by System A; b) unilateral manipulation by System B; c) simultaneous manipulations by both systems in their beneficial directions.

For each of the manipulations, we tracked the actual savings of players as well as their revealed and unrevealed components. Figures 4.2 (a) and (b) show that an increase in the unrevealed component (dashed lines) outweighs the decline in the revealed savings allocation. Thus, for each of the systems, there exist a beneficial direction of manipulation that leads to an increase in the system's actual savings. We denote these directions by the colored arrows at the points of no deviation. It is worth mentioning that in case only one of the systems manipulating, the actual total savings do not change in the considered range of deviations. This signifies that the same amount of power is being traded through the interconnection. The expansion plan remains optimal, while the allocation of actual savings changes due to the manipulations. However, simultaneous cost function manipulations by both systems could lead to suboptimal expansion plans with reduced transmission capacity and actual savings, as shown in Figure 4.2 (c). It is also seen that if manipulating in the same range, both systems remain in equal positions. Their actual savings do not change, while more savings become unrevealed.

The presented manipulability analysis for the two-system case shows that even in bilateral cooperation on power interconnection projects, participants have incentives to manipulate the allocation rule. The identified beneficial directions of manipulation have a clear economic interpretation: exporters try to increase the contract price, whereas importers pretend to have lower costs. Unfortunately, such manipulations can lead to an unfair distribution of savings and efficiency degradation of cooperation on cross-border expansion planning.

4.3 The Three-System Case Study - Manipulability Analysis

We repeat the manipulability analysis for the three-system case (first introduced in Section 3.3) to examine incentives to manipulate cost functions in projects with more than two players involved in a transmission expansion plan. The case was introduced and thoroughly analyzed in Section 3.3.2. It was estimated that Systems A and B (the power exporter and importer) are the most useful participants of cooperation, who are allocated the greater share of the total savings. We also analyzed the maximum surpluses among the players and found that these two systems have the prevailing position in cooperation with higher bargaining power. System C, however, turns out to be a transfer participant, who is supposed to transmit cheaper power from System A through lines 2 and 3 to System B. It is, therefore, a less useful participant with a low share of the total savings and low bargaining power.

We now perform the simulations of possible deviations in the declared cost functions and estimate the beneficial manipulation directions for each of the systems. We again consider deviations in the constant parts of the functions (presented in Table 3.2) in the range of ± 10 \$/MWh. The Shapley value is considered as the allocation rule that players agreed to use in the project. The effect of the manipulations is illustrated in Figure 4.3.

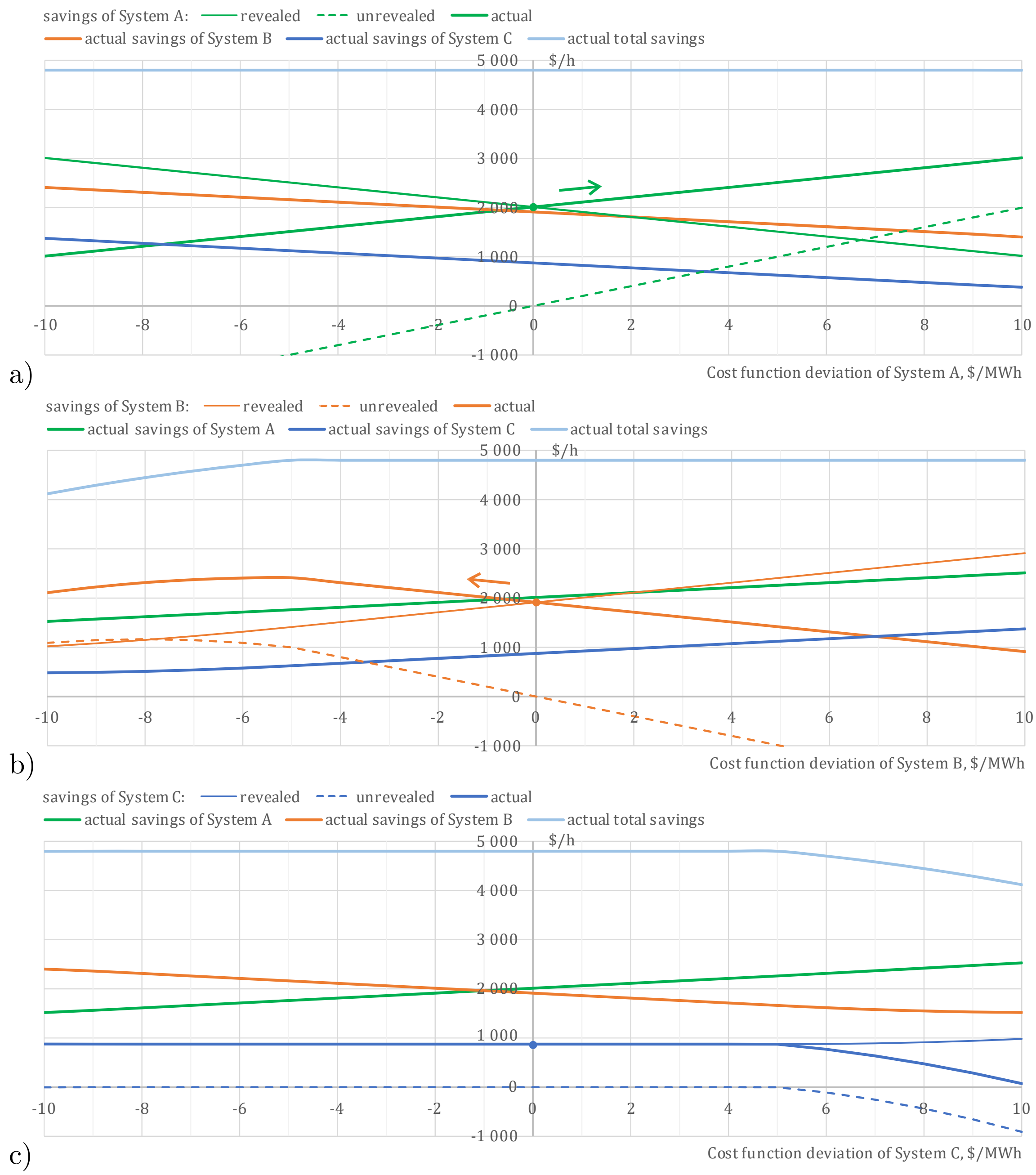


Figure 4.3: The effect of the cost function manipulations on savings allocation in the three-system case: a) unilateral manipulation by System A; b) unilateral manipulation by System B; c) unilateral manipulation by System C.

It is seen that System A and B have incentives to manipulate their cost functions due to the significant increase in the unrevealed component of savings depicted by the dashed lines in Figure 4.3 (a), (b). We denote the beneficial directions of the manipulation by the colored arrows: System A pretends to have a higher cost function, while System B declares a lower cost. Regarding System C, it has no room for cost function manipulation at all, as shown in Figure 4.3 (c). Because of its interim position in the electricity trading, System C neither exports nor imports power in the grand coalition. It, therefore, has no unrevealed component of savings and cannot successfully manipulate the allocation rule. Any cost deviation by System C would cause a decline in its efficiency for the project and a subsequent decline in the allocation of the total revealed savings. Moreover, a significant deviation may lead to a situation where System C would import power at a higher price, harming its own interest (the decline in the blue curves at the right part of the figure). We can state that the reasonable strategy for players in such interim positions is not to manipulate the allocation rule and report their information truthfully.

We also modeled simultaneous manipulation by all the participants. It was supposed that every player tries to manipulate cost function in its own beneficial direction. System C was declaring true information not to bear additional losses. We found that Systems A and B can successfully manipulate the allocation rule and increase their shares of savings, whereas System C gradually loses its influence in the project. However, beyond a certain range of deviations, the actual total savings of cooperation start declining, which signifies that the transmission plan becomes suboptimal with less power traded among the systems.

The presented examples of manipulations show that depending on the topology of power interconnections and position in electricity trading, there always would be some players with incentives to manipulate the allocation rule. Major power exporters and importers have the upper hand in such manipulations because of the wider range of possible deviations. It is worth mentioning that all of the discussed solution concepts (the Shapley value, the Nucleolus, and equal sharing) fail to prevent the strategic behavior of players and stimulate them to report information truthfully. This makes the implementation of the Cooperative Game Theory concepts in projects of cross-border TEP controversial.

4.4 Summary and Conclusions

In this chapter, we highlighted the issues related to players' strategic behavior and manipulability of allocation rules. The need for giving players incentives to report their information truthfully led to the development of strategyproof mechanisms, which are the research subject of Algorithmic Mechanism Design. The lack of strategyproofness could lead to manipulations by players and nullify the useful properties of a cooperation mechanism. Through a series of simulations, we have demonstrated that cooperation in TEP based on Cooperative Game Theory solution concepts is prone to manipulations. We have also analyzed the incentives of players depending on their positions in electricity trading. The key insight is that power exporters might declare higher cost functions than the real ones, while power importers might do the opposite. Unfortunately, such cost deviations can lead to an unfair distribution of savings and efficiency degradation in cooperation on cross-border expansion planning.

In the following chapter, we will introduce the TEP model that incorporates Cooperative Game Theory principles into the planning algorithm. It enables making planning decisions in an anticipating manner to reach the predefined properties of cooperation over an expansion plan. We then discuss how this approach can be used to prevent manipulations in cross-border TEP projects.

Chapter 5

Incorporating Cooperative Game Theory Principles into the Transmission Expansion Planning Algorithm

When you see a good move,
look for a better one.
- Emanuel Lasker
World chess champion 1894-1921

As identified by the citation network analysis in Chapter 1, one of the major drawbacks of Cooperative Game Theory applications in power systems research is that the solution concepts are usually implemented in an ex-post analysis. In expansion planning, first, the optimal transmission plan is identified using mathematical programming. Then, a cooperative game is formulated with a characteristic function representing expansion plans of possible coalitions. Depending on the coalitional structure and the characteristic function of the game, the allocation solutions are derived using the discussed concepts. In this manner, it is possible to suggest a mechanism for allocating costs and savings of the optimal expansion plan among the participants. As demonstrated in Section 3.3.2, it is also possible to estimate the stability of cooperation and bargaining power of players. However, some participants may have additional expectations or requirements on their minimal share of benefits or levels of usefulness in the coalition. A group of players (and regulatory or coordinating entities, if any) may also want to reach a cooperation with a desired level of stability. For some regions, energy cooperation projects with a severe imbalance in parties' positions may be considered unreliable or politically unacceptable. Finally, some power interconnection projects could lead to nonconvex cooperative games with small or even empty Core, with no rational allocation solutions. In such cases, the approach of finding the optimal expansion plan may not lead to the formation of the grand coalition and the establishment of regional energy cooperation.

Key point: include the game theory principles into the TEP itself, rather than thinking of it as an ex post step.

To guarantee a predefined level of stability in cooperation, we suggest incorporating Cooperative Game Theory principles into the TEP algorithm. Such an approach can identify optimal planning decisions in an anticipating manner, subject to desired properties of a resulting cooperative game. In the following sections, we describe the mathematical formulation of the model and provide an example of a TEP project where the proposed approach might be necessary to use. We then discuss how the inclusion of Cooperative Game Theory principles into TEP algorithms could be used for preventing manipulations and developing strategyproof mechanisms of cooperation.

5.1 Bilevel TEP Model Formulation

To incorporate Cooperative Game Theory principles into the TEP algorithm, we rely on complementarity modeling [35] and formulate our optimization model as a bilevel problem. Specifically, we consider the optimization of planning decisions constrained by the maximum surpluses among the players. Since the estimation of surpluses is itself a collection of optimization problems (3.28)-(3.31), the resulting problem can be characterized as a mathematical program with equilibrium constraints (MPEC). We first reformulate the TEP model (2.1)-(2.5) using the corresponding Karush-Kuhn-Tucker (KKT) conditions, as shown below. Note that for convex problems, KKT conditions are both necessary and sufficient optimality conditions.

Indeed, but any actual TEP problem is non-convex because of binaries to represent build or not build decisions.

$$\frac{dCG_n(p_{n,sc})}{dp_{n,sc}} + \lambda_{n,sc} - \mu_{n,sc}^{p1} + \mu_{n,sc}^{p2} = 0 \qquad \forall n, sc \tag{5.1}$$

$$\sum_{n \in \mathcal{N}} \lambda_{n,sc} B_{n,l} - \mu_{l,sc}^{f1} + \mu_{l,sc}^{f2} = 0 \qquad \forall l, sc \tag{5.2}$$

$$CI_l - \mu_{l,sc}^{f1} - \mu_{l,sc}^{f2} + \mu_{l,sc}^{F} = 0 \qquad \forall l, sc \tag{5.3}$$

$$\mu_{n,sc}^{p1} \geq 0, \mu_{n,sc}^{p2} \geq 0 \qquad \forall n, sc \tag{5.4}$$

$$\mu_{l,sc}^{f1} \geq 0, \mu_{l,sc}^{f2} \geq 0 \qquad \forall l, sc \qquad (5.5)$$

$$\mu_{l,sc}^{F} \geq 0 \qquad \forall l, sc \qquad (5.6)$$

$$\mu_{n,sc}^{p1}(-p_{n,sc}) = 0 \qquad \forall n, sc \qquad (5.7)$$

$$\mu_{n,sc}^{p2}(p_{n,sc} - P_n^{max}) = 0 \qquad \forall n, sc \qquad (5.8)$$

$$\mu_{l,sc}^{f1}(-f_{l,sc} - F_{l,sc}) = 0 \qquad \forall l, sc \qquad (5.9)$$

$$\mu_{l,sc}^{f2}(f_{l,sc} - F_{l,sc}) = 0 \qquad \forall l, sc \qquad (5.10)$$

$$\mu_{l,sc}^{F}(F_{l,sc} - F_l^{max\prime}) = 0 \qquad \forall l, sc \qquad (5.11)$$

$$F_l^{max\prime} \leq F_l^{max} \qquad \forall l \qquad (5.12)$$

primal feasibility constraints: (2.2)-(2.5)

Constraints (5.1)-(5.3) are the stationarity conditions that state that the gradients of the Lagrangian of the initial problem (2.1)-(2.5) should be zero at the optimal solution. Inequalities (5.4)-(5.6) are the dual feasibility conditions, where dual variables $\mu_{n,sc}^{p1}$ and $\mu_{n,sc}^{p2}$ correspond to the generation output constraints (2.3), $\mu_{l,sc}^{f1}$ and $\mu_{l,sc}^{f2}$ correspond to the power flow limits (2.4), and $\mu_{l,sc}^{F}$ relates to the maximum line capacity conditions (2.5). The dual variable $\lambda_{n,sc}$ is associated with the nodal power balance constraints (2.2). Equalities (5.7)-(5.11) state the complementary slackness conditions. Unfortunately, these conditions make the optimization problem nonlinear and nonconvex. We use the Fortuny-Amat and McCarl linearization [149] (also known as the Big-M approach) to transform the problem into a MIP. The primal feasibility conditions are added at the end of the formulation as constraints (2.2)-(2.5) from the initial problem. All of the mentioned conditions are stated for every possible scenario of cooperation (coalition of players). In this manner, we add all of the expansion problems simultaneously to the optimization model, which allows us to explicitly derive a characteristic function of a resulting cooperative game. We should highlight that a modification has been added to the KKT conditions in constraints (5.11) and (5.12) by introducing an interim capacity variable $F_l^{max\prime}$. This variable serves as a coordinator among TEP decisions in different scenarios of cooperation. Namely, it forbids changing lines capacity limits in one of the scenarios while not applying the same limits to other scenarios. We also keep the objective function (2.1) active in our bilevel optimization model to speed up the identification of desired TEP solutions.

By formulating the TEP KKT conditions and modifying them, we achieved the desired hierarchy in the upper-level of the model: only capacity investment decisions can be changed externally. This relationship could be explained in the following way. It could happen that game-theoretic restrictions at the lower-level force the characteristic function of a cooperative game to change, which means that expansion planning decisions of several or all the coalitions should change accordingly. In such cases, our formulation allows changing the characteristic function solely by tuning the limits of the capacity investment decisions. The subsequent expansion planning stays optimal for every scenario of cooperation, subject to the interim capacity limits. Without the KKT optimality conditions, it is possible to mistakenly obtain meaningless TEP solutions with meaningless power flows (in some cases, even directed from nodes with higher electricity prices to nodes with lower prices).

Having defined the equivalent KKT conditions for the TEP problem at the upper-level of the model, we now introduce the lower-level restrictions based on the Cooperative Game Theory principles. Our goal is to identify expansion plans where a certain level of stability and equality among players would be guaranteed. For this reason, we exploit the coalitional excess theory and use the maximum surpluses among players as the metric of imbalance of players' positions in cooperation. As discussed in Section 3.2.3, the computation of each surplus among a pair of players can be done using the linear optimization problem (3.28)-(3.31). However, in the lower-level, we need to define all the surpluses among players, which requires solving a series of interrelated optimization problems. We again rely on complementarity modeling [35] and formulate an equilibrium problem by jointly considering the following KKT conditions for problem (3.28)-(3.31).

$$-1 + \sum_{i \in S \subset N, j \notin S} \mu_{i,j}^{s} = 0 \qquad \forall i, j \quad i \neq j \tag{5.13}$$

$$\mu_{i,j}^{s} \geq 0 \qquad \forall i,j \quad i \neq j \tag{5.14}$$

$$\mu_{i,j}^{s}\left(s_{ij} - v(S) + \sum_{k \in S} x_k\right) = 0 \qquad \forall i,j \quad i \neq j \tag{5.15}$$

primal feasibility constraints: (3.29)-(3.31)

Constraint (5.13) is the stationarity condition with the dual variables $\mu_{i,j}^{s}$ corresponding to the inequality constraints (3.29) of the initial surplus maximization problem. Constraints (5.14) and (5.15) state the dual feasibility and complementary slackness conditions. We again use the Fortuny-Amat and McCarl linearization [149] to transform the slackness conditions into linear constraints. The primal feasibility constraints (3.29)-(3.31) are added at the end of the formulation. They contain the coalitional rationality and efficiency conditions and, therefore, define the Core of a cooperative game. The characteristic function, $v(S)$, represents the costs of the coalitions, which we estimate for each scenario of cooperation using subscript "sc". The above formulation represents the necessary and sufficient optimality conditions for the surplus optimization problem (3.28)-(3.31). It, therefore, provides the maximum surpluses among players subject to the characteristic function and imputation $x(N; v)$.

At this stage, the bilevel TEP model is almost complete. In the upper-level, we simultaneously solve TEP problems for all possible scenarios of cooperation. Then, the coalitional structure and the characteristic function, v, are derived to form a cooperative game. In the lower-level, we impose conditions on the cooperative game, stating that the allocation solution must be within the Core of the game. We also compute the maximum surpluses among players to evaluate the stability of cooperation, subject to the characteristic function and the imputation. However, we have not imposed restrictions on the maximum surpluses yet. Depending on a case study and preferences of a coordinating entity, maximum surpluses for all pairs of players may be limited from below (setting the lower bound), from above (setting the upper bound), or equalized. We provide the formulations of such restrictions below.

$$s_{ij} \geq \underline{s} \qquad \forall i,j \quad i \neq j \tag{5.16}$$

$$s_{ij} \leq \overline{s} \qquad \forall i,j \quad i \neq j \tag{5.17}$$

$$s_{ij} = s \qquad \forall i,j \quad i \neq j \tag{5.18}$$

Now we are ready to summarize the section and provide the complete formulation of the bilevel TEP model with incorporated Cooperative Game Theory principles.

$$\underset{p_{n,sc}, f_{l,sc}, F_{l,sc}, F_l^{max},}{\text{Min}} \quad \sum_{sc \in B} \left(\sum_{n \in \mathcal{N}} CG_n(p_{n,sc}) + \sum_{l \in \mathcal{L}} F_{l,sc} \cdot CI_l \right) \tag{5.19}$$

s.t.:

the upper-level (TEP optimality conditions): (5.1)-(5.12)

$$v(sc) = \sum_{n \in \mathcal{N}} p_{n,sc} \cdot CG_n \cdot \pi_{sc}^n + \sum_{l \in \mathcal{L}} F_{l,sc} \cdot CI_l \cdot \pi_{sc}^l \qquad \forall sc \in B \tag{5.20}$$

where $\pi_{sc}^n = \begin{cases} 1, & if\ n \in sc \\ 0, & otherwise \end{cases}$, $\pi_{sc}^l = \begin{cases} 1, & if\ l \in sc \\ 0, & otherwise \end{cases}$

the lower-level (optimality conditions of the maximum surpluses among players): (5.13)-(5.15)

restrictions of the maximum surpluses: (5.16) or (5.17) or (5.18)

The objective function (5.19) minimizes the investment and operating costs for every possible scenario of cooperation (coalition)[4]. The characteristic function of a cooperative game is obtained in (5.20) by collecting the optimized costs of the coalitions. For each scenario in the coalitional structure B, we count only the cost of generators and lines that can be operated by the players in the coalition. The cost of the remaining players is not included in the value of the coalition. Finally,

[4] Note that the current formulation is similar to a multiobjective optimization problem where each coalition has equal weight (importance). By adjusting the weights, it becomes possible to prioritize the cost reduction in the grand coalition or coalitions with higher numbers of players. Further research is needed to estimate the effects of coalitions prioritization on the performance of the bilevel TEP approach.

the lower-level EP and restrictions of the maximum surpluses are added to the formulation. The resulting model is a MILP problem that can be solved within off-the-shelf solvers such as Gurobi of CPLEX. The model is able to identify expansion planning decisions in an anticipating manner, depending on the maximum surpluses of players in the cooperative game. We illustrate the framework of the bilevel TEP approach in Figure 5.1.

