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A strategic investment model for multinational transmission expansion planning

Comparing competitive and centrally planned solutions for a North Sea Offshore Grid

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Abstract

Proper transmission expansion planning (TEP) is important to create an efficient electricity market that provide both economic and environmental benefits. However, if the expansion planner do not consider how the market agents act, situations may arise where market power can be exploited. To prevent this outcome, we propose a trilevel TEP problem where a market operator is in the lower level, multiple strategic countries trying to maximise their own welfare are in the intermediate and a benevolent system planner is in the upper level. Their actions will anticipate the behaviour of the other market participants.

When transforming the trilevel problem to a mixed-integer liner program (MILP), we use Karush–Kuhn–Tucker (KKT) conditions as optimality conditions for the lower level problem. The non-convex complementarity constraints are linearised into disjunctive constraints. To generate the intermediate problem optimality conditions, we again use KKT conditions, but exploit the relationship between the binary variables of the disjunctive constraints and the dual variables. We extend on current methodology which has to scan through multiple equilibria to find or guarantee the best solution, by providing a method of solving the trilevel TEP problem as a MILP directly to a global optimum.

The method is demonstrated on a case study consisting of Germany, Great Britain and Norway. Strategic countries are only trying to maximise their consumer surplus, because the non-convex bilinear expressions of producer surplus and congestion rents prevents necessity and sufficiency of KKT conditions. The minimisation of domestic prices is therefore the main objective of the strategic countries. Compared to a centrally planned expansion, which can be accomplished if the countries cooperate towards a supra-national regulator, the strategic framework deploy their generation assets less efficiently. The countries are focused on their individual goals and over-invest in domestic production. Consequently, there is less need for transmission expansion because the countries become more self-sufficient. As a result, the countries cannot diversify the risk of intermittent renewable production among each other, and are still dependent on more expensive fossil fuel generation. For the case study, a significant increase of five times the original generation investment cost was necessary for the countries to become sufficiently reluctant to invest for the transmission planner to deem it appropriate to invest in corridors. The centrally planned framework, on the other hand, invests in a lot of transmission capacity and little generation. She is able to use the system assets more efficiently and make a larger transition into renewable generation. Our case study show potential of decreasing total cost if a system moves from a strategic framework towards central planning. However, if strategic countries also try to maximise producer surplus and congestion rent they would gain an incentive to perform trade, which they lack when only consumer surplus is included.

Sammendrag

Omtenksom planlegging av transmisjonsnettet, omtalt som et TEP problem, er viktig for å skape et effektivt elektrisitetsmarked som tilbyr både økonomiske og miljøvennlige fordeler. Hvis utbyggingen ikke tar hensyn til oppførselen til deltagerne i et marked, kan det oppstå situasjoner hvor markedsmakt misbrukes. Vi foreslår dermed en trilevel TEP problem for å unngå dette. Nedre nivå vil bestå av en markedsoperatør, midterste nivå består av flere strategiske land som vil maksimere deres egen velferd, imens en velvillig transmisjonsplanlegger er i øverste nivå. Alle valg de forskjellene aktørene gjør vil være påvirket av hvordan de forventer at de andre deltagerne vil respondere.

Når vi omformer trilevel problemet til et lineært blandet heltallsprogram (MILP) bruker vi Karush-Kuhn-Tucker (KKT) betingelsene som optimalitetsbetingelser for problemet i nedre nivå. De ikke-konvekse komplementær restriksjonene er lineærisert til adskilte restriksjoner med binære variabler. For å produsere optimalitetsbetingelser for midterste nivå brukes KKT betingelsene igjen. Vi vil derimot utnytte forholdet mellom de binære variablene fra lineariseringen av komplementær restriksjonene og dualvariablene. Eksisterende metoder for å løse trilevel problemer krever algoritmer for å søke igjennom flere likevektspunkt for å finne det optimale. Vi utvider nåværende løsninger ved å foreslå en metode for å løse et trilevel TEP problem som en MILP direkte til globalt optimum.

Metoden er demonstrert på en studie av Tyskland, Storbritannia og Norge. De strategiske landene maksimerer kun konsumentoverskudd ettersom produsentoverskudd og handelsprofitt har ikke-konvekse uttrykk som gjør at KKT betingelsene ikke er nødvendige eller tilstrekkelige. Dermed vil landene ha som mål å redusere sine egne priser mest mulig. Vi sammenligner det strategiske tilfellet med en situasjon hvor både investeringer i kraftproduksjon og transmisjon blir gjort av en sentral planlegger. Dette kan for eksempel oppnås om landene samarbeider for å skape en supra-nasjonal regulator. De strategiske landene utnytter produksjonsenhetene mindre effektivt enn en sentral planlegger. Siden landene er kun opptatt av egne mål så overinvesterer de i ny kraftproduksjon. Dermed vil det ikke være behov for transmisjonsutbyggeren å investere ettersom landene bli selvforsynt. Som konsekvens vil ikke landene ha mulighet til å diversifisere risiko av variabel fornybar produksjon mellom hverandre, og blir i større grad avhengig av fossil kraft. Inndataen krevde fem ganger nåværende investeringskostnad for ny kraftproduksjon før landene investerte såpass lite at det ble gunstig for transmisjonsplanleggeren å investere i kabler. Sentralplanleggeren derimot vil investere i mye transmisjon og lite i ny kraftproduksjon. Hun klarer å utnytte eksisterende ressurser bedre, og kan gjøre en større vending mot fornybar produksjon. Vår studie viser potensiale for å redusere totale kostnader ved å skifte fra strategisk oppførsel mot en sentral planlegger. Det er viktig å påpeke at landene ikke har insentiver for å overføre kraft med nabolandene når bare konsumentoverskudd er inkludert. Dette vil derimot endres om produsentoverskudd og handelsprofitt inkluderes.

Preface

This Master's thesis was written at the Department of Electric Power Engineering at the Norwegian University of Science and Technology (NTNU) during the spring semester 2018.

I want to thank my supervisors Professor Magnus Korpås and Ph.D. candidate Martin Kristiansen for allowing me to work with such an interesting topic, encouragement throughout the process and rewarding discussions about the results. They have also been a motivation and support for my wish to contribute to scientific work, which has resulted in one accepted conference paper and a working paper.

Gratitude is also extended to postdoctoral fellow Paolo Pisciella who have contributed significantly with interesting discussions, recommendations and methodology. I am fortunate to be able to continue the work with him and my supervisors when we plan to extend this thesis into a paper. Gurobi Optimization is also acknowledged for being able to use of their solver under academic licence.

Trondheim, June 10, 2018
Simon Indrøy Risanger

Acronyms and abbreviations

CAPEX	Capital expenditure.
ENTSO-E	European Network of Transmission System Operators for Electricity.
EPEC	Equilibrium Program with Equilibrium Constraints.
KKT	Karush–Kuhn–Tucker.
MILP	Mixed-Integer Linear Program.
MINLP	Mixed-Integer Non-Linear Program.
MPEC	Mathematical Program with Equilibrium Constraints.
NLP	Non-Linear Problem.
NSOG	North Sea Offshore Grid.
OPEX	Operating expense.
OWP	Offshore Wind Production.
PV	Photovoltaic.
RES	Renewable Energy Sources.
TEP	Transmission Expansion Planning.
TSO	Transmission System Operator.
TYNDP	Ten-Year Network Development Plan.

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Chapter 1

Introduction

The North Sea Offshore Grid (NSOG) has been identified as a priority project by the European Commission (The Council of the European Union 2013). The project possess a twofold purpose of integrating both renewable resources and regional markets, resulting in environmental and economic benefits. The European Commission (2014a) portrays the progress for an internal energy market. This report emphasises that an integrated energy market is a fundamental requirement for obtaining environmentally sustainable, competitively priced and secure energy supply. Transmission grids are a vital element to provide an integrated electricity market. Decision support tools for transmission expansion planning (TEP) is therefore becoming increasingly important in order to gain insights and knowledge about a complex and relevant problem.

Despite the benefits, there are challenges regarding transmission investments. Among others, there is no supra-national authority to facilitate the process (Lumbreras and Ramos 2016) and outcomes can become unevenly distributed (Egerer, Kunz, and Hirschhausen 2013). A study of incentives for multinational transmission investments by Buijs, Bekaert, and Belmans (2010) concludes that the current frameworks are not sufficient to adapt a full system perspective for investments. This may motivate countries to act strategically in order to maximise their own benefits. If transmission expansion planning do not consider strategic behaviour, countries are able to exploit the expansions. According to David and Wen (2001), market power in electricity markets can be applied by influencing prices or exploiting import and export by strategic line congestion. Countries are able to strengthen their position by for instance generation investments. The goal of this thesis is to model how strategic countries behave, so we can investigate how they react in transmission expansions and conduct optimal TEP for systems with strategic actors.

Both the The European Commission (2014b), the network of transmission system operators (TSOs) in Europe (ENTSO-E 2016) and academic studies (Gorenstein Dedecca and Hakvoort 2016) agree that the NSOG adds significant value to the European power system with regard to security of supply, economic and environmental metrics. Hence, we should work towards a more interconnected grid. Two main approaches are to perform TEP centrally and have allocation mechanisms where no countries withdraw from the cooperative agreement, or invest in transmission with the anticipation of strategic behaviour of countries. While the former introduces the opportunity for system optimal expansion, sovereign countries will have the opportunity to act strategically if they choose. Moreover, the dependence on side payments, which are not always physically or politically feasible, is also a limitation

(Sauma and Oren 2007). Strategic expansion, on the other hand, will likely produce suboptimal system results compared to centrally planned, but is not dependent upon side payments and can prevent market power.

By incorporating a strategic approach we are able to represent the different objectives of the market participants. Each actor will solve an individual optimisation problem in order to best achieve their goals. Because their actions will be dependent upon each other the problems are not isolated. Hence, we can utilise multilevel problem structures to accurately represent the power market under strategic behaviour. Bilevel or trilevel models are hierarchical optimisation problems where the solution at the different problems are dependent upon the other problems. A trilevel problem can thus consists of market operator, producers and TSO with different objectives. The expansion planner will then anticipate the actions of other market agents. Consequently, the optimal expansion will not only consider expansions to remove contingencies, but also additional objectives such as reducing market power. The original form of multilevel problems have multiple objective functions, which can be hard to solve directly. Optimality conditions, which is an equivalent representation of an optimisation problem as constraints, are therefore introduced to transform the trilevel problem into a single problem formulation.

A specialisation project prior to this Master thesis investigated how to facilitate stable and fair allocations of costs and benefits for a centrally planned system optimal TEP of the NSOG[1]. The goal was to create incentives for the countries to cooperate towards a system optimal solution. The strategic TEP model fomulated in this thesis is not only interesting with respect to investigate how strategic actors behave, but we can also determine the value of cooperation as the cost differences between the two expansion solutions.

A common limitation of the current trilevel models for power systems are that they do not find a global optimum directly and they are dependent upon algorithms to find good solutions. In addition, there may often exist feasible solutions outside the search region of the algorithm. The problem also generally become non-linear which makes them hard to solve and time consuming, especially when an algorithm has to solve it several times. Current models and their challenges are presented in the literature review in chapter 3, after an introduction to relevant background theory in chapter 2.

To extend on the current literature we introduce a new methodology of solving trilevel problems in chapter 4. Our approach transforms the trilevel problem into a mixed-integer problem and can be solved to global optimum, given that the original trilevel problems do not have any functions which violates the necessity and sufficiency of the Karush-Kuhn-Tucker (KKT) conditions[2]. The approach is implemented into a strategic TEP problem where countries try to maximise their own welfare, while the market operator and expansion planner wants to maximise the system total welfare.

We demonstrate our model on a case study of the NSOG and present results and discussion in chapter 5. The strategic approach is compared towards a centrally performed expansion, which can represent a cooperative case. This will provide useful information for multinational projects. We can determine the value of cooperation and investigate how strategic countries will act in a multinational TEP setting. Chapter 6 concludes the thesis.

[1] A paper version of the specialisation project was written concurrent with this thesis and is included in Appendix D.

[2] KKT conditions are optimality conditions and will be explained in section 2.4. Non-convex functions will for instance generally produce not necessary nor sufficient KKT conditions.

The scope of the thesis can be summarised as:

- Improve the current methodology of trilevel modelling, especially with respect to strategic TEP problems.
- Demonstrate the method on a case study of the NSOG solved as a trilevel TEP problem.
- Perform a comparison between strategic TEP and the centrally performed TEP which occur under full cooperation of the NSOG. While the case study is aggregated and stylised, we can observe some general trends which can be useful in decision support for multinational projects. However, the application of the trilevel model is the main objective.
- Investigate possible extensions and improvements on the proposed model, and discuss its challenges. Especially how to include non-convex producer surplus and congestion rent functions.

Chapter 2

Background

2.1 Transmission expansion planning

Generation and transmission are two essential functions of the electricity network. TEP is the process of identifying optimal reinforcements for an electricity network. The objective is to facilitate energy exchange between consumers and producers. TEP is a decision making problem at its core. The goal is to find cost-optimal extensions and upgrades of current infrastructure, under expected demand growth and generation mix. The operation of the transmission network is a natural monopoly due to economies of scale (Arslan and Kazdağli 2011). Hence the work is commissioned to a transmission system operator (TSO) or independent system operator (ISO).

The process of solving TEP problems often become complex due to certain characteristics. First and foremost, the problem is multiobjective. It should facilitate trade of energy in a fair manner, provide engineering reliability for all its users and try to minimise costs or maximise social welfare. Moreover, the planning horizons span decades, making the planning long-term. Consequently, this represents uncertainty with respect to, for instance, demand growth, availability of existing generation units and investments in new generation. The latter is of particular importance. Generation investments performed by private actors and has a shorter installation time than transmission investments. However, they are dependent upon each other, which provide difficulties when planning how to expand.

TEP can therefore be performed by either ignoring capacity investments, assume that a central planner also performs generation expansion, or anticipating strategic expansion from the countries. The first option has the limitation of not considering the future condition of the grid when planning. Because the transmission investments has an expected financial lifetime of over 30 years, it should try to somehow anticipate the future state of the system. If we assume that the central planner also performs generation expansion, we get what is commonly abbreviated G&TEP problem. This formulation will solve for a system efficient system, but assumes that producers will behave according to system benefit. Although this may be achieved under strong regulation, it is likely that producers to some extent will behave in a profit maximising manner, which may be conflicting with the best system outcome. Consequently, we can perform TEP where an expansion planner will anticipate the actions of the producers when she performs investments. A system optimal result will then also include an attempt to limit market power. A method to model a scenario of multiple decision makers which are dependent upon each other is hierarchical optimisation. For more information regarding TEP, see the textbook by

Conejo et al. (2016) or the literature review by Hemmati, Hooshmand, and Khodabakhshian (2013).

2.2 Hierarchical optimisation

The subsequent sections provide an overview of the theory necessary to understand multistage programming. Basic knowledge of linear programming problems is assumed throughout. Let us first consider a general continuous and constrained minimisation problem of decision variable $x \in \mathbb{R}^n$, as formulated in (2.1). Function $f_0 : \mathbb{R}^n \to \mathbb{R}$ denote the objective, while $f_i : \mathbb{R}^n \to \mathbb{R}$ and $h_j : \mathbb{R}^n \to \mathbb{R}$ describe the functions of the inequality and equality constraints, respectively. The dual variables, also known as Lagrange multipliers, for the constraints are given in parentheses.

$$\min_{x} \quad f_0(x) \tag{2.1a}$$

subject to

$$f_i(x) \leq 0 \qquad (\lambda_i) \qquad \text{for } i = 1, \ldots, m \tag{2.1b}$$

$$h_j(x) = 0 \qquad (\nu_j) \qquad \text{for } j = 1, \ldots, p \tag{2.1c}$$

$$x \in \mathbb{R}^n \tag{2.1d}$$

Any combination of x satisfying (2.1b) and (2.1c) is called a feasible solution. Moreover, the solution which minimise (2.1a) in the feasible region is the optimal solution. For the present problem, the decision maker have full control of all decision variables in the problem. However, this may not necessarily be the case. Especially in a real world scenario, where decisions are often a reaction toward the behaviour of other actors. If optimisation problems are influence by each others variables they become embedded, and their solutions depend upon each other. The simplest form of two optimisation problems are called bilevel optimisation.

When considering two objective functions in a nested structure, stages or levels are often considered corresponding to how the decision makers influence each other. In the general representation of a bilevel optimisation problem in (2.2), the upper level problem concerns itself with all variables in the problem, both $x \in X \subseteq \mathbb{R}^n$ and $y \in \mathbb{R}^m$. In contrast, the lower level actor can only control the lower level variable y. While the upper level decision maker can only directly control the upper level variable x, how he decides it influence how the lower level problem selects y. The selection process is governed by the objective functions $F : \mathbb{R}^{n+m} \to \mathbb{R}$ and $f : \mathbb{R}^{n+m} \to \mathbb{R}$. Inequality constraints are defined by functions $G : \mathbb{R}^{n+m} \to \mathbb{R}^{m_0}$ and $g : \mathbb{R}^{n+m} \to \mathbb{R}^{m_1}$. Do note how the upper level problem is restricted by the the lower level problem through (2.2c) and (2.2d).

$$\min_{x,y} \quad F(x, y) \tag{2.2a}$$

subject to

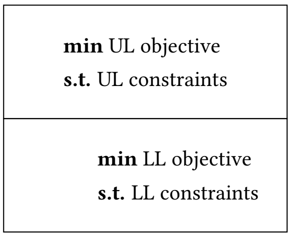
$$G(x, y) \leq 0 \tag{2.2b}$$

$$\min_{y} f(x, y) \tag{2.2c}$$

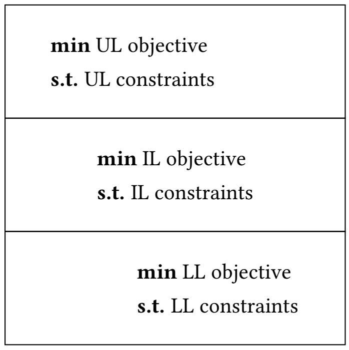
$$g(x, y) \leq 0 \tag{2.2d}$$

An early and practical example of a bilevel problem is the leader-follower model by Stackelberg (1952), commonly referred to as a Stackelberg game. Consider a market with multiple competitors who act in a sequential matter. The leader is able to make the first move, and will determine its quantity based on the expected response of the followers. Consequently, the Stackelberg leader will decide the quantity which maximises the profit when responses from the followers are taken into account. For a Stackelberg game, the upper level problem is considered the leader problem, while the lower level becomes the follower problem. The example shows the strong ties between multilevel programming and game theory, in addition to how an optimal solution of (2.2) will be an equilibrium between the upper and lower level problem.

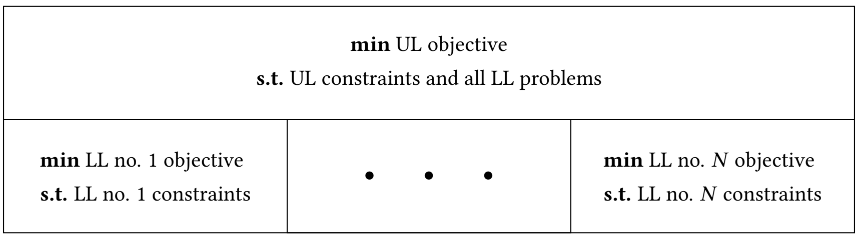
It is also possible to have multiple lower level problems, where all are dependent upon the upper level problem. Another possibility is to add more levels to the bilevel problem, creating a multistage problem[1]. For the remainder of this chapter we will focus on three levels, which is the form of the TEP problem considered in the thesis. Figure 2.1 provides an illustration of the main problem types within multistage optimisation[2]. The different levels are connected by common variables. If multiple problems are at the same level, such as the lower level problems in Figure 2.1c, the decision makers will also find an equilibrium amongst themselves.



(a) Bilevel problem



(b) Trilevel problem



(c) Bilevel problem with multiple lower level problems

Figure 2.1: Illustration of common hierarchical problem structures, containing an upper level (UL), intermediate level (IL) and lower level (LL). The blocks signify separate problems, but the levels are connected by shared variables.

Common for all multistage problems is the presence of multiple objective functions. As a consequence, they become challenging to model and solve in their original state. Therefore we consider

[1]For more information regarding bilevel optimisation, see for instance the textbook by Bard (1998), the overview by Colson, Marcotte, and Savard (2007) or the review by Sinha, Malo, and Deb (2018).

[2]The figures present in the thesis are the author's own attempt to visualise the theory and methodology.

methods of presenting optimisation problems as optimality conditions, which represent the optimal solution without solving for an objective function. The most common method to do this is to utilise the Karush-Kuhn-Tucker conditions of optimality (Bard and Falk 1982; Dempe, Dutta, and Lohse 2006). Another option can be to exploit strong duality (Luo, Pang, and Ralph 1996). Optimality conditions are simply represented as constraints which will yield the same optimal solution as its original problem will. However, because they represent a solution in an equilibrium, the optimality conditions will include equilibrium constraints, such as variational inequalities or complementarity constraints. If an upper level problem in Figure 2.1 are subjected to optimality conditions instead of optimisation problems, the hierarchical structure is removed and the problem become a *mathematical program with equilibrium constraints* (MPEC).

The process of transforming a bilevel problem with multiple lower level problems into an MPEC is illustrated in Figure 2.2. Each lower level problem generates seperate optimality conditions, which is included as constraints in the upper level problem. The MPEC problem has only the upper level objective function to solve for. However, the optimality conditions will restrict the solution space to guarantee an equilibrium solution amongst all the market agents.

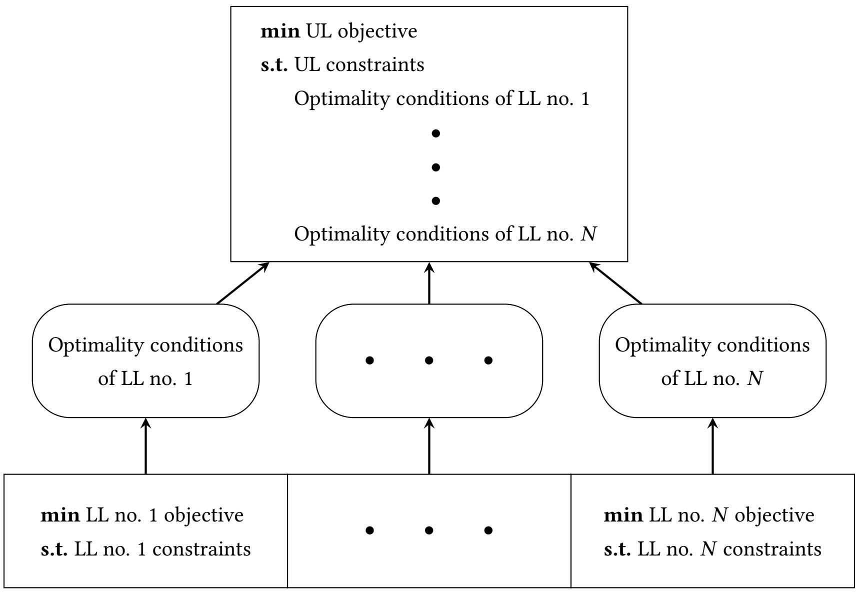
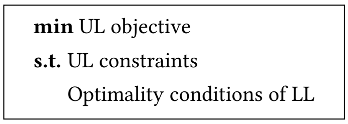
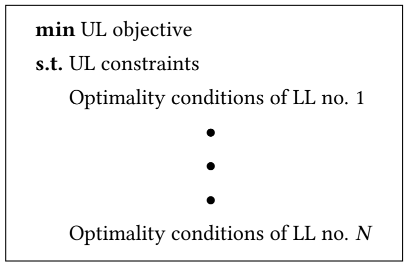


Figure 2.2: Transformation of a bilevel problem of multiple lower level problems into an MPEC.