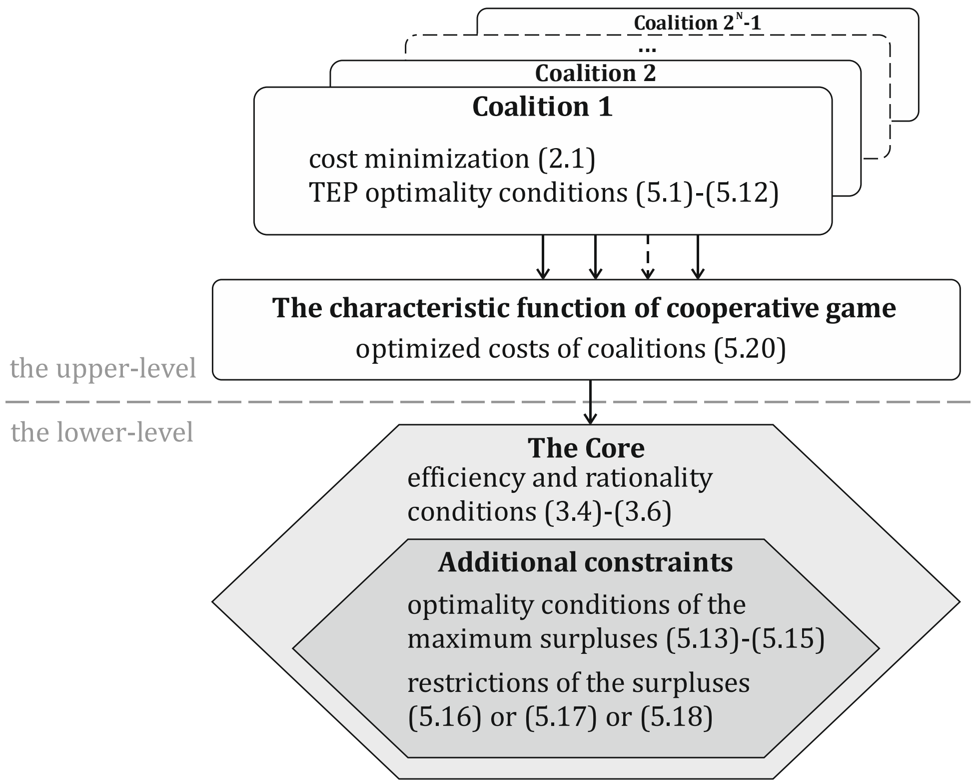


Figure 5.1: The bilevel TEP framework.

We believe that identification of suboptimal (in terms of cost savings) expansion planning solutions could be extremely useful in the projects of cross-border energy cooperation, where a certain level of cooperation stability should be guaranteed. In the next section, we introduce a four-system case study and illustrate the potential of the developed bilevel TEP approach.

5.2 The Four-System Case Study – Bilevel TEP

To shed more light on the features of the bilevel TEP approach, we introduce the four-system case study. The topology of the possible interconnections (Figure 5.2) and parameters of the systems (Table 5.1) lead to a highly nonconvex cooperative game where certain players could be underestimated in the grand coalition. It is assumed that the five power lines with the maximum capacity of 100 MW each and investment cost 10 $/MWh are a subject of the transmission expansion discussion. Unlike the previous cases, we impose additional constraints on the generators and limit their outputs to the installed capacities of the systems.

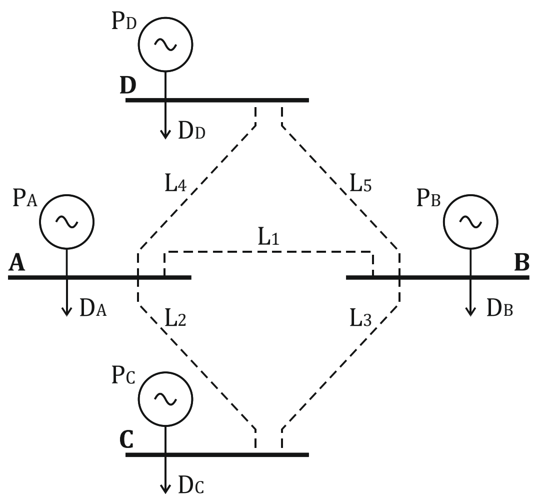


Figure 5.2: Model of the four-system case power interconnections.

Table 5.1: The four-system case study data.

Parameter	System A	System B	System C	System D
Supply function ($/MWh)	$12 + 0.025p_A$	$13 + 0.03p_B$	$11 + 0.02p_C$	$10 + 0.01p_D$
Power demand (MW)	2 300	2 500	1 000	1 000
Installed capacity (MW)	2 400	2 600	1 110	1 110

The single-level TEP model, (2.1)-(2.5), identifies the least-cost expansion plan depicted in Figure 5.3 (a). The optimal solution implies maximizing the export of the cheaper power from Systems C and D towards System B, which has the highest electricity price in the region. This expansion plan leads the cost savings of 10 475.3 \$/h (around 4.1% total cost decrease from 255 975 to 245 499.7 \$/h). To formulate a cooperative game over the interconnections, 2^4-1=15 scenarios of cooperation (coalitions) must be considered. The resulting game has a nonempty Core, which means that cooperation on the optimal expansion plan is theoretically possible. We show the allocations by different solution concepts and the initial costs of the systems in Table 5.2.

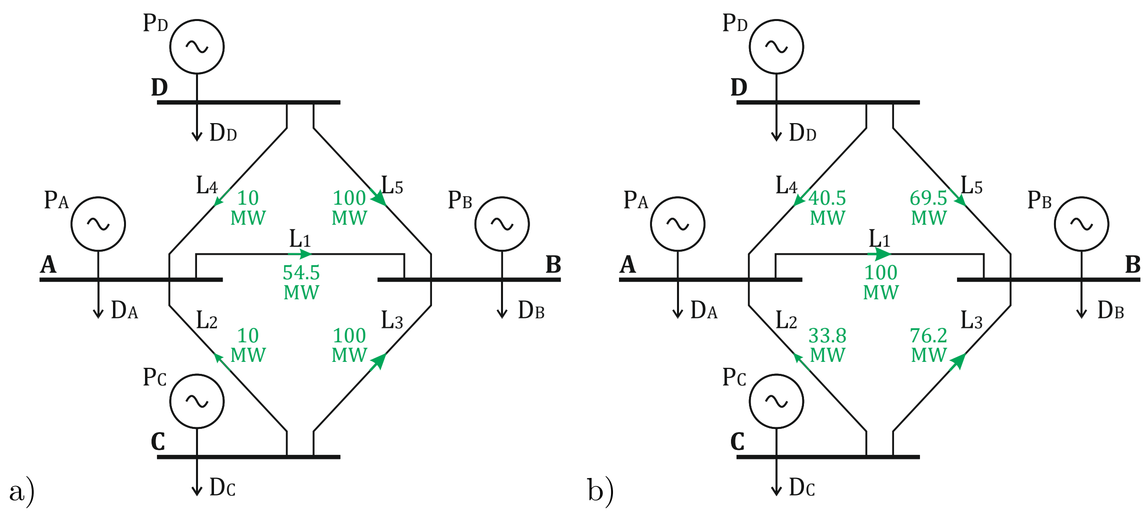


Figure 5.3: TEP solutions for the four-system case: a) the least-cost expansion plan; b) a suboptimal plan with equal maximum surpluses among players.

Table 5.2: Allocation solutions for the four-system case optimal transmission expansion plan.

Solution concept	Allocation of costs (savings) ($/h)			
	System A	System B	System C	System D
The Shapley value	92 346.1 (1 378.9)	123 062.7 (3 187.3)	18 448.8 (2 551.2)	11 642 (3 358)
The Nucleolus	93 362.3 (362.7)	123 802 (2 448)	17 772.8 (3 227.2)	10 562.5 (4 437.5)
Equal sharing	91 106.2 (2 618.8)	123 631.2 (2 618.8)	18 381.2 (2 618.8)	12 381.2 (2 618.8)
No cooperation	93 725 (0)	126 250 (0)	21 000 (0)	15 000 (0)

However, the cooperative game on the optimal expansion plan turns out to be nonconvex, which can be verified by the multiple violations of the convexity condition (3.3). For example, the marginal contribution by System A to coalition {A,C,D} reaches -6 150 $/h (the negative value indicates cost decrease). Its contributions to coalitions {A,C} and {A,D} are -2 625 and -3 775 $/h respectively. But, in the grand coalition, {A,B,C,D}, System A is not such an important player and brings only -725.3 $/h of cost reduction. Thus, we face a situation where marginal contributions do not grow once more players join the coalitions. This is an undesirable condition which may leave some players underestimated. System A is a perfect example of such a player. It is a valuable participant of many coalitions: it may export power when cooperating with System B or obtain significant cost savings while importing power from Systems C and D. Unfortunately, in the grand coalition, there is no room for much electricity trading with System A.

Considering the contributions to all possible coalitions, the Shapley value acknowledges the importance of System A and allocates it around 13% of the total savings. But, the cooperative game is such a highly nonconvex that the Shapley value falls out of the Core. It may not be, therefore, considered as a reasonable solution due to the violation of the coalitional rationality condition (3.6). On the bright side, the solution by the Nucleolus is guaranteed to be within the Core. It satisfies the rationality conditions and allocates System A barely 3.5% of the grand coalition's savings. Even though the nonemptiness of the Core signifies that cooperation over the optimal expansion plan is theoretically possible, it is clear that there exists a severe imbalance in player's positions in the cooperation. Moreover, as we will show soon, the Core of this game is rather small in volume compared to the set of imputations, which is another indicator of possible stability issues in cooperation on the project.

We formally describe the imbalance using the coalitional excess theory and analyzing maximum surpluses among the players. Taking the Nucleolus as the imputation $x(N;v)$ that is a part of the Kernel and the Core, we can evaluate the maximum surpluses for any distinct pair of players, $s_{ij}(x)$, as defined in (3.28)-(3.31). It occurs that the lowest of the surpluses, 362.7 \$/h, are the ones related to System A: s_{BA}, s_{CA}, and s_{DA}. As discussed in the previous sections, the surpluses in cost games can be interpreted as bilateral threats with positive values – the subsequent cost increase of a player who executes the threat. Thus, the low values of surpluses against System A indicate that other systems would not lose much if not cooperating with the system. The threats against other players are less reasonable. For example, the maximum surplus of System B over System C, s_{BC}, equals 964.8 \$/h, over System D, s_{BD}, is 1 025.1 \$/h.

To change the situation, we use the bilevel TEP model formulation (5.19)-(5.20) and impose an additional constraint of equality for all the surpluses among the players (5.18). The resulting suboptimal solution is depicted in Figure 5.3 (b). According to the new plan, less capacity is allowed to be exported to System B via lines 3 and 5. Instead, the cheaper power is transmitted to System A, which in turn transfers a share of it to System B. The cost savings decreased to 9 929.8 \$/h compared to the optimal solution (3.9% cost decrease from 255 975 to 246 045.2 \$/h). But, at the price of the tolerable increase in the total cost, we obtained much more balanced cooperation. We show the allocation solutions for the suboptimal transmission plan in Table 5.3. Now, the Shapley value and the Nucleolus allocate System A 20.7% and 13.7% of the total savings, respectively. The cooperative game still violates condition (3.3) and, therefore, is nonconvex. However, the Shapley value becomes an element of the Core, which increased in volume significantly. Regarding the bilateral threats, we see that all of the surpluses are equal to 1 359.85

\$/h (for the Nucleolus imputation). Under the new expansion plan, there are no players who outweigh the others. A multi-bilateral equilibrium has been reached.

Table 5.3: Allocation solutions for the four-system case suboptimal transmission expansion plan with the enhanced stability of cooperation.

Solution concept	Allocation of costs (savings) (\$/h)			
	System A	System B	System C	System D
The Shapley value	91 673.9 (2 051.1)	123 684.1 (2 565.9)	18 679.7 (2 320.3)	12 007.6 (2 992.4)
The Nucleolus	92 365.1 (1 359.9)	124 080.1 (2 169.9)	18 375 (2 625)	11 225 (3 775)
Equal sharing	91 242.6 (2 482.4)	123 767.6 (2 482.4)	18 517.6 (2 482.4)	12 517.6 (2 482.4)
No cooperation	93 725 (0)	126 250 (0)	21 000 (0)	15 000 (0)

The presented suboptimal solution is not the unique one of interest. There exist multiple suboptimal expansion plans with multi-bilateral equilibrium. Moreover, there may be no need to reach equilibrium. For some problems, it may be enough to limit the maximum surpluses among players, therefore, setting a desirable range of bilateral threats. We visualize the possible outcomes of the bilevel TEP by gradually tuning lower and upper bound constraints of the maximum surpluses among the players in (5.16) and (5.17). The influence of these constraints on the expansion decisions, savings allocation, maximum surpluses, and changes in the total cost are illustrated in Figures 5.4 and 5.6. We also present several snapshots of the set of imputations and the Core of the game in Figures 5.5 and 5.7 to show the evolution of cooperation on possible planning decisions.

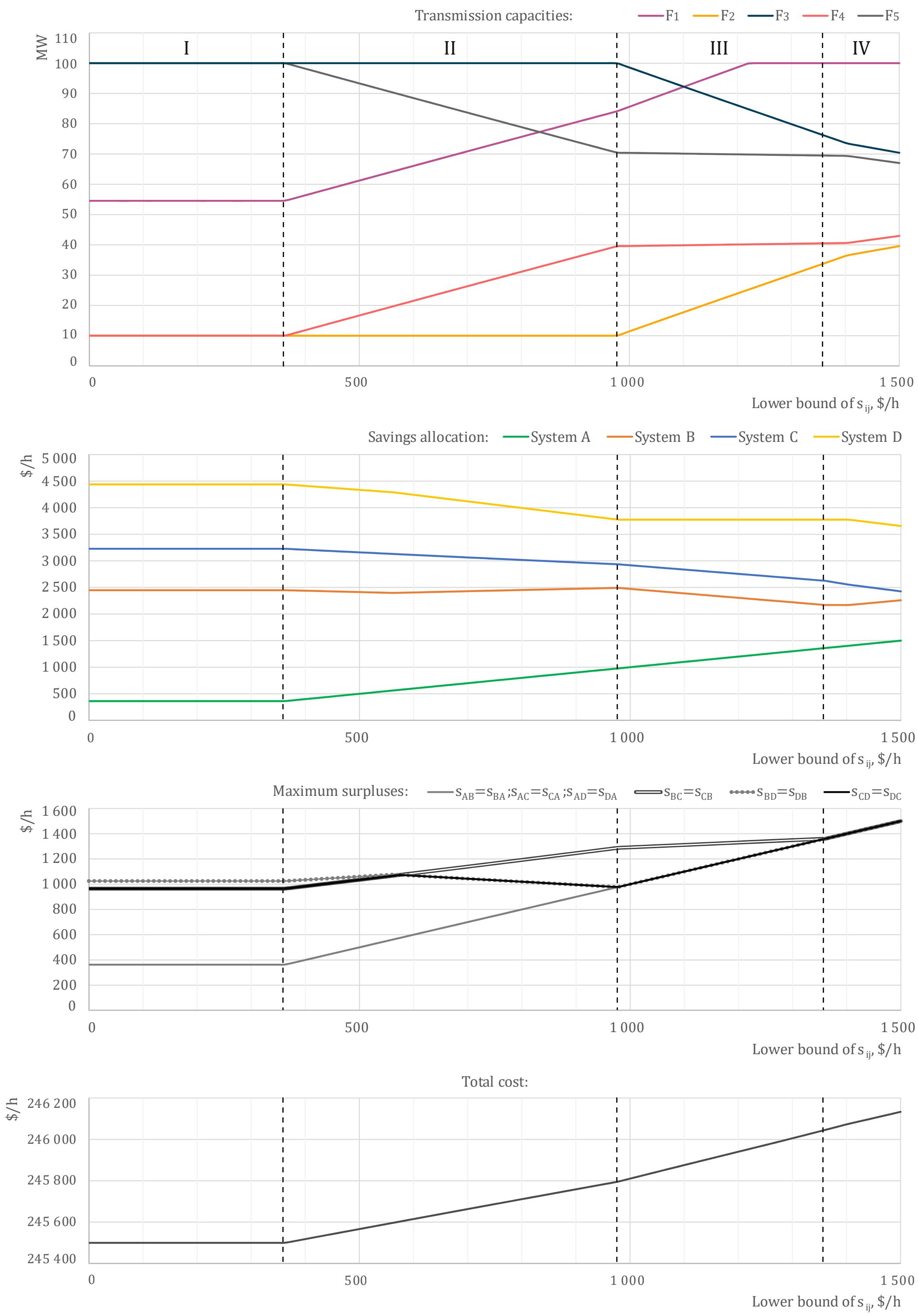


Figure 5.4: Dependence of the four-system case expansion plan and the cooperative game on the lower bound of the maximum surpluses among players.

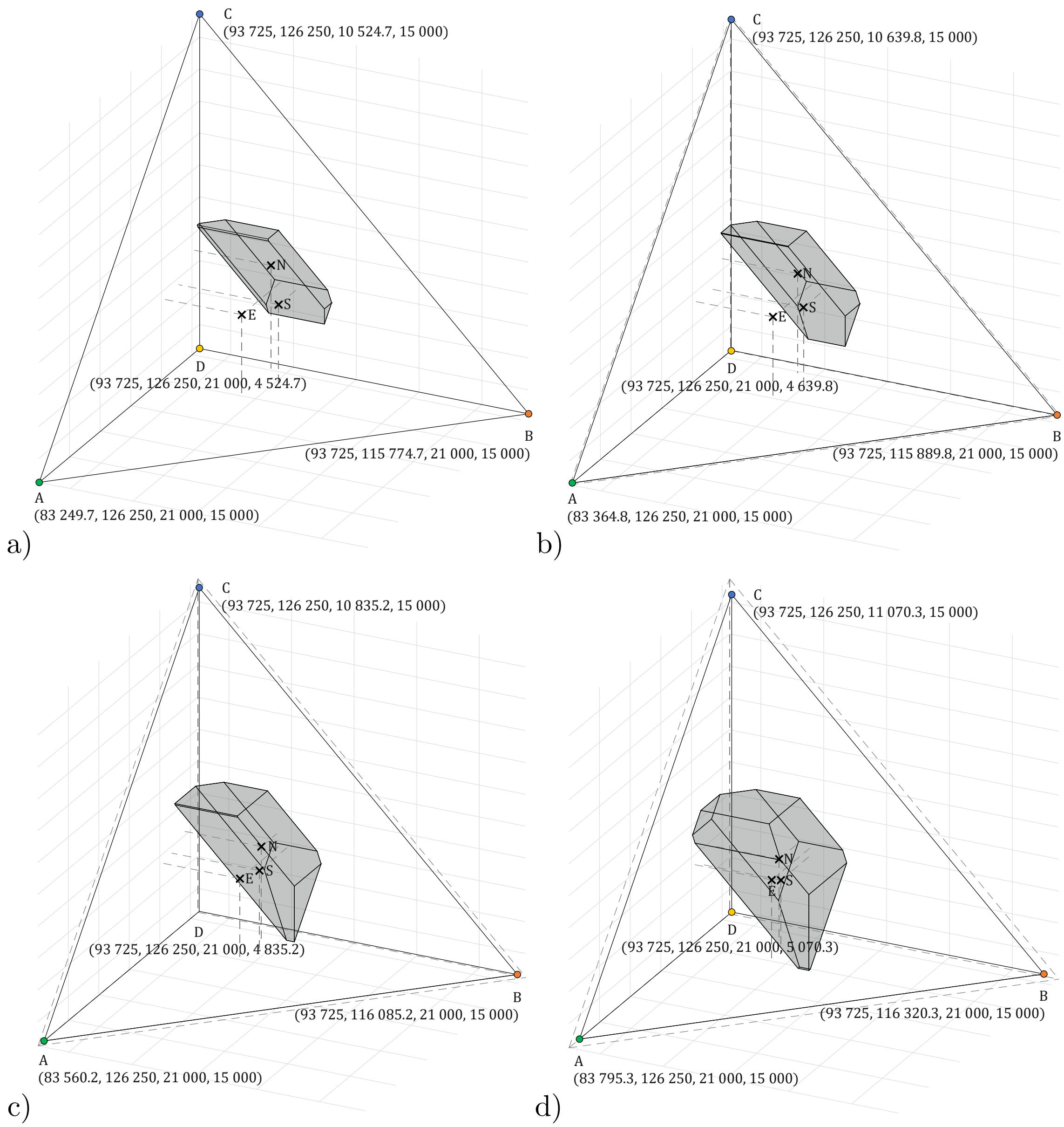


Figure 5.5: The set of imputations and the Core of the cooperative games for the four-system case with different lower bounds imposed on the maximum surpluses among players $s_{ij}(x)$: a) 200 \$/h; b) 600 \$/h; c) 1000 \$/h; d) 1360 \$/h. The allocation solutions are denoted as follows: S - the Shapley value, N - the Nucleolus, E - equal sharing point.

We first discuss the changes caused by the lower bound constraints (Figures 5.4 and 5.5). The general interpretation of such constraints is that we limit the differences in players' surpluses from below. Thus, we seek for solutions were everyone has unreasonable threats (with high surplus) against the others. For the sake of clarity, we break the range into four regions, as shown in Figure 5.4, and give the detailed explanations below:

I. Imposing a lower bound constraint in the range 0 - 362.7 \$/h makes no changes to the optimal transmission plan resulting from the bilevel TEP model (5.19)-(5.20). We observe a static picture of the unbalanced cooperative game that is a result of the expansion plan presented in Figure 5.3 (a). The Core of this cooperative game is small compared to the set of imputations, as shown in Figure 5.5 (a). Moreover, the Shapley value (point S) is out of the Core.

II. While increasing the lower bound of $s_{ij}(x)$ and reaching the threshold of 362.7 \$/h (the lowest surpluses in the game), we start modifying the expansion plan to increase the surpluses related to System A. One may notice that there is less power allowed to be transferred through line 5 to System B. Instead, System A is becoming more involved in the cooperation by importing more power through line 4 and exporting more via line 1. Its importance starts gradually growing, as shown by the changes in the savings allocation. In Figure 5.5 (b), we see the set of imputations and the Core for the expansion plan with a lower bound of $s_{ij}(x)$ equal 600 \$/h, which is within the considered range. The Shapley value is still out of the Core. However, the Core grew in volume and stretched towards the vertex A. We should also mention that the modified set of imputations shrank compared to the initial one (the grey dashed tetrahedron). This indicates that there are fewer savings to share among the players under the suboptimal expansion plan.

III. The further increase in the lower bound leads to the solutions where all pairs of players except Systems B and C are equalized in bilateral threats. Figure 5.5 (c) shows that the Core increased even more in volume, and the Shapley value became a part of it. Of course, this improvement came at the price of savings decrease and shrinking of the set of imputations.

IV. Finally, when reaching the limit of 1 359.85 \$/h, all the surpluses among the players become equal. There is no point in further increasing the lower bound and searching for less optimal solutions. We can state that the expansion plan presented in Figure 5.3 (b) is the least-cost solution among all suboptimal plans with multi-bilateral equilibrium. Figure 5.5 (d) shows that the Core expanded significantly. It now contains not only the Shapley value but also the equal sharing point. However, the modified cooperative game remains nonconvex.

It is also worth highlighting that the modified expansion plan depicted in Figure 5.3 (b) does not lead to a trivial cooperative game, with all the players being symmetric to each other. To verify this, one may check that the Core is not symmetric, and the Shapley value does not allocate the savings equally among the players. Thus, the proposed bilevel TEP approach does not aim to set equal conditions for all the participants. Instead, it seeks for solutions with no significant imbalance in players' bilateral surpluses, effectively expanding the bargaining space and making the cooperation more stable.

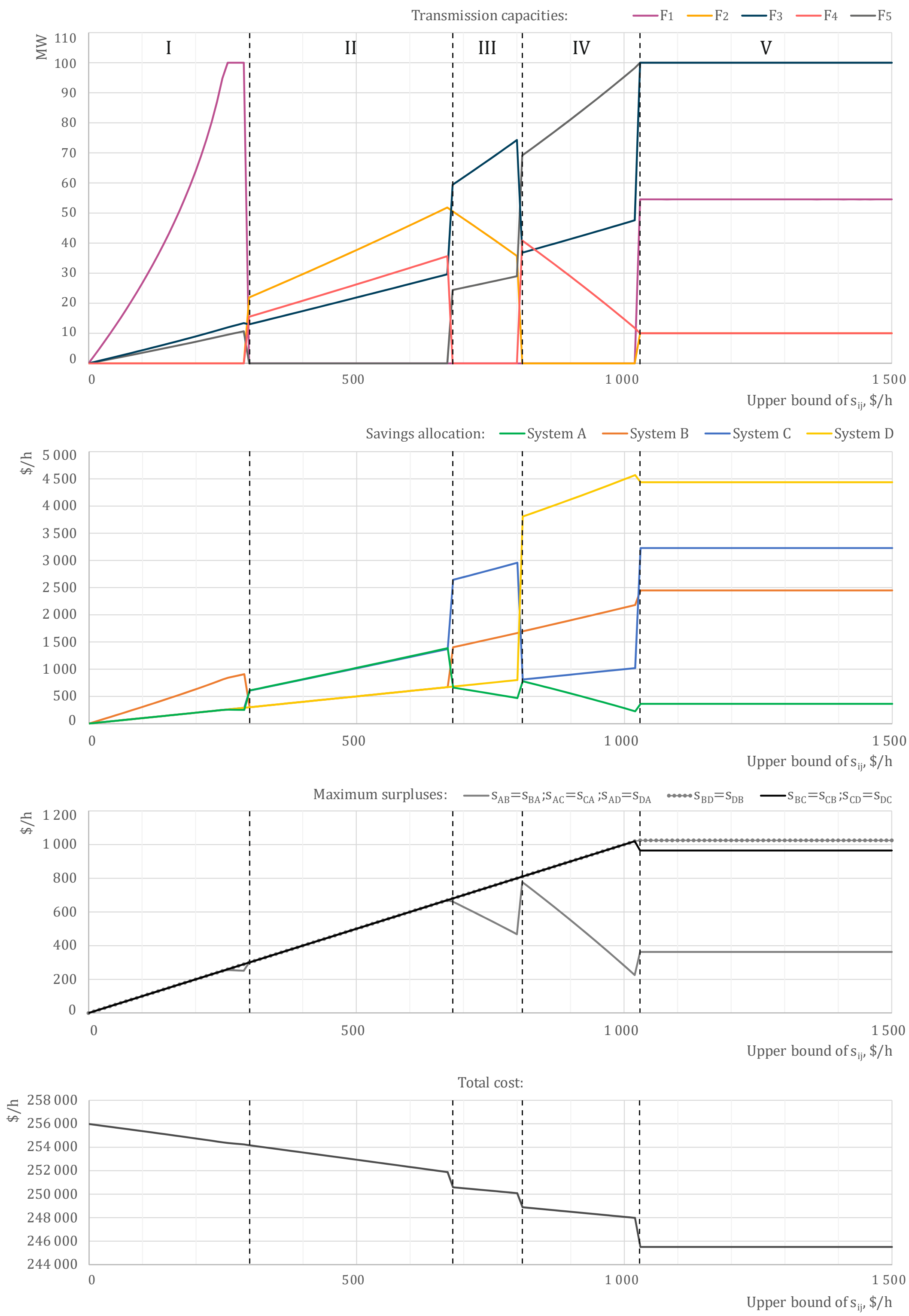


Figure 5.6: Dependence of the four-system case expansion plan and the cooperative game on the upper bound of the maximum surpluses among players.

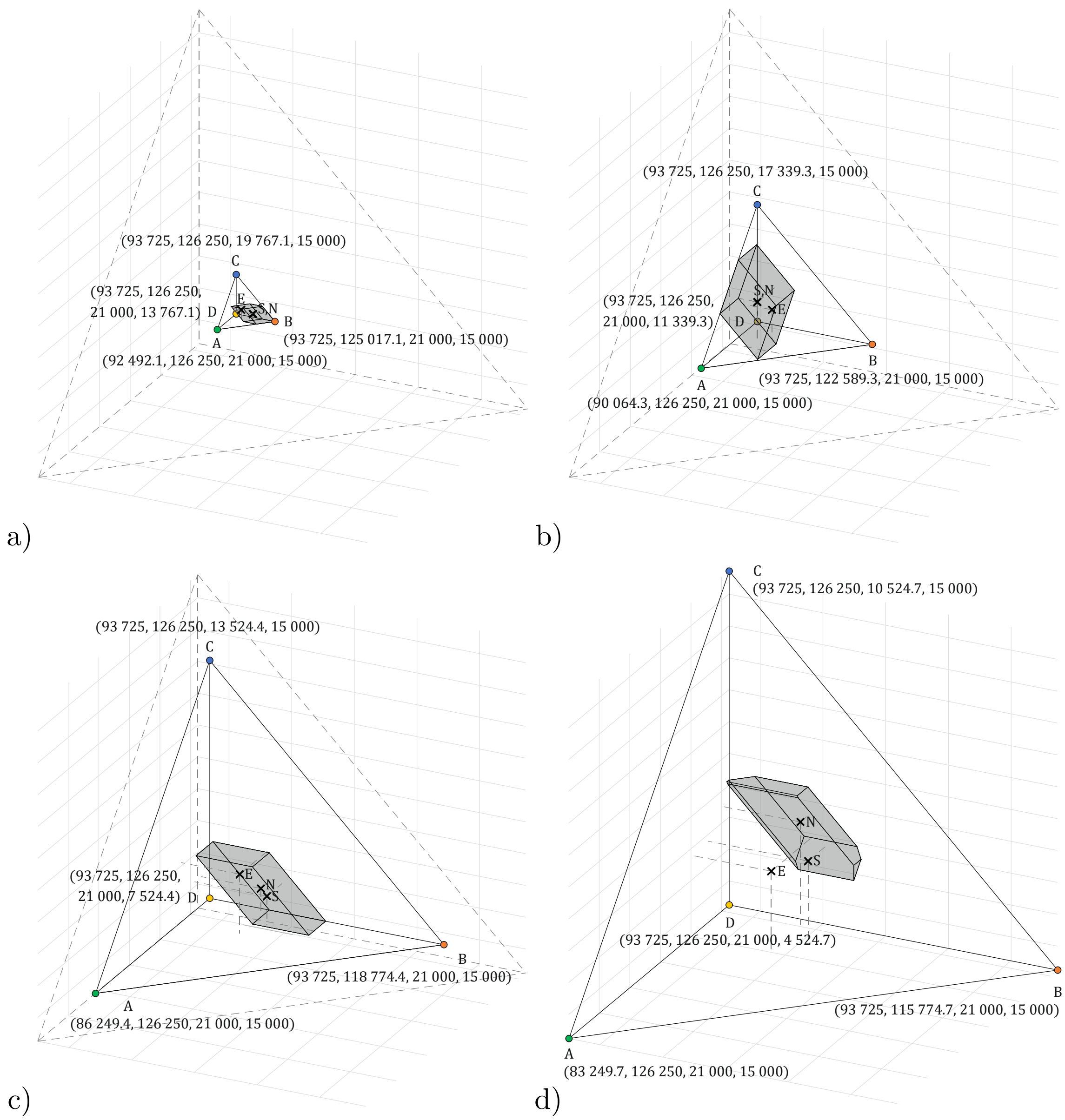


Figure 5.7: The set of imputations and the Core of the cooperative games for the four-system case with different upper bounds imposed on the maximum surpluses among players $s_{ij}(x)$: a) 200 \$/h; b) 600 \$/h; c) 900 \$/h; d) 1026 \$/h. The allocation solutions are denoted as follows: S - the Shapley value, N - the Nucleolus, E - equal sharing point.

By varying the lower bound of the maximum surpluses among the players, we demonstrated how the optimal solution could be modified to reach the least-cost alternative with a multi-bilateral equilibrium. However, we did not cover the entire range of possible suboptimal solutions. Another approach of identifying suboptimal plans lies in varying the upper bound of surpluses. By limiting the bilateral threats from above, it is possible to model a range of interim expansion decisions from the case of no cooperation to the optimal expansion plan. We illustrate the changes in the expansion decisions and the subsequent cooperative games in Figures 5.6 and 5.7. The evolution of the planning decisions is more complicated than in the case of tuning the lower bound of $s_{ij}(x)$. We identify the five distinct regions and provide the explanations below:

I. The first region of the solutions starts with the case of no cooperation: no lines are allowed to be built to nullify players' surpluses. With the increase in the upper bound, more capacity is added to interconnect the systems. The least effective expansion decision, power export from System A to B via line 1, is made to keep the players in a multi-bilateral equilibrium while minimizing the total cost. As shown in Figure 5.7 (a), the Shapley value belongs to the Core. However, the set of imputations contracted dramatically due to the drop in the cost savings. It is also worth mentioning that even such an extremely suboptimal expansion plan does not lead to a convex game. There still exist multiple violations of the convexity condition (3.3), meaning that players bring more contribution to subcoalitions than to the grand coalition.

II. With a further increase in the upper bound of players' surpluses, it becomes not optimal to keep the expansion plan from the previous region. Instead, it is possible to utilize more efficient interconnections: lines 2, 3, and 4. Bilateral threats among the players are kept equal, and the Shapley value is still a part of the Core. By looking at the shape of the Core in Figure 5.7 (b), we may notice that the structure of the cooperative game changed cardinally. The Core shifted towards the A vertex, making System A one of the most valuable players in the cooperation, with the total savings of 33% allocated by both the Shapley value and the Nucleolus. Even though we saw that System

A is the less valuable player in the cooperation on the optimal expansion plan, its position may change significantly if additional constraints are imposed on the planning decisions. As follows from Figure 5.6, there are multiple shifts in the planning paradigm that provide a "menu" of possible suboptimal solutions subject to the limits on players' surpluses.

III. In this region, the surpluses among the players start diverging. The first deviation is observed in the surpluses related to System A: s_{BA}, s_{CA}, and s_{DA}. The expansion decisions start approaching the optimal expansion plan. Therefore, the position of System A deteriorates.

IV. Another shift in the planning decisions leads to cooperative games that resemble the cooperation on the optimal expansion plan. Figure 5.7 (c) shows that the Core is located far from the A vertex, and the Shapley almost falls out of it. The difference in surpluses among the players diverged even further.

V. With the upper bound higher than 1 025.1 \$/h, we impose no additional restrictions on the TEP model. Thus, we observe the optimal expansion plan with a significant imbalance in players' positions. The shape of the Core depicted in Figure 5.7 (d) is identical to the one in Figure 5.5 (a).

By showing the range of possible expansion decisions depending on the lower and upper bounds of players' surpluses, we demonstrated how many of the reasonable suboptimal transmission plans might be revealed and reasoned. The question arises, what is the possible implementation and justification of the bilevel TEP approach for real-world projects? After a series of discussions, we came with the two following explanations of why the developed approach should be useful in reality:

- First, the restriction of player's surpluses in energy cooperation reflects the sanctions approach, where an international entity may be willing to diversify its energy supply by limiting export from certain counterparts. This issue is especially acute in natural gas supply. For example, the works [150], [151], [152], [153] highlighted the bargaining power imbalance in the Eurasian natural gas supply chain. The proposed bilevel TEP approach can be used to wisely select sanctions while minimizing the overall cost of a project.

- Second, the revealed suboptimal transmission plans may reflect decentralized solutions of a bargaining process over the expansion project. The idea of imposing limits on bilateral threats captures the psychological behavior of players, who may not be willing to participate if being not valuable enough in the coalition. Therefore, a different expansion plan may be agreed upon to take into account the expectations of all participants.

The above justification for the suboptimal planning solutions is meaningful under the assumption that the players are somehow obliged to form the grand coalition. Then, it becomes possible to suggest a compromise between the economic efficiency of a transmission plan and the stability of cooperation. A suboptimal plan with a multi-bilateral equilibrium, such as the one depicted in Figure 5.3 (b), may be considered. However, if acting rationally without additional obligations, the players may not necessarily form the grand coalition. A suboptimal expansion plan may not be incentive-compatible for certain players. In the mentioned example, the obtained allocation solutions for the cooperation on the suboptimal plan (the Shapley value, the Nucleolus, and the equal sharing point) belong to the modified Core, as shown in Figure 5.5 (d). But, all of these solutions fall out of the initial Core related to the optimal transmission plan, violating the coalitional rationality constraint (3.6) for systems B, C, and D. Thus, instead of approving the suboptimal transmission plan, these systems would form the subcoalition {B,C,D} where they can achieve higher cost savings.

To avoid such outcomes, additional constraints should be imposed on the bilevel TEP model to force the allocation solution for a modified expansion plan stay within the Core of the initial game over the optimal plan. We introduce this rationality-preserving constraint for systems B, C, and D by stating that the systems must be allocated no more cost in the grand coalition than they can obtain on their own without external restrictions and obligations: $x_B + x_C + x_D \leq v'(\{B, C, D\})$. In numbers, coalition {B,C,D} should be allocated no more than

152 500 \$/h of cost, which is equivalent to allocating no less than 9 750 \$/h of savings. Under the new constraints, the Core cannot expand as vastly as it was shown in Figure 5.5. The lower bound of the maximum surpluses can be increased only up to 606.8 \$/h. At this point, we obtain a suboptimal expansion plan with the allocation solution (in this case, the Nucleolus) lying at the border of the initial Core. We visualize the impact of the rationality-preserving constraint by combining the sets of imputations for the initial and modified cooperative games in Figure 5.8. It is seen that the Core of the modified cooperative game (highlighted blue) expanded towards the A vertex. But, its expansion was limited by the new Nucleolus solution (point N2), which must stay within the initial Core (highlighted grey). Such an expansion plan may improve the stability of the cooperation by enlarging the Core of the game while satisfying the initial rationality constraints.