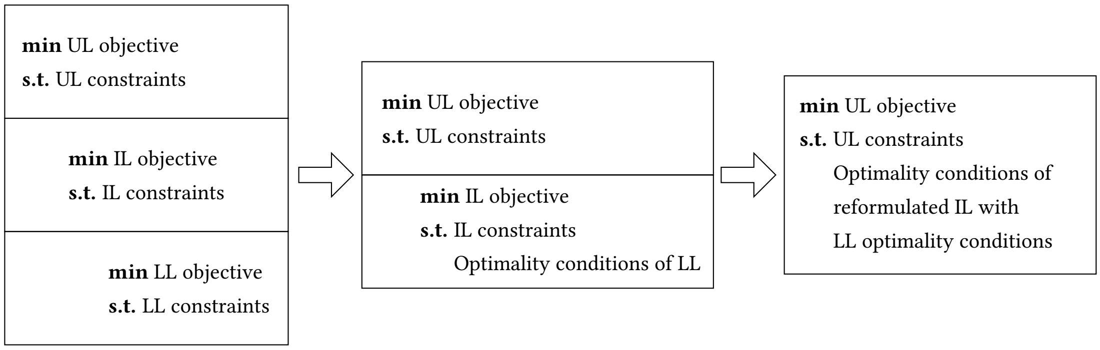
Figure 2.3 display the MPEC representation of the hierarchical problems from Figure 2.1. All the problems have only one objective function and can thus be more conveniently formulated in algebraic modelling languages and solved by commercial solvers. For multistage problems, it is important to properly consider the hierarchical structure, as exemplified for a trilevel problem in Figure 2.3c. If we simply include all the optimality conditions of LL and IL problems, we will treat it equivalently as a bilevel problem with multiple lower level problems, which is not the case. Consequently, a multistage problem gradually develop from the bottom to the top problem. Figure 2.3c shows how the middle step has a lower level problem different from both the IL problem and LL problem in the original trilevel structure. It contains the optimality conditions of the LL problem as constraints, and is currently a bilevel problem with an MPEC as a lower level problem. When transforming further to remove the levels, both the optimality conditions of the IL objective with its constraints and the optimality conditions of the lower level problem has to be taken into consideration. This will result in a final problem which is different than if its IL and LL optimality conditions are included directly. Moving on, we will consider how to develop optimality conditions for problems using strong duality and KKT conditions.



(a) Bilevel problem as MPEC



(b) Bilevel problem with multiple lower level problems as MPEC



(c) Transformation of a trilevel problem to an MPEC

Figure 2.3: Illustration of the MPEC representation of the common hierarchical optimisation problems from Figure 2.1

2.3 Strong duality

Duality theory of linear problems are a well covered topic by most textbooks on mathematical optimisation. We therefore concern our self with the more general topic of Lagrange duality. The section is based on Boyd and Vandenberghe (2004). Again we consider the general minimisation problem formulated in (2.1). The domain created by the problem is given by $\mathcal{D} = \bigcap_{i=0}^{m} \textbf{dom}\, f_i \cap \bigcap_{j=0}^{p} \textbf{dom}\, h_j$, and the Lagrangean of (2.1) is given by (2.3).

$$L(x, \lambda, \nu) = f_0(x) + \sum_{i=1}^{m} \lambda_i f_i(x) + \sum_{j=1}^{p} \nu_j h_j(x) \tag{2.3}$$

From $L(x, \lambda, \nu)$, the Lagrange dual function, $g(\lambda, \nu)$, is found and expressed in (2.4), where $\lambda \in \mathbb{R}^m$ and $\nu \in \mathbb{R}^p$.

$$g(\lambda, \nu) = \inf_{x \in \mathcal{D}} L(x, \lambda, \nu) = \inf_{x \in \mathcal{D}} \left(f_0(x) + \sum_{i=1}^{m} \lambda_i f_i(x) + \sum_{i=j}^{p} \nu_j h_j(x) \right) \tag{2.4}$$

Each (λ, ν) with $\lambda \geq 0$ produces a lower bound for p^*, the solution of the primal problem (2.1). Consequently, some (λ, ν) have to produce the best lower bound. This combination is found by solving the Lagrange dual problem of (2.1), as portrayed in (2.5).

$$\max_{\lambda, \nu} \quad g(\lambda, \nu) \tag{2.5a}$$

$$\text{subject to} \quad \lambda \geq 0 \tag{2.5b}$$

The optimal solution of the Lagrange dual problem, (2.5), is denoted d^*, and represents the best lower bound of p^*. A consequence of this is the property of *weak duality*, as shown in (2.6). The difference between the two optimal solutions, $p^* - d^*$, is known as the *optimal duality gap*.

$$d^* \leq p^* \tag{2.6}$$

For the situation where the optimal duality gap is zero, *strong duality* occurs, as portrayed in (2.7).

$$d^* = p^* \tag{2.7}$$

If a problem has a formulation that ensure strong duality to be valid, this can be exploited to create optimality conditions. An optimal solution will provide equal primal and dual objective values under strong duality. This can be represented as a constraint where the objective function of the primal and dual problem has to be equal. Moreover, to ensure the feasibility of the problem, both primal and dual constraints have to be included. Now we have an alternative representation of a problem without including the process of maximising or minimising an objective function. For more information regarding strong duality optimaliy condition, see Luo, Pang, and Ralph (1996). A noteworthy challenge with this method is to calculate the Lagrange dual function in (2.4). However, for linear problems it is generally quite straightforward to formulate the dual problem.

2.4 Karush–Kuhn–Tucker conditions

The Karush-Kuhn-Tucker (KKT) conditions are optimality conditions, which under certain requirements are both *necessary* and *sufficient* to determine an optimum (Kuhn and Tucker 1951). If the conditions are necessary, the optimal solutions will always satisfy the conditions. Moreover, if sufficiency holds, the KKT conditions are enough to guarantee an optimal solution. When the KKT conditions are both necessary and sufficient they are guaranteed to represent the global optimal solution.

Bazaraa, Sherali, and Shetty (2005) and Boyd and Vandenberghe (2004) are sources used for this subsection, and the reader is referred to them for further information. KKT conditions are explained for a general minimisation problem, as portrayed in (2.1), which has the Lagrangian function of (2.3). The procedure is equivalent for a maximisation problem.

All functions in (2.1) are assumed to be continuously differentiable. The KKT conditions are presented in (2.8), where (2.8a) is the differential of the Lagrangian function (2.3). It represents the stationary condition. Restrictions from the primal problem are still required to ensure feasible solutions. They are represented in (2.8b) and (2.8c). Complementarity slackness is represented by (2.8d), and states which inequalities that are binding for a solution x. Finally, (2.8e) and (2.8f) provide features for the dual variables. λ is non-negative because it belongs to a primal inequality, while ν is free because of its corresponding equality constraint.

$$\nabla f_0(x) + \sum_{i=1}^{m} \lambda_i \nabla f_i(x) + \sum_{j=1}^{p} \nu_j \nabla h_j(x) = 0 \tag{2.8a}$$

$$f_i(x) \leq 0 \qquad \text{for } i = 1, \ldots, m \tag{2.8b}$$

$$h_j(x) = 0 \qquad \text{for } j = 1, \ldots, p \tag{2.8c}$$

$$\lambda_i f_i(x) = 0 \qquad \text{for } i = 1, \ldots, m \tag{2.8d}$$

$$\lambda_i \geq 0 \qquad \text{for } i = 1, \ldots, m \tag{2.8e}$$

$$\nu_i, \text{ free} \qquad \text{for } j = 1, \ldots, p \tag{2.8f}$$

We want the KKT conditions to guarantee an optimal solution, which require necessity and sufficiency. Whether this is the case or not, depend upon the formulation of the problem. It has to satisfy certain *constraint qualifications* (CQs), in order for the KKT conditions to be necessary and sufficient. Certain CQs are also necessary for strong duality to be valid. For this thesis, only linear problems will be considered. It is therefore only necessary to present the *linearity constraint qualification* (LCQ), which simply states that f_i and g_i of (2.1) have to be *affine* functions[3]. Strong duality is valid and KKT conditions are necessary and sufficient under LCQ. For a quick overview of other constraint qualifications see for instance Eustaquio, Karas, and Ribeiro (2007).

KKT conditions (2.8b), (2.8d) and (2.8e) form *complementarity constraints*, because they express how the product of two or more decision variables or functions of decision variables must be zero (Billups and Murty 2000). For (2.8d) to be satisfied, either $f_i(x)$ or λ_i must be bound to zero. A common equivalent representation of (2.8b), (2.8d) and (2.8e) are presented in (2.9c). The *perp* operator $\perp$ simply states that the inner product of two vectors is equal to zero, and thus creates a more compact representation. Consequently, the KKT conditions are formulated as (2.9).

$$\nabla f_0(x) + \sum_{i=1}^{m} \lambda_i \nabla f_i(x) + \sum_{j=1}^{p} \nu_j \nabla h_j(x) = 0 \tag{2.9a}$$

$$h_j(x) = 0 \qquad \text{for } j = 1, \ldots, p \tag{2.9b}$$

$$0 \leq -f_i(x) \perp \lambda_i \geq 0 \qquad \text{for } i = 1, \ldots, m \tag{2.9c}$$

$$\nu_i, \text{ free} \qquad \text{for } j = 1, \ldots, p \tag{2.9d}$$

2.5 Solution methods for MPEC problems

When a KKT conditions are used as optimality conditions, complementarity constraints (2.8b), (2.8d) and (2.8e) of non-linear nature are included in the problem. The MPEC feasible region is therefore generally non-convex (Billups and Murty 2000; Gabriel et al. 2013). As a consequence, there is significant risk of a local solution, which also satisfy the KKT conditions. Furthermore, because no feasible

[3] An affine function is the composition of a linear function with a translation. A general mathematical representation is $f(x) = ax - b$, where a and b are constants and x is a variable.

solution satisfies all the complementarity constraints strictly, the Mangasarian-Fromovitz constraint qualification often utilised when solving non-linear programming (NLP) problems is violated (Scheel and Scholtes 2000).

While solving MPECs directly is a challenging task, it is not impossible. Fletcher and Leyffer (2004) examine the opportunity to solve problems with complementarity constraints using standard NLP solvers. They indicate that sequential quadratic programming (SQP) methods is well suited for the task, and studies the approach further in Fletcher et al. (2006) and Leyffer (2006). Other approaches do also exist, see for instance the overview by Ralph (2008), but a common limitation is the possibility of local optimal solutions due to the non-convex feasible region.

To solve multistage problems globally, we therefore need to do some clever adjustments to prevent complementarity constraints to exist in their original form in the problem. One method is to prevent them from entering the MPEC in the first place by using alternative optimality conditions instead of KKT. An example being the strong duality approach discussed in section 2.3. Another option is to reformulate the complementarity constraints into a more convenient structure. Fortuny-Amat and McCarl (1981) present how to linearise the complemenarity constraints into disjunctive constraints, while Siddiqui and Gabriel (2013) utilises Schur's decomposition. The reformulations are done at the expense of introducing binary variables in the former and SOS-1 type variables in the latter. Our solution method for solving a trilevel exploit relationships between variables in a disjunctive constraint structure. Hence we move forward with this technique.

2.6 Disjunctive constraints reformulation

Consider the general MPEC problem with complementarity constraints formulated in (2.10), where a y is included as a variable. The problem is non-linear and non-convex due to constraint (2.10c), which forces $g(x, y) \geq 0$, $y \geq 0$ and $y^T g(x, y) = 0$.

$$\min_{x} \quad f_0(x, y) \tag{2.10a}$$

subject to

$$h(x, y) = 0 \tag{2.10b}$$

$$0 \leq g(x, y) \perp y \geq 0 \tag{2.10c}$$

$$x \in \mathbb{R} \tag{2.10d}$$

Observe that restriction (2.10c) can be considered as a statement where either $g(x, y)$ or y must be bound to zero in order to satisfy $y^T g(x, y) = 0$. This is the idea behind the disjunctive constraint reformulation of Fortuny-Amat and McCarl (1981). Binary variables and sufficiently large parameters, commonly termed big-M, can be used to force either $g(x, y)$ or y to zero, while the other remains free to take a non-zero value. The disjunctive constraints reformulation is shown in (2.11), where z is a binary variable and M represent a sufficiently large parameter. Because the bilinear term $y^T g(x, y)$ is removed we have a MILP or a mixed-integer non-linear programming (MINLP) problem.

$$\min_{x} \quad f_0(x, y) \tag{2.11a}$$

subject to

$$h(x, y) = 0 \tag{2.11b}$$

$$0 \leq g(x, y) \leq Mz \tag{2.11c}$$

$$0 \leq y \leq M(1 - z) \tag{2.11d}$$

$$z \in \{0, 1\} \tag{2.11e}$$

$$x \in \mathbb{R} \tag{2.11f}$$

The disjunctive constraint reformulation has the advantage of providing a common problem structure which can be interpreted by commercial solvers. MILP problems, and some cases of MINLP, can be solved to global optimum by approaches such as *branch and bound*[4]. Challenges associated with disjunctive constraints include the introduction of binary variables and the selection of big-M parameters. Mixed integer programs are inherently hard to solve and even more so when they become large (Klotz and Newman 2013). Each complementarity constraint produces a binary variable when it is reformulated, and consequently the problem can quickly accumulate a significant amount of binary variables. Another important consideration is that big-M parameters must be selected with care. The disjunctive constraint reformulation is not valid if they are binding, while too large parameters may cause numerical errors (Gabriel and Leuthold 2010).

2.7 Trilevel TEP models

Trilevel models are often used to represent TEP problems because they accurately describe the relationship between market operators, participators and regulators. In a national context, the lower level problem can be considered as a market operator deciding the dispatch, which is dependant on the bids from the producers who form multiple intermediate problems. How they invest in generation facilities are influenced by both the price and the actions of the regulator or TSO. Finally, the regulator or TSO decide transmission expansion based on anticipated investments by the producers. If a multinational context is considered instead, the countries may be considered as intermediate level agents. In this scenario, the market operator has to be international and the regulator must be of supra-national authority. Both contexts will have the similar trilevel structure as presented in Figure 2.4.

As previously discussed, when considering multistage models above bilevel, it is important to respect the hierarchy and move from the bottom problem to the top. Figure 2.5 show in detail how the problem in Figure 2.4 is transformed into a single problem. Because there are several intermediate

[4]Branch and bound is a common solution algorithm for problems containing integers. It enumerates all candidate solutions. In the process it forms a rooted three, where the algorithm explores branches and compare the solutions to upper and lower bounds from previous branches and a potential previous feasible solution. Branches are created by splitting the solution space using restrictions and they lead to nodes. A problem where integer characteristics are relaxed is solved at the nodes. If the solution is integer feasible it is compared to the current solution and replaces it if it is superior. However, if the solution is not integer feasible, the node is either pruned or branched further depending on bounds and current feasible solution. See for instance Clausen (1999) for additional information.

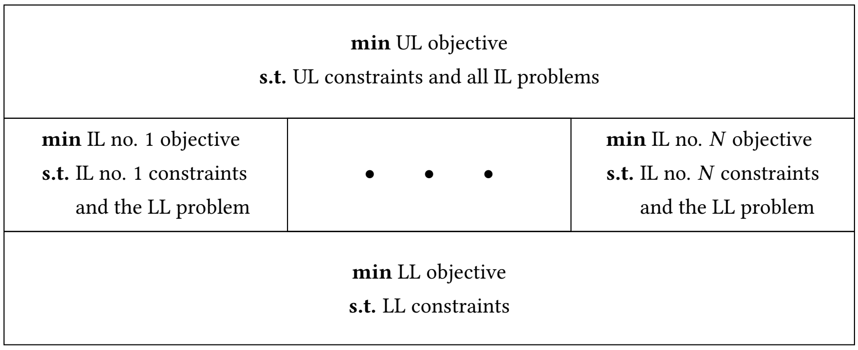


Figure 2.4: Representation of a trilevel problem with multiple intermediate level problems

problems, their decisions will be influenced by how their peers invest. Consequently, they form an equilibrium amongst themselves. We therefore get an *equilibrium program with equilibrium constraints* (EPEC) as our final problem in Figure 2.5.

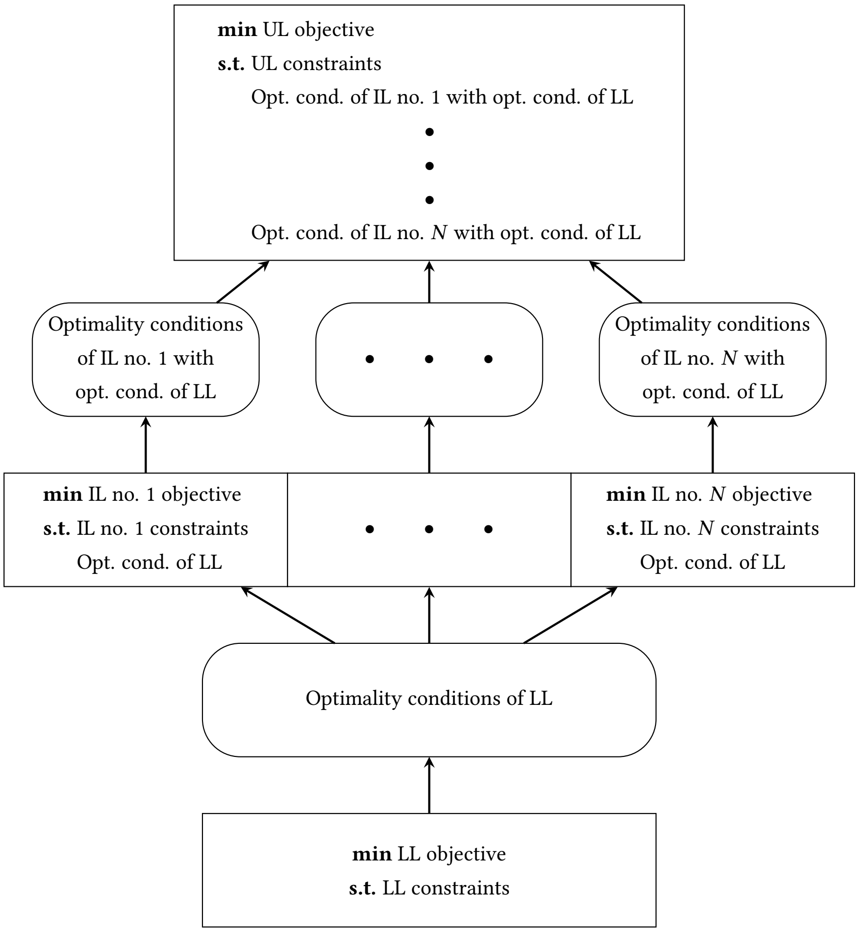


Figure 2.5: Transformation of a bilevel problem of multiple lower level problems into an MPEC.

Chapter 3

Literature review

3.1 Electricity infrastructure investment design

Within the jurisdiction of a TSO or independent system operator (ISO), transmission expansion and operation are a natural monopoly and corresponding activities are centralised. In a situation without a system authority, however, such processes become decentralised. An example being cross-border investments. Decentralised market design do incorporate the risk of market power with the potential to decrease market efficiency. Contreras et al. (2009) argue that fully decentralised schemes can produce situations where objectives of market efficiency compete with the profit maximisation of the stakeholders. David and Wen (2001) suggest two main forms of abuse, namely market dominance and transmission constraints. The former enables an actor to influence prices, while the latter provide the opportunity to strategically exploit import and export, or intentionally congest lines to manipulate market conditions. Additional factors such as incentives of producers, elasticity of demand and price-responsive competitors also influence market power possibilities (Borenstein, Bushnell, and Knittel 1999). See the review by Karthikeyan, Raglend, and Kothari (2013) for more information on market power in electricity markets.

Although the amount of producers in European countries generally increased from 2005 to 2015, we are still exposed to a few main generating companies (Eurostat 2017). Consequently, the decentralised market is in danger of operating as a oligopoly rather than full competition. Bye and Hope (2005) outline the Norwegian experience of deregulation and Nordic market integration. While they conclude that market power have not apparently been abused, it is recognised as a continual challenge. Multinational projects with sovereign countries do form a decentralised system. Compared to a national system with a regulator, there are no supra-national regulators with authority. Traditional TEP problems have mainly concerned themselves with a centralised planner (Hemmati, Hooshmand, and Khodabakhshian 2013; Krishnan et al. 2016). More realistic result can thus be obtained by considering TEP problems under decentralised generation expansion.

3.2 Challenges related to multinational projects

Buijs, Bekaert, and Belmans (2010) investigates current incentives for multinational transmission expansion and derive two main motivations for joint projects to be multilateral or supra-national. The former is a bottom-up approach mainly concerned with national interests. Concurrent benefits for all participating parties are necessary for cooperation. The latter adapt a top-down system perspective. According to the authors, cooperation on multilateral basis is the only viable foundation for multinational expansion at the moment. The current incentives, such as the TEN-E program and Inter-TSO compensation (ITC) mechanism, is not sufficient to adapt a full system perspective for investments. Self-financing is still the most important element for cross-border investments, but the authors discuss the opportunity of congestion revenue as an additional motivator. It is necessary to change the cross-border investment focus from bilateral to regional in order to accomplish European environmental and market integration goals.

The intersection between investment cost and ensuring an efficient market has been a topic for discussion after the deregulation of the power market. Bushnell and Stoft (1996) discuss the opportunity for Transmission Congestion Contracts (TCCs), by appropriate rules, to make the electricity market able to carry out grid expansion efficiently by itself. Incentives may also come in the form of reimbursements where individual actors can be compensated in order to accomplish system best results. By utilising such an approach, investments can be performed as system maximisation under the assurance that all stakeholders are compensated. An important aspect is the beneficiaries pay principle, where those who benefit compensate the actors who are worse off (Hogan 2011). Konstantelos et al. (2017) propose an allocation mechanism based on the proportional net benefits the actors receive. A cooperative game theory approach is taken in Kristiansen et al. (2017), where distributions are based on the Shapley value. A specialisation project prior to this thesis examines a centrally performed expansions where incentives for cooperation is pursued by using cooperative game theory. Allocation of benefits and costs from an unaltered outcome, the Shapley value and nucleolus was compared against each other. The project was written into a paper, which is included in Appendix D. While centralised cooperative approaches can enable system optimal results, there are challenges in applying cost benefit allocations in general (Hogan 2008). Sauma and Oren (2007) argues that side-payments are hard to implement and we therefore should perform TEP in a manner that includes strategic behaviour.