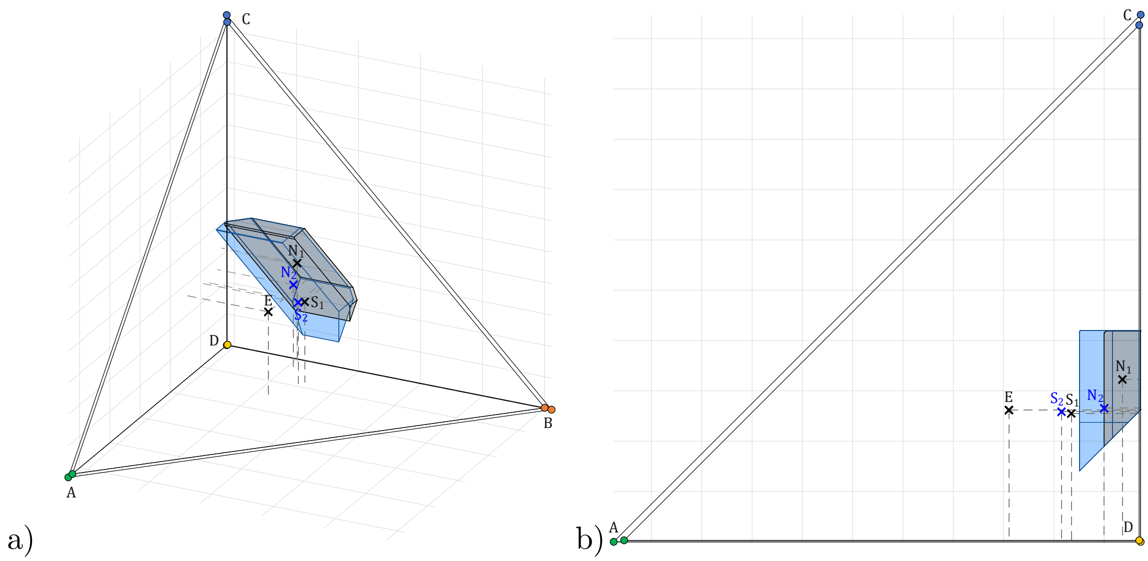


Figure 5.8: The combined sets of imputations and the Cores for the four-system case cooperative game on the initial optimal expansion plan (grey) and the modified cooperative game on the suboptimal plan with the lower bound of maximum surpluses 606.8 \$/h (blue): a) the four-player set of imputations in the barycentric coordinates; b) projection onto the A-D-C set. Index “1” of the allocation solutions relates to the optimal plan, index “2” - to the suboptimal one.

This section illustrated the idea of embedding the Cooperative Game Theory principles into TEP algorithms, which is the novel contribution by the thesis. Adjustment of the investment decisions in an anticipating manner depending on the players' positions in cooperation has never been suggested nor implemented in power systems research. The proposed bilevel modeling approach paves the way for new implementations of the mechanism design and algorithmic game theory in power systems and other fields. While highlighting the usefulness of the examined bilevel TEP model and the identified suboptimal solutions, we acknowledge that further research is needed on the allocation mechanisms. It is necessary to reach the incentive-compatible solutions by taking into account both the cooperative and noncooperative nature of negotiations over cross-border transmission expansion projects. In this regard, we consider the recently formulated class of biform games [154] as a promising tool for addressing cooperating and competition issues in planning and operation tasks. Finally, more effort is needed to develop electricity trading mechanisms consistent with the Cooperative Game Theory framework. The coordinated multilateral trading [155] or other emerging operating paradigms could be implemented to ensure the stability of cooperation and fair savings allocation while preserving efficient competition among market participants.

5.3 Discussion of Strategyproof TEP Mechanisms

In this section, we discuss how the proposed bilevel TEP model can be useful for developing strategyproof mechanisms of cooperation. We again perform the manipulability analysis for the three-system case study. In Section 4.2, we demonstrated that Systems A and B could successfully manipulate the allocation rule in a wide range of cost deviations. In this section, we impose additional game-theoretic constraints on the lower-level of the TEP model. Namely, we restrict the maximum surpluses among the players depending on the total savings of cooperation. The total savings, TS, are estimated as the difference between the sum of players' individual costs and the cost of the grand coalition, $v(N)$, as stated by the following equation.

$$TS = \sum_{k \in N} v(k) - v(N) \tag{5.21}$$

In the optimal expansion plan (described in Section 3.3.2), the total savings of cooperation amounted to 4 800 \$/h. We use conditions (5.16) and (5.17) to impose reasonable upper and lower bounds on the maximum surpluses among the players. We state that there must be no surpluses lower than 30% of the total savings, $\underline{s} = 0.3 \cdot TS$, and no surpluses higher than 40% of the savings, $\overline{s} = 0.4 \cdot TS$. Under such conditions, the bilevel TEP model provides a suboptimal expansion plan with total savings of 3 232.3 \$/h. The capacity of line 1 (between Systems A and B) was reduced to 40.16 MW, which made surpluses among the players more balanced. We visualize the changes in the set of imputations and the Core of the game in Figure 5.9. Because of the reduced savings, the set of imputations shrank from ABC to A'B'C'. The Core of the game and the allocation solutions became more centralized - the players are now in similar conditions. The grey dashed lined depict the initial Core of the game, which was far more distant from System C. We see that the suboptimal expansion plan suggests a compromise between the stability and the economic efficiency of cooperation.

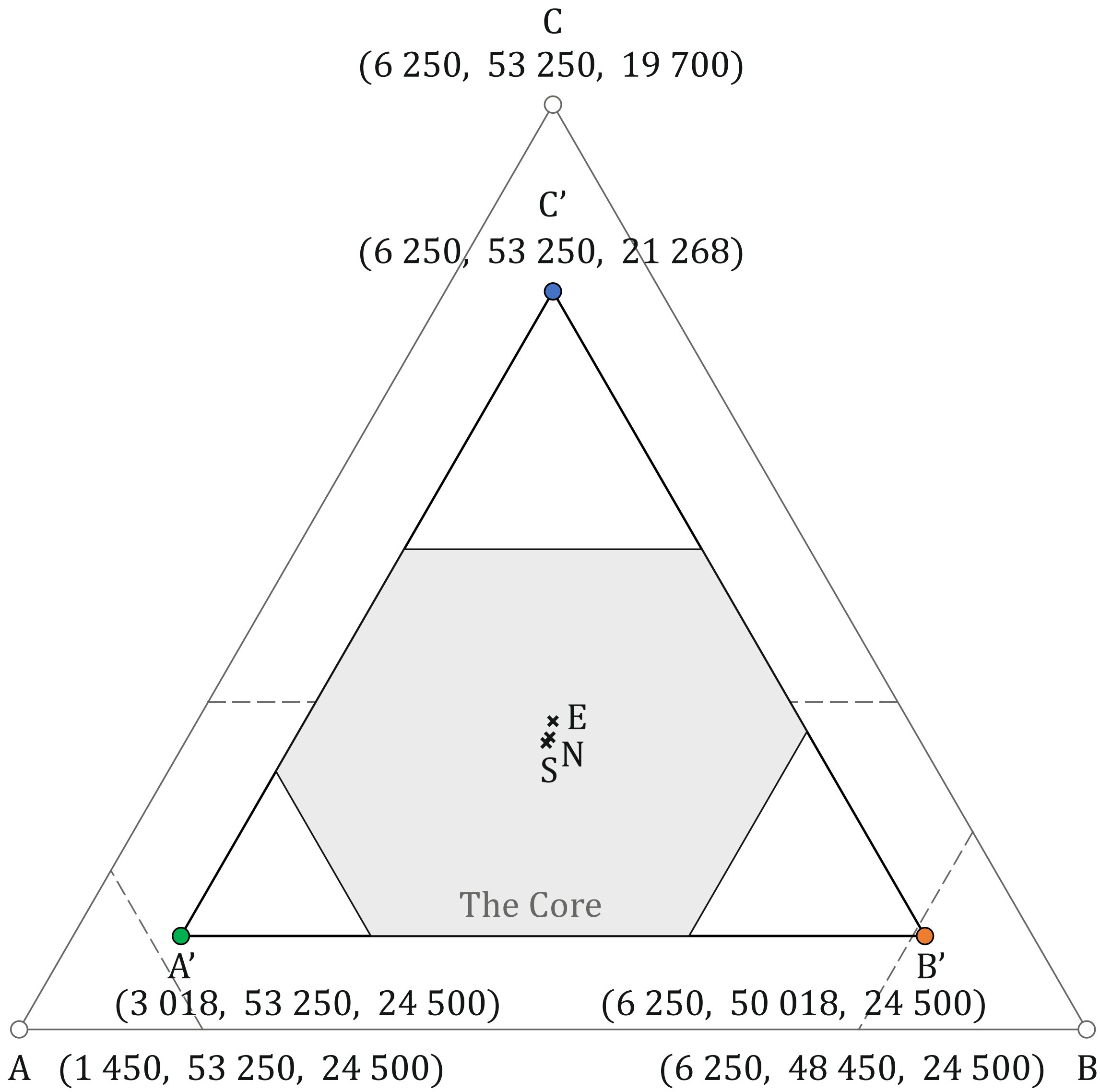


Figure 5.9: The set of imputations and the Core of the modified cooperative game for the three-system case. The values represent the corresponding costs for (A, B, C) in \$/h. The allocation solutions are denoted as follows: S - the Shapley value, N - the Nucleolus, E - equal sharing point.

Now we simulate the unilateral cost function manipulations by the players under the described bilevel TEP model. The effect of the manipulations on actual savings allocation is illustrated in Figure 5.10.

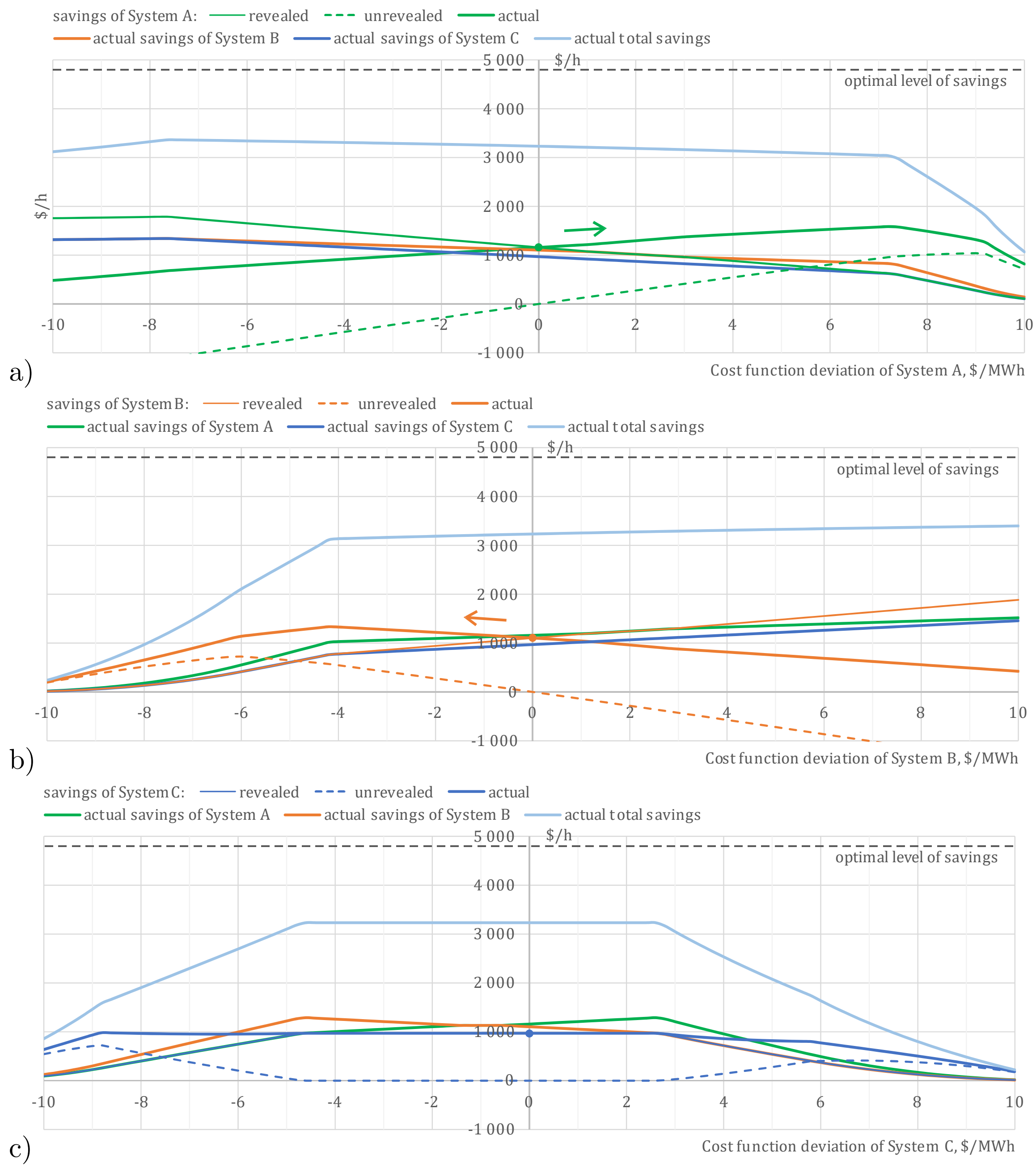


Figure 5.10: Cost function manipulations in the three-system case under the bilevel TEP approach: a) unilateral manipulation by System A; b) unilateral manipulation by System B; c) unilateral manipulation by System C.

We cannot state that the proposed bilevel approach completely prevents manipulations in TEP. Systems A and B still have beneficial directions of cost function deviation that we denote by the arrows. However, we see that players have a reduced range of possible deviations and fewer incentives to manipulate the allocation rule. This happens due to the fact that the bilevel TEP approach modifies the capacity of lines depending on the cost functions declared by the players. Thus, the planning model proactively reacts to the changes in the revealed share of savings. When deviating a lot, players activate the game-theoretic constraints and make the transmission plan even less efficient.

The inclusion of Cooperative Game Theory concepts into TEP algorithms paves the way for new mechanism designs of energy cooperation. We believe that there is room for further research on more complex and effective designs. For example, coordinating entity can set a function of coalitions imbalance level depending on the total savings. Such a function would allow significant differences in players' bargaining power only when an interconnection project becomes efficient enough. Otherwise, a less profitable but equal cooperation will be formed. It is also worth implementing iterative mechanisms and auctions suggested by the Algorithmic Mechanism Design studies such as [148], [156].

The ideas presented in this chapter can be extended beyond the transmission planning problems. Operation of power markets and international grids could also be restricted by the game-theoretic principles in order to keep the players more balanced or give them incentives to reveal true cost functions.

5.4 Summary and Conclusions

In this chapter, we demonstrated that finding the optimal (least-cost) expansion plan might not be enough to guarantee the stability of cooperation. Some projects of power interconnections could lead to nonconvex cooperative games. The Core of such games can be small in volume or even be an empty set, which means that some players get underestimated in the grand coalition and might refuse cooperation. To avoid such issues, it becomes necessary to consider suboptimal expansion plans with a predefined level of cooperation stability.

The question arises, how to measure the level of stability in cooperation? In this work, we decided to rely on the coalitional excess theory and use the maximum surpluses among players as the metric of stability. The maximum surpluses (also called bilateral threats) allowed us to identify the usefulness and interdependence of players. To include this metric into the planning model, we formulated the bilevel TEP approach, where the upper-level contains TEP problems for different coalitions of players, and the lower-level states the resulting cooperative game. We found that imposing upper and lower bounds on the surpluses of players can significantly improve the stability of cooperation. However, this improvement comes at the price of efficiency degradation. By varying the game-theoretic constraints, it becomes possible to suggest a variety of suboptimal expansion plans and find a compromise between the economic efficiency and the stability of cooperation. We believe that the proposed bilevel approach could be used in numerous applications to justify the effects of sanctions or simulate decentralized planning in a bargaining process.

Finally, we discussed the usefulness of the bilevel approach for developing strategyproof mechanisms of cooperation. We performed the manipulability analysis of cooperation in TEP with restrictions of maximum surpluses among the players. The results showed that the anticipative nature of the bilevel approach could decrease players' incentives to manipulate the allocation rule. The main advantage of the approach lies in the ability to not only change the shares of savings but also modify transmission capacities of interconnections.

However, we want to highlight that the proposed bilevel TEP approach is by no means complete. Further research is needed for analyzing different metrics of stability and effectively formulating the planning model with game-theoretic constraints. As we will discuss in the next chapter, the current formulation of the bilevel approach experience scalability issues when applied to realistic case studies. Including a high number of variables and constraints into the model leads to a large-scale MILP. Such a model becomes computationally hard to solve. Moreover, we did not succeed in completely preventing cost function manipulations by players. It is necessary to apply recent advances from Algorithmic Mechanism Design to develop strategyproof mechanisms. Thus, the presented bilevel approach is just an attempt to address the issues of cooperation stability in TEP.

Chapter 6

Northeast Asia Cross-Border Power Interconnections

The hardest game to win
is a won game.

- Emanuel Lasker
World chess champion 1894-1921

At the end of the thesis, we address the questions that our research initially started with. We aimed to promote international cooperation in electricity trade and developed the mathematical framework for TEP and cost-benefit allocation in cross-border power interconnection projects. We illustrated that the proposed approach enables identification of the optimal investment decisions while allocating the savings of the cooperation according to Cooperative Game Theory solution concepts. We also introduced the bilevel TEP model that guarantees that a desired level of stability will be reached in cooperation over an interconnection project. However, it is not yet clear how the discussed solution concepts should be implemented in real-world projects? What mechanisms need to be developed to guarantee fair and stable cooperation?

To get the complete picture of cooperation on cross-border power interconnection projects, in this chapter, we introduce a real-world case study of potential power interconnections in Northeast Asia. The case is of particular interest since it involves six players (countries) cooperating and has a rather complex topology of the interconnections, which allows us to open the discussion of possible cooperation and compensation mechanisms.

6.1 Case Study Description

Potential cross-border power interconnections in Northeast Asia have been the subject of political and academic discussions 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. Over time, such initiatives expanded and merged. Nowadays, the projects of cross-border power interconnections in Northeast Asia got the name "Asian Super Grid", which is actively used in the media to highlight the scale of cooperation. We refer to studies [157], [158] that describe a general concept of the Asian Super Grid and provide a historical background of the cross-border interconnection initiatives. It is worth mentioning 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 electricity trade in the region was examined in [16], [91], [159]. The results of existing studies show possible annual benefits that all the countries can obtain if being interconnected. These benefits are usually quantified in billions of US dollars of cost savings per year, gigawatts of generation capacity decrease, and megatonnes of annual CO_2 emissions reduction. However, the issue of costs and savings allocation was not addressed in the studies. In this chapter, we quantify the potential cost savings of cooperation on the cross-border power interconnections, based on publicly available data. Then, we apply the developed game-theoretic framework to allocate savings among the participating countries. We also analyze the cost allocation of the capital intensive HVDC interconnections and discuss the ways of arranging payments for power exports.

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 the benefits of potential interconnections. We identified nine power systems in our model: Russia and China are represented by several nodes, while other countries are given only by a single node per power system. The case study was composed in May 2018 on the basis of International Energy Agency World Energy Outlook [160] and local technical reports and documents, such as Chinese electric power yearbook [161], reports of the Institutes of Energy Economics (Japan) [162], long-term energy supply and demand outlook (Japan) [163], and the basic plan for long-term electricity supply and demand (the ROK) [164]. The proposed scheme of cross-border interconnections is presented in Figure 6.1. It is based on the schemes used in the studies [16], [159] and engineering judgment of the author. Only the interconnection between North and Northeast Chinese power systems (line 6-7) is considered operating. Other interconnections (dashed lines) are not built yet. Their construction is under consideration in our model. We consider that the proposed interconnections will be realized using HVDC technology. Therefore, the assumptions of our TEP model (such as the omission of the Kirchhoff's voltage law) will be reasonable for the analysis of the project.

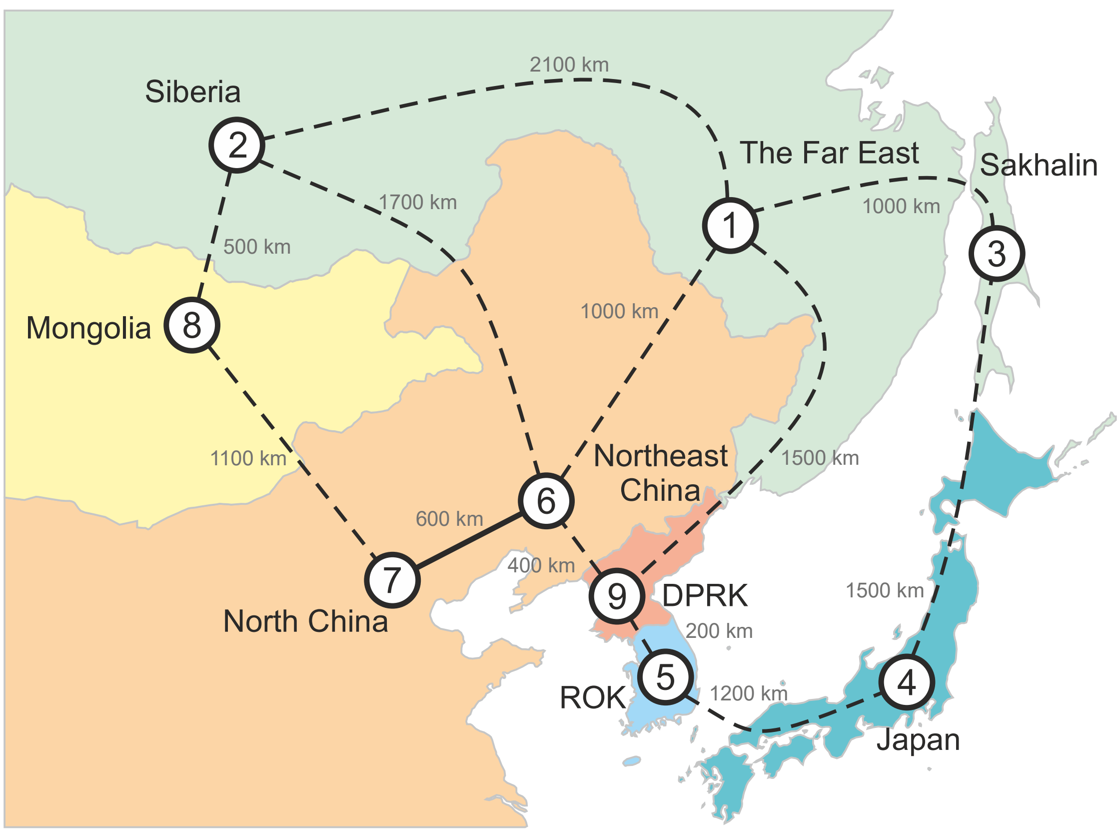


Figure 6.1: Scheme of potential cross-border power interconnections in Northeast Asia.

The forecast of the seasonal changes in power demand is presented in Figure 6.2. We observe a vast difference in power consumption among the countries. One may suppose that China, Japan, and the ROK are the main participants of cooperation that would influence regimes and prices of the future interconnected systems. We rely on generation expansion plans made at the national level of each country, given in Table 6.1, and do not perform generation capacity expansion. Cost assumptions for different types of generators are listed in Table 6.2. 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.

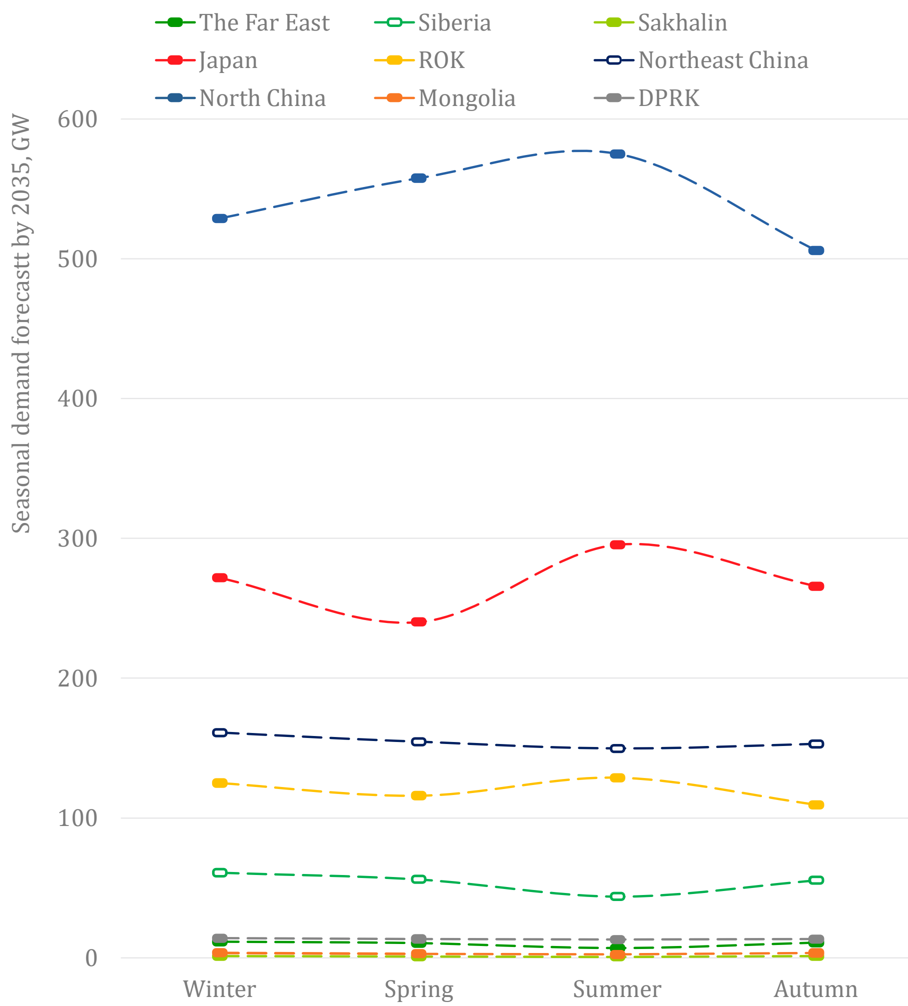


Figure 6.2: Seasonal demand curves forecast.

Table 6.1: 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 6.2: The levelized cost of electricity assumptions.

	Levelized cost of electricity by generation type ($/MWh)						
	Nuclear	Coal	Gas	Oil	Hydro	Wind	PV
The Far East	—	50,00	60,00	—	32,00	71,40	89,00
Siberia	27,00	50,00	60,00	—	32,00	71,40	89,00
Sakhalin	—	50,00	70,00	150,00	—	75,00	—
Japan	79,34	116,31	140,65	261,46	99,18	90,16	108,19
ROK	51,37	83,83	126,00	220,00	103,00	111,64	101,86
Northeast China	65,77	64,21	117,45	—	54,81	62,64	86,13
North China	65,77	64,21	117,45	—	54,81	62,64	86,13
Mongolia	—	75,00	—	—	60,00	95,00	100,00
DPRK	—	60,00	120,00	250,00	100,00	120,00	130,00

We assume that demand curves in each country are perfectly inelastic. The power supply functions can be represented by an arrangement of generators' costs in ascending order. We extend the diversity of the generation bids by splitting the cost of each technology into twenty blocks with values ranging from -5% to 5% of the costs in Table 6.2. By doing this, we keep the supply functions constant, which allows us to formulate a linear TEP problem and avoid some numerical issues in the future. The resulting generation supply curves for all the systems in the region are illustrated in Figure 6.3.

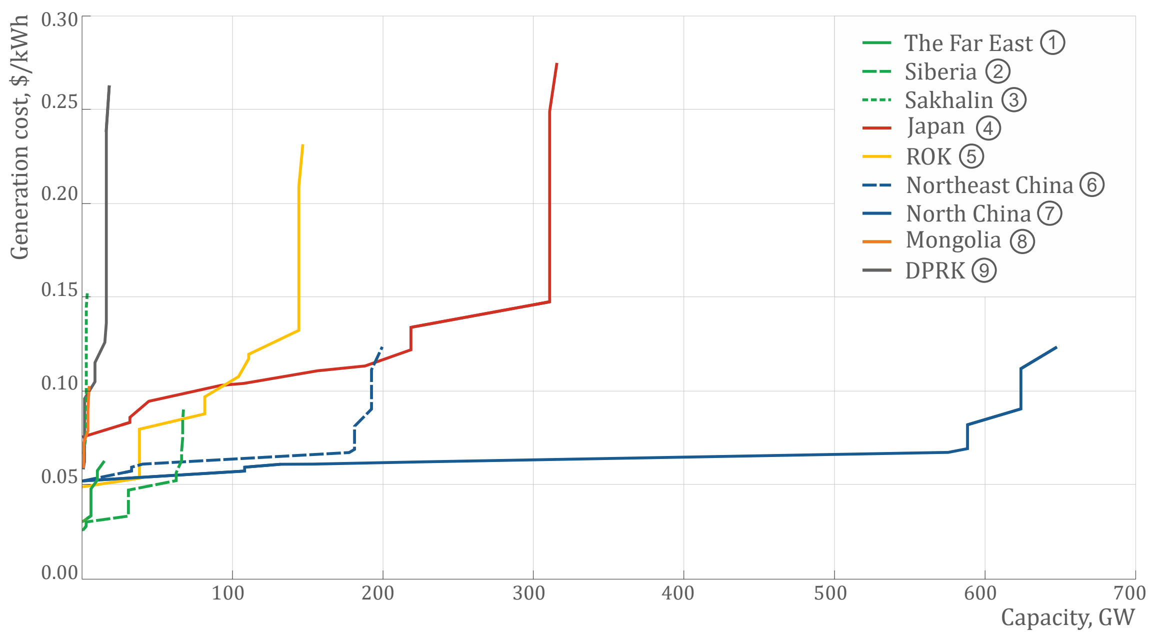


Figure 6.3: Northeast Asia generation supply functions forecast.

It is seen that generation costs and capacities vary significantly in the considered countries. This creates an opportunity for electricity trading, which could replace expensive generation with more affordable or clean energy sources. To assess the effectiveness of building the cross-border power lines, we use the annualized cost of transmission investment expressed in per unit of capacity. A similar approach was used by *Otsuki et al.* in [16]. A 25-year investment return period is considered with a 10% interest rate. Annualized net present costs of transmission lines are presented in Table 6.3. We impose technical limits on cross-border power lines capacity: no more than 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.

Table 6.3: Annualized transmission cost assumptions.

	Line	Length (km)	Annualized cost ($/MW/year)
2-1	Siberia – The Far East	2 100	84 000
2-8	Siberia – Mongolia	500	20 000
2-6	Siberia – North China	1 700	68 000
1-3	The Far East - Sakhalin	1 000	45 000
1-6	The Far East – North China	1 000	40 000
1-9	The Far East – DPRK	1 500	60 000
3-4	Sakhalin – Japan	1 500	256 000
8-7	Mongolia – North China	1 100	44 000
6-7	Northeast China – North China	600	—
6-9	Northeast China – DPRK	400	16 000
9-5	DPRK – ROK	200	8 000
5-4	ROK – Japan	1 200	88 000

6.2 Results and Discussion

We now present the analysis of the Northeast Asia case study using the developed game-theoretic framework. We first consider the optimal expansion plan and cost allocation solutions. Then we open a discussion of the practical implementation of the results and address the stability issues of the cooperation on the project.

6.2.1 Optimal Expansion Plan

The TEP problem was formulated as a linear programming model (2.1)-(2.5). It was solved using the Gurobi Optimizer v9.0.0 under JuMP v0.20.1 in Julia v1.1.1 programming language. The model contained 5 102 continuous variables, which, after the presolve stage [165], were reduced to 1 904 variables. To illustrate the effects of the cross-border power interconnections, we compare the two scenarios of cooperation: no cooperation (no cross-border power lines can be built) and complete cooperation (the grand coalition where all power lines can be constructed). The optimal transmission capacities and power flow directions for these scenarios are illustrated in Figure 6.4. The two-headed arrows depict reversible power flows that change their direction depending on seasons. The detailed information on power flows, market prices, generation and investment costs is given in Tables 6.4, 6.5, and 6.6. When no interconnections are allowed, there exist only two power flows between the systems: from Northeast China towards North China, and from the Far East towards Sakhalin. Line 1-3 is newly constructed (does not exist until 2035) with optimal capacity 596 MW and an annualized investment of 26.79 million US dollars per year.

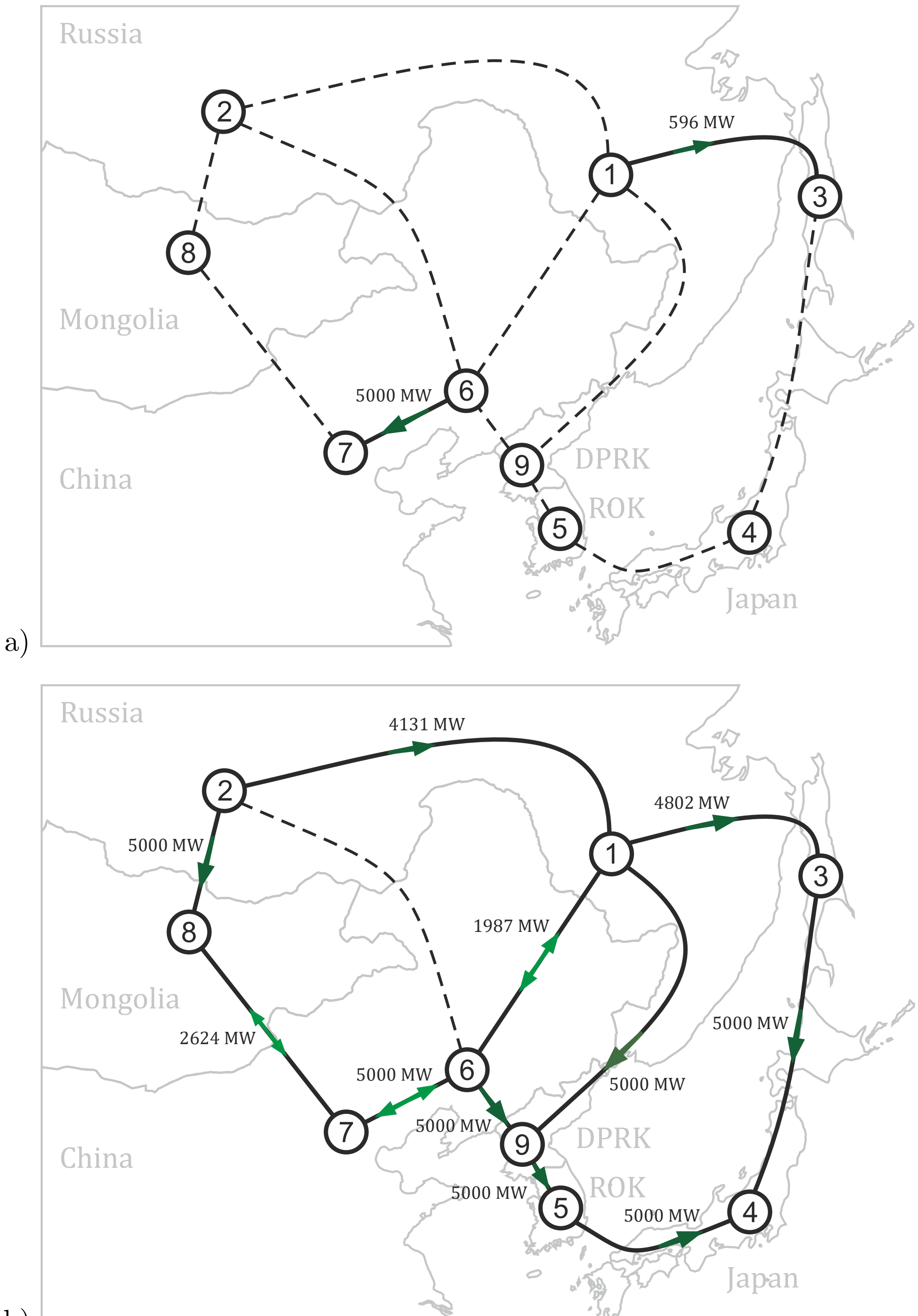


Figure 6.4: Optimal transmission capacities and power flow directions in case of no cross-border interconnections (a) and complete cooperation (b).

Table 6.4: Comparison of the scenarios: generation and investment costs.

	No cooperation	Complete cooperation
Total generation cost (million $/year)	756 949.72	746 846.86
Annualized investment cost (million $/year)	26.79	2 998.05

Table 6.5: Comparison of the scenarios: power flows.

	Line	Seasons			
		Winter	Spring	Summer	Autumn
Power flows in the case of no cooperation (MW)	2-1	—	—	—	—
	2-8	—	—	—	—
	2-6	—	—	—	—
	1-3	596	596	486	596
	1-6	—	—	—	—
	1-9	—	—	—	—
	3-4	—	—	—	—
	8-7	—	—	—	—
	6-7	4 760	5 000	5 000	4 400
	6-9	—	—	—	—
	9-5	—	—	—	—
	Line	Seasons			
		Winter	Spring	Summer	Autumn
Power flows in the case of complete cooperation (MW)	2-1	4 131	4 131	4 131	4 131
	2-8	1 414	5 000	5 000	5 000
	2-6	—	—	—	—
	1-3	4 680	4 802	4 802	4 802
	1-6	-1 987	-1 078	1 987	-1 423
	1-9	5 000	5 000	5 000	5 000
	3-4	5 000	5 000	5 000	5 000
	8-7	-1 466	2 624	2 624	2 336
	6-7	-2 227	5 000	5 000	467
	6-9	5 000	5 000	5 000	5 000
	9-5	5 000	5 000	5 000	5 000

Table 6.6: Comparison of the scenarios: electricity market prices.

	Node	Seasons			
		Winter	Spring	Summer	Autumn
Market prices in the case of no cooperation ($/MWh)	1	59.7	58.5	49.5	58.8
	2	52.3	51.5	49.8	51.5
	3	67.6	58.5	49.5	66.9
	4	142.1	137.1	146.6	141.4
	5	125.4	121.6	126.6	115.5
	6	66.8	66.5	66.5	66.5
	7	66.8	67.1	67.4	66.5
	8	78.0	76.5	75.0	77.3
	9	124.2	123.0	121.8	122.4
	Node	Seasons			
		Winter	Spring	Summer	Autumn
Market prices in the case of complete cooperation ($/MWh)	1	78.8	66.8	62.4	66.5
	2	66.8	60.9	51.0	60.0
	3	78.8	72.8	70.4	73.1
	4	140.7	135.7	144.2	139.9
	5	125.4	121.6	126.6	115.5
	6	66.8	66.8	66.5	66.5
	7	66.8	67.1	67.4	66.5
	8	66.8	61.5	51.0	66.5
	9	114.6	104.5	104.0	104.5

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 an additional interconnection between Russia and China. The general direction of the power flows is from Russia, Mongolia, and China towards the Korean peninsula and Japan. As expected, the cheaper energy flows towards the markets with higher prices, which leads to changes in market prices. Importers such as Japan experience a decrease in prices, while exporters as Russia have an increase in the price of electricity and generation cost. Nevertheless, with an annual investment cost of 2.99 billion US dollars, it is possible to get the total cost savings of 7.1 billion US dollars per year. Unfortunately, enumerating the total savings is not enough to persuade the countries to participate in the project. It is necessary to share the savings in a fair way and develop mechanisms for investment cost allocation and payments between the countries.

6.2.2 Cost and Savings Allocation

To address the cost allocation issues and evaluate the stability of cooperation, we use the Cooperative Game Theory solution concepts introduced in Chapter 3. These concepts require accounting for all possible scenarios of cooperation (coalitions of players). In the case of 6 players (countries), there are 2^6-1=63 scenarios to consider. For each scenario, we run the TEP model (2.1)-(2.5) to find the optimal planning decisions. For the sake of clarity, we present the costs for all of the possible coalitions in Figure 6.5. We see that coalition #6, the grand coalition, is indeed the least-cost scenario for the region. The optimized values from the objective function (2.1) for players participating in a coalition were used to compose the characteristic function of the cooperative game according to the following principle. If two neighboring countries join a coalition, a cross-border power line could be built, and some cost savings may be achieved. Otherwise, there is no way to build any lines when neighboring countries do not join the same coalition. It is worth mentioning that other approaches to coalition formation are possible. For example, *Kristiansen et al.* [54] considered combinations of interconnections to form the coalitional structure of a cooperative game, not combinations of players.