Generation investments are generally made by private actors in a market who aim for profit maximisation. Market operation and transmission expansion are regulated to give system best results. Alayo, Rider, and Contreras (2017) show strong inter-dependencies between transmission and generation investments, and uncoordinated investments may lead to negative externalities. Rosellón (2003) stresses the importance of anticipating generation investments when performing TEP. Generation investments can be modelled by the benevolent expansion planner, or by independent strategic actors. While the former is simpler to model, it is unlikely that the producers will act in accordance to the total welfare objective of the regulator. To deal with the different objectives of market agents, multilevel models have been proposed as more accurate representations of behaviour in electricity markets (Ralph and Smeers 2006).

3.3 Strategic TEP models

Multilevel models consider the electricity market as an hierarchy. Transmission expansion, generation investment and market operations are dependent upon each other and have different objectives.

Murphy and Smeers (2005) and Sauma and Oren (2006, 2007) are early examples of models using a multilevel approach. Because the different objectives depend upon each other, the final solution becomes an equilibrium. This is equivalent to equilibria from game theory, which is the field of study regarding interactions between participants with self-interest. Multilevel problems are generally solved by reformulation into problems containing equilibrium constraints. Electricity markets are usually represented as bilevel or trilevel problems. The former is easier to solve, but the latter gives a more accurate representation. A trilevel problem will generally have a market operator in the lower level problem providing market clearing. The intermediate level often contains strategic producers, but may have have other decision makers. Finally, the upper level problem consists of a benevolent expansion planner. How producers invest are dependent upon new transmission capacity and prices from the market clearing. Likewise, the market operator are dependent upon the generation capacity or bids by the producer and the expansion planner anticipate the generation dispatch. A bilevel problem can only represent the interaction between two levels. If a multinational perspective is considered, then the producers can be exchanged by strategic countries trying to maximise their own welfare. The market operation and expansion planner then become multinational and still try to maximise social welfare.

Wang et al. (2009) and Kazempour, Conejo, and Ruiz (2011) are examples of bilevel models containing strategic producers and a single market clearing. The former uses a co-evolutionary algorithm combined with pattern search to find Nash equilibria among producers, while the latter considers a single producer and reformulates the problem into an MPEC. Daxhelet and Smeers (2007) examines a bilevel problem between different regional regulators and the energy market. Another example of bilevel problems is Tohidi and Hesamzadeh (2014) who investigate the relationship between the market clearing and separate strategic expansion planners investing within their jurisdiction.

Trilevel models will produce more accurate representation of the power system, but is more complex. The challenges are mainly in the transformation from the intermediate to the upper level problem, because the optimality conditions of the lower level problem have included either bilinear terms or binary variables. Because there are no apparently best approach, there are several proposed techniques of solving trilevel problems.

Jin and Ryan (2014a) propose an approach where the EPEC of the lower and intermediate level problems are solved by the diagonalisation method of Hu and Ralph (2007). Results from the EPEC are inserted into a trilevel representation of the problem. The performance of the hybrid iterative solution mechanism is shown in Jin and Ryan (2014b). Like all diagonalisation methods it has the drawback of not providing a guarantee for global optimum.

Pozo, Sauma, and Contreras (2013) present a trilevel expansion model which utilises binary expansion of Pereira et al. (2005) to discretise all generation investment strategic variables and hence removes bilinear terms. Nash equilibria can then be represented as finite set of inequalities. However, the solution are not guaranteed to be unique. Pozo, Contreras, and Sauma (2013) expand the method by presenting a search technique of adding new constraints when a solution is found in order to find the best one. Challenges of this approach is the amount of equilibria processed before the optimal and how to set the new constraints.

Although Ruiz, Conejo, and Smeers (2012) do not have an upper level problem, they extract two optimality conditions to solve a bilevel problem of multiple producers as a single EPEC problem. Strong duality is used as lower level optimality conditions, which makes it possible to use KKT conditions when moving toward the upper level problem. By introducing disjunctive constraints, the problem becomes a MILP, but strong duality introduces bilinear terms. Hence the solutions may be Nash equilibria, local equilibria or saddlepoints and it is necessary to do a search through all solutions to find the best one.

A trilevel problem have an optimisation problem for all decision makers. Both the original forms and the reformulated problems with optimality conditions must give the same solution. Taheri, Kazempour, and Seyedshenava (2017) solve the trilevel problem using strong duality followed by KKT conditions and utilise an *ex-ante* verification proposed by Kazempour, Conejo, and Ruiz (2013). Transmission investments then become fixed, and the intermediate and lower level are solved. If the equilibria is valid, they will render the same solutions as the full problem. If not, other solutions has to be found and checked.

Huppmann and Egerer (2015) and Zerrahn and Huppmann (2017) also uses the strong duality followed by KKT conditions. The former studies strategic transmission investments for different regions, while the latter examines strategic dispatch of producers. However, the challenges of no guarantee for global optimum are still present. Both papers propose an algorithm to scan through all KKT points and choosing the best one. Cuts are added to prevent already found solutions of reoccurring.

A common challenge for all existing strategic TEP models is the possibility of local optimums and saddlepoints instead of global optimum. Although several algorithmic approaches are proposed, they can be time consuming and inefficient. The amount of solutions necessary to be checked is uncertain, and the full TEP problems often become complex problems to solve. For instance if Fortuny-Amat and McCarl (1981) linearisation is used, the problems quickly scale to large MILPs or MINLPs. Moreover, the strong duality approach of Ruiz, Conejo, and Smeers (2012), which has the benefit of avoiding complementarity constraints from the lower level problem and thus can use KKT conditions towards the upper level problem, introduces bilinear terms. Because the KKT conditions become not necessary nor sufficient, there may exist optimal solutions outside the KKT points, which methods using this approach are not able to check. Another important consideration is that bilinear terms also makes the problem non-linear, which increases the difficulty and time of solving it. While global solvers such as BARON (Sahinidis 2017; Tawarmalani and Sahinidis 2005) do exist, it becomes time consuming when multiple problems have to be solved in an algorithmic approach.

3.4 Contributions

Based on the literature review we observe that hierarchical optimisation have advantageous features for TEP problems. A challenge is that no current methods can guarantee a global optimum for trilevel problems. Consequently, algorithmic approaches which can be both time consuming and hard to implement must be utilised. We therefore extend the current literature on trilevel TEP models by:

- Developing a new approach of solving the trilevel problem as a MILP to global optimum. As long as the original lower, intermediate and upper level formulations produce necessary and sufficient KKT conditions, our optimality conditions will produce global optimum.
- Presenting an alternative approach to the current methods of solving trilevel models as a single problem. We utilise KKT conditions instead of strong duality optimality conditions from lower

to intermediate level. After the Fortuny-Amat and McCarl (1981) linearisation we observe that the binary variables decides which KKT conditions which are introduced into the upper level problem. We exploit this to generate optimality conditions.

- Demonstrating the method on a case study of the NSOG and interpreting the results. We are able to investigate how strategic countries will behave and compare the outcomes to a centrally performed system optimal expansion to determine the value of cooperation.
- Discussing the performance of the approach and opportunities of including expressions with bilinear terms into our model. Both producer surplus and congestion rent have bilinear terms which make them non-convex and consequently the KKT conditions where they are present become not necessary nor sufficient. The TEP model become more realistic if they are included.

Chapter 4

Methodology

4.1 KKT conditions of complementarity constraints

Complementarity constraints are non-convex and its KKT conditions become not necessary nor sufficient in its original form. While the Fortuny-Amat and McCarl (1981) approach linearise the complementarity conditions, it has the disadvantage of creating binary variables. In a trilevel model this will result in a intermediate problem which is not fully linear, and consequently its KKT-conditions cannot be further utilised to the upper level problem in its original form. Instead we utilise the approach introduced in the Ph.D. thesis by Pisciella (2012) which exploit the fact that if further KKT-conditions are developed, there exist a close relationship between the binary and dual variables. To demonstrate this phenomena, consider a general representation of a lower level complementarity constraint as shown in (4.1), where $g(x)$ is a function, x and λ are primal and dual variables, respectively.

$$0 \leq -g(x) \quad \perp \quad \lambda \geq 0 \tag{4.1}$$

Complementarity constraint (4.1) are linearised into (4.2) by the disjunctive constraint representation by Fortuny-Amat and McCarl (1981). M represent a large constant, equivalent to the big-M method, z is a binary variable, while $\overline{\theta}$, $\underline{\theta}$ and ϕ represent dual variables.

$$g(x) \leq 0 \qquad (\overline{\theta}) \tag{4.2a}$$

$$-g(x) \leq Mz \qquad (\underline{\theta}) \tag{4.2b}$$

$$\lambda \leq M^{\lambda}(1 - z) \qquad (\phi) \tag{4.2c}$$

$$z \in \{0, 1\} \tag{4.2d}$$

Because (4.2b) and (4.2c) contain binary variables, the constraints are no longer linear. In order to analyse the relationship between the binary and dual variables, we presently consider z as a parameter to develop the KKT-conditions of (4.2), as presented in (4.3).

$$g(x) \leq 0 \tag{4.3a}$$
$$-g(x) \leq Mz \tag{4.3b}$$
$$\lambda \leq M^{\lambda}(1-z) \tag{4.3c}$$
$$\overline{\theta}\,(-g(x)) = 0 \tag{4.3d}$$
$$\underline{\theta}\,(g(x)+Mz) = 0 \tag{4.3e}$$
$$\phi\,(M(1-z)-\lambda) = 0 \tag{4.3f}$$
$$\overline{\theta}, \underline{\theta}, \phi, \lambda \geq 0 \tag{4.3g}$$

We know that z can only take two values, either 0 or 1. First, let us consider the KKT conditions if $z = 0$:

- $g(x) = 0$ by (4.3a) and (4.3b).
- $\overline{\theta} \geq 0$ by (4.3d) when $g(x) = 0$.
- $\underline{\theta} \geq 0$ by (4.3e) when $g(x) = 0$ and $z = 0$.
- $\lambda \geq 0$ by (4.3c).
- $\phi = 0$ by (4.3f) when $z = 0$.

For the situation when $z = 1$, (4.3b) do not enforce anything on (4.3a). $g(x)$ can be both zero or non-negative if it chooses. Consequently, $\overline{\theta}$ is not decided a priori and (4.3d) may hold for either $\overline{\theta}$ or $g(x)$ set to zero. Let us consider if $g(x)$ was forced to zero. This means that (4.3a) is restricted to equality, but its corresponding variable λ is also forced to zero already. However, we could achieve the same by $z = 0$, where we also would have $\lambda \geq 0$, and thus a less restricted problem. To have $g(x) = 0$ at $z = 1$ is therefore not a rational option because it restrict the problem unnecessary. The effect of $z = 1$ then becomes:

- $g(x) \geq 0$ by (4.3a), (4.3b) and argument above.
- $\overline{\theta} = 0$ by (4.3d) when $g(x) \geq 0$.
- $\underline{\theta} = 0$ by (4.3e) when $z = 1$.
- $\lambda = 0$ by (4.3c).
- $\phi \geq 0$ by (4.3f) when $\lambda = 0$ and $z = 1$.

From the discussion above, we observe how the KKT conditions of complementarity conditions as disjunctive constraints depend upon the binary variables. Expressed mathematically, the KKT conditions of the disjunctive constraints (4.2) become (4.4).

$$g(x) \leq 0 \tag{4.4a}$$

$$-g(x) \leq Mz \tag{4.4b}$$

$$\lambda \leq M^{\lambda}(1 - z) \tag{4.4c}$$

$$\overline{\theta} \leq M^{\overline{\theta}}(1 - z) \tag{4.4d}$$

$$\underline{\theta} \leq M^{\underline{\theta}}(1 - z) \tag{4.4e}$$

$$\phi \leq M^{\phi}z \tag{4.4f}$$

$$z \in \{0, 1\} \tag{4.4g}$$

4.2 Trilevel TEP model formulation

To gain a realistic representation of the transmission expansion environment we want to represent different groups and how they interact. In our multinational context this includes a market operator, countries and a benevolent expansion planner. Figure 4.1 show how the different market actors influence each other.

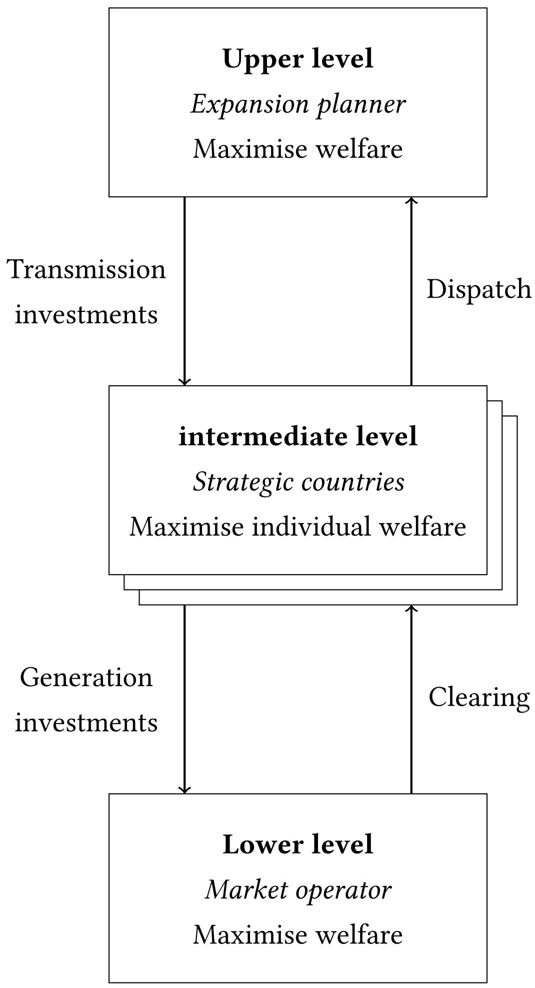


Figure 4.1: Representation of tri-level structure.

Each agent in Figure 4.1 have their own objectives and consequently, an individual optimisation problem to solve. The problems are not independent, but restricted by the action of the other market participators. Each level consist of a problem, except the intermediate problem which has one for each country. The lower level problem is a market clearing problem performed by a market operator. We assume an efficient market, which corresponds to a system optimal clearing. The clearing is dependent upon the generation capacity available in the countries. Similarly, the strategic countries anticipate the market clearing before investing in additional capacity.

The intermediate level, represented by multiple problems for each country, experience most dependencies of the levels. Strategic behaviour of a country is dependent upon the anticipated investments of the other countries, transmission expansions by the upper level planner, and the market clearing. In contrast to the expansion planner and market operator, the countries are strategic and trying to maximise their own social welfare through generation capacity investments.

Finally, the upper level problem consist of a benevolent system planner performing transmission expansions. Her decisions are influenced by the anticipated investments in generation capacity by the countries. Because all the agents are dependent on other optimisation problems the model becomes a hierarchical problem, where the solution is an equilibrium amongst all the participators.

The model will systematically be developed from the lower level to the upper, consistent with the theory of chapter 2. We use KKT conditions of the lower level problem to guarantee optimality. The approach of Fortuny-Amat and McCarl (1981) is used to linearise the complementarity conditions. To guarantee optimality in the upper level problem, we exploit the relationship between dual and binary variables in the intermediate problems, as explained in the previous section. All notation used are presented in Table 4.1.

4.2.1 The lower level problem: Market clearing

The lower level problem in (4.5) represent an efficient market clearing where all generation units in the system participate. A market operator tries to minimise the electricity cost, as shown in the objective (4.5a). She controls decision variables of production, g_{it}, load shedding, s_{nt}, and flow of electricity f_{bt}. Expenses are marginal cost of electricity, MC_i, cost of CO_2 emission, $CO2_i$, and the value of lost load, $VOLL$. The latter are only enforced if load shedding, s_{nt}, occurs, meaning that a country are not able to meet its demand. Market clearing is a short time operation that decide the generation dispatch g_{it} for the different generation units $i \in G$ at the different time periods $t \in T$. The upper and intermediate level problems concern themselves with investments, where the full investment lifetime has to be considered. Hence, we introduce a sample factor, W_t, to make our time periods represent a full year and an annuity factor, A, to discount the hourly dispatch results of the lower level problem over the financial lifetime.

Restriction (4.5b) ensures that the nodes $n \in N$ meet their demand, D_{nt}, at all times. This is done by their own production, load shedding or import. Export is also included in (4.5b). We assume an inelastic demand to simplify the model formulation and because it is challenging to find appropriate open source demand elasticities for aggregated countries. If elastic demand is considered instead, the objective function (4.5a) would become a convex function and the demand would be a decision variable of the lower level problem. KKT conditions would still be sufficient and necessary, so the same methodology could be used.

Table 4.1: Notation for the trilevel model

Sets and mappings	
$n \in N$	: nodes
$i \in G$	: generators
$b \in B$	: branches
$t \in T$	: time steps, hour
$n \in B_n^{in}, B_n^{out}$	: branch in/out at node n
$c \in C$	: countries
$n(i)$	: node mapping to generator i
Parameters	
A	: annuity factor
W_t	: weighting factor for hour t (number of hours in a sample/cluster) $[h]$
$VOLL$	: value of lost load (cost of load shedding) $[EUR/MWh]$
MC_i	: marginal cost of generation, generator i $[EUR/MWh]$
$CO2_i$	: CO_2 emission costs, generator i $[EUR/MWh]$
D_{nt}	: demand at node n, hour t $[MW]$
B, B^d, B^{dp}	: branch mobilization $[EUR]$, fixed cost $[EUR/km]$ and variable cost $[EUR/kmMW]$
CS_b, CS_b^p	: fixed cost [EUR] and variable cost $[EUR/MW]$ of onshore/offshore switchgear, branch b
CX_i	: capital cost for generator capacity, generator i $[EUR/MW]$
P_i^0	: existing generation capacity, generator i $[MW]$
$P_i^{max\ new}$	: maximum new generation capacity, generator i $[MW]$
η_{it}	: factor for available generator capacity, generator i, hour t
F_b^0	: existing branch capacity, branch b $[MW]$
$F_b^{max\ line}$	: maximum new capacity for a line, branch b $[MW]$
$F_b^{max\ new}$	: maximum new branch capacity, branch b $[MW]$
L_b^{km}	: distance/length, branch b $[km]$
F_b^{loss}	: transmission losses (fixed and variable w.r.t. distance), branch b
M	: a sufficiently large number
Primal variables	
y_b^{num}	: number of new transmission lines/cables, branch b
y_b^{cap}	: new transmission capacity, branch b $[MW]$
x_i	: new generation capacity, generator i $[MW]$
g_{it}	: power generation dispatch, generator i, hour t $[MW]$
f_{bt}	: power flow, branch b, hour t $[MW]$
s_{nt}	: load shedding, node n, hour t $[MW]$
z	: binary variable connected to disjunctive constraints

Production is restricted by an upper limit consisting of existing capacity, P_i^0 and newly invested generation capacity, x_i, as shown in (4.5c). Notice that x_i is a decision variable in the intermediate problem. Because the market operator has no authority over it, we can only treat it as a constant in the lower level problem. To represent the intermittent behaviour of renewable production, η_{it} is introduced as a factor of available generation capacity. For renewable sources, the factor follows a wind or solar radiation profile. Constraints (4.5d) and (4.5e) state the maximum and minimum transmission capacity of branches $b \in B$, respectively. The power flow, f_{bt}, is a free variable and can thus take both positive and negative values. Finally, (4.5f) and (4.5g) ensure non-negativity for the electricity production and load shedding.

Dual variables of restrictions in (4.5) are given in parentheses. We are especially interested in the dual variable of the energy balance (4.5b). Dual variables can also be considered as shadow prices. Consequently, p_{nt} represent the value of increasing the demand by one unit. In other words, p_{nt} is an *endogenously* given price for the node. When the intermediate and upper level decision makers are considering investment, they will do so with respect to prices generated by the market itself. This is a considerable advantage of the model with respect to realistic behaviour.

The market clearing representation in (4.5) only include the absolute minimum of necessary restrictions. When transforming trilevel problems to MILP form, the constraints start to accumulate quite significantly. We therefore continue with the minimal model of (4.5) because it is more clear to see the connections than with larger amounts of constraints. Appendix B include an extended model where energy storage and minimum production is also included, if interested. Further extensions are also possible, as long as the constraints ensure that the KKT conditions are still necessary and sufficient.

$$\min_{g_{it}, s_{nt}, f_{bt}} \quad \sum_{t \in T} A \cdot W_t \left(\sum_{i \in G} (MC_i + CO2_i) g_{it} + \sum_{n \in N} VOLL \cdot s_{nt} \right) \tag{4.5a}$$

subject to

$$D_{nt} - \sum_{i \in G_n} g_{it} - s_{nt} - \sum_{b \in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b \in B_n^{out}} f_{bt} = 0 \qquad (p_{nt}) \quad \forall n, t \in N, T \tag{4.5b}$$

$$g_{it} - \eta_{it}(P_i^0 + x_i) \le 0 \qquad \left(\overline{\alpha}_{it}^{LL}\right) \quad \forall i, t \in G, T \tag{4.5c}$$

$$f_{bt} - (F_b^0 + y_b^{cap}) \le 0 \qquad \left(\overline{\gamma}_{bt}^{LL}\right) \quad \forall b, t \in B, T \tag{4.5d}$$

$$-(F_b^0 + y_b^{cap}) - f_{bt} \le 0 \qquad \left(\underline{\gamma}_{bt}^{LL}\right) \quad \forall b, t \in B, T \tag{4.5e}$$

$$g_{it} \ge 0 \qquad \forall i, t \in G, T \tag{4.5f}$$

$$s_{nt} \ge 0 \qquad \forall n, t \in N, T \tag{4.5g}$$

$$f_{bt} \in \mathbb{R} \qquad \forall b, t \in B, T \tag{4.5h}$$

We use KKT conditions as optimality conditions for the lower level problem. The Lagrangian, $L\left(g_{it}, s_{nt}, f_{bt}, p_{nt}, \overline{\alpha}_{it}^{LL}, \overline{\gamma}_{bt}^{LL}, \underline{\gamma}_{bt}^{LL}\right)$, of (4.5) is portrayed in (4.6). Both primal and dual variables from (4.5) are included.

$$
\begin{aligned}
L = & \sum_{t\in T} A \cdot W_t \left(\sum_{i\in G} (MC_i + CO2_i) g_{it} + \sum_{n\in N} VOLL \cdot s_{nt} \right) \\
& + \sum_{n\in N} \sum_{t\in T} p_{nt} \left(D_{nt} - \sum_{i\in G_n} g_{it} - s_{nt} - \sum_{b\in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b\in B_n^{out}} f_{bt} \right) \\
& + \sum_{i\in G} \sum_{t\in T} \overline{\alpha}_{it}^{LL} \left(g_{it} - \eta_{it}(P_i^0 + x_i) \right) \\
& + \sum_{b\in B} \sum_{t\in T} \overline{\gamma}_{bt}^{LL} \left(f_{bt} - (F_b^0 + y_b^{cap}) \right) + \sum_{b\in B} \sum_{t\in T} \underline{\gamma}_{bt}^{LL} \left(-(F_b^0 + y_b^{cap}) - f_{bt} \right)
\end{aligned} \tag{4.6}
$$

The KKT conditions of the lower level problem is presented in (4.7). Stationary conditions (4.7a), (4.7b) and (4.7c) are derivatives of the Lagrangian with respect to the primal variables. Because g_{it} and s_{nt} are non-negative, we represent their stationary conditions as complementarity conditions[1]. Conditions (4.7d) to (4.7g) are the constraints of problem (4.5). KKT conditions of the inequality constraints become complementarity conditions with their corresponding dual variables.

Stationary conditions of free variables:

$$0 = -p_{n(b^{in})t}(1 - F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} \quad , \quad f_{bt} \text{ (free)} \qquad \forall b, t \in B, T \tag{4.7a}$$

Stationary conditions of non-free variables:

$$0 \leq A \cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}_{it}^{LL} \quad \perp \quad g_{it} \geq 0 \qquad \forall i, t \in G, T \tag{4.7b}$$

$$0 \leq A \cdot W_t \cdot VOLL - p_{nt} \quad \perp \quad s_{nt} \geq 0 \qquad \forall n, t \in N, T \tag{4.7c}$$

Primal equality constraints:

$$0 = D_{nt} - \sum_{i\in G_n} g_{it} - s_{nt} - \sum_{b\in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b\in B_n^{out}} f_{bt} \quad , \quad p_{nt} \text{ (free)} \qquad \forall n, t \in N, T \tag{4.7d}$$

Complementarity conditions:

$$0 \leq -g_{it} + \eta_{it}(P_i^0 + x_i) \quad \perp \quad \overline{\alpha}_{it}^{LL} \geq 0 \qquad \forall i, t \in G, T \tag{4.7e}$$

$$0 \leq -f_{bt} + (F_b^0 + y_b^{cap}) \quad \perp \quad \overline{\gamma}_{bt}^{LL} \geq 0 \qquad \forall b, t \in B, T \tag{4.7f}$$

$$0 \leq (F_b^0 + y_b^{cap}) + f_{bt} \quad \perp \quad \underline{\gamma}_{bt}^{LL} \geq 0 \qquad \forall b, t \in B, T \tag{4.7g}$$

[1]The equivalent alternative is to introduce dual variables of non-negativity constraints (4.5f) and (4.5g). In this case, the stationary conditions will be equal to zero and include the new dual variables. (4.5f) and (4.5g) must also be included as complementarity constraints with non-negativity of their corresponding duals. Because the dual variables are only included in two constraints, where one is a non-negativity restriction, they can be rewritten into the current formulation of (4.7b) and (4.7c). Although both representations are equivalent, the one chosen produces less constraints and variables.

4.2.2 The intermediate level problem: Strategic countries

The intermediate level problem consists of countries trying to maximise their own welfare. Hence, their actions are based on their own gains and not system achievements. Total welfare consists of the sum of congestion rent, consumer and producer surplus as shown in (4.8), where $c \in C$ denote countries.

$$PS_c = \sum_{t \in T} \sum_{i \in G_c} A \cdot W_t \left(p_{n(i)t} - MC_i - CO2_i \right) g_{it} \tag{4.8a}$$

$$CS_c = \sum_{t \in T} \sum_{n \in N_c} A \cdot W_t \left(VOLL - p_{nt} \right) D_{nt} \tag{4.8b}$$

$$CR_c = \frac{1}{2} \sum_{t \in T} A \cdot W_t \left(\sum_{b \in B_c^{in}} \left(p_{n^{from}(b)t} - p_{n^{to}(b)t} \right) f_{bt} + \sum_{b \in B_c^{out}} \left(p_{n^{to}(b)t} - p_{n^{from}(b)t} \right) f_{bt} \right) \tag{4.8c}$$

Unfortunately, both (4.8a) and (4.8c) contain different variables multiplying each other, and thus non-convex bilinear terms. As a consequence, the KKT conditions of the intermediate problem become not necessary and insufficient. We therefore have to either reformulate the producer surplus and congestion rent into a convex representation or omit them. Because the reformulation process can quickly become quite complex[2], we deem it out of scope to try different linearisation techniques when the focus of this thesis is on the modelling aspect of trilevel models. However, we do offer a discussion in section 5.6 of methods to include producer surplus and congestion rent. To only include consumer surplus as the objective of the countries do introduce some limitations on the realistic nature of the model. The countries will now act in a way that benefits their consumers and will always try to minimise their own prices. If producer surplus was included, the countries would try to maximise the distance between prices and marginal costs. Congestion rent would introduce strategic trade behaviour. As a result, the current scheme of minimising prices do not comply to realistic behaviour, but shows an extreme case of consumer centred behaviour.

The intermediate problem for a single country is presented in (4.9). Countries are able to invest in generation capacity, x_i, of cost CX_i. The objective of the country is to maximise its total welfare, which in our case is only represented by consumer surplus. This is done by minimising the cost of investments in new capacity and the negative consumer surplus. New investments are restricted by the max capacity $P_i^{max\ new}$ and cannot be negative, as ensured by (4.9b) and (4.9c). Moreover, the actions of the country is dependent on the optimal solution of the lower level problem, represented by the KKT conditions in (4.7). These are consequently included as constraints (4.9d) to (4.9o), where the complementarity constraints are linearised into disjunctive constraints. The linearisation introduce binary variables and big-M parameters, as represented by z and M, respectively. Dual variables of the constraints are presented in parantheses.

[2]We performed some experiments of linearisation by using the lower level KKT conditions in (4.7). This would be valid if only one country is considered. However, for multiple countries, only nodes, branches and generators included in their country is considered. Hence, the KKT conditions in (4.7) which considers all nodes, branches and generators cannot be used.

$$\min_{x_{i\in G_c},\text{all } z, g_{it}, s_{nt}, f_{bt}, p_{nt}, \overline{\alpha}_{it}^{LL}, \overline{\gamma}_{bt}^{LL}, \underline{\gamma}_{bt}^{LL}} \quad -\sum_{t\in T}\sum_{n\in N_c} A\cdot W_t\,(VOLL - p_{nt})\,D_{nt} + \sum_{i\in G_c} CX_i x_i \tag{4.9a}$$

Subject to

$$x_i - P_i^{max\ new} \leq 0 \quad (\delta_i) \quad \forall i \in G_c \tag{4.9b}$$

$$x_i \geq 0 \quad \forall i \in G_c \tag{4.9c}$$

Non-complementarity KKT conditions of lower level problem

$$D_{nt} - \sum_{i\in G_n} g_{it} - s_{nt} - \sum_{b\in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b\in B_n^{out}} f_{bt} = 0 \quad (\epsilon_{ntc}) \quad \forall n,t \in N,T \tag{4.9d}$$

$$-p_{n(b^{in})t}(1 - F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} = 0 \quad (\zeta_{btc}) \quad \forall b,t \in B,T \tag{4.9e}$$

Complementarity KKT conditions of lower level problem as disjunctive constraints

$$0 \leq A\cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}_{it}^{LL} \leq M_{it}^g z_{it}^g \quad (\theta_{itc}) \quad \forall i,t \in G,T \tag{4.9f}$$

$$0 \leq g_{it} \leq M_{it}^g(1 - z_{it}^g) \quad (\kappa_{itc}) \quad \forall i,t \in G,T \tag{4.9g}$$

$$0 \leq A\cdot W_t \cdot VOLL - p_{nt} \leq M_{nt}^s z_{nt}^s \quad (\lambda_{ntc}) \quad \forall n,t \in N,T \tag{4.9h}$$

$$0 \leq s_{nt} \leq M_{nt}^s(1 - z_{nt}^s) \quad (\mu_{ntc}) \quad \forall n,t \in N,T \tag{4.9i}$$

$$0 \leq -g_{it} + \eta_{it}(P_i^0 + x_i) \leq M_{it}^{\overline{\alpha}^{LL}} z_{it}^{\overline{\alpha}^{LL}} \quad (\nu_{itc}) \quad \forall i,t \in G,T \tag{4.9j}$$

$$0 \leq \overline{\alpha}_{it}^{LL} \leq M_{it}^{\overline{\alpha}^{LL}}(1 - z_{it}^{\overline{\alpha}^{LL}}) \quad (\xi_{itc}) \quad \forall i,t \in G,T \tag{4.9k}$$

$$0 \leq -f_{bt} + (F_b^0 + y_b^{cap}) \leq M_{bt}^{\overline{\gamma}^{LL}} z_{bt}^{\overline{\gamma}^{LL}} \quad (\phi_{btc}) \quad \forall b,t \in B,T \tag{4.9l}$$

$$0 \leq \overline{\gamma}_{bt}^{LL} \leq M_{bt}^{\overline{\gamma}^{LL}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) \quad (\chi_{btc}) \quad \forall b,t \in B,T \tag{4.9m}$$

$$0 \leq (F_b^0 + y_b^{cap}) + f_{bt} \leq M_{bt}^{\underline{\gamma}^{LL}} z_{bt}^{\underline{\gamma}^{LL}} \quad (\psi_{btc}) \quad \forall b,t \in B,T \tag{4.9n}$$

$$0 \leq \underline{\gamma}_{bt}^{LL} \leq M_{bt}^{\underline{\gamma}^{LL}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) \quad (\omega_{btc}) \quad \forall b,t \in B,T \tag{4.9o}$$

Each country is facing an MPEC, because their problem is restricted by the optimality conditions of the lower level market clearing. An intermediate problem has both primal and dual variables of the lower level problem as decision variables in addition to their own. This is because the actions of the intermediate level decision makers can influence how the lower level choose their decision variables. Because the KKT conditions of the market operator is present in the intermediate level problem, the lower level will always respond according to their optimal response to the actions of the countries. When considering the MPECs of all the countries, the problem becomes an EPEC. The KKT conditions of (4.9) becomes (4.10) and (4.11), when the KKT conditions of disjunctive constraints of (4.9f) to (4.9o) are found by the exploitation of binary and dual variables approach from section 4.1.

Stationary conditions of free variables:

$$0 = -(1 - F_b^{loss})\epsilon_{n(b^{in})tc} + \epsilon_{n(b^{out})tc} + \underline{\phi}_{btc} - \overline{\phi}_{btc} - \underline{\psi}_{btc} + \overline{\psi}_{btc} \quad , \quad f_{bt} \text{ (free)} \quad \forall b, t \in B, T \tag{4.10a}$$

$$\begin{aligned} 0 = A \cdot W_t \cdot D_{nt} - \sum_{b \in B_n^{in}} (1 - F_b^{loss})\zeta_{btc} + \sum_{b \in B_n^{out}} \zeta_{btc} \\ + \sum_{i \in G_n} \underline{\theta}_{itc} - \sum_{i \in G_n} \overline{\theta}_{itc} + \underline{\lambda}_{ntc} - \overline{\lambda}_{ntc} \quad , \quad p_{nt} \text{ (free)} \quad \forall n, t \in N, T \end{aligned} \tag{4.10b}$$

Stationary conditions of non-free variables:

$$0 \leq CX_i + \delta_i - \sum_{t \in T} \eta_{it} \underline{\nu}_{itc} + \sum_{t \in T} \eta_{it} \overline{\nu}_{itc} \quad \perp \quad x_i \geq 0 \quad \forall i \in G_c \tag{4.10c}$$

$$0 \leq -\epsilon_{n(i)tc} + \kappa_{itc} + \underline{\nu}_{itc} - \overline{\nu}_{itc} \quad \perp \quad g_{it} \geq 0 \quad \forall i, t \in G, T \tag{4.10d}$$

$$0 \leq -\epsilon_{ntc} + \mu_{ntc} \quad \perp \quad s_{nt} \geq 0 \quad \forall n, t \in N, T \tag{4.10e}$$

$$0 \leq -\underline{\theta}_{itc} + \overline{\theta}_{itc} + \xi_{itc} \quad \perp \quad \overline{\alpha}_{it}^{LL} \geq 0 \quad \forall i, t \in G, T \tag{4.10f}$$

$$0 \leq \zeta_{btc} + \chi_{btc} \quad \perp \quad \overline{\gamma}_{bt}^{LL} \geq 0 \quad \forall b, t \in B, T \tag{4.10g}$$

$$0 \leq -\zeta_{btc} + \omega_{btc} \quad \perp \quad \underline{\gamma}_{bt}^{LL} \geq 0 \quad \forall b, t \in B, T \tag{4.10h}$$

Equality constraints:

$$0 = D_{nt} - \sum_{i \in G_n} g_{it} - s_{nt} - \sum_{b \in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b \in B_n^{out}} f_{bt} \quad , \quad \epsilon_{ntc} \text{ (free)} \quad \forall n, t \in N, T \tag{4.10i}$$

$$0 = -p_{n(b^{in})t}(1 - F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} \quad , \quad \zeta_{btc} \text{ (free)} \quad \forall b, t \in B, T \tag{4.10j}$$

Complementarity conditions from inequality constraint:

$$0 \leq -x_i + P_i^{max\ new} \quad \perp \quad \delta_i \geq 0 \quad \forall i \in G_c \tag{4.10k}$$

KKT conditions of disjunctive constraints (4.9f) to (4.9o):

$$0 \leq A \cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}_{it}^{LL} \quad , \quad 0 \leq \underline{\theta}_{itc} \leq M_{it}^{\underline{\theta}}(1 - z_{it}^{g}) \quad \forall i,t,c \in G,T,C \tag{4.11a}$$

$$0 \leq M_{it}^{g} z_{it}^{g} - A \cdot W_t(MC_i + CO2_i) + p_{n(i)t} - \overline{\alpha}_{it}^{LL} \quad , \quad 0 \leq \overline{\theta}_{itc} \leq M_{it}^{\overline{\theta}}(1 - z_{it}^{g}) \quad \forall i,t,c \in G,T,C \tag{4.11b}$$

$$0 \leq M_{it}^{g}(1 - z_{it}^{g}) - g_{it} \quad , \quad 0 \leq \kappa_{itc} \leq M_{it}^{\kappa} z_{it}^{g} \quad \forall i,t,c \in G,T,C \tag{4.11c}$$

$$0 \leq A \cdot W_t \cdot VOLL - p_{nt} \quad , \quad 0 \leq \underline{\lambda}_{ntc} \leq M_{nt}^{\underline{\lambda}}(1 - z_{nt}^{s}) \quad \forall n,t,c \in N,T,C \tag{4.11d}$$

$$0 \leq M_{nt}^{s} z_{nt}^{s} - A \cdot W_t \cdot VOLL + p_{nt} \quad , \quad 0 \leq \overline{\lambda}_{ntc} \leq M_{nt}^{\overline{\lambda}}(1 - z_{nt}^{s}) \quad \forall n,t,c \in N,T,C \tag{4.11e}$$

$$0 \leq M_{nt}^{s}(1 - z_{nt}^{s}) - s_{nt} \quad , \quad 0 \leq \mu_{ntc} \leq M_{nt}^{\mu} z_{nt}^{s} \quad \forall n,t,c \in N,T,C \tag{4.11f}$$

$$0 \leq -g_{it} + \eta_{it}(P_i^0 + x_i) \quad , \quad 0 \leq \underline{\nu}_{itc} \leq M_{it}^{\underline{\nu}}(1 - z_{it}^{\overline{\alpha}^{LL}}) \quad \forall i,t,c \in G,T,C \tag{4.11g}$$

$$0 \leq M_{it}^{\overline{\alpha}^{LL}} z_{it}^{\overline{\alpha}^{LL}} + g_{it} - \eta_{it}(P_i^0 + x_i) \quad , \quad 0 \leq \overline{\nu}_{itc} \leq M_{it}^{\overline{\nu}}(1 - z_{it}^{\overline{\alpha}^{LL}}) \quad \forall i,t,c \in G,T,C \tag{4.11h}$$

$$0 \leq M_{it}^{\overline{\alpha}^{LL}}(1 - z_{it}^{\overline{\alpha}^{LL}}) - \overline{\alpha}_{it}^{LL} \quad , \quad 0 \leq \xi_{itc} \leq M_{it}^{\xi} z_{it}^{\overline{\alpha}^{LL}} \quad \forall i,t,c \in G,T,C \tag{4.11i}$$

$$0 \leq -f_{bt} + (F_b^0 + y_b^{cap}) \quad , \quad 0 \leq \underline{\phi}_{btc} \leq M_{bt}^{\underline{\phi}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{4.11j}$$

$$0 \leq M_{bt}^{\overline{\gamma}^{LL}} z_{bt}^{\overline{\gamma}^{LL}} + f_{bt} - (F_b^0 + y_b^{cap}) \quad , \quad 0 \leq \overline{\phi}_{btc} \leq M_{bt}^{\overline{\phi}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{4.11k}$$

$$0 \leq M_{bt}^{\overline{\gamma}^{LL}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) - \overline{\gamma}_{bt}^{LL} \quad , \quad 0 \leq \chi_{btc} \leq M_{bt}^{\chi} z_{bt}^{\overline{\gamma}^{LL}} \quad \forall b,t,c \in B,T,C \tag{4.11l}$$

$$0 \leq (F_b^0 + y_b^{cap}) + f_{bt} \quad , \quad 0 \leq \underline{\psi}_{btc} \leq M_{bt}^{\underline{\psi}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{4.11m}$$

$$0 \leq M_{bt}^{\underline{\gamma}^{LL}} z_{bt}^{\underline{\gamma}^{LL}} - (F_b^0 + y_b^{cap}) - f_{bt} \quad , \quad 0 \leq \overline{\psi}_{btc} \leq M_{bt}^{\overline{\psi}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{4.11n}$$

$$0 \leq M_{bt}^{\underline{\gamma}^{LL}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) - \underline{\gamma}_{bt}^{LL} \quad , \quad 0 \leq \omega_{btc} \leq M_{bt}^{\omega} z_{bt}^{\underline{\gamma}^{LL}} \quad \forall b,t,c \in B,T,C \tag{4.11o}$$

4.2.3 The upper level problem: System optimal transmission expansion

A benevolent system planner performs transmission expansion in the upper level problem (4.12) and (4.13). The objective is to reduce cost of investments, as shown in (4.12a). Expenses are dependent both upon the number of new lines, y_b^{num}, and capacity, y_b^{cap}. Costs are divided into a branch mobilisation cost, B, fixed cost per unit length, B^d and B^{dp}, in addition to the cost of switch-gear for moving from onshore to offshore branches, CS_b and CS_b^p. New branch capacity is dependent upon the number of new lines, where each has a maximum capacity of $F_b^{max\ line}$. The total capacity of a branch cannot exceed the total maximum limit of $F_b^{max\ new}$, as enforced by (4.12b). New branch capacity is also non-negative, while number of new lines are integers, as portrayed by (4.12c) and (4.12d).

The upper level problem are restricted by the intermediate problems. Because optimality conditions of the lower level problem is already included in the intermediate problem, the upper level become restricted by it as well. KKT conditions (4.10) and (4.11) are included as constraints in the upper level problem (4.12) and (4.13). The complementarity constraint of (4.10), namely (4.10c) to (4.10h) and (4.10k), are linearised into disjunctive constraints in the upper level problem as restrictions (4.12i) to (4.12v). Notice that the all primal and dual variables of the lower and intermediate level problem, in addition to the binary variables become decision variables for the upper level problem.

$$\min_{y_b^{num}, y_b^{cap}, \text{all } z, \text{primal and dual variables of (4.9)}} \sum_{b \in B} \left((B + B^d L_b^{km} + 2CS_b) y_b^{num} + (B^{dp} L_b^{km} + 2CS_b^p) y_b^{cap} \right) \tag{4.12a}$$

Subject to

$$y_b^{cap} \leq F_b^{max\ line} y_b^{num} \leq F_b^{max\ new} \quad \forall b \in B \tag{4.12b}$$

$$y_b^{cap} \geq 0 \quad \forall b \in B \tag{4.12c}$$

$$y_b^{num} \in \mathbb{Z}_{\geq 0} \quad \forall b \in B \tag{4.12d}$$

Equality KKT conditions of intermediate problem:

$$-(1 - F_b^{loss}) \epsilon_{n(b^{in})tc} + \epsilon_{n(b^{out})tc} + \underline{\phi}_{btc} - \overline{\phi}_{btc} - \underline{\psi}_{btc} + \overline{\psi}_{btc} = 0 \quad \forall b, t, c \in B, T, C \tag{4.12e}$$

$$\begin{aligned} A \cdot W_t \cdot D_{nt} - \sum_{b \in B_n^{in}} (1 - F_b^{loss}) \zeta_{btc} + \sum_{b \in B_n^{out}} \zeta_{btc} \\ + \sum_{i \in G_n} \underline{\theta}_{itc} - \sum_{i \in G_n} \overline{\theta}_{itc} + \underline{\lambda}_{ntc} - \overline{\lambda}_{ntc} = 0 \quad \forall n, t, c \in N, T, C \end{aligned} \tag{4.12f}$$

$$D_{nt} - \sum_{i \in G_n} g_{it} - s_{nt} - \sum_{b \in B_n^{in}} f_{bt} (1 - F_b^{loss}) + \sum_{b \in B_n^{out}} f_{bt} = 0 \quad \forall n, t, c \in N, T, C \tag{4.12g}$$

$$-p_{n(b^{in})t} (1 - F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} = 0 \quad \forall b, t, c \in B, T, C \tag{4.12h}$$