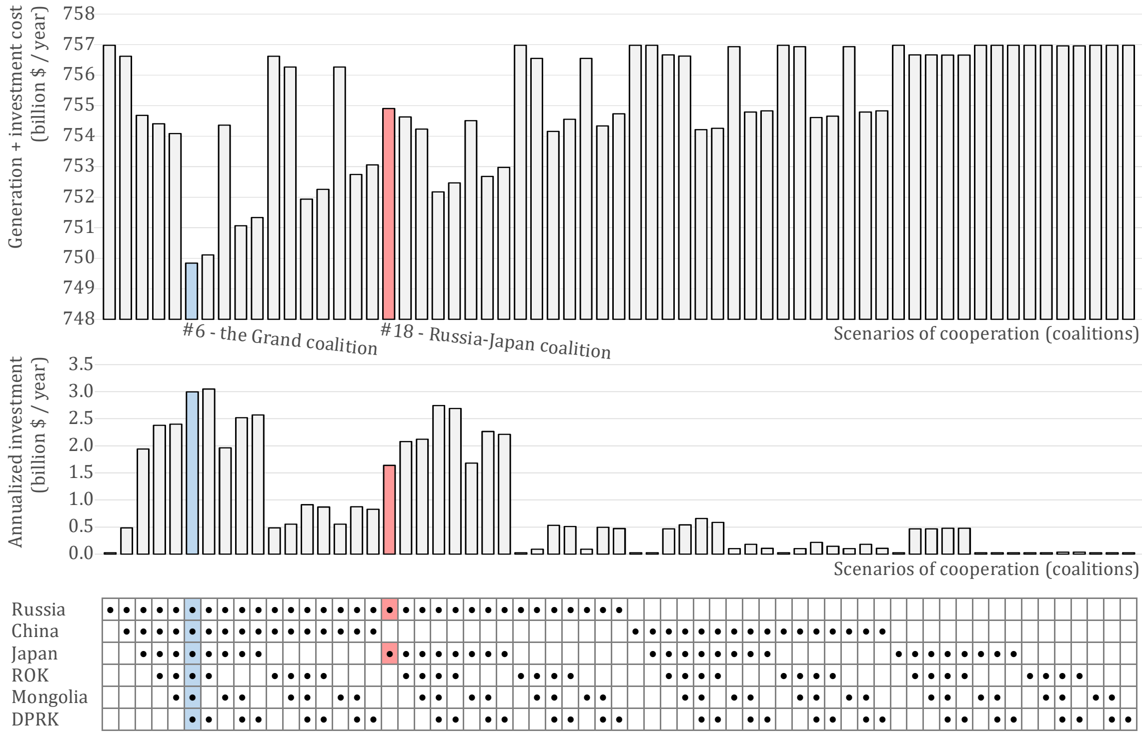


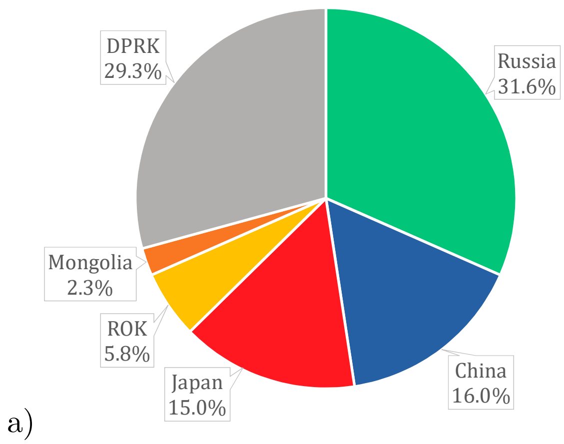
Figure 6.5: Generation costs and annualized investment costs of possible coalitions: (top) total costs; (mid) annualized investment costs; (bottom) the coalitional structure.

Even though the grand coalition turns out to be the most effective one, there is a need to persuade countries to join it. The point is that some countries may not be satisfied with an allocation solution and, therefore, would not join the grand coalition. For example, Russia and Japan may form their own subcoalition (#18 in Figure 6.5). In such a case, the power export "Siberia – The Far East – Sakhalin – Japan" of 5 GW would allow getting cost reduction up to 2.06 billion US dollars per year that can be split in half among the two countries. In order to prevent such situations, each country should be allocated more savings than it can get in any possible subcoalition. This condition states the Core of the game. In Table 6.7 we present the allocation solutions by the Shapley value and the Nucleolus. We also verify whether these solutions belong to the Core by checking conditions (3.5) and (3.6) for each of the 63 coalitions.

Table 6.7: Costs and savings allocation among the countries.

	Russia	China	Japan	ROK	Mongolia	DPRK
Generation and investment costs of the countries in case of no cooperation (billion \$/year)	22.48	378.51	256.26	86.69	1.90	12.14
Cost allocation by the Shapley value (billion \$/year)	20.23	377.37	255.19	85.28	1.73	10.05
Savings allocation by the Shapley value (billion \$/year)	2.25	1.14	1.07	0.41	0.17	2.09
Allocation belongs to the Core?	Yes					
Cost allocation by the Nucleolus (billion \$/year)	20.24	377.39	255.21	85.08	1.17	10.15
Savings allocation by the Nucleolus (billion \$/year)	2.24	1.12	1.05	0.61	0.13	1.98
Allocation belongs to the Core?	Yes (Theorem 3.4)					

As mentioned earlier, the optimized values from the objective function (2.1) was used to compose the characteristic function of the cooperative game. Thus, the obtained allocation solutions show how much of the total generation cost and total investment cost should be allocated to a country. The difference between the costs in the scenario of no cooperation and the allocated values shows the savings that a country should get if joining the grand coalition. Since there is no distinction between the generation and investment costs in the characteristic function, we refer to these solutions as allocation of the total cost and total savings. The allocation of the total savings by the Shapley value and the Nucleolus is visualized using the pie charts in Figure 6.6.



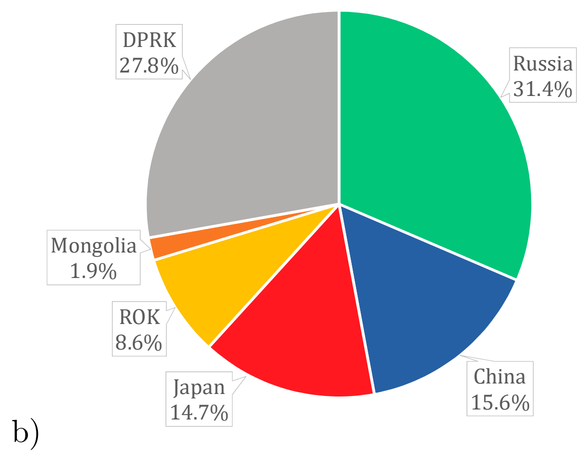


Figure 6.6: The allocation of the total saving (7.1 billion US dollars per year) among the countries by the Shapley value (a) and by the Nucleolus (b).

According to the results of the total cost allocation, it is possible to assure that each country may be compensated enough to stay in the grand coalition. The Core of the game is nonempty, which means that the development of cross-border power interconnections in Asia should be economically feasible and stable, at least theoretically. However, one can observe that the shares of savings that countries can claim differ significantly. This happens due to the difference in countries' bargaining power, which, in its turn, is explained by the topology of the cross-border interconnections and generation supply functions. For instance, the DPRK possesses a significant bargaining power while not being a major power exporter or importer. However, the DPRK is in a crucial location for the power interconnection in the region: it is on the way of power export towards the ROK and Japan. If the DPRK vetoes this power export direction, a significant share of savings would be lost. This "topological advantage" of the DPRK is identified by both the Shapley value and the Nucleolus. To change the situation, other plans of cross-border interconnections may be considered. For example, China may propose constructing an undersea cable directly linking mainland China and the ROK. Such an interconnection would lower the bargaining power of the DPRK and reallocate the cost savings among the countries.

It is seen that not only the shares of savings differ significantly, but also solutions by the Shapley value and the Nucleolus do not coincide. As discussed in

Chapter 3, the Shapley value allocates a value of cooperation by summing the marginal contributions of each player to possible coalitions, while satisfying the desired solution properties. Because of its properties, the Shapley value is often referred to as a fair solution concept. The Nucleolus maximizes the excess of the most dissatisfied coalitions and provides an allocation that is guaranteed to be a part of the Core. For this reason, the Nucleolus is often referred to as a stable solution concept. In this case study, both the Shapley value and the Nucleolus belong to the Core. We decide to use the allocation by the Shapley in our further analysis.

However, there is no guarantee that the Shapley value would remain in the Core under certain data permutations. As stated by Theorem 3.3, the Shapley value is guaranteed to belong to the Core only for the class of convex cooperative games. In such games, the marginal contribution of any fixed player i to coalition S increases as more players join the coalition. Unfortunately, the Northeast Asia cross-border interconnections case turns out to be a nonconvex game when formulated in terms of costs. To prove this, we introduce a counterexample. We computed the marginal contributions of Russia and the ROK to possible coalitions they may join. The values are presented as a bar diagram in Figure 6.7.

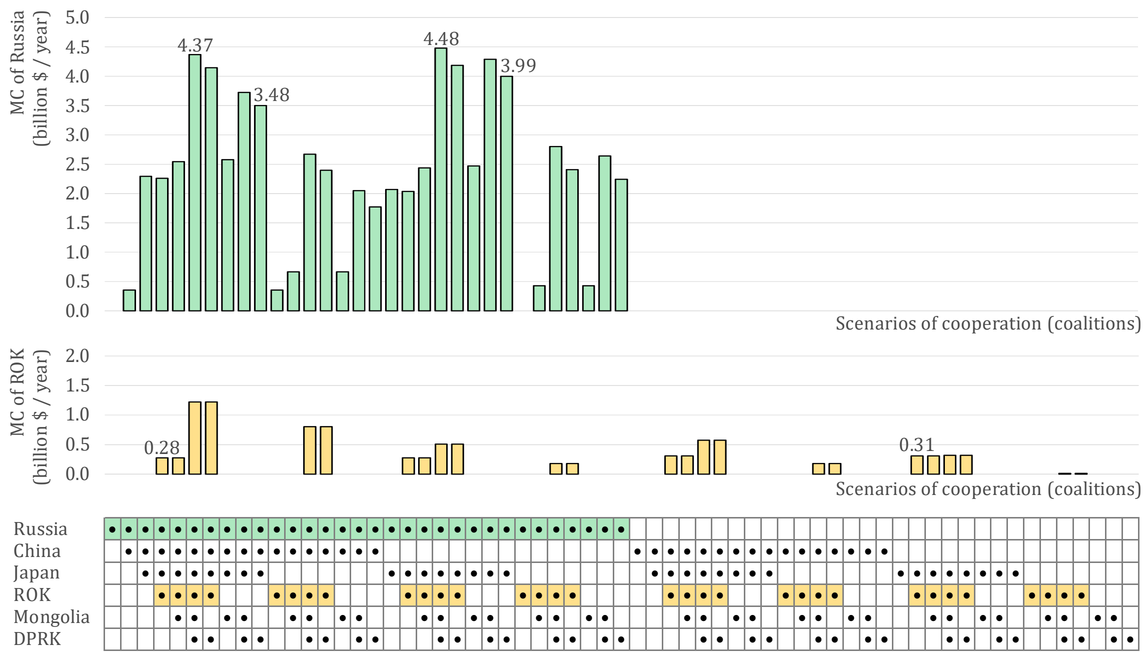


Figure 6.7: Marginal contributions (MC) of Russia and the ROK to the coalitions they may join. Positive values reflect increase in the total cost savings.

A marginal cost reduction of 4.37 billion US dollars per year could be achieved when Russia joins the grand coalition. However, an even greater cost reduction of 4.48 billion US dollars per year occurs when Russia joins the subcoalition Russia-Japan-ROK-Mongolia-DPRK (excluding China). Similarly, the marginal cost reduction of joining the coalition Russia-Japan-DPRK (3.99 billion US dollars per year) is higher than joining the coalition Russia-China-Japan-DPRK (3.48 billion US dollars per year). We also present marginal contribution by the ROK. It is seen that the ROK contribution is higher when cooperating directly with Japan compared to larger coalitions such as Russia-China-Japan-ROK. Here are just a few counterexamples of decreasing marginal contribution to the coalitions with a larger number of players. Thus, the convexity condition (3.3) does not hold. The cooperative game is nonconvex. In such cases, it should be preferred to choose the Nucleolus as a solution concept that is guaranteed to provide an allocation within the Core of the game. Interestingly, the cooperative game in TEP is not a market game, even though we simulated trading in electricity markets. The reasoning lies in topological constraints and technical limits imposed on the market.

Unfortunately, for nonconvex games, even the Core could be an empty set (Theorem 3.2), which signifies that the formation of the grand coalition is not incentive-compatible for some players. We consider it is important to report, while not including all the details in the thesis, that after a series of experiments with a six-system case data, we found that there exist interconnection schemes that lead to cooperative games with an empty Core. Such cases are similar to the cooperative game of the four-system case considered in Section 5.2: one or several players become underestimated in the grand coalition and, therefore, do not have incentives to join it. The conclusion is that Cooperative Game Theory solution concepts can be applied to this particular case study of cross-border power interconnections in Northeast Asia. However, due to the nonconvexity, there could be other cases where it would not be possible to suggest an incentive-compatible allocation solution and persuade players to join the grand coalition. We believe that the bilevel TEP approach presented in Section 5.1 might be especially useful to promote regional cooperation in such cases.

6.2.3 Practical Implementation Issues

The presented allocations indicate the ways of sharing the total cost and savings of the project among the countries. As mentioned, we choose the Shapley value as the allocation rule for this case study. We verified that the Shapley value belongs to the Core of the game, and, therefore, concluded that cooperation on the project should be feasible. However, to implement the Cooperative Game Theory solution concepts in practice, two more questions are needed to be addressed. First, it is necessary to suggest a mechanism of investment in cross-border power lines to make the countries understand what amount of money they are going to invest, and in which power lines.

Common transmission pricing mechanisms such as the MW-mile method can be implemented to address this question. However, we want to be consistent with our game-theoretic framework and suppose that the obtained allocation by the Shapley value is used for the investment cost allocation. That is, we share the investment cost of the interconnections among the countries in the same ratio~~n~~s as the total savings of cooperation. In this way, we identify how much each country should invest in the project. But, it is still not clear how to allocate investment of every single line. 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 a 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. In other coalitions, when there exists power export through Mongolia, line 2-6 is not built at all. Clearly, the cooperative game formulated in terms of the capacity of the interconnections is also nonconvex. Thus, Cooperative Game Theory solution concepts may provide results that are hardly interpretable in practice (such as, some players should compensate their neighbors for not building certain power lines).

To further analyze the applicability of the investment cost allocation by the Shapley value, we empirically distribute the individual costs of the power 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. The resulting investment scheme is presented in Figure 6.8, where diameters of the pie charts are set proportional to the annualized investment costs of the lines. We want to highlight that the presented scheme is by no means not the only possible solution. Other rules of individual investment costs allocation may be suggested. However, even the presented allocation scheme shed some 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 chosen solution concept. 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 the DPRK. This can be interpreted in the following way: China and the 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 investment cost allocation implies that Japan should cover only a share of the undersea cables cost and, therefore, should not invest abroad.

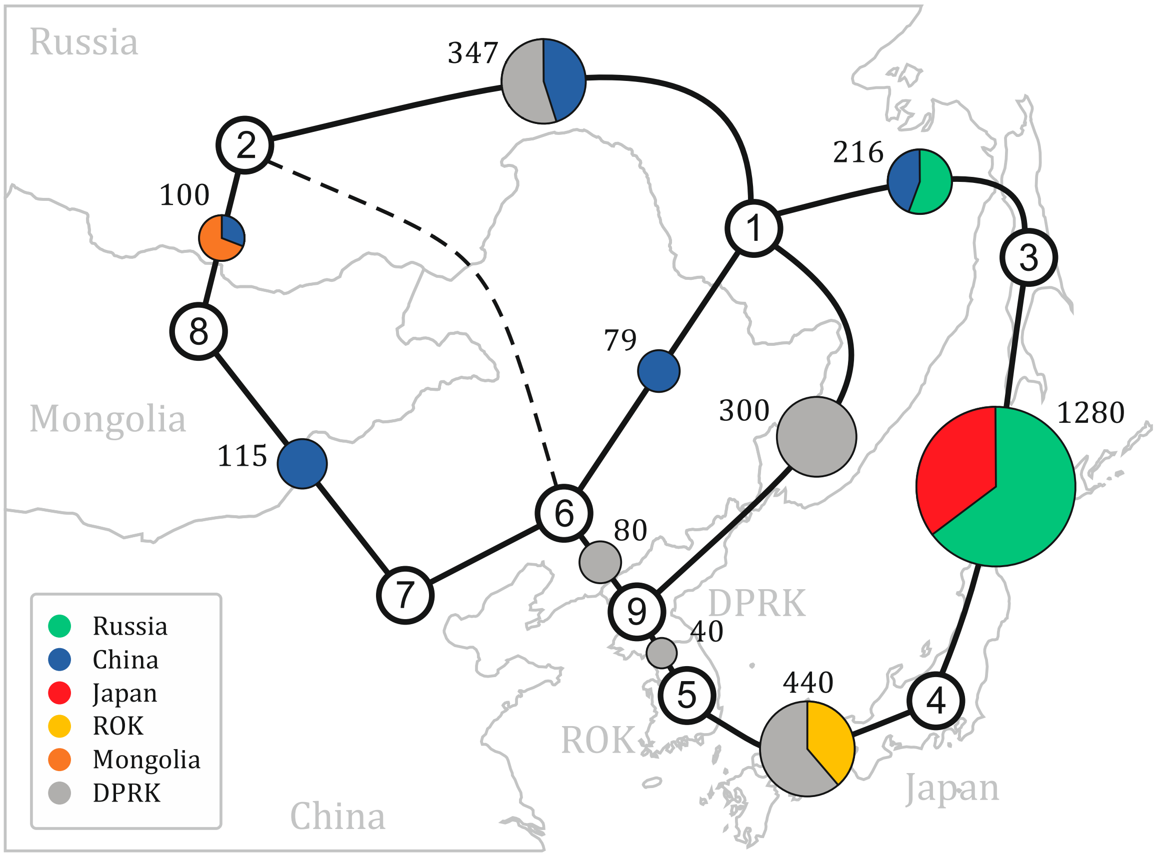


Figure 6.8: Power lines investment allocation scheme, in millions of US dollars per year.

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 6.7). As an example, we show the calculation of the payment to Russia. Before joining the project of cross-border power interconnections, the generation cost of the three Russian power systems reached 22.48 billion US dollars per year. In the grand coalition, Russia mainly acts as a power exporter, transferring about 75 TWh per year to its neighbors. The generation and investment cost of Russia grows up to 30.08 billion

US dollars per year in this scenario. According to the Shapley value allocation, the total cost allocated to Russia should equal 20.23 billion US dollars per year. Thus, it is necessary to arrange money transfers towards Russia to compensate 30.08-20.23=9.85 billion US dollars per year. Japan, on the contrary, is a power importer. Its payment to the exporters can be estimated through a similar calculation. We illustrate the possible money flows among the countries in Figure 6.9.

As in the previous case of investment cost allocation, there is no unique solution for setting money transfers among the countries. The Northeast Asia case study topology allows numerous combinations of the money flows that lead to the desired cost allocation. Ideally, if a money flow can be settled between countries in advance, it would make possible to sign long-term bilateral contracts with respect to the cost allocation solution.

In order to suggest a meaningful solution, we compose an optimization problem that minimizes the sum of all bilateral money transfers. It is supposed that bilateral contracts should be signed between neighboring countries that physically transfer power. Bilateral contract prices are obtained as a solution of the problem. We visualize the bilateral contracts and the related prices in Figure 6.9. 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 value should not exceed the price at an importer's node and should not be lower than the price 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 [4]. Namely, exporters sell energy at prices lower than their marginal costs. This example indicates that bilateral contracts may not assure the cost allocation suggested by the Shapley value. There is a need for developing new mechanisms for international power trading that would enable using Cooperative Game Theory solution concepts. A possible solution could be the establishment of an international coordinator in charge of collecting and distributing money among the participants.

this needs more explanation!