KKT conditions (4.10c) to (4.10h) and (4.10k) as disjunctive constraints:

$$0 \leq CX_i + \delta_i - \sum_{t \in T} \eta_{it} \underline{\nu}_{itc(i)} + \sum_{t \in T} \eta_{it} \overline{\nu}_{itc(i)} \leq M_i^x z_i^x \quad \forall i \in G \tag{4.12i}$$

$$0 \leq x_i \leq M_i^x (1 - z_i^x) \quad \forall i \in G \tag{4.12j}$$

$$0 \leq -\epsilon_{n(i)tc} + \kappa_{itc} + \underline{\nu}_{itc} - \overline{\nu}_{itc} \leq M_{itc}^{g^{IL}} z_{itc}^{g^{IL}} \quad \forall i, t, c \in G, T, C \tag{4.12k}$$

$$0 \leq g_{it} \leq M_{itc}^{g^{IL}} (1 - z_{itc}^{g^{IL}}) \quad \forall i, t \in G, T \tag{4.12l}$$

$$0 \leq -\epsilon_{ntc} + \mu_{ntc} \leq M_{ntc}^{s^{IL}} z_{ntc}^{s^{IL}} \quad \forall n, t, c \in N, T, C \tag{4.12m}$$

$$0 \leq s_{nt} \leq M_{ntc}^{s^{IL}} (1 - z_{ntc}^{s^{IL}}) \quad \forall n, t, c \in N, T, C \tag{4.12n}$$

$$0 \leq -\underline{\theta}_{itc} + \overline{\theta}_{itc} + \xi_{itc} \leq M_{itc}^{\overline{\alpha}^{IL}} z_{itc}^{\overline{\alpha}^{IL}} \quad \forall i, t, c \in G, T, C \tag{4.12o}$$

$$0 \leq \overline{\alpha}_{it}^{LL} \leq M_{itc}^{\overline{\alpha}^{IL}} (1 - z_{itc}^{\overline{\alpha}^{IL}}) \quad \forall i, t, c \in G, T, C \tag{4.12p}$$

$$0 \leq \zeta_{btc} + \chi_{btc} \leq M_{btc}^{\overline{\gamma}^{IL}} z_{btc}^{\overline{\gamma}^{IL}} \quad \forall b, t, c \in B, T, C \tag{4.12q}$$

$$0 \leq \overline{\gamma}_{bt}^{LL} \leq M_{btc}^{\overline{\gamma}^{IL}} (1 - z_{btc}^{\overline{\gamma}^{IL}}) \quad \forall b, t, c \in B, T, C \tag{4.12r}$$

$$0 \leq -\zeta_{btc} + \omega_{btc} \leq M_{btc}^{\underline{\gamma}^{IL}} z_{btc}^{\underline{\gamma}^{IL}} \quad \forall b, t, c \in B, T, C \tag{4.12s}$$

$$0 \leq \underline{\gamma}_{bt}^{LL} \leq M_{btc}^{\underline{\gamma}^{IL}} (1 - z_{btc}^{\underline{\gamma}^{IL}}) \quad \forall b, t, c \in B, T, C \tag{4.12t}$$

$$0 \leq -x_i + P_i^{max\ new} \leq M_i^{\delta} z_i^{\delta} \quad \forall i \in G \tag{4.12u}$$

$$0 \leq \delta_i \leq M_i^{\delta} (1 - z_i^{\delta}) \quad \forall i \in G \tag{4.12v}$$

KKT conditions (4.11):

$$0 \leq A \cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}_{it}^{LL} \quad , \quad 0 \leq \underline{\theta}_{itc} \leq M_{it}^{\underline{\theta}}(1 - z_{it}^{g}) \quad \forall i,t,c \in G,T,C \tag{4.13a}$$

$$0 \leq M_{it}^{g} z_{it}^{g} - A \cdot W_t(MC_i + CO2_i) + p_{n(i)t} - \overline{\alpha}_{it}^{LL} \quad , \quad 0 \leq \overline{\theta}_{itc} \leq M_{it}^{\overline{\theta}}(1 - z_{it}^{g}) \quad \forall i,t,c \in G,T,C \tag{4.13b}$$

$$0 \leq M_{it}^{g}(1 - z_{it}^{g}) - g_{it} \quad , \quad 0 \leq \kappa_{itc} \leq M_{it}^{\kappa} z_{it}^{g} \quad \forall i,t,c \in G,T,C \tag{4.13c}$$

$$0 \leq A \cdot W_t \cdot VOLL - p_{nt} \quad , \quad 0 \leq \underline{\lambda}_{ntc} \leq M_{nt}^{\underline{\lambda}}(1 - z_{nt}^{s}) \quad \forall n,t,c \in N,T,C \tag{4.13d}$$

$$0 \leq M_{nt}^{s} z_{nt}^{s} - A \cdot W_t \cdot VOLL + p_{nt} \quad , \quad 0 \leq \overline{\lambda}_{ntc} \leq M_{nt}^{\overline{\lambda}}(1 - z_{nt}^{s}) \quad \forall n,t,c \in N,T,C \tag{4.13e}$$

$$0 \leq M_{nt}^{s}(1 - z_{nt}^{s}) - s_{nt} \quad , \quad 0 \leq \mu_{ntc} \leq M_{nt}^{\mu} z_{nt}^{s} \quad \forall n,t,c \in N,T,C \tag{4.13f}$$

$$0 \leq -g_{it} + \eta_{it}(P_i^0 + x_i) \quad , \quad 0 \leq \underline{\nu}_{itc} \leq M_{it}^{\underline{\nu}}(1 - z_{it}^{\overline{\alpha}^{LL}}) \quad \forall i,t,c \in G,T,C \tag{4.13g}$$

$$0 \leq M_{it}^{\overline{\alpha}^{LL}} z_{it}^{\overline{\alpha}^{LL}} + g_{it} - \eta_{it}(P_i^0 + x_i) \quad , \quad 0 \leq \overline{\nu}_{itc} \leq M_{it}^{\overline{\nu}}(1 - z_{it}^{\overline{\alpha}^{LL}}) \quad \forall i,t,c \in G,T,C \tag{4.13h}$$

$$0 \leq M_{it}^{\overline{\alpha}^{LL}}(1 - z_{it}^{\overline{\alpha}^{LL}}) - \overline{\alpha}_{it}^{LL} \quad , \quad 0 \leq \xi_{itc} \leq M_{it}^{\xi} z_{it}^{\overline{\alpha}^{LL}} \quad \forall i,t,c \in G,T,C \tag{4.13i}$$

$$0 \leq -f_{bt} + (F_b^0 + y_b^{cap}) \quad , \quad 0 \leq \underline{\phi}_{btc} \leq M_{bt}^{\underline{\phi}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{4.13j}$$

$$0 \leq M_{bt}^{\overline{\gamma}^{LL}} z_{bt}^{\overline{\gamma}^{LL}} + f_{bt} - (F_b^0 + y_b^{cap}) \quad , \quad 0 \leq \overline{\phi}_{btc} \leq M_{bt}^{\overline{\phi}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{4.13k}$$

$$0 \leq M_{bt}^{\overline{\gamma}^{LL}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) - \overline{\gamma}_{bt}^{LL} \quad , \quad 0 \leq \chi_{btc} \leq M_{bt}^{\chi} z_{bt}^{\overline{\gamma}^{LL}} \quad \forall b,t,c \in B,T,C \tag{4.13l}$$

$$0 \leq (F_b^0 + y_b^{cap}) + f_{bt} \quad , \quad 0 \leq \underline{\psi}_{btc} \leq M_{bt}^{\underline{\psi}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{4.13m}$$

$$0 \leq M_{bt}^{\underline{\gamma}^{LL}} z_{bt}^{\underline{\gamma}^{LL}} - (F_b^0 + y_b^{cap}) - f_{bt} \quad , \quad 0 \leq \overline{\psi}_{btc} \leq M_{bt}^{\overline{\psi}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{4.13n}$$

$$0 \leq M_{bt}^{\underline{\gamma}^{LL}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) - \underline{\gamma}_{bt}^{LL} \quad , \quad 0 \leq \omega_{btc} \leq M_{bt}^{\omega} z_{bt}^{\underline{\gamma}^{LL}} \quad \forall b,t,c \in B,T,C \tag{4.13o}$$

4.3 Centrally performed generation and transmission investments

We want to compare our strategic model against a framework where all countries cooperate to achieve system optimal results. A benevolent system planer are expected to perform investments in both transmission and generation on behalf of the countries. The intermediate level problem will therefore cease to exist, because the generation investment decisions are made by the central planner in the upper level problem. As a result, the trilevel problem is reduced to a bilevel problem where the central planner has the upper level problem and market operation is at the lower level, as shown in Figure 4.2.

By assuming a welfare maximising central planner and perfect competition, the bilevel problem becomes equivalent to a co-optimisation model minimising both investment and operational costs (Samuelson 1952). The perfect competition assumption includes the expectation of a considerable amount of producers who provide cost-efficient bids. The problem is presented in (4.14). It contains all the objectives and restrictions of the trilevel problem, but all decisions are taken by a system authority to achieve system optimal results.

The objective is to minimise both investment and operational costs, as shown in (4.14a). Investment cost in (4.14b) consist of transmission and generation investment costs. Operating costs in (4.14c) are equivalent to the short-term market clearing of the lower level problem. Restrictions (4.14f) to (4.14j) are the same as those enforced at the different stages of the trilevel problem. The energy balance is enforced

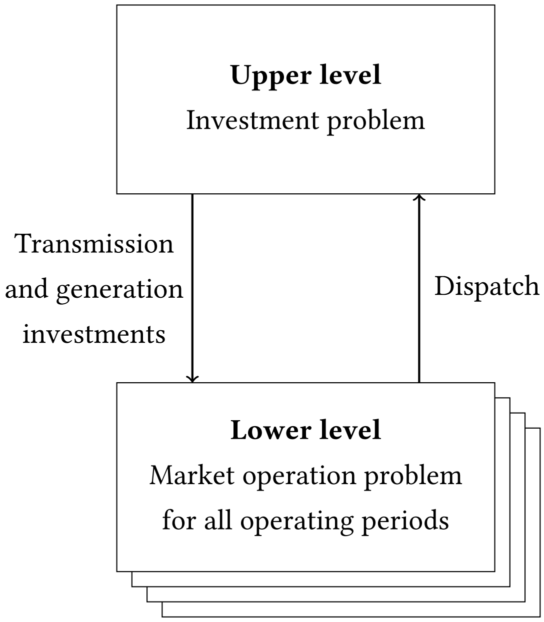


Figure 4.2: Representation of bilevel investment and market operation problem.

by (4.14f), while (4.14g) limits production to the maximum generation capacity. Constraint (4.14h) limits the amount of new generation investment. Transmission capacities are not violated because of (4.14i) and new transmission investments are restricted by (4.14j). Nomenclature is equal to the one presented in Table 4.1.

$$\min_{x_i, y_b^{num}, y_b^{cap}, g_{it}, f_{bt}, s_{nt}} \quad IC + A \cdot OC \tag{4.14a}$$

where

$$IC = \sum_{b \in B} (C_b^{fix} y_b^{num} + C_b^{var} y_b^{cap}) + \sum_{i \in G} CX_i x_i \tag{4.14b}$$

$$OC = \sum_{t \in T} W_t (\sum_{i \in G} (MC_i + CO2_i) g_{it} + \sum_{n \in N} VOLL s_{nt}) \tag{4.14c}$$

$$C_b^{fix} = B + B^d L_b^{km} + 2CS_b \qquad \forall b \in B \tag{4.14d}$$

$$C_b^{var} = B^{dp} L_b^{km} + 2CS_b^p \qquad \forall b \in B \tag{4.14e}$$

subject to

$$\sum_{l \in L_n} D_{lt} = \sum_{i \in G_n} g_{it} + \sum_{b \in B_n^{in}} f_{bt}(1 - F_b^{loss}) - \sum_{b \in B_n^{out}} f_{bt} + s_{nt} \qquad \forall n, t \in N, T \tag{4.14f}$$

$$g_{it} \leq \eta_{it}(P_i^0 + x_i) \qquad \forall i, t \in G, T \tag{4.14g}$$

$$x_i \leq P_i^{max\ new} \qquad \forall i \in G \tag{4.14h}$$

$$-(F_b^0 + y_b^{cap}) \leq f_{bt} \leq (F_b^0 + y_b^{cap}) \qquad \forall b, t \in B, T \tag{4.14i}$$

$$y_b^{cap} \leq F_b^{max\ line} y_b^{num} \leq F_b^{max} \qquad \forall b \in B \tag{4.14j}$$

$$x_i, y_b^{cap}, g_{it}, s_{nt} \geq 0, \quad f_{bt} \in \mathbb{R}, \quad y_b^{num} \in \mathbb{Z}^+$$

4.4 The North Sea Offshore Grid representation

The North Sea Offshore Grid model considered in this thesis is an aggregated representation of the actual network. All generation and demand are aggregated at a single node for a country. To have a computationally tractable model, we only include Germany (DE), Great Britain (GB), and Norway (NO). They represent the largest countries with respect to generation capacity and demand. As of 2018, no interconnectors exist between them, and the expansion planner has the opportunity to build the corridors[3]. An illustration of the grid is shown in Figure 4.3. Dashed lines are optional for investments, while the solid lines are expected to be present.

Twelve nodes are present in the system. One node per country provides an aggregate representation of its demand and generation. Hub nodes are used for offshore interconnection between countries and offshore wind production. An accurate representation of all nodes is provided in Table A.1 in Appendix A.

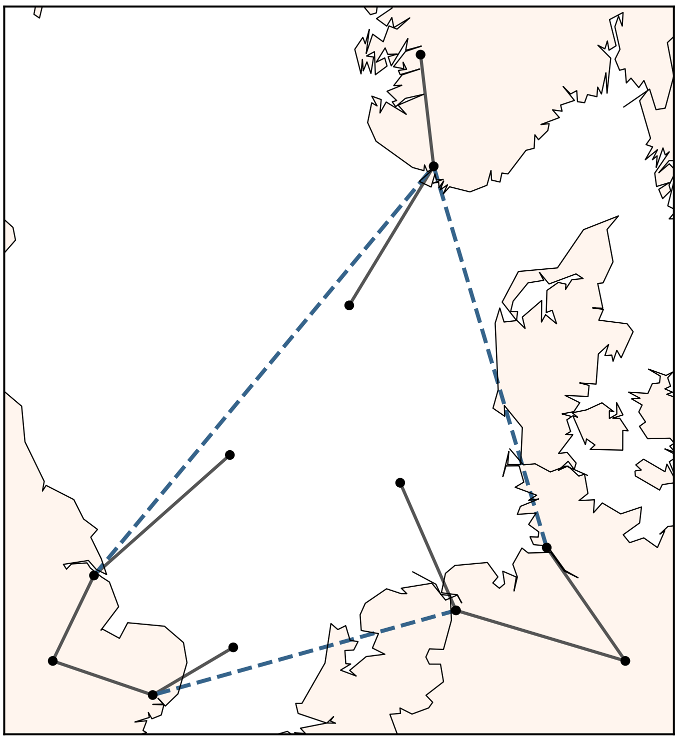


Figure 4.3: Representation of the North Sea offshore grid infrastructure and nodes for the case study

[3] Do note that corridors from Denmark to Norway (NordLink) and Great Britain to Norway (North Sea Link) are planned and have expected operation in 2020 and 2021, respectively (National Grid and Statnett 2018; Statnett 2018)

4.5 Input data to model

The goal for the input data is to use reliable open source data. It is preferable to be consistent with data sources and only add additional data sources when the existing are inadequate or lacking. This is done to stay coherent to one scenario, because different sources are likely to have different motivations and assumptions. If data are given for different years, 2015 is consequently chosen. A discount rate of 5% and 30 years are chosen whenever needed in the model. Accurately choosing discount factors are beyond the scope of this report, hence a neutral rate is selected. TEP have long lifetimes and is likely to be utilised for longer than 30 years. However, the investors would like to earn back their expenditures within a reasonable time. The section dealing with finding and processing input data is from a specialisation project prior to this thesis. Data for all the countries bordering to the North Sea is included for interest, but only Germany, Great Britain and Norway will be used in the model[4].

4.5.1 ENTSO-E Ten Year Network Development Plan

Every other even year, ENTSO-E publishes its Ten-Year Network Development Plan (TYNDP) (ENTSO-E 2016). This plan investigates ongoing projects and future development in the electric power grid in Europe. In addition, the report studies potential future scenarios of development (ENTSO-E 2015). ENTSO-E includes public consultation and values stakeholder interaction when producing TYNDP. The modelling data from the scenarios are also publicly available. For these two reasons the TYNDP modelling data will be used as a main source of input data.

The TYNDP scenario development report presents four different scenarios, called visions, for 2030. Vision 4 is the most ambitious with respect to European cooperation and transition to more renewable electricity production. This creates an adequate base for an interesting case study of investing in North Sea infrastructure. Hence modelling data from vision 4 will be used for installed capacities, fuel and CO_2 prices, load profiles, and generation efficiency.

Vision 4 includes significant investments in renewable electricity production. The electricity market design is favourable for trade and development of technology. Carbon prices are assumed to be high. The demand is expected to increase, mainly due to electrification of transport, heating and cooling. Vision 4 also utilises demand response to shift peaks. Nuclear production is being phased out, mainly due to lack of flexibility and not being competitive compared to renewable production. See ENTSO-E (2015, 2017) for further information about the visions, their construction and downloads.

4.5.2 Generation capacity

Installed generation capacity is from ENTSO-E (2015) Vision 4, with the exception of offshore wind. TYNDP does only present a single wind production where both onshore and offshore are not separated. Hence WindEurope (2017) scenarios is used to classify the amount of offshore wind. In addition, the offshore wind production is subtracted from the total Vision 4 wind production to find an estimate for

[4]The original objective was to perform strategic TEP on all NSOG countries. However, the model did not become computationally tractable for acceptable time sample sizes when solving for the full NSOG. Input data of Belgium, Denmark and the Netherlands are included to provide guidance of where to find open source data about them which may be relevant for future work.

onshore wind. Because Vision 4 is the main base of data, onshore wind scenarios is not taken from WindEurope but calculated to achieve total wind production assumption. Vision 4 assumes 29% of the total wind production to be located offshore, according to ENTSO-E (2014a). The WindEurope High scenario is chosen because it has the closest total wind production to the Vision 4 estimate. There are no offshore estimates for Norway. Hence an assumption of 29% of total wind production for offshore production is used, in the lack of better sources.

ENTSO-E Vision 4 presents two categories called *Others RES* and *Others non-RES* which needs to be classified. It is assumed that *Others RES* consists of different types of biofuels, and hence is added to the biofuel generation capacity. The reason for this assumption is that biofuels are classified as renewables and consists of a large number of different fuel products. For instance, the International Energy Agency (2013) presents a German biomass electricity production of $5569 MW$ in 2013, while no specific biofuel production is included in ENTSO-E Vision 4. For *Others non-RES*, the TYNDP for 2014 include an overview of the amount of gas shares in the *Others non-RES* (ENTSO-E 2014b). This was a significant amount and hence the *Others non-RES* is added to gas generation capacity. The generation capacities are given in Table A.2 in Appendix A.

4.5.3 Emission input data

Estimates for CO_2 emission from electricity generation are taken from the *CO_2 Emissions From Fuel Combustion Highlights 2016* report by the International Energy Agency (2016). It is assumed that the generalised *hard coal* classification used by ENTSO-E has the emission factor of *other bituminous coal*. The emission rates used as input are given in Table A.3 in Appendix A.

4.5.4 Cost of generation

The cost of generation depend on two factors, the efficiency of the technology and the fuel cost. Technology efficiencies for the different Vision 4 generation methods are provided by ENTSO-E (2017). However, the efficiencies presented are a range where we choose the middle value. Gas and oil production give different production options, each rendering their own middle value. Although a rough estimate, the middle value of those are chosen to represent the whole category. The values are given in Table A.4 in Appendix A. Fuel prices are also provided by ENTSO-E (2017). They are given in the unit $EUR/netGJ$, while our model uses EUR/MWh. The units are converted by the relationship $1MWh = 3.6GJ$, and the input marginal cost, MC, of generation is then calculated by (4.15).

$$MC = \frac{3.6 \cdot p_{fuel}}{\eta_{tech}} \tag{4.15}$$

The fuel cost of biomass is not given by ENTSO-E and is hard to estimate due to its wide range of possible sources. Hence it is assumed to have have the same price as primary fuel type (ENTSO-E 2014b), which is chosen to be gas. Hydro power is chosen arbitrary to have a input price of $10EUR/MWh$ for all countries except Norway who utilises a production profile. This price is chosen because not all hydro power is run of river, and thus contains a value due to storage possibilities. Hence a price of zero will make hydro power dispatch compete against intermittent wind and solar production. Setting it equal to fossil fuel prices will also be misrepresenting because the marginal cost is lower. The fuel and input prices are given in Table A.5 in Appendix A.

4.5.5 Cost of generation investments

For investments in grid capacity the capital expenditures (CAPEX) is taken from the Roadmap 2050 report by the European Climate Foundation (2010). The goal of the report is to create a practical, independent and objective analysis of how to achieve a low-carbon Europe. From the range of possible CAPEX the report proposes, where the middle value is assumed for all technologies. These values are discounted by an assumed interest rate of 5% and paid over a period of 30 years. Hence a yearly investment cost is used for each unit produced power. The values from Roadmap 2050 and the input data is shown in Table A.6 in Appendix A.

4.5.6 Renewable production and load profiles

Load and renewable production vary with time. Profiles are used to depict this. ENTSO-E (2017) provides a hourly load profile to the Vision 4 scenario. However, no wind or solar profiles are given by ENTSO-E. Hence these are found from the *renewables.ninja* tool, which provide hourly power output profiles in fractions of maximum output. Methods to generate profiles are given in Pfenninger and Staffell (2016a,b) for solar PV and wind production, respectively. Profiles used are country aggregated and downloaded from the *renewables.ninja* webpage (Pfenninger and Staffell 2017). For solar PV the *MERRA-2* simulations are used for having long term stability and consistency. The wind simulations are separated between onshore and offshore production for the countries, which is an advantage. Here the simulation called *current* is used.

Norway has a significant amount of hydro production in its electricity market, which at 2015 was at 96% (International Energy Agency 2017). As a consequence, the electricity prices depend on a calculated water value of the reservoirs. This changes with weather conditions, current reservoir levels and expected future inflow and consumption. Hence a price profile for Norwegian hydro power is needed to accurately depict its production. Under the assumption of marginal cost bidding, the prices from the power exchange Nord Pool (2017) is used to represent the water value. Market clearing from southern Norway is used because it is closest to where the interconnectors are installed. A major shortcoming of this approach is the presence of prices concerning a 2015 market when the rest is upgraded to a 2030 scenario. Hence there will be a mismatch because the demand and generation portfolios will be different. Regardless, in the lack of reliable open source water value profiles this is the chosen method.

4.5.7 Grid data

The model uses the transfer capacity costs representation presented in Härtel et al. (2017) for the investment opportunities. The Electricity Ten Year Statement (ETYS) from National Grid, the British TSO, was found to be most accurate in the paper. While the 2013 version was slightly more accurate, the 2015 data is chosen to have updated data from National Grid (2015). The input variables are given in Table A.7, A.8 and A.9 in Appendix A, calculated in accordance to the method presented in Härtel et al. 2017. Losses are implemented by a loss fraction approach. The power loss constant is 1.6% for AC/DC converters. Transmission have a power loss slope of 0.005% for AC technology and 0.003% for DC technology per kilometre. Investment costs were calculated and estimated by the developers of PowerGAMA (Svendsen 2017; Svendsen and Spro 2016), an open source Python package for modelling power systems, and used with allowance from them.

4.5.8 Quality of data

While ENTSO-E Vision 4 gives a adequate foundation, it has the drawback of not providing all the necessary inputs. Mainly regarding offshore wind production. This provide a mismatch between sources and their underlying assumptions. The range of technology efficiencies is also a weakness. Especially with regards to gas production which represent a significant amount of production. The ranges are quite wide, between 25% and 42% for conventional gas. While this may be representative for the available technology, it is hard to determine whether it is descriptive of the aggregated production values ENTSO-E provides.

Another shortcoming of the ENTSO-E data is the generalised categories of *Others RES* and *Others non-RES*. These are hard to determine, and ENTSO-E provide little documentation regarding their origin. Similarly, no estimate on biomass price also provides issues by having to utilise a rough assumption of gas prices. It is also worth repeating the already discussed flaw of using 2015 clearing prices in southern Norway as estimates for 2030 water value profiles.

The input data is crucial for providing reliable and realistic results. Hence they should be chosen with utmost care. The mentioned weaknesses should be taken into consideration when presenting the results because they represent a limitation of the work. A summary of the most important input data is portrayed in Table 4.2.

4.5.9 Selection of big-M parameters

While big-M parameters theoretically represents infinitely high values, in practical terms they do only need to be sufficiently large. We can achieve this by selecting the big-M parameters slightly higher than the maximum values of the variables present in the constraint. Primal variables often has natural bounds, for instance maximum generation production or new investments. However, the selection becomes slightly more challenging for dual variables, especially in the trilevel model which accumulates a lot of dual variables through two levels.

Because we have problems accurately selecting big-M parameter values for all values in our model we can do an iterative approach of testing an increasing number of big-M values and observe when results start to behave consistent and not produce give warnings about possible numerical errors. Both too low and too high values create difficulties. From the input data and a random sample of 25 time steps, Gurobi announces the maximum right hand side (RHS) coefficient to be at magnitude $9 \cdot 10^6$, when units are converted from *MW* to *GW* and *EUR* ot *kEUR*. The big-M needs to exceed this value. However, the maximum integer feasibility tolerance Gurobi manages to produce feasible results from is 10^{-8}. Constraints containing Mz will therefore not be forced fully to zero in the worst case scenarios for large big-M, in addition to other potential numerical errors. Consequently, we choose all $M = 1 \cdot 10^7$. Worst case situations will produce $Mz = 1 \cdot 10^7 \cdot 10^{-8} = 0.1$ for $z = 0$, which is not favourable for *GW* units. For higher values of big-M, Gurobi gave warnings of maximum constraints violations. At lower values, it would start to interfere with the constraints in the problem. This is a short-coming of our input data, where daily use are calculated in the same model as investments of 30 years financial lifetime. The broad range of variable values is numerically difficult for the solver to handle. Computational challenges are discussed further in section 5.5.

Table 4.2: Supply, demand and fuel price data from ENTSO-E Vision 4 (ENTSO-E 2015). Onshore and offshore wind capacities are divided according to data from WindEurope (2017). CO_2 price is $76 EUR$/tonCO_2 and VOLL $1000 EUR$/MWh. Capital expenditure (CAPEX) given by ECF Roadmap 2050 (European Climate Foundation 2010)

Supply/	Fuel price	Capacity $[MW]$			Max new cap	CAPEX
Demand	$[EUR/MWh_e]$	DE	GB	NO	$[MW]$	$[EUR/(MWh\,yr)]$
Bio	50	9340	8420	0	5000	113840
Gas	65	45059	40726	855	5000	48789
Hard coal	21	14940	0	0	5000	97577
Hydro	10	14505	5470	48700	0	121971
Lignite	10	9026	0	0	5000	97577
Nuclear	5	0	9022	0	0	195154
Oil	140	871	75	0	5000	48789
Solar PV	0	58990	11915	0	5000	78062
Onshore wind	0	76967	27901	1771	5000	68204
Offshore wind	0	20000	30000	724	5000	143113
Total supply	-	249698	133529	52050	-	-
Peak demand	-	81369	59578	24468	-	-

Chapter 5

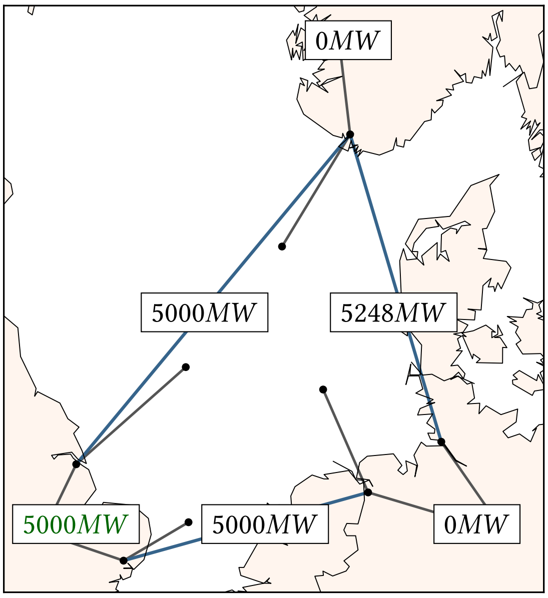
Results and discussion

The model outlined in section 4.2 is formulated in Pyomo (Hart et al. 2017; Hart, Watson, and Woodruff 2011), a mathematical programming package for Python, and solved by the Gurobi solver. Because only consumer surplus is included, the countries only have the objective of maximising the welfare of their consumers. The case study will both indicate whether the model behaves as expected, and illustrate an extreme case of countries who are only focused on minimising their own prices. A centrally planned generation and transmission expansion, and thus perfectly system efficient, will be used as a reference which the strategic results are compared against. A random sample of 25 time steps are used in the model. No further amount of steps are included to make the model tractable for an acceptable solution time. All results are deviated from the same random sample, and consequently compared at an equal foundation. Generation units have a maximum new investment capacity of 5000MW and corridors are restricted to max 10000MW. We also assume no transmission loss in the system.

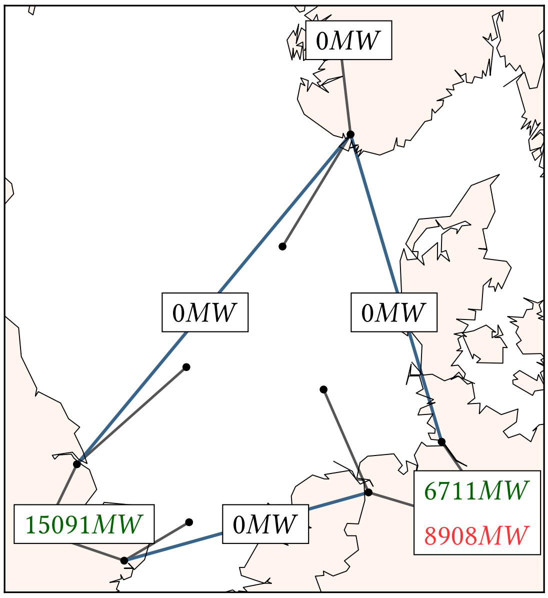
5.1 Case study results

An overview of investments actions are shown in Figure 5.1. We observe two contrasting situations. The central planner in Figure 5.1a performs major investments in all lines, and only a single generation investment of 5000MW wind production in Great Britain. Figure 5.1b portrays how the strategic planner invests in no corridors, but in significant generation capacity in Germany and Great Britain, compared to the central planner. Norway is self-sufficient with hydropower and performs no investments in both cases.

The strategic countries wants to decrease the costs for themselves, regardless of the system. As a consequence, countries will always supply their own demand first. Renewable production may exceed the demand. Because countries already have fulfilled their demand, they will become indifferent to this production. The expansion planner can then only expand with respect to the surplus production. However, there are more situations where demand is not met than surplus energy. Strategic countries will then invest in additional generation capacity, because it is too risky to be dependent upon the surplus production of the other countries. As the countries become more self-sufficient, the expansion planner will gradually lose the incentive to invest because the surplus electricity at a country become less valuable when the other countries are self-sufficient at the same time. In the case study, the central planner has lost all incentives to invest in lines. The self-sufficiency of the countries will make trans-



(a) Centrally performed investments



(b) Strategically performed investments

Figure 5.1: New generation and transmission expansions. Green values are renewable investments, while red are non-renewable at the countries.

mission investments a misuse of public capital. Table 5.1 presents a detailed overview of the generation expansion. Countries do prefer renewable production because of low marginal costs, however they are exposed to the risk of intermittent production. Germany do even invest in additional hard coal and lignite capacity to cover periods of low renewable production.

The central planner wants to decrease the costs of the whole system and consider all countries as equally important. She is therefore able to dispatch the most beneficial generation resource at any period of time. Renewable production, such as wind and solar, has the advantage of low marginal costs, but the risk of intermittent behaviour. In a system perspective the variable renewable are diversified to different locations, while strategic countries only have their own location. The central planner will then perform investments in the network in order to better utilise the system resources. We observe in Figure 5.1a how efficient strategy this is. The system takes more advantage of existing production facilities, and only apply some additional wind investments in Great Britain.

Table 5.1 show how only Germany manages to reduce their prices by $1.2 EUR/MWh$ compared to a centrally planned system. Great Britain experience $2.7 EUR/MWh$ higher prices in the strategic setting. Norway who are self-sufficient with hydropower in both cases experience no changes.

Both investment and operational costs for the system are outlined in Table 5.2. The central planner outperforms the strategic situations at both instances. The strategic countries' reluctance of sharing generation capacity lead to over-investments in new generation capacity in order to meet their own demand. Surplus renewable generation are wasted, because there are no transfer opportunities. Low marginal cost production is thus lost in the strategic scenario, but utilised in the central expansion. The strategic countries are also exposed to the risk of intermittent production in their own countries. They

Table 5.1: Generation investments from strategic and centrally planned model.

	Centrally planned new capacity $[MW]$			Strategic new capacity $[MW]$		
	DE	GB	NO	DE	GB	NO
Bio	0	0	0	1412	1421	0
Gas	0	0	0	0	0	0
Hard coal	0	0	0	5000	0	0
Hydro	0	0	0	0	0	0
Lignite	0	0	0	3908	0	0
Nuclear	0	0	0	0	0	0
Oil	0	0	0	0	0	0
Solar PV	0	0	0	2148	1137	0
Onshore wind	0	5000	0	241	5000	0
Offshore wind	0	0	0	2910	7533	0
Total new RES	0	5000	0	6711	15091	0
Total new non-RES	0	0	0	8908	0	0
Average price $[EUR/MWh]$	61.3	41.4	19.9	60.1	44.1	19.9

consequently have to cover low renewable production with fossil fuel or biogas with higher marginal costs. The central planner, on the other hand, diversifies the risk of renewables throughout the system. She can utilise a larger extent of low marginal cost intermittent production. The probability of three countries at separate locations experience a concurrent low renewable production is less than for a single country. We observe this by the lower operational costs in Table 5.2 and no non-renewable investments of the central planner compared to the strategic countries.

Table 5.2: Comparison of system costs in the models.

Model	Investment costs $[mEUR]$	Operational costs $[mEUR]$	Total costs $[mEUR]$
Strategic	50731.2	351378.4	402109.6
Centrally planned	33237.1	309640.3	342877.4
Difference	17494.1	41738.1	59232.2

The total cost difference of $59232.2mEUR$ provide an opportunity for the strategic countries to decrease system costs by 14.7% if they move towards a centrally planned system[1]. A way to accomplish

[1] The ratio between best equilibrium and the centrally planned solution are known as the *price of stability* in game theory, and is 1.173 in our case. In order to guarantee a stable situation we must multiply the centrally performed best costs by the price of stability ratio.

this is to cooperate in the creation of a supra-national regulator who will at all times do the system best investments. Countries must then subject themselves to the decision of the regulator. If they deviate the system can become worse off. For instance Norway may refuse to share their low cost and flexible hydropower in an European system, and provide their own users with cheap electricity instead. Our strategic model will produce a stable global optimal equilibrium, which there are no incentives for the countries to deviate from in the given framework.

5.2 Sensitivity analysis

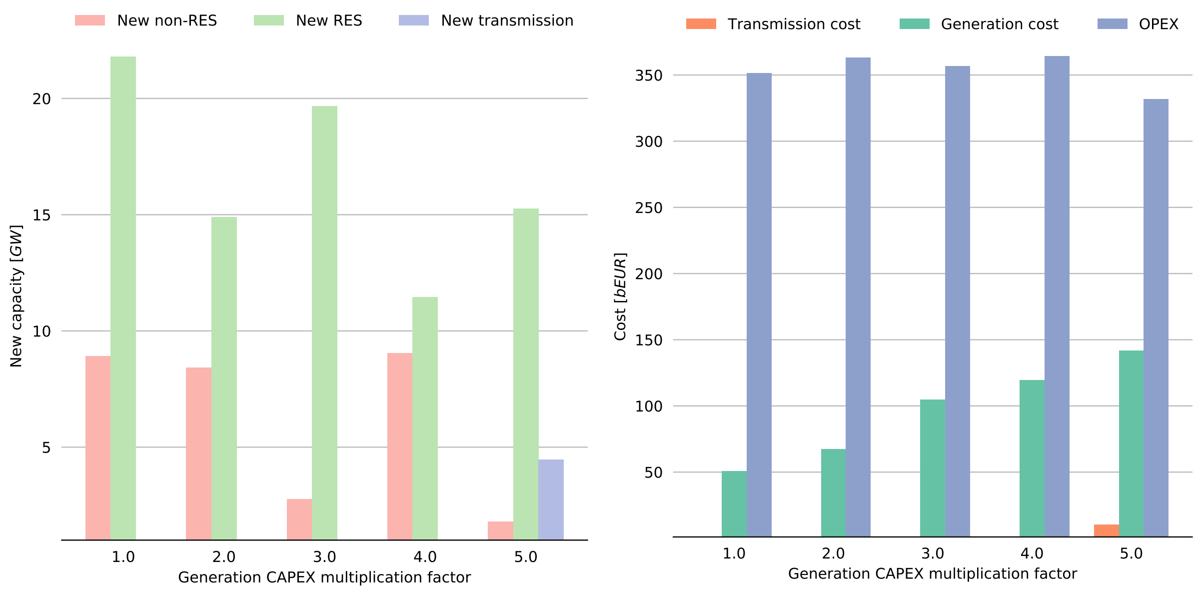
We will now investigate how different changes in inputs may initiate changes in the behaviour of the strategic countries. Two main observed tendencies are over-investment in generation and a preference to be self-sufficient. We address both these challenges by two sensitivity analyses. First, we gradually increase the cost of new generation investments, and afterwards we increase the price of CO_2 emissions, which will increase the operational costs. Generation CAPEX is gradually increased until it is five times its original value, while CO_2 price is gradually increased until twice its original value. Multiplication factor 1.0 represent the case study from the previous section.

5.2.1 Increase in generation CAPEX

Generation investment costs are increased until a transmission expansion response is triggered by the strategic countries. Figure 5.2 and 5.3 give an overview of changes in capacity expansions and investment costs for the strategic and centrally planned framework, respectively. See Table C.1 and C.2 in Appendix C for a numeric representation of the results in the figures.

The strategic countries and the central planner react differently to the increase in generation investment cost. A double generation CAPEX is sufficient for the central planner to stop generation investments. Figure 5.3b show a slight increase in operational costs, which signify that existing fossil fuel are used to cover the load supplied by the new renewable capacity in factor 1.0. The central planner performs no further transmission expansions when generation CAPEX increases. This indicates that the grid investments performed in the original case study of section 5.1 are sufficient to properly allocate the renewable production. After multiplication factor 2.0, the central planner is completely indifferent to the increase in generation CAPEX because she has no generation investments. Consequently, the total cost will remain at the same level from factor 2.0 to 5.0.

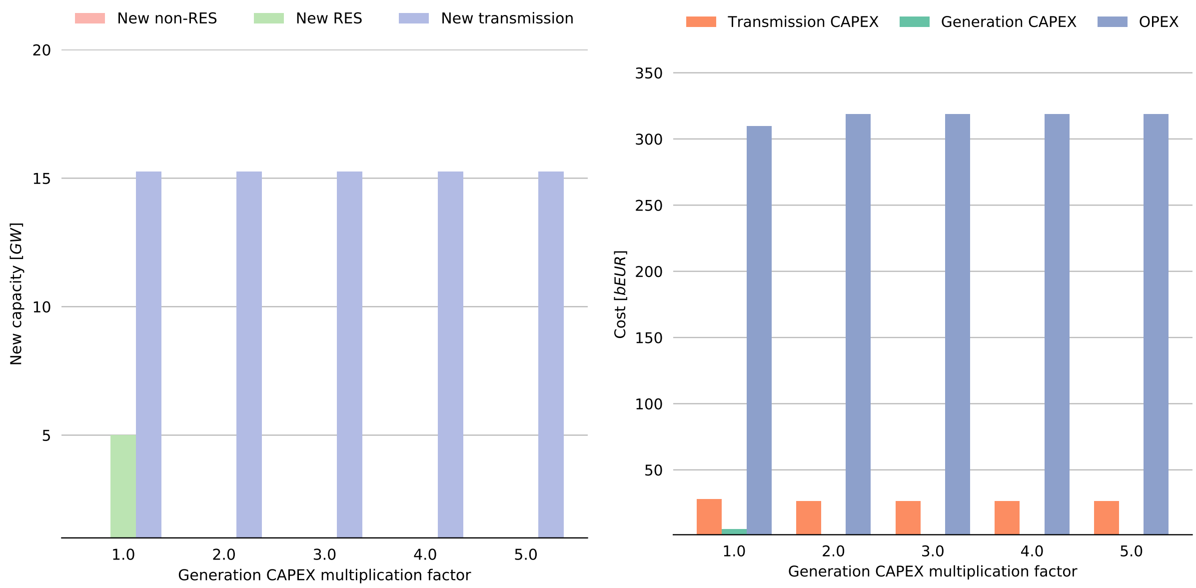
As the cost of new generation capacity increases, the strategic countries invest in less new capacity and utilise more of their existing units. The effect is largest when moving towards double CAPEX, where the total new production facilities are decreased by $7395MW$. From multiplication factor 2.0 to 3.0 and 3.0 to 4.0, the reduction is only approximately $1000MW$ and $2000MW$, respectively. Non-RES investment remain quite consistent at around $9000MW$, with the exception of the scenario with multiplication factor 3.0. Note that the lower non-renewable investments at factor 5.0 is due to transmission investments, as discussed later. Decrease in capacity investment are thus generally at the expense of renewable expansions, which are more capital intensive investments. Moreover, fossil fuels are a more flexible alternative for the countries, and the operational costs of fossil fuels become comparatively smaller than investment cost as CAPEX increases.



(a) Capacity expansions

(b) Investment and operational costs

Figure 5.2: Strategic model output when generation CAPEX is increased.



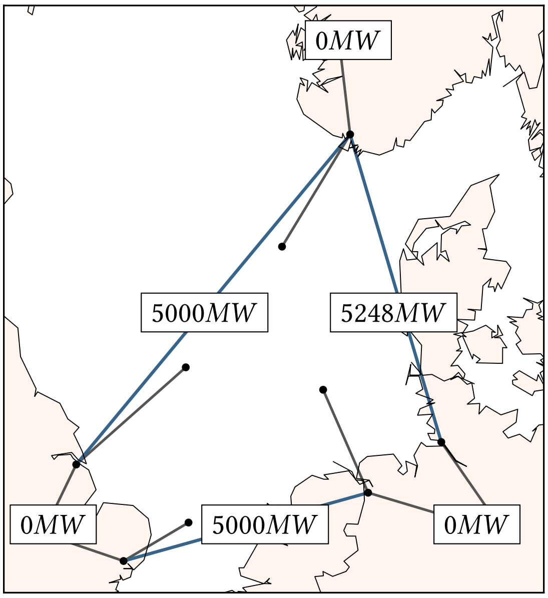
(a) Capacity expansions

(b) Investment and operational costs

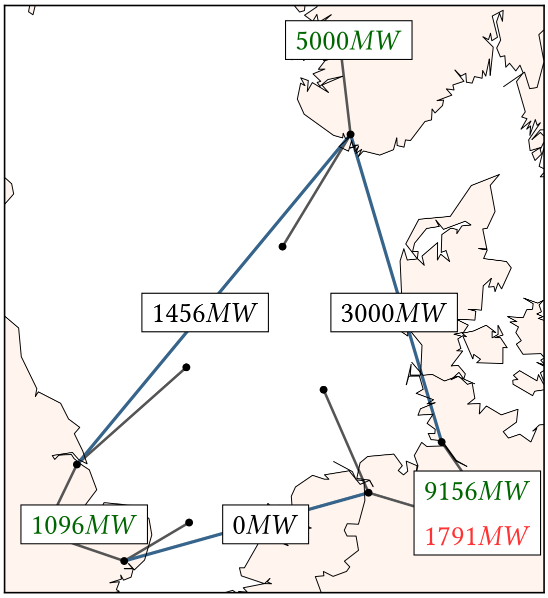
Figure 5.3: Centrally planned model output when generation CAPEX is increased.

The multiplication factor 3.0 scenario investment decisions deviate from both scenario 2.0 and 4.0 by decreasing fossil fuel investments and increasing renewable production. Expected behaviour would be to follow the trend of decreasing renewable investments and keeping fossil fuels constant. Figure 5.2b indicate a sharper increase in generation investment costs from factor 2.0 to 3.0, than any of the other. Similarly, we can observe a decrease in the operational expenses compared to both factor 2.0 and 4.0. Hence, the renewable investments are done with the objective of decreasing the operational expenses. We therefore cannot conclude whether factor 3.0 created a different effective strategy for the given costs, or is due to a numerical error in the solver.

For multiplication factor 5.0, the reluctance of the countries to invest and consequently high marginal costs for the market operator, will initiate transmission expansion from the central planner. Figure 5.2b show how the transmission expansion creates a significant reduction in operational cost, compared to the other cases without transmission lines. The strategic countries are now experiencing the benefit of better utilisation of renewable capacities. Intermittent renewable production is now diversified throughout the system, and the market operator can take advantage of surplus renewable production. This leads to a decrease in fossil duel investments compared to the original case and multiplication factors 2.0 and 4.0. Total generation are decreased further by approximately 3000MW from multiplication factor 4.0, but renewable is responsible for a majority of the newly installed capacity. It is noteworthy that a significant increase of five times the original generation CAPEX is necessary for the strategic countries to reduce their investment sufficiently for the central planner to invest in transmission.



(a) Centrally performed investments



(b) Strategically performed investments

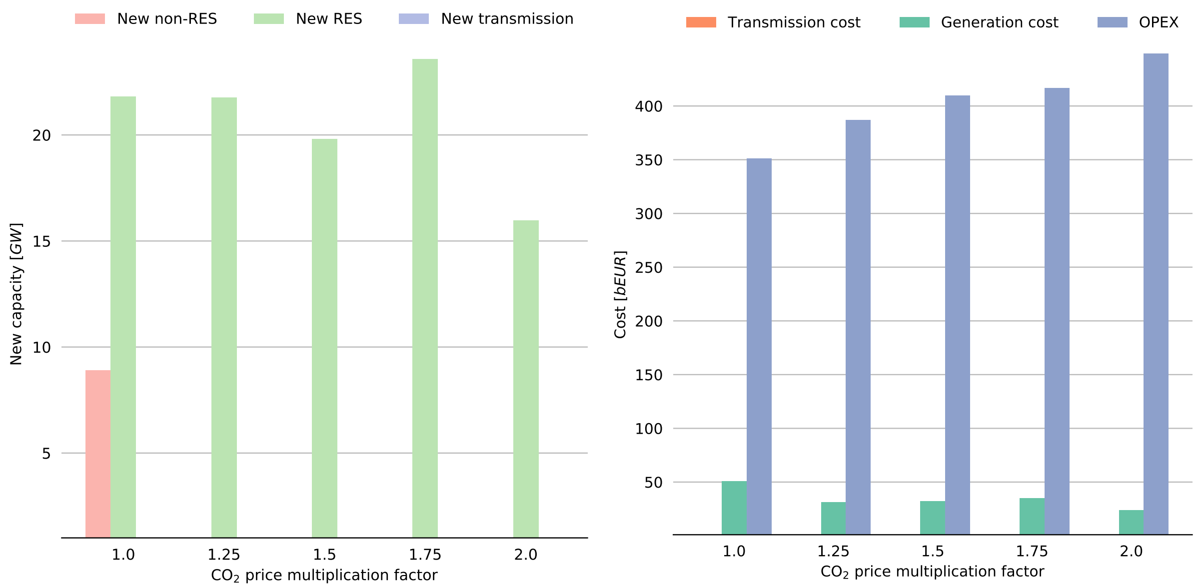
Figure 5.4: New generation and transmission expansions. Green values are renewable investments, while red are non-renewable. Generation CAPEX multiplied by 5.0.