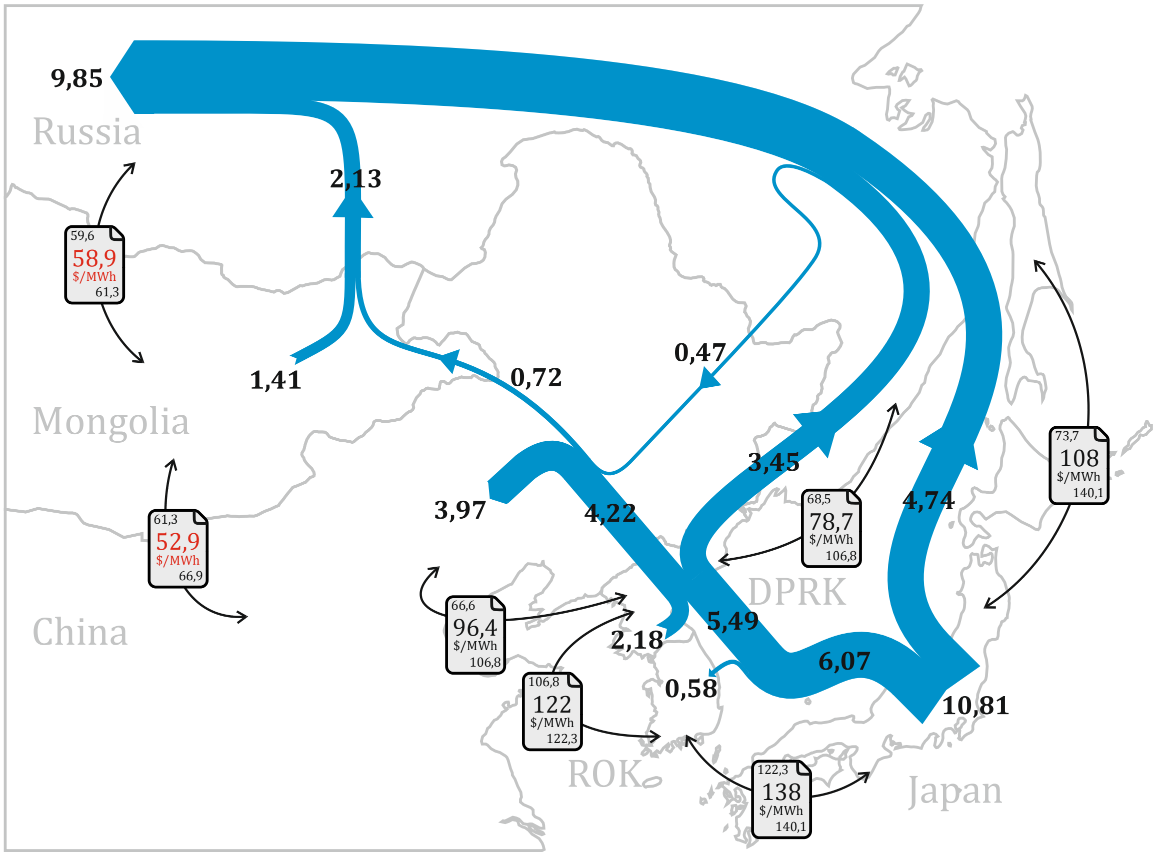


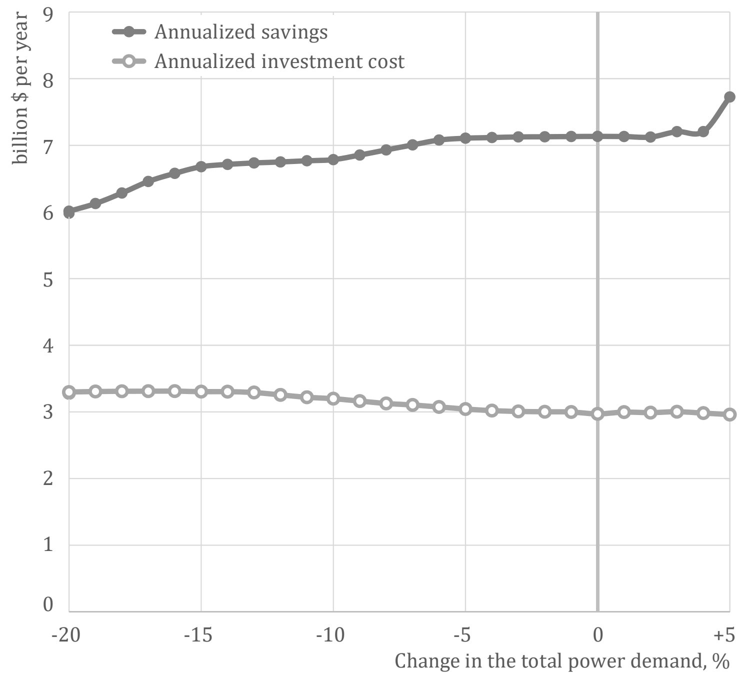
Figure 6.9: Scheme of the money flows among the countries according to the Shapley value allocation (in billions of US dollars per year) and bilateral contracts prices (in US dollars per MWh).

We want to note that selecting the Nucleolus instead of the Shapley value as the allocation rule does not solve the mentioned problem. It would still be impossible to suggest money transfers that do not violate the nodal pricing theory. To overcome this issue and make bilateral power purchase contracts feasible, one could implement the bilevel TEP model (presented in Section 5.1) and suggest a suboptimal expansion plan.

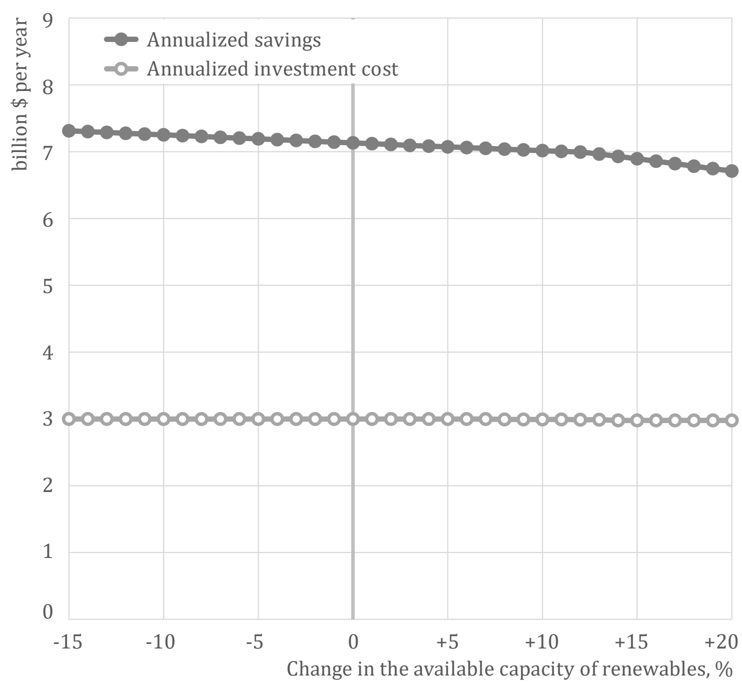
6.2.4 Sensitivity Analysis

Having analyzed possible cost allocation solutions and the ways of implementing them, we now focus on the stability issues of the project. First, we perform a sensitivity analysis to verify that the proposed expansion plan remains effective under moderate changes in the data. We varied the power demand of the systems from -20% up to +5% and estimated the changes in the total savings of cooperation, as shown in Figure 6.10 (a). We conclude that the deviations of the total savings and investment costs are not significant around the point of our forecast. Further increase in demand leads to a rather sharp growth of the savings, whereas investment does not change significantly. The deviations higher than +5% lead to infeasible solutions since the power balance cannot be met for some nodes. When the demand forecast is decreased until the level -5%, the total savings do not change significantly. Further decrease leads to a decline in the savings and makes the project less effective. We also performed a sensitivity analysis for the availability of renewable energy resources, as presented in Figure 6.10 (b). 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 costs and the price differences between power exporters and importers, making the interconnections less profitable. However, the slope of this curve is rather low. We can, therefore, state that our TEP solution is not sensitive to moderate changes in the demand and renewable generation forecasts.

How about sensitivity to transmission capital costs? Eg, initial estimates for CREZ transmission in Texas came in at around $5 billion and cost-benefit studies were based on this number and partly used to justify construction. However, actual transmission construction costs were around $7 billion, ie 40% more than estimated. Using the actual transmission cost, and everything else equal, the cost-benefit studies would have indicated that CREZ was not economic from the perspective of avoiding gas generation costs. (The cost-benefit study ignored carbon benefits of renewables, but used much higher gas prices than turned out because increased fracking meant that gas generation prices were much lower than assumed in the cost-benefit studies.)



a)



b)

Figure 6.10: Sensitivity analysis for power demand forecast (a) and renewable generation forecast(b).

6.2.5 Stability of Cooperation

As discussed earlier, we formally verified that the Shapley value belongs to the Core by checking conditions (3.5) and (3.6). The allocation solution is, therefore, incentive-compatible for the players and might be considered rational. However, we believe that the analysis of the stability of cooperation cannot be complete without examining the size and shape of the Core. As discussed in Sections 3.3.2 and 5.2, these parameters can indicate the "reserve" of an allocation solution and give insights into players' positions in the cooperation.

The Core of the Northeast Asia cooperative game is a six-dimensional polyhedron defined by a finite number of half-spaces according to (3.6). Unfortunately, it is impossible to depict the entire Core using the barycentric coordinates, since we are limited by three-dimensional figures that can represent a cooperative game of no more than four players. Therefore, we decided to visualize projections of the Core onto subspaces containing cooperative games between four out of the six players. To do this, we need to fix the imputations of the remaining two players at the Shapley value or the Nucleolus (or any other rational imputation). The obtained projections are presented in Figure 6.11. We interpret the results below.

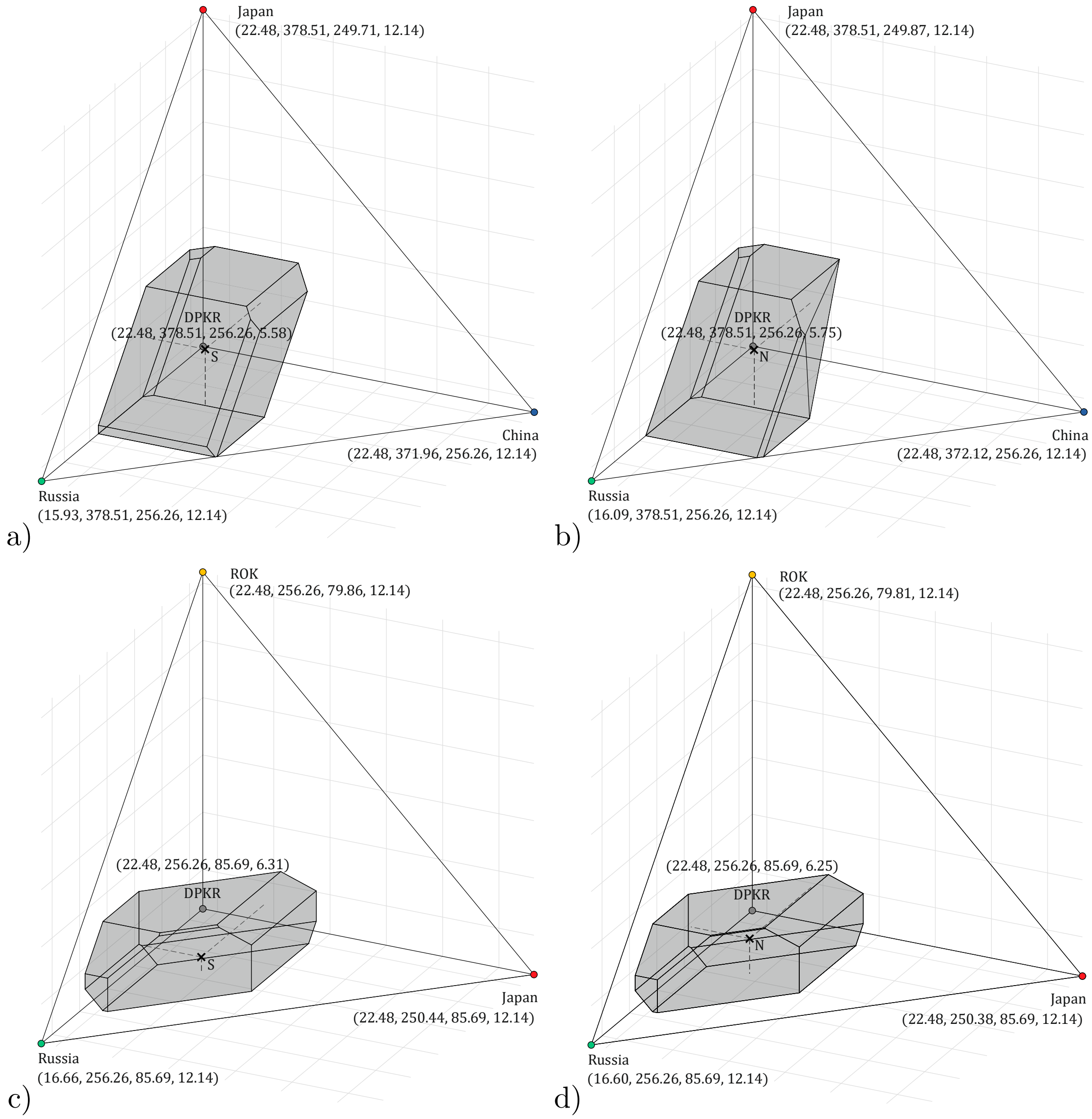


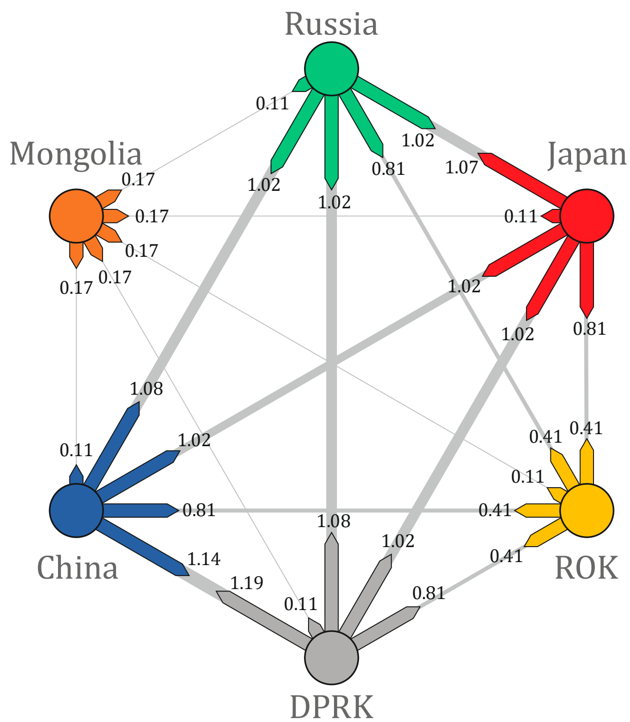
Figure 6.1111: Projections of the set of imputations and the Core of the cooperative game for the Northeast Asia case: a) and b) are the projections onto the Russia-China-Japan-DPRK cooperative game; c) and d) - projections onto the Russia-Japan-ROK-DPRK cooperative game. The values represent the costs allocated to the countries in billions of US dollars per year. The allocation solutions are denoted as follows: S - the Shapley value, N - the Nucleolus.

In Figures 6.11 (a) and (b), we see the projections of the cooperative game onto the four-player game between Russia, China, Japan, and the DPRK. The vertices of the tetrahedron correspond to the points where one of the countries gets all the savings of cooperation (except the fixed shares of Mongolia and the ROK). One may notice that points of the Shapley value and the Nucleolus do not differ significantly for this projection. Indeed, the allocation of savings does not change much for these countries, as shown in Table 6.7 and Figure 6.6. Only the shape of the Core modifies slightly due to the differences in fixed allocations to the not displayed players. The Russia-China-Japan-DPRK projection of the cooperative game does not reveal any stability issues of cooperation. Both the Shapley value and the Nucleolus are located close to the center of the Core, which is large enough in volume. To interpret the parallelepiped-like shape of the Core, we might consider the Russia-Japan-DPRK projection: it is seen that the DPRK cannot get the utmost share of savings because there is a possibility of power export from Russia to Japan. Without this interconnection (line 3-4), the DPRK would become the main player of the game with dominating bargaining power.

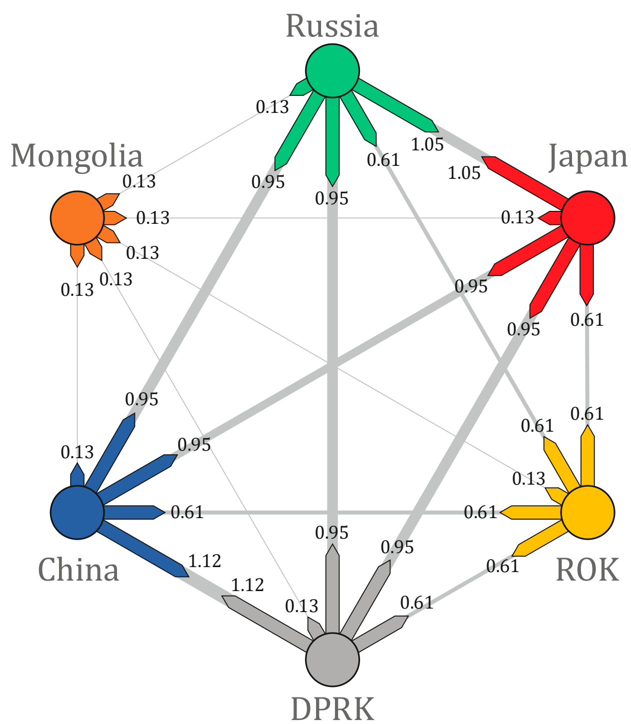
However, not all of the projections confirm the stability of cooperation. We noticed that one of the main differences between the Shapley value and the Nucleolus lies in the shares allocated to the ROK. As shown in Figure 6.6, the ROK share of savings varies between 5.8 % (at the Shapley value) and 8.6 % (at the Nucleolus). We, therefore, focused on the part of the system related to the ROK and examined the projection onto the Russia-Japan-ROK-DPRK cooperative game. As follows from Figures 6.11 (c) and (d), the Russia-Japan-ROK-DPRK projection of the Core has a completely different shape. The Core is rather distant from the ROK, which corresponds to its low bargaining power. We can clearly see the difference between the Shapley value and the Nucleolus. The Shapley value considered the marginal contributions by the ROK and suggested a solution that is close enough to the borders of the Core. The Nucleolus was responsive to the excesses of the coalitions and suggested the solution that is more centralized in the Core and, therefore, stable. It turned out that under the Shapley value, the ROK was a member of the most dissatisfied coalitions (with the lowest excesses). The Nucleolus maximized those excesses and significantly changed the allocation of savings to the ROK.

We admit that the above discussion of the Core's projections and stability of cooperation is somewhat informal. Our goal was to demonstrate that while players with significant bargaining power might have a large space of rational imputations, other players might experience stability issues and get allocation solutions close to the coalitional rationality constraints. To formally describe the imbalance in players' positions, we used the coalitional excess theory introduced in Section 3.2.3 and calculated the maximum surpluses for each distinct pair of players. The obtained thirty values for the six-player game can be presented in matrix form, similarly as we did for the three-system case in Section 3.3.2. However, to provide intuitive information, we developed a bilateral values diagram presented in Figure 6.12.

The length of each arrow in the diagram corresponds to a maximum surplus of one player over another. The thickness of the lines between a pair of players is set proportional to the sum of their surpluses. We can, therefore, clearly see what players are more interrelated with each other. As discussed in Section 3.3.2, for cost games, a positive value of surplus corresponds to an increase in cost (reduction of cost savings) for a player who threatens to leave the grand coalition. Thus, if a maximum surplus of player i over player j, s_{ij}, is higher than surplus s_{ji}, player i benefits more from player j not leaving the grand coalition. The imputation given by the Shapley value results in surpluses not being pairwise equal, as shown in Figure 6.12 (a). For example, we might say that Mongolia is interested in other countries more than any other country is interested in Mongolia joining the grand coalition. On the contrary, the ROK turns out to be less incentivized in cooperation with other countries, while others are pleased to cooperate with the ROK. The imputation by the Nucleolus is proved to be a part of the Kernel. It, therefore, equalizes maximum surpluses in pairs of players. In Figure 6.12 (b), we see that a multi-bilateral equilibrium has been reached under the Nucleolus.



a)



b)

Figure 6.12: Diagram of players' maximum surpluses (in billion dollars per year): a) for the Shapley value; b) for the Nucleolus.

Having analyzed the Core of the game and the maximum surpluses of players, we might state that the Nucleolus provides a solution with a higher stability of cooperation. Nonetheless, the Nucleolus cannot change the severe imbalance in players' positions. The ROK and Mongolia remain the countries with the least bargaining powers. To change the situation, we could implement the bilevel TEP approach introduced in Section 5.1 and identify suboptimal expansion plans with a compromise between the economic efficiency and the stability of cooperation.