Figure 5.4 show a detailed comparison between actions of the central planner and strategic countries when the generation CAPEX is multiplied by 5.0. Transmission capacity in the strategic scenario are 3000MW from Germany to Norway and 1456MW from Great Britain to Norway. Both countries connect to Norway because of the low marginal cost hydropower production, which will become available to them because in a shared grid. In contrast to the original case study, Norway will now perform an investment. To prevent her prices from increasing due to the new interconnections, Norway invests in 5000MW offshore wind production, which has lower marginal cost than hydropower in our model. The initial wind capacity is much higher in Germany and Great Britain, hence the Norwegian investment will become a further diversification of wind production when she is interconnected to both countries. The central planner will not perform any generation investments and maintain the transmission investments done in the original case study, as already discussed.

5.2.2 Increase in CO_2 prices

Figure 5.5 and 5.6 show the behaviour when CO_2 prices are gradually increased until twice its original value for the strategic and centrally planned model, respectively. Table C.3 and C.4 in Appendix C provide a numeric representation of the results in the figures. While the strategic countries do not perform any investments in non-renewables when the CO_2 price is increased, they do not increase their renewable portfolio either. A more expected behaviour would be what is observed in Figure 5.6a, where the central planner gradually increase the renewable capacity as the CO_2 price increases because investment in additional renewables become comparatively cheaper than the cost of fuel for non-renewable production.

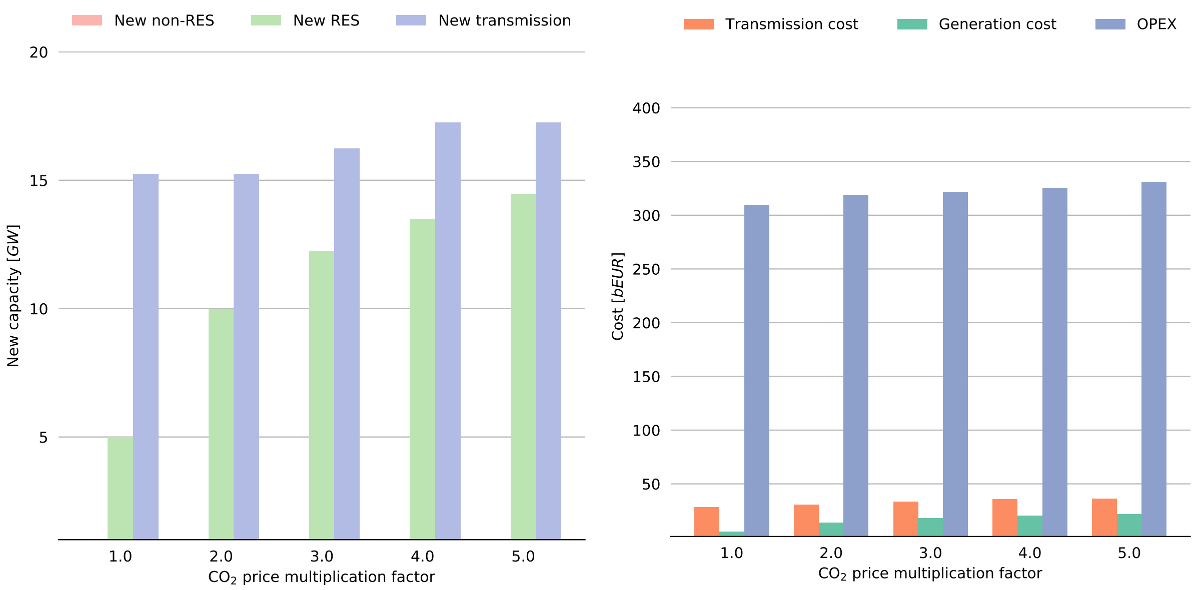
The strategic countries show no particular trends in their investments in new renewable generation as the CO_2 price increases. Multiplication factor 2.0 does do even provide the lowest new renewable generation. Figure 5.5b shows that factor 1.75 of most renewable investments provide smaller increase in its OPEX from the previous factor. Hence, it should be in the interest of the countries to invest in more renewable generation or for the central planner to initiate transmission expansion. When experiments with larger multiplication factors was tested, similarly unreasonable results still appeared. Due to large values of the input data, the big-M parameter is defined quite tight, so it may be that it interferes with the results. The CO_2 price interferes with operational costs, which creates high values in the model when an hourly operation is multiplied by the annuity factor and samplefactor. We continue the analysis on the centrally planned system and continue the discussion of computational challenges in section 5.5.



(a) Capacity expansions

(b) Investment and operational costs

Figure 5.5: Strategic model output when CO_2 price is increased.



(a) Capacity expansions

(b) Investment and operational costs

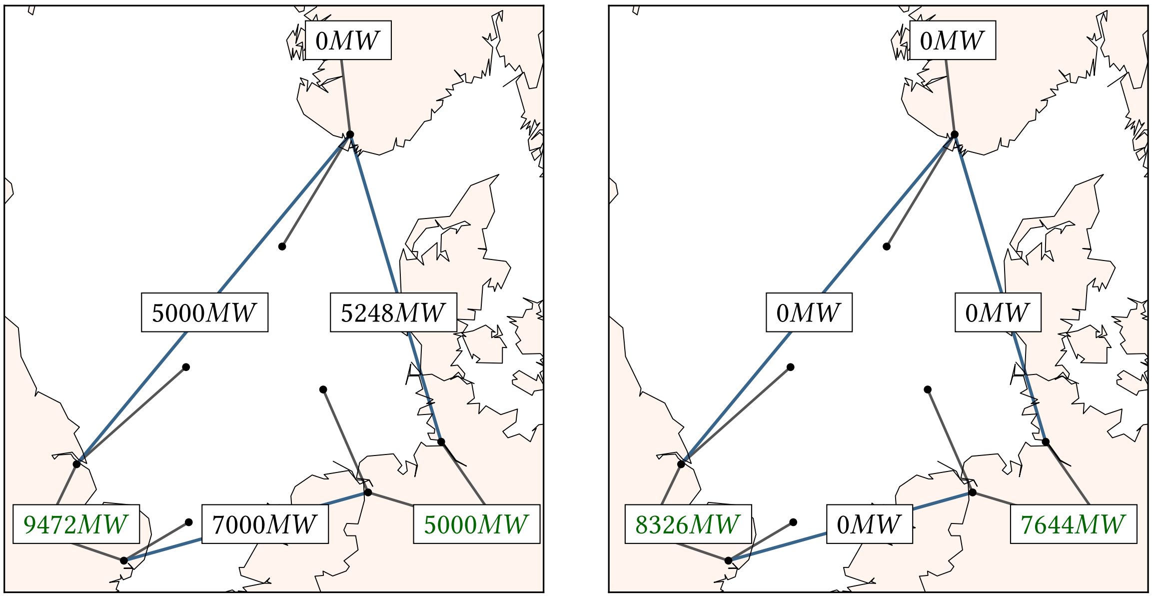
Figure 5.6: Centrally planned model output when CO_2 price is increased.

The central planner in Figure 5.6 reacts to the increase in CO_2 prices by gradually increasing the investments in renewables and transmission capacity. Consequently, she starts phasing out the fossil fuel production. It is comparatively cheaper to invest in more renewables and corridors, than continue to use fossil fuels. Figure 5.6b show how the centrally planned system manages limit the increase in operational cost as the CO_2 price increases. The strategic countries, who do not increase their renewable production experience an OPEX increase, as shown in Figure 5.5b. As the central planner increases the renewable portfolio, additional transmission capacity is necessary to facilitate more trade of intermittent production.

A comparison between the centrally planned and strategic expansion at multiplication factor 2.0 is portrayed in Figure 5.7. With the precaution of numerical errors for the values for the strategic case in Figure 5.7b, Germany and Great Britain will invest in similar amounts of solar and wind production. The central planner in Figure 5.7a continues with a major wind production investment in Great Britain of $4472MW$, in addition to a maximum investment of $5000MW$ biogas for both Germany and Great Britain. This is a clever use of resources, because she is able to use a flexible fuel resource without the CO_2 emission expenses. The strategic countries do not utilise this opportunity in their own countries, which emphasise the suspicion of strange behaviour of the strategic model when CO_2 prices increases.

5.3 Validity of results

Do note that the model formulation in section 4.2 do not take storage into account. To have a equal basis for comparison, it was not included in the centrally planned model either. The values for Norway and effect of connection to Norway are therefore more optimistic than what is expected. Because Norwegian spot prices are used as approximations for Norwegian hydropower, the cost will be higher than renewables, such as solar and wind, but lower than fossil fuels. This resulted in an unrealistically



(a) Centrally performed investments

(b) Strategically performed investments

Figure 5.7: New generation and transmission expansions. Green values are renewable investments. CO_2 prices are multiplied by 2.0.

high production of hydropower compared to storage facilities. Appendix B presents an extended model where a storage restriction is included as a maximum limit of energy available each year. This can for instance be the expected amount of inflow in hydropower reservoirs. The storage constraint is not included in the model used for case studies because the yearly disposable energy of a storage created numerical problems for the solver due to its large size. However, this is mainly dependent upon input data, and can be enforced at case studies of smaller numerical magnitudes.

The results are also subject to full flexibility of all generation sources. Generation dispatch problems do often incorporate some kind of start-up behaviour for less flexible production units such as fossil and nuclear[2]. Such behaviour are dependent upon some kind decision variable to initiate or terminate a production unit, generally a binary variable. Dispatch is done in the lower level problem. When binary variables are introduced in constraints the KKT conditions become not necessary nor sufficient. As a result, the non-renewable production units are provided more flexibility than they should have ideally. In the extend model in Appendix B, a restriction of minimum production is also included. While it do not help with the flexibility issues, one can provide a lower limit of base production which non-renewables has to produce. Another interesting feature of this constraint can be to investigate how the system behaves if one enforces a minimum amount of renewable production.

The use of 25 random samples are also an area of precaution. Academic studies such as Härtel, Kristiansen, and Korpås (2017) and Kristiansen, Korpås, and Härtel (2017) show that the performance of random samples are acceptable compared to more sophisticated techniques such as k-means. How-

[2]Such problems are commonly referred to as *unit commitment* problems. See for instance Hobbs et al. (2001) for more information

ever, it is unlikely that 25 samples represent a full year of 8760 hours properly. Hence, if some extreme cases are included in the random sample, it will gain more weight in the model than it should realistically. Ideally, we should include more random samples to decrease the weighting on each sample to provide a more accurate representation of the system. Trötscher and Korpås (2011) show for instance convergence after approximately 200 random samples for an NSOG TEP problem. However, as we will discuss later, the increase of samples scales the problem and introduces more binary variable which can make it computationally challenging to solve.

Aggregated input data will be optimistic towards the size and benefits of transmission expansions. In reality, the countries have both demand and production at different domestic locations. Our model assumes that all production are readily available from an aggregated node, and that all demand must be met here as well. Countries are likely to experience both internal congestions and losses when transferred at long distances. It is also worth mentioning that all countries are modelled as independent, but especially Germany and Norway are well integrated in the European grid. While the NSOG results may not be accurate, the concepts of strategic behaviour in a multinational transmission grid are still valid.

5.4 The approach and its limitations

The model show promising results and performance for solving trilevel problem to a global optimum as a MILP problem. Despite some numerical difficulties, later discussed in section 5.5, we are able to solve a twelve nodes, twelve branches, 26 generation units and 25 time steps in reasonable time. The input produces a 24465 continuous and 8864 integer variables, which the presolver reduces to 12060 continuous and 3293 integer variables. Gurobi solves the original case study in 395 seconds on a 2.2GHz quad-core Intel i7 processor and 16GB memory computer. However, when generation CAPEX or CO_2 price changes the solution time vary dependent upon how quickly the branch-and-bound process finds the optimal solution.

Except for the case of increasing CO_2 prices, the model acts in accordance with expected behaviour of strategic countries who want to minimise their prices. A country will always prioritise their own demand before the system. This decreases the incentives for transfers between the countries and leads to over-investment in production. Because countries become self-sufficient, the system planner will not expand because it is misuse of public capital. When generation CAPEX increase to the amount where the countries become hesitant to invest, the system planner will invest in transmission corridors to better use existing resources. Although it did require a large increase of five times the original generation CAPEX to initiate transmission investments.

A common limitation for all trilevel problems are the accumulation of constraints. Especially for lower level restrictions. Our approach are more exposed to constraint accumulation than strong duality methods. The Fortuny-Amat and McCarl (1981) linearisation will produce four constraints for each complementarity constraints, which is further increased to six KKT conditions by our approach in section 4.1. The extended model representation in Appendix B shows how the final MILP problem increases just by adding two more lower level constraints.

Another precaution by our approach is the amount of binary variables. While commercial solvers has powerful techniques of solving MILP problems, it is a still a computationally hard class of problems. More input data will increase the amount of binary variables, and consequently the problem becomes harder. A 25 time steps case study of the NSOG also including Belgium, Denmark and the Netherlands, proved too time consuming to be finished within a day and was thereby terminated.

Based on the implementation and results of this thesis, the proposed model show great potential for improving the current trilevel methodology. Especially if producer surplus and congestion rent is included, which is discussed in section 5.6. A strategic TEP model solved as a trilevel problem can provide important information regarding decision support. Domestically, it can show how the TSO may expand in a manner to avoid market power to the producers. For multinational settings, it can be used for similar studies as the one performed in this thesis. Namely, how to expand to reduce market power or to find the value of a centrally performed expansion achieved through cooperation. The latter can be useful information for regulators who are facing multinational project. The approach is also not restricted to TEP problems, but can be implemented on similar trilevel structures.

5.5 Computational challenges

Although the performance of the model is promising, it is exploited to some numerical challenges. An aggregated representation of country demands and capacities, in addition to investment costs give large numeric values in the model. The limitation of this becomes especially apparent when selecting big-M parameters. Because the objective of the final problem becomes equal to the objective of the upper level problem the solver experienced little bound progression. The mobilisation cost of a transmission corridor is large, and the solver becomes reluctant to make the leap. The branch-and-bound process are therefore not able to exploit bounds to create a faster solution process.

5.5.1 Precautionary actions in the solver settings

The input data has several numerically challenging features, namely large ranges, big-M parameters and integer variables. To reduce the risk of numerical errors we include some precautionary steps in the solver. Gurobi has several parameters which decides the solver behaviour. Originally these are set to default values, but some of them were changed in order to reduce the risk of numerical errors. The *NumericFocus* parameter is set to its highest value, meaning that the solver uses more resources to reduce potential numerical errors and check that they do not occur. Moreover, the integer feasibility tolerance parameter, *IntFeasTol*, are reduced from its default 10^{-5} to 10^{-8} because of binary variables being multiplied by big-M parameters. We also checked that no results were exposed to warning messages from the solver.

5.5.2 Sensitivity of big-M parameters

Big-M selection proved to be sensitive for the model, despite the effort to minimise its implications in Gurobi. The main challenge was the trade-off between large big-M values to not restrict the problem, and low enough to ensure that expressions were forced to zero by Mz when $z = 0$. Because the results changes with the selection of big-M, it is likely that it influence the problem and thereby the results.

This may have lead to a more relaxed or restricted problem solutions, dependent on how the big-M interfered with the solution.

A relaxed or restricted problem may lead to an other equilibrium than the global optimal. We solved the model on both a computer and a computer cluster. On some choices of big-M there was deviations between the two results. However, for our chosen big-M the output was similar. The unexpected results when CO_2 price was increased are likely due to large input data starting to interfere with the big-M. We did not choose to alter the big-M for the CO_2 price study because the big-M would start to influence other constraints, and thus give a different reference scenario when the multiplication factor is 1.0.

To avoid big-M complications, a smarter choice of input variables should have been chosen. The range between the largest units, such as investment costs, and smaller inputs, such as hourly dispatch, should be minimised as much as possible. Ways to prevent this include choosing other input data or investigating other case studies of smaller magnitudes. Converting the units from MW to GW and EUR to $kEUR$ improved the computational efficiency. However, a caveat of doing this was small hourly dispatch process, which is now performed in GW. It can be harder for the solver to be exact at small values.

The sensitivity of big-M parameters on the results represent the most prominent limitation of the results. Theoretically, the big-M should represent an infinitely high value, which is not the case at the moment. Further work include to study the relationship between the big-M parameter further. More thorough selection of input data or a case study of smaller magnitudes are recommended. The sensitivity of big-M values provide some lack of confidence in the precision of the results. However, this challenge is due to the input data and not the method in itself. Any approach that uses big-M parameters are exposed to such challenges.

5.6 Strategies to implement producer surplus and congestion rent

The NSOG case study only represent an extreme situation where countries are only focused by decreasing the prices to their own consumers. As discussed in the case study result, this creates an reluctance to invest in transmission capacity. However, if the countries are also trying to make profit the situation would likely change. By including producer surplus, the countries become more focused on also increasing the distance between their marginal cost and the market price. Congestion rent will apply incentives of performing trade of low marginal cost electricity to areas of higher prices to create a trade surplus. In other words, the strategic countries have an incentive for participating in cross border trade, which can motivate the expansion planner to invest.

Because both the expression for producer surplus and congestion rent are bilinear non-convex functions they create not necessary nor sufficient KKT conditions. There are however methods to introduce them. First and foremost, we could just include them as they are and will likely end up in a local equilibrium. We can check whether it is stable by inserting the upper level decisions in the intermediate and lower level problems. An algorithm can be included to scan through all equilibria by adding cuts which prevents previous solutions, and selecting the best solution at the end. This approach will resemble the method of Huppmann and Egerer (2015) and Zerrahn and Huppmann (2017), except that their full problem are a MINLP. While the model in this thesis is a MILP, it contains significantly more integer variables than the MINLP utilising the strong duality optimality conditions.

Another algorithmic approach can be to separate the bilinear term into a sum of two terms containing a constant and variable term. Expression (5.1) provides an example of this approach for the producer surplus bilinear term.

$$p_{it}g_{it} = \frac{1}{2}\hat{p}_{it}g_{it} + \frac{1}{2}p_{it}\hat{g}_{it} \tag{5.1}$$

Both $\hat{p}_{it}$ and $\hat{g}_{it}$ are constants chosen by the user. The problem is then solved iteratively, where $\hat{p}_{it}$ and $\hat{g}_{it}$ are updated for each iteration until $\hat{p}_{it} = p_{it}$ and $\hat{g}_{it} = g_{it}$. However, there are several shortcomings present. The method requires action from the user, and it may be hard to determine how to update $\hat{p}_{it}$ and $\hat{g}_{it}$. We are not sure how many iterations it will require, which can become cumbersome if the problem require some time to solve. It may also be hard to determine the accepted deviation required to accept $\hat{p}_{it} = p_{it}$ and $\hat{g}_{it} = g_{it}$. It may also exist several valid combinations of $\hat{p}_{it} = p_{it}$ and $\hat{g}_{it} = g_{it}$. Consequently, all of them has to be explored in order to select the feasible pair that give the best solution.

Linearisation may be an option to the algorithmic approaches. A simple method to linearise the bilinear term is to use McCormick (1976) envelopes. This approach requires upper and lower bounds to over- and underestimators for a linearised representation. The NSOG case study can produce large ranges in over- and underestimators. For instance will maximum price be the value of lost load, while the upper bound of onshore wind power in Germany becomes $76967MW$ plus possible investments of $5000MW$. Consequently, the estimators are likely to relax the problem quite significantly. Another option is to investigate whether the *reformulation-linearization technique* (RLT) which provide tighter linearisation may be an applicable (Sherali and Adams 1999). Whenever linearisations are introduced it is important to remember that the model is concerned with equilibria. Hence if we relax the problem it may be a danger of creating optimal solutions which represent equilbria which is not valid in the actual model.

It is also possible to investigate exact linearisation techniques. Further extension of this thesis is to implement an exact linearisation of the bilinear terms by extending the approach of Pisciella (2012). If we manage to implement this approach the TEP model can be solved to global optimum with producer surplus and congestion rent included. A working paper of the thesis that has the objective of being extended to include exact linearisation is included in Appendix E.

Chapter 6

Conclusion and further work

6.1 Conclusion

Transmission expansion planning (TEP) is an important decision making process which is crucial for the integration of electricity markets. If performed correctly, the expansions produce substantial economic and environmental benefits. The European Commission emphasises the importance of integrated electricity markets by making the North Sea Offshore Grid (NSOG) one of its priority projects. Despite the benefits, multinational transmission expansion do not have an established framework. This can lead to strategic behaviour of countries which exploit market power.

Instead of planning generation and transmission expansion centrally, one can choose grid investments by anticipating the strategic behaviour of the market participants. Because the actors will be dependent upon each other, we formulate the problem as a trilevel hierarchical optimisation problem. The lower level problem consists of a market operator who performs dispatch with respect to the generation capacities of strategic countries in the intermediate level problem. Strategic countries perform generation capacity investment by both anticipating the market dispatch and how the upper level transmission planner invest. The decisions of the upper level problem is dependent upon the generation investments of the countries. As a result, we have several optimisation problems that are dependent upon each other. The market operator and transmission planner try to maximise system welfare, while the strategic countries will maximise their own. A system optimal solution will be an equilibrium amongst the actors in which none will deviate from their strategy.

It is challenging to solve the trilevel problem in its original form because it contains several objective functions. An optimisation can be reformulated into optimality conditions, which under certain conditions are only fulfilled for the global optimum. Two main approaches to generate optimality conditions are strong duality and Karush-Kuhn-Tucker (KKT) conditions. By reformulating the lower level problem as optimality conditions, they can be included in the intermediate level problem. The reformulated intermediate level problems with the lower level optimality conditions are also reformulated as optimality conditions and added to the upper level problem. As a result, the trilevel problem becomes reformulated into a single problem.

If strong duality is used on the lower level problem, non-convex bilinear terms are included in the reformulated intermediate level problem. Consequently, the KKT conditions become not necessary nor sufficient. If KKT conditions are generated from the lower level problem, non-convex complementarity conditions are included instead. Consequently, the current trilevel solution methods cannot solve directly for a global optimum and must utilise algorithmic approaches to scan through equilibria to find the best one. This thesis introduces an alternative method where the lower level KKT conditions are linearised and we exploit the relationship between the binary and variables of the complementarity conditions. The approach is implemented on a trilevel TEP problem and demonstrated on a NSOG case study of Germany, Great Britain and Norway.