6.2.6 Scalability of the Bilevel TEP Approach

Unfortunately, we have found that the bilevel approach experiences scalability problems. As mentioned at the beginning of this section, a single scenario of the Asian Super Grid model contains about 1 900 continuous variables. The bilevel model formulation (5.19)-(5.20) considers KKT conditions for all the 63 coalitions as well as the optimality conditions of the maximum surpluses. The lower level of the model represents an equilibrium problem where maximized surpluses of players depend on the expansion decisions in each coalition. The resulting formulation contains 61 814 continuous and 41 238 binary variables for this particular case study. Such a large-scale MILP model becomes hard to solve directly by off-the- shelf MIP solvers such as Gurobi or CPLEX. The core algorithm of such solvers is the branch-and-bound (B&B), also called branch-and-cut (B&C), when it is combined with cut generation [165]. Although MILP problems are combinatorial problems, the B&B and B&C are efficient algorithms that can obtain optimal solutions without exploring all possible combinations. However, two problem instances of the same size could have drastically different times of resolution. This happens since B&B algorithms rely on several heuristics (e.g., choosing which variables and nodes to branch, finding feasible upper bounds). But most importantly, the problem structure and the problem parameters are responsible for inducing branch pruning, i.e., reducing the size of solution space to explore [166].

In our game-theoretic formulation, each planning decision in one of the 63 coalitions affects the decisions in the remaining coalitions via the characteristic function and the game-theoretic constraints, which leads to combinatorial optimization. It is, therefore, hard to provide a suboptimal solution with equal maximum surpluses among players or calculate a "menu" of suboptimal expansion plans as we did for the four-system case study in Section 5.2. This is the reason why we did not manage to solve the developed bilevel TEP approach for the Northeast Asia case study as the execution time of our code has started to grow to unacceptable levels approaching several days. Hence the results presented in this chapter are based on the ex-post game-theoretic analysis of the project rather than bilevel optimization. It does not mean that the problem of the anticipating bilevel TEP planning is unsolvable – but it means that there is a need to reformulate and decompose the model with incorporated Cooperative Game Theory principles. This is the subject of further research.

We found that several studies ran into similar scalability issues while implementing Cooperative Game Theory solution concepts in power systems. *Freire et al.* [167] and latter *Du et al.* [96] used Benders decomposition to calculate the Nucleolus for cooperative games with a large number of players. In [167], the authors suggested an approach for sharing quotas of a renewable energy sources pool among different companies. Pools with up to fifty companies have been studied, which led to cooperative games with up to $1.1 \cdot 10^{15}$ coalitions. An optimization model similar to (3.19)-(3.23) failed to compute the Nucleolus for such games. However, the proposed decomposition procedure was able to find it through a series of Benders cuts. In [96], the authors considered the coordination of multiple microgrids to minimize total operation cost. They followed the same decomposition logic and effectively allocated the cost in a cooperative game among thirty microgrids. We consider these works as reference points for further research on cooperative games decomposition. Alternating direction method of multipliers [168] and other decomposition methods might also be applied to decompose the problem by coalitions and find a suboptimal expansion plan.

Regarding the possible outcomes of the bilevel TEP for the Northeast Asia case, we anticipate that suboptimal expansion plans would come at a price of dramatic efficiency reduction. The least effective players as Mongolia do not have much room for increasing their imports or exports. Therefore, the maximum surpluses equality constraints would decrease the contribution of other players and reduce the volume of electricity trade.

6.2.7 Manipulability Analysis

As discussed in Chapter 4, one of the major drawbacks of the Cooperative Game Theory solution concepts is their dependence on the accuracy of information. In this case, we assumed that cooperation happens under perfect information about the involved power systems. However, it would not be easy in reality to aggregate information about each generator cost function in every country. To achieve such information transparency, it would be necessary to establish a centralized coordinating entity similar to the ENTSO-E in Europe [169].

Moreover, as we demonstrated for the two-system and three-system cases, the allocation mechanisms are not free of manipulations. Once players know the allocation rule, they may misreport information to get more benefits. For example, a power exporter might submit a higher generation cost function than the real one. By doing so, he would not only get a share of the total savings but also hide 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 functions are lower than the true ones. Such manipulations can be harmful for the overall cooperation, especially at the planning stage.

Similarly to the manipulability analysis presented in Chapter 4, we performed a series of simulations for the Northeast Asia case. The Shapley value was selected as the allocation rule. By changing the declared cost functions of the participating counties, we identified the beneficial directions of manipulations. We found that every country can increase its share of the actual saving by manipulating the allocation rule, as shown in Figure 6.13. The results are consistent with our predictions of players' strategic behavior. We see that power exporters (Russia) deviate by declaring a higher cost function, while power importers (Japan) decrease its revealed cost.

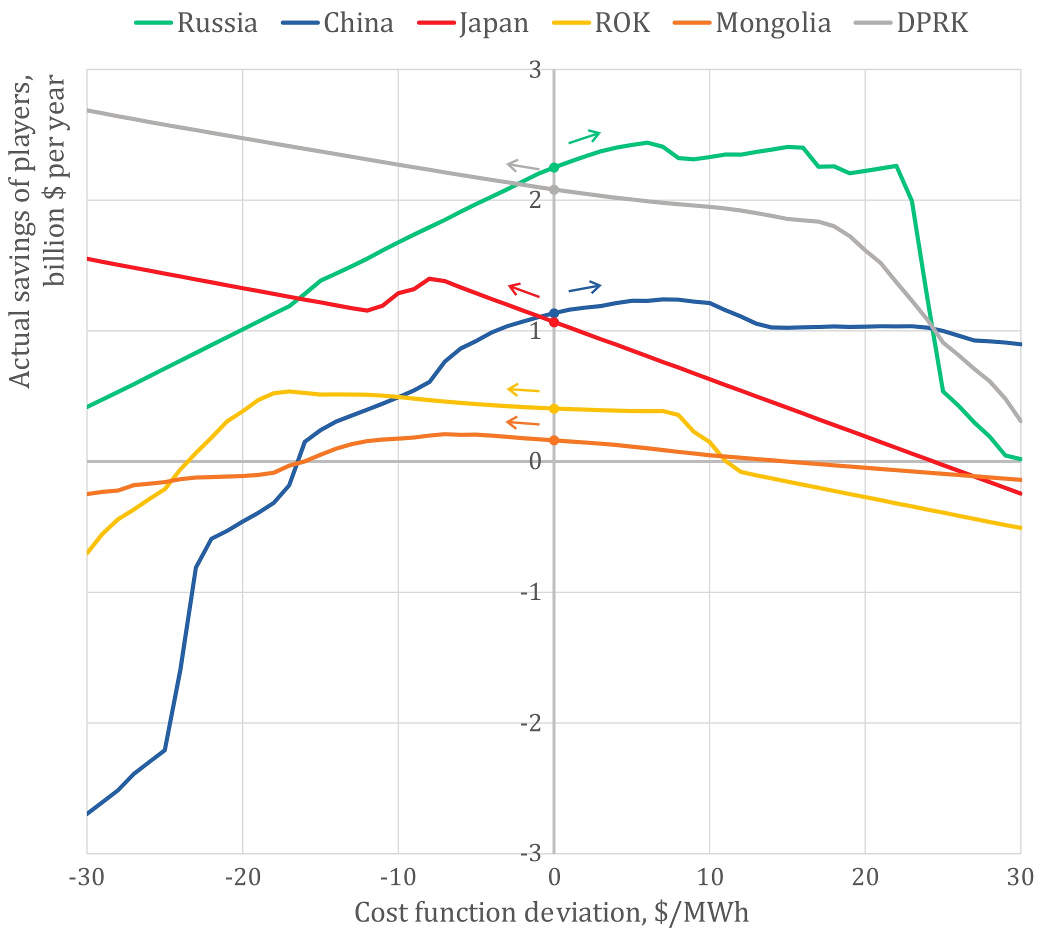


Figure 6.13: The effects of the unilateral cost function manipulations on the actual savings allocation in the Northeast Asia case.

Unfortunately, none of the manipulation strategies keeps the totals savings at the optimum level. As soon as one of the countries misreports its information, the total savings of cooperation can be reduced. To illustrate such outcomes, in Figure 6.14, we present a hypothetical situation where Japan claims to have a cost not higher than the South Korean one. Under the new information, there would be no point in building the ROK-Japan cable interconnection (line 5-4). The ROK would change its role from a transferring country to a power importer. The total savings of the cooperation would decrease by 0.418 billion US dollars per year compared to the optimal interconnection scheme. However, Japan would increase its actual savings from 1.07 to 1.55 billion US dollars per year. Such strategic behavior has the following reasoning. It should be more profitable for Japan to refuse the plan of building two power lines (ROK-Japan, Sakhalin-Japan – 10 GW in total) in favor of building only the line to Russia. This would allow importing less electricity but at a much lower price.

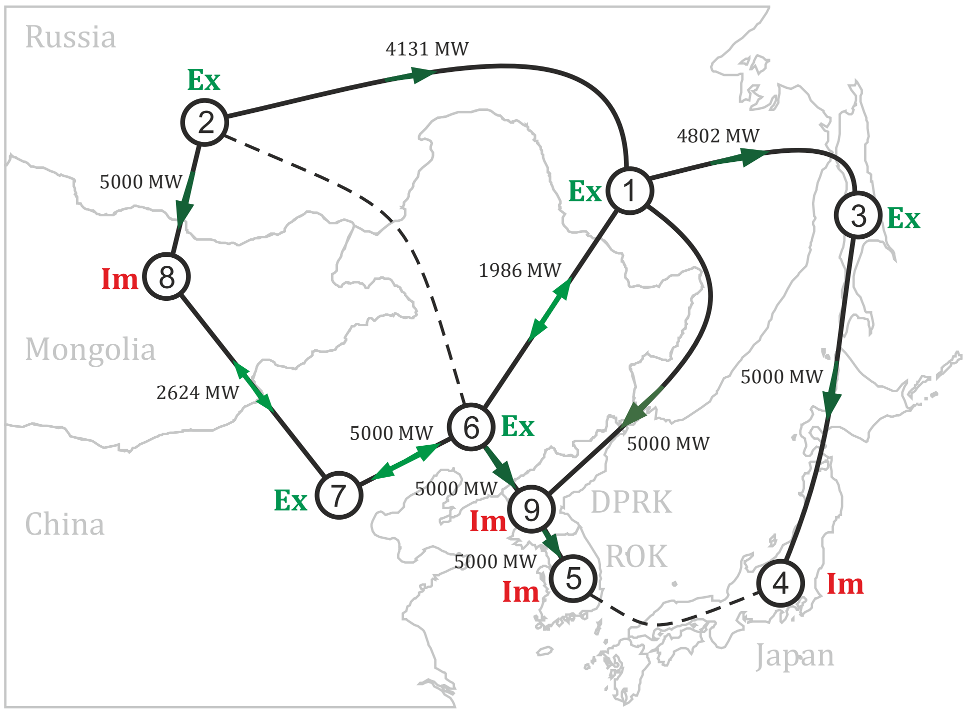


Figure 6.14: The suboptimal scheme of cross-border electrical interconnections in Northeast Asia driven by Japanese strategic behavior. "Ex" and "Im" label power exporters and importers.

We also modeled the simultaneous manipulations where all the countries deviate in their beneficial directions. We observed the same principle as in Section 4.3: only the major power exporter and importer can successfully manipulate the allocation rule. Other players in the interim positions fail to increase their shares of the actual total cost savings. Unfortunately, the resulting manipulation game might lead to highly suboptimal equilibrium solutions of TEP or even cooperation without forming the grand coalition. We hereby again emphasize the need for developing new strategyproof mechanisms of cooperation on cross-border power interconnection projects.

6.3 Summary and Conclusions

Existing studies of cross-border power interconnections demonstrate the potential benefits of cooperation, which can be estimated in generation cost savings, changes in electricity prices, a decrease in consumer's payment, and CO_2 emissions reduction. However, the analysis of a power interconnection project cannot be complete without costs and benefits allocation among countries. It is necessary to estimate what contribution could be made by each country and how it should be rewarded if joining the coalition.

In this chapter, we showed how the Cooperative Game Theory solution concepts can be implemented in a realistic case of cross-border power interconnection in Northeast Asia. On the basis of the total cost and savings allocation, it becomes possible to suggest a scheme of investment in the power lines and set payments among the countries. We calculated the allocation of the total cost and savings using the Shapley value and the Nucleolus. Then, we opened a discussion on the applicability of the investment and payment schemes among the countries.

We also thoroughly studied the stability of cooperation on the project. Having performed the sensitivity analysis and analyzed the Core of the game, we concluded that the formation of the grand coalition should be incentive-compatible for the countries. Cross-border power interconnections in Northeast Asia bring enough cost savings to persuade the countries to join the project and build fair and stable cooperation. However, there exists a severe imbalance in the players' positions in cooperation. Players as Mongolia and the ROK could become less interested in the project than other countries. To avoid such situations, it might not be enough to change the allocation rule. In this regard, the proposed bilevel TEP approach might be useful in identifying suboptimal expansion plans with a higher stability of cooperation. Unfortunately, as reported in Section 6.2.6, we were not able to implement the bilevel TEP model in this case study due to scalability issues. Thus, our analysis of cooperation stability is based on the ex-post game-theoretic approach.

The manipulability analysis again revealed that cooperation mechanisms based on the Cooperative Game Theory solution concepts are not strategyproof. The allocation of the savings highly depends on data accuracy and can be easily manipulated by the countries. There is a need for developing new strategyproof mechanisms of cross-border TEP and establishing international coordinating entities to facilitate projects like the Asian Super Grid.

Chapter 7

Conclusions and Future Work

Winning is not a secret that belongs to a very few, winning is something that we can learn by studying ourselves, studying the environment and making ourselves ready for any challenge that is in front of us

- Garry Kasparov
World chess champion 1985-1993

The presented work is interdisciplinary research that combines electrical engineering, mathematical optimization, Game Theory, and economics. Throughout the manuscript, we addressed multiple features of cooperation on cross-border power interconnection projects. We proposed a novel bilevel TEP model that can be a useful planning tool for establishing stable cooperation among independent players. In this chapter, we summarize the main findings and contributions of the work, draw the conclusions, and formulate the future research directions.

7.1 Thesis Summary

This thesis has emphasized the importance of international cooperation in TEP and electricity trade. Despite the fact that there exist numerous studies and initiatives to establish regional electricity cooperation, very few projects are currently being realized. We identified the major issues and obstacles to cooperation on such projects and dedicated our effort to cover the research gap on costs and benefits allocation mechanisms. Cooperative Game Theory was chosen as the main tool of our analysis.

Research on allocation issues in power systems, including a game-theoretic analysis, has a significant background. We identified the main studies on transmission expansion cost allocation and performed a citation analysis to get a solid grasp on the topic. More than 3 000 papers have been analyzed, which allowed us to classify the main research directions and achievements. We found that there is ongoing research on Cooperative Game Theory applications in power systems. The topic is attracting increasing attention over recent years. The citation network analysis also allowed us to justify the novelty of our work. In the beginning, we followed the way of existing studies in solving TEP models (Chapter 2), formulating cooperative games over expansion plans, and using well-known solution concepts (Chapter 3). But, in Chapter 4, we went beyond and presented the manipulability analysis of allocation rules. In Chapter 5, we proposed the novel bilevel TEP approach that incorporates Cooperative Game Theory principles. Such ideas have never been formulated nor implemented in power systems research. Finally, in Chapter 6, we presented a real-world case study of cross-border power interconnections in Northeast Asia. We illustrated how the cost allocation solutions may be obtained using Cooperative Game Theory concepts and discussed the practical implementation issues. We then performed the manipulability analysis and examined the stability of cooperation.

Summing up, our work presents a comprehensive analysis of Cooperative Game Theory applications for cost allocation in cross-border power interconnection projects. Through a series of case studies, we explained the mechanisms of cooperation, interpreted the results of the game-theoretic analysis, and illustrated the usefulness of the developed bilevel TEP approach. We believe that our contributions not only shed light on cooperation issues in expansion planning but would also encourage academia and industry to integrate Cooperative Game Theory into existing mechanisms of cooperation in power systems, and beyond.

7.2 Conclusions

We drew several conclusions on Cooperative Game Theory applications for TEP cost allocation throughout the manuscript. Most of them concerned the stability of cooperation, applicability issues, and the interpretation of the game-theoretic analysis. In this section, we present the general conclusions to summarize the main messages of our research:

- Cooperative Game Theory provides a rich theoretical background for the analysis of cooperation in cross-border power interconnection projects. The presented solution concepts can be integrated into cooperation mechanisms to identify reasonable allocation solutions while satisfying some desired properties of cooperation. The game-theoretic analysis can also be used to estimate the bargaining power of players (countries) and suggest alternative expansion decisions if needed.
- Cooperative games on TEP are superadditive since the total cost of interconnected systems is minimized for every scenario of cooperation (coalition). However, capacity limits and topology of interconnections often lead to nonconvex cooperative games. The Core of such games can be an empty set, which means that there exist no incentive-compatible allocations. Due to the nonconvexity, there could be TEP projects where it would not be possible to persuade some players to join the grand coalition.
- The straightforward implementation of the Cooperative Game Theory solution concepts cannot create strategyproof mechanisms. One or several players might have incentives to misreport their data and manipulate the allocation rule. Such a strategic behavior could lead to a manipulation game, which outcome could be a suboptimal expansion plan with fewer savings or even a failure to form the grand coalition. To overcome this issue, there is a need for development of more advanced mechanisms of cooperation. The recent achievements from the Algorithmic Mechanism Design could be adapted for TEP tasks.
- Cooperative Game Theory is usually implemented in an ex-post manner to analyze the outcome of cooperation. However, a more promising approach is incorporating the Cooperative Game Theory solution concepts into TEP algorithms, for example, by means of bilevel modeling. Such models can identify optimal planning decisions

in an anticipating manner, subject to desired properties of the resulting cooperative game. We thoroughly examine this approach in Chapter 5.

- The considered solution concepts, such as the Shapley value, are applicable for cooperative games with a moderate number of players (in this work, we considered games with no more than six players). However, with a larger number of players, there appear numerical issues due to an increased amount of possible coalitions (scenarios of cooperation). Therefore, other solution concepts, such as the Aumann–Shapley value, are of great interest.
- The proposed bilevel TEP model also experience scalability issues. The equivalent MILP formulation of the model has a sharp increase in the binary variables when more players are considered in a project. To overcome this issue, there is a need to use recent advances in decomposition techniques and equilibrium problem algorithms.

7.3 Future Research Trajectory

We see the following challenges that may be further investigated. TEP of cross-border power interconnections could be studied along with demand response programs and other policy implications that could cause cross-subsidies between systems. Such policies can be treated as externalities or be included in the cooperative game, for example, as additional decision variables. It might also be useful to consider a more detailed representation of power systems and include uncertainties in TEP models (gas prices, renewable generation). Moreover, analysis of cooperation on integrated planning of energy systems (for example, gas and electricity) might provide more information on the bargaining power of participating countries.

In a middle-term research trajectory, we aim to overcome the computational issues that arise when cooperative games are formulated as multilevel optimization models with thousands of binary variables. Mathematically, these issues are similar to the problems that arise in complementarity modeling of equilibrium problems, where several interacting optimization problems are solved simultaneously.

However, our preliminary results showed that the developed bilevel TEP approach could be far more computationally harder than common complementarity models. The point is that complementarity models are used to represent interacting decision-makers or different optimization stages. Usually, each of the interrelated optimization problems involves the same model and data input. However, our bilevel approach includes all possible scenarios of cooperation (coalitions) and, thus, requires the simultaneous optimization of multiple problems over multiple models. Since the number of models grows exponentially with the number of players, it requires much more computational effort to implement the bilevel TEP modeling for real-world case studies. Moreover, the resulting structure of the problem can make an algorithm iterating between the optimization models without finding new feasible solutions. Existing branch-and-bound algorithms fail to find a solution with adequately small gaps for large-scale MIP with additional lower-level Cooperative Game Theory constraints. There is a need for effectively formulating and solving such problems.

Once we overcome the scalability issues, we will apply the bilevel TEP approach to the real-world case studies of cross-border power interconnections. We intend to show how countries in different regions may cooperate in a way that none of them would be underestimated, while time keeping the total savings as high as possible. Then, the developed approach could be extended to much broader fields, such as transportation and communication systems. It could contribute to many applications in Operations Research and Applied Mathematics.

The major challenge, yet, is the development of strategyproof mechanisms of cooperation. To this end, we hope that recent advances in Algorithmic Mechanism Design could be adopted to establish mechanisms and protocols that prevent the selfish behavior of participants.

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