A central generation and transmission investment planner is used as a benchmark for system optimal results. If countries accept to cooperate in the establishment of a supra-national regulator, those could become the results. Because of non-convex terms in producer surplus and congestion rent, only producer surplus are included for the strategic countries in order to have necessary and sufficient KKT conditions. This represent the extreme case of countries who only want to minimise the prices for her consumers.

The strategic countries will always utilise the cheapest generation source themselves, and will therefore only consider transfer if they have surplus renewable production. However, this will lead to over-investments in domestic generation. Because the countries start to become self-sufficient the system planner do not invest in transmission capacity because it will be a misuse of public money. When the cost of new generation units increase, the countries will gradually reduce their new investments. Five times the original generation investment cost was necessary for the countries to invest conservatively enough to motivate transmission investments by the system planner.

A central planner will always utilise the most efficient resource in the system. Consequently, she will invest in considerable transmission capacity among all countries to always be able to utilise the cheapest generation units. This creates a more efficient use of the existing resources and no new generation investments are made, except for wind production in Great Britain. A well connected grid diversifies the risk of intermittent renewable production over different locations. Independent countries are exposed to varying renewable production from their location and consequently has to cover periods of low renewable production by fossil fuel generation. As a result, the central planner achieves lower investment and operational costs than the strategic system. For our input data, a total cost decrease of 14.7% can be achieved by moving from a strategic to a centrally planned operation.

The method shows promising performance and give solutions which are expected actions from strategic countries. However, we do experience some computational challenges. The input data provide large ranges because it compares hourly dispatches with investment decision of 30 years financial lifetime. Large numerical values made the model sensitive to the selection of big-M parameters. An example of this is the strange solutions when the CO_2 price is increased. The accumulation of binary variables also restrict the amount of time steps for the model. Consequently, the model may put too much weight on samples which are not fully representational. These limitations are due to the input data, and can be removed by another selection or by investigating other case studies.

Despite its challenges, the model are able to reformulate a problem into a MILP and solve it to a global optimum. This is an improvement to the current methods that has to utilise algorithmic approaches to investigate all equilibria to find the best one. Ideally, the TEP model should include producer surplus and congestion rent, but these are non-convex functions introduced externally and not by the approach. Solving the strategic TEP can provide useful information for countries when they are discussing multinational expansion projects. It shows how to expand the network to prevent exploitation of market power, and provide estimates of the value of cooperation which can work as a motivator to achieve system optimal results.

6.2 Further work

The main objective of further work is to include an exact linearisation of producer surplus and congestion rent. This will improve the TEP model significantly and increase the realistic behaviour of strategic countries. Such an accurate representation will provide a more useful tool for decision makers, transmission system operators and regulators. The plan of the author is to include an extended method of a linearisation technique proposed in Pisciella (2012).

Other advances which improves the model accuracy should also be pursued. Appendix B show an expanded model where storage and minimum generation capacities included. This is just some examples of possible model extensions. Another improvement would be if fossil fuel and nuclear generation are not provided full flexibility as they are now.

The input data has been a source of some numerical issues due to its large ranges and high values. Ideally, the model should be tested for more systems in order to properly verify its performance. A smaller test system than the one provided in this thesis is recommended. For the selection of input data, it should be of importance to remove any sensitivity towards big-M parameters.

This thesis has mainly focused developing an alternative methodology of solving trilevel TEP problems. The chosen case study of the NSOG is important for the future development of the European electricity market. It would therefore be interesting with a more thorough energy policy study of the NSOG using the model. Even more so if producer surplus and congestion rent is included. The results concern itself about system results, but it is interesting to investigate the domestic distribution of costs and benefits. It would also be relevant to compare this to a central planner where allocations are determined by cooperational game theory. We may experience that some countries are individually better of in the strategic situation, even if the system is not. What incentives and actions can then be considered to motive a cooperative solution that is best for the system?

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Appendix A

Input data

Table A.1: Overview of nodes in the NSOG represenetation.

Node	Country	Latitude [°]	Longitude [°]	Offshore	Type	Function
2	DE	54.68	6.16	Yes	DC	OWP
4	GB	55.01	2.65	Yes	DC	OWP
5	GB	52.67	2.72	Yes	DC	OWP
8	NO	56.74	5.11	Yes	DC	OWP
22	DE	53.13	7.31	No	AC	Connecting hub
24	GB	53.56	-0.15	No	AC	Connecting hub
25	GB	52.07	1.06	No	AC	Connecting hub
27	NO	58.28	6.85	No	AC	Connecting hub
28	DE	53.9	9.18	No	AC	Connecting hub
91	NO	59.47	6.58	No	AC	Aggregated country
93	DE	52.5	10.8	No	AC	Aggregated country
96	GB	52.5	-1	No	AC	Aggregated country

Table A.2: Input generation data from ENTSO-E (2015) Vision 4. Offshore wind (except NO) from WindEurope (2017).

Generation	**Installed capacity** $[MW]$					
technology	**BE**	**DE**	**DK**	**GB**	**NL**	**NO**
Biofuels	2500	9340	1720	8420	5080	0
Gas	10040	45059	3746	40726	14438	855
Hard coal	0	14940	410	0	0	0
Hydro	2226	14505	9	5470	38	48700
Lignite	0	9026	0	0	0	0
Nuclear	0	0	0	9022	486	0
Oil	0	871	735	75	0	0
Solar	4925	58990	1405	11915	9700	0
Onshore wind	3518	76967	6695	27901	5495	1771
Offshore wind	4000	20000	6130	30000	4500	724
Total	27209	249698	20850	133529	39739	52050

Table A.3: CO_2 emission factors from polluting electricity generation given by International Energy Agency (2016) and used as emission rate input.

Fuel	**Emission factor** $[tCO_2/MWh]$
Other bituminous coal (hard coal)	0.870
Lignite	1.030
Natural gas	0.405
Fuel oil	0.670

Table A.4: Technology efficiencies for ENTSO-E (2017) Vision 4, and assumed efficiency used to calculate prices.

Technology	Technology efficiency range	Assumed efficiency
Nuclear	0.30 - 0.35	0.33
Lignite	0.30 - 0.46	0.38
Hard coal	0.30 - 0.46	0.38
Gas conventional	0.25 - 0.42	
Gas CCGT	0.33 - 0.60	
Gas OCGT	0.35 - 0.44	
Assumed gas mix		0.40
Light oil	0.32 - 0.38	
Heavy oil	0.25 - 0.43	
Oil shale	0.28 - 0.39	
Assumed oil mix		0.34

Table A.5: Input prices, calculated from fuel prices and technology efficiency for ENTSO-E (2015) Vision 4. Hydro price is assumed.

Product	Fuel prices $[EUR/net\ GJ]$	Assumed efficiency	Input price $[EUR/MWh]$
Nuclear	0.46	0.33	5
Lignite	1.1	0.38	10
Hard coal	2.19	0.38	21
Gas	7.23	0.40	65
Oil	13.26	0.34	140
Hydro (except NO)			10
CO_2			76

Table A.6: Capital expenditure (CAPEX) given by European Climate Foundation (2010) Roadmap 2050 and yearly discounted CAPEX used as input for different generation technologies.

Generation technologies	**CAPEX 2030 from Roadmap** $[EUR/kW]$	**Assumed CAPEX** $[EUR/kW]$	**Yearly discounted CAPEX** $[EUR/(MWh\ year)]$
Coal conventional	1400 - 1600	1500	97577
Gas conventional	700 - 800	750	48789
Gas CCS	1000 - 1200	1100	71557
Oil	700 - 800	750	48789
Nuclear	2700 - 3300	3000	195154
Wind onshore	900 - 1200	1050	68204
Wind offshore	2000 - 2400	2200	143113
Solar PV	1000 - 1400	1200	78062
Biomass	1600 - 1900	1750	113840
Hydro	1750 - 2000	1875	121971

Table A.7: Cost per branch parameters for new transmission corridors.

Type	B_d $[kEUR/km]$	B_{dp} $[kEUR/kmMW]$	B $[kEUR]$
AC	1193	1.416	312
DC-mesh	1236	0.578	312
DC-direct	1236	0.578	312
Converter	0	0	0
AC overhead line	1187	0.394	0

Table A.8: Cost per branch endpoint parameters for new transmission corridors.

Type	C_p^L $[kEUR/MW]$	C^L $[kEUR]$	C_p^S $[kEUR/MW]$	C^S $[kEUR]$
AC	0	1562	0	5437
DC-mesh	1562	0	5437	
DC-direct	93.2	58209	107.8	453123
Converter	46.6	28323	53.9	20843
AC overhead line	0	1562		

Table A.9: Cost parameters for new nodes.

Type	N^L $[kEUR]$	N^S $[kEUR]$
AC node	1	50000
DC node	1	406000

Table A.10: Input demand data from ENTSO-E (2015, 2017) Vision 4.

Country	**Peak daily demand** $[MWh]$	**Annual demand** $[GWh]$
BE	13486	93247
DE	81369	547178
DK	6623	41219
GB	59578	368084
NL	18751	122577
NO	24468	145806

Appendix B

Extended TEP model

The model formulated in in section 4.2 contains a minimal market clearing formulation. To show possible extensions, we will include some constraints to make the market clearing more realistic. The market clearing problem of (B.1) is the same as (4.5), except that it also contains restrictions (B.1d) and (B.1e). The former constraint enforces a minimum generation limit. This may be relevant for fossil fuels or nuclear, which is not flexible and cannot be turned of. Minimum production P_i^{min} may also be expressed in a manner that enforces a minimum amount of renewable production. Restriction (B.1e) is relevant for production methods dependent on storage. An example is hydro power, where the total amount of generation over a year cannot exceed the disposable energy E_i.

$$\min_{g_{it}, s_{nt}, f_{bt}} \quad \sum_{t \in T} A \cdot W_t \left(\sum_{i \in G} (MC_i + CO2_i) g_{it} + \sum_{n \in N} VOLL \cdot s_{nt} \right) \tag{B.1a}$$

subject to

$$D_{nt} - \sum_{i \in G_n} g_{it} - s_{nt} - \sum_{b \in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b \in B_n^{out}} f_{bt} = 0 \qquad (p_{nt}) \quad \forall n, t \in N, T \tag{B.1b}$$

$$g_{it} - \eta_{it}(P_i^0 + x_i) \leq 0 \qquad \left(\overline{\alpha}_{it}^{LL}\right) \quad \forall i, t \in G, T \tag{B.1c}$$

$$P_i^{min} - g_{it} \leq 0 \qquad \left(\underline{\alpha}_{it}^{LL}\right) \quad \forall i, t \in G, T \tag{B.1d}$$

$$\sum_{t \in T} W_t g_{it} - E_i \leq 0 \qquad \left(\beta_i^{LL}\right) \quad \forall i \in G \tag{B.1e}$$

$$f_{bt} - (F_b^0 + y_b^{cap}) \leq 0 \qquad \left(\overline{\gamma}_{bt}^{LL}\right) \quad \forall b, t \in B, T \tag{B.1f}$$

$$-(F_b^0 + y_b^{cap}) - f_{bt} \leq 0 \qquad \left(\underline{\gamma}_{bt}^{LL}\right) \quad \forall b, t \in B, T \tag{B.1g}$$

$$g_{it} \geq 0 \qquad \forall i, t \in G, T \tag{B.1h}$$

$$s_{nt} \geq 0 \qquad \forall n, t \in N, T \tag{B.1i}$$

$$f_{bt} \in \mathbb{R} \qquad \forall b, t \in B, T \tag{B.1j}$$

Problem (B.1) is reformulated to the intermediate level problem as outlined in section 4.2. Likewise for the refurmulated intermediate level problem, which produces the upper level problem as shown in (B.2) and (B.3). We can see that the problem scales significantly when new constraints are added in the lower level problem. Nevertheless, it indicates how the model can be extended and become more realistic.

$$\min \sum_{b \in B} \left((B + B^d L_b^{km} + 2CS_b) y_b^{num} + (B^{dp} L_b^{km} + 2CS_b^p) y_b^{cap} \right) \quad \text{(B.2a)}$$

Subject to

$$y_b^{cap} \leq F_b^{max\ new} y_b^{num} \leq F_b^{max} \quad \forall b \in B \quad \text{(B.2b)}$$

$$-y_b^{cap} \leq 0 \quad \forall b \in B \quad \text{(B.2c)}$$

$$y_b^{num} \in \mathbb{Z}_{\geq 0} \quad \forall b \in B \quad \text{(B.2d)}$$

$$-(1 - F_b^{loss}) \epsilon_{n(b^{in})tc} + \epsilon_{n(b^{out})tc} + \underline{\phi}_{btc} - \overline{\phi}_{btc} - \underline{\psi}_{btc} + \overline{\psi}_{btc} = 0 \quad \forall b, t, c \in B, T, C \quad \text{(B.2e)}$$

$$\begin{aligned} W_t D_{nt} - &\sum_{b \in B_n^{in}} (1 - F_b^{loss}) \zeta_{btc} + \sum_{b \in B_n^{out}} \zeta_{btc} \\ &+ \sum_{i \in G_n} \underline{\theta}_{itc} - \sum_{i \in G_n} \overline{\theta}_{itc} + \underline{\lambda}_{ntc} - \overline{\lambda}_{ntc} = 0 \quad \forall n, t, c \in N, T, C \end{aligned} \quad \text{(B.2f)}$$

$$D_{nt} - \sum_{i \in G_n} g_{it} - s_{nt} - \sum_{b \in B_n^{in}} f_{bt} (1 - F_b^{loss}) + \sum_{b \in B_n^{out}} f_{bt} = 0 \quad \forall n, t, c \in N, T, C \quad \text{(B.2g)}$$

$$-p_{n(b^{in})t} (1 - F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} = 0 \quad \forall b, t, c \in B, T, C \quad \text{(B.2h)}$$

$$0 \leq CX_i + \delta_i - \sum_{t \in T} \eta_{it} \underline{\nu}_{itc(i)} + \sum_{t \in T} \eta_{it} \overline{\nu}_{itc(i)} \leq M_i^x z_i^x \quad \forall i \in G \quad \text{(B.2i)}$$

$$0 \leq x_i \leq M_i^x (1 - z_i^x) \quad \forall i \in G \quad \text{(B.2j)}$$

$$0 \leq -\epsilon_{n(i)tc} + \kappa_{itc} + \underline{\nu}_{itc} - \overline{\nu}_{itc} - \underline{\pi}_{itc} + \overline{\pi}_{itc} + W_t \underline{\sigma}_{ic} - W_t \overline{\sigma}_{ic} \leq M_{itc}^{g^{IL}} z_{itc}^{g^{IL}} \quad \forall i, t, c \in G, T, C \quad \text{(B.2k)}$$

$$0 \leq g_{it} \leq M_{itc}^{g^{IL}} (1 - z_{itc}^{g^{IL}}) \quad \forall i, t \in G, T \quad \text{(B.2l)}$$

$$0 \leq -\epsilon_{ntc} + \mu_{ntc} \leq M_{ntc}^{s^{IL}} z_{ntc}^{s^{IL}} \quad \forall n, t, c \in N, T, C \quad \text{(B.2m)}$$

$$0 \leq s_{nt} \leq M_{ntc}^{s^{IL}} (1 - z_{ntc}^{s^{IL}}) \quad \forall n, t, c \in N, T, C \quad \text{(B.2n)}$$

$$0 \leq -\underline{\theta}_{itc} + \overline{\theta}_{itc} + \xi_{itc} \leq M_{itc}^{\overline{\alpha}^{IL}} z_{itc}^{\overline{\alpha}^{IL}} \quad \forall i, t, c \in G, T, C \quad \text{(B.2o)}$$

$$0 \leq \overline{\alpha}_{it}^{LL} \leq M_{itc}^{\overline{\alpha}^{IL}} (1 - z_{itc}^{\overline{\alpha}^{IL}}) \quad \forall i, t, c \in G, T, C \quad \text{(B.2p)}$$

$$0 \leq \underline{\theta}_{itc} - \overline{\theta}_{itc} + \rho_{itc} \leq M_{itc}^{\underline{\alpha}^{IL}} z_{itc}^{\underline{\alpha}^{IL}} \quad \forall i, t, c \in G, T, C \quad \text{(B.2q)}$$

$$0 \leq \underline{\alpha}_{it}^{LL} \leq M_{itc}^{\underline{\alpha}^{IL}} (1 - z_{itc}^{\underline{\alpha}^{IL}}) \quad \forall i, t, c \in G, T, C \quad \text{(B.2r)}$$

$$0 \leq \sum_{t \in T} W_t (-\underline{\theta}_{itc} + \overline{\theta}_{itc}) + \tau_{ic} \leq M_{ic}^{\beta^{IL}} z_{ic}^{\beta^{IL}} \quad \forall i, c \in G, C \quad \text{(B.2s)}$$

$$0 \leq \beta_i^{LL} \leq M_{ic}^{\beta^{IL}} (1 - z_{ic}^{\beta^{IL}}) \quad \forall i, c \in G, C \quad \text{(B.2t)}$$

$$0 \leq \zeta_{btc} + \chi_{btc} \leq M_{btc}^{\overline{\gamma}^{IL}} z_{btc}^{\overline{\gamma}^{IL}} \quad \forall b, t, c \in B, T, C \quad \text{(B.2u)}$$

$$0 \leq \overline{\gamma}_{bt}^{LL} \leq M_{btc}^{\overline{\gamma}^{IL}} (1 - z_{btc}^{\overline{\gamma}^{IL}}) \quad \forall b, t, c \in B, T, C \quad \text{(B.2v)}$$

$$0 \leq -\zeta_{btc} + \omega_{btc} \leq M_{btc}^{\underline{\gamma}^{IL}} z_{btc}^{\underline{\gamma}^{IL}} \quad \forall b, t, c \in B, T, C \quad \text{(B.2w)}$$

$$0 \leq \underline{\gamma}_{bt}^{LL} \leq M_{btc}^{\underline{\gamma}^{IL}} (1 - z_{btc}^{\underline{\gamma}^{IL}}) \quad \forall b, t, c \in B, T, C \quad \text{(B.2x)}$$

$$0 \leq -x_i + P_i^{max\ new} \leq M_i^{\delta} z_i^{\delta} \quad \forall i \in G \quad \text{(B.2y)}$$

$$0 \leq \delta_i \leq M_i^{\delta} (1 - z_i^{\delta}) \quad \forall i \in G \quad \text{(B.2z)}$$

$$0 \leq A \cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}_{it}^{LL} - \underline{\alpha}_{it}^{LL} + W_t\beta_i^{LL} \quad , \quad 0 \leq \underline{\theta}_{itc} \leq M_{it}^{\underline{\theta}}(1 - z_{it}^{g}) \quad \forall i,t,c \in G,T,C \tag{B.3a}$$

$$0 \leq M_{it}^{g} z_{it}^{g} - A \cdot W_t(MC_i + CO2_i) + p_{n(i)t} - \overline{\alpha}_{it}^{LL} + \underline{\alpha}_{it}^{LL} - W_t\beta_i^{LL} \quad , \quad 0 \leq \overline{\theta}_{itc} \leq M_{it}^{\overline{\theta}}(1 - z_{it}^{g}) \quad \forall i,t,c \in G,T,C \tag{B.3b}$$

$$0 \leq M_{it}^{g}(1 - z_{it}^{g}) - g_{it} \quad , \quad 0 \leq \kappa_{itc} \leq M_{it}^{\kappa} z_{it}^{g} \quad \forall i,t,c \in G,T,C \tag{B.3c}$$

$$0 \leq A \cdot W_t \cdot VOLL - p_{nt} \quad , \quad 0 \leq \underline{\lambda}_{ntc} \leq M_{nt}^{\underline{\lambda}}(1 - z_{nt}^{s}) \quad \forall n,t,c \in N,T,C \tag{B.3d}$$

$$0 \leq M_{nt}^{s} z_{nt}^{s} - A \cdot W_t \cdot VOLL + p_{nt} \quad , \quad 0 \leq \overline{\lambda}_{ntc} \leq M_{nt}^{\overline{\lambda}}(1 - z_{nt}^{s}) \quad \forall n,t,c \in N,T,C \tag{B.3e}$$

$$0 \leq M_{nt}^{s}(1 - z_{nt}^{s}) - s_{nt} \quad , \quad 0 \leq \mu_{ntc} \leq M_{nt}^{\mu} z_{nt}^{s} \quad \forall n,t,c \in N,T,C \tag{B.3f}$$

$$0 \leq -g_{it} + \eta_{it}(P_i^0 + x_i) \quad , \quad 0 \leq \underline{\nu}_{itc} \leq M_{it}^{\underline{\nu}}(1 - z_{it}^{\overline{\alpha}^{LL}}) \quad \forall i,t,c \in G,T,C \tag{B.3g}$$

$$0 \leq M_{it}^{\overline{\alpha}^{LL}} z_{it}^{\overline{\alpha}^{LL}} + g_{it} - \eta_{it}(P_i^0 + x_i) \quad , \quad 0 \leq \overline{\nu}_{itc} \leq M_{it}^{\overline{\nu}}(1 - z_{it}^{\overline{\alpha}^{LL}}) \quad \forall i,t,c \in G,T,C \tag{B.3h}$$

$$0 \leq M_{it}^{\overline{\alpha}^{LL}}(1 - z_{it}^{\overline{\alpha}^{LL}}) - \overline{\alpha}_{it}^{LL} \quad , \quad 0 \leq \xi_{itc} \leq M_{it}^{\xi} z_{it}^{\overline{\alpha}^{LL}} \quad \forall i,t,c \in G,T,C \tag{B.3i}$$

$$0 \leq -P_i^{min} + g_{it} \quad , \quad 0 \leq \underline{\pi}_{itc} \leq M_{it}^{\underline{\pi}}(1 - z_{it}^{\underline{\alpha}^{LL}}) \quad \forall i,t,c \in G,T,C \tag{B.3j}$$

$$0 \leq M_{it}^{\underline{\alpha}^{LL}} z_{it}^{\underline{\alpha}^{LL}} + P_i^{min} - g_{it} \quad , \quad 0 \leq \overline{\pi}_{itc} \leq M_{it}^{\overline{\pi}}(1 - z_{it}^{\underline{\alpha}^{LL}}) \quad \forall i,t,c \in G,T,C \tag{B.3k}$$

$$0 \leq M_{it}^{\underline{\alpha}^{LL}}(1 - z_{it}^{\underline{\alpha}^{LL}}) - \underline{\alpha}_{it}^{LL} \quad , \quad 0 \leq \rho_{itc} \leq M_{it}^{\rho} z_{it}^{\underline{\alpha}^{LL}} \quad \forall i,t,c \in G,T,C \tag{B.3l}$$

$$0 \leq -\sum_{t \in T} W_t g_{it} + E_i \quad , \quad 0 \leq \underline{\sigma}_{ic} \leq M_i^{\underline{\sigma}}(1 - z_i^{\beta^{LL}}) \quad \forall i,c \in G,C \tag{B.3m}$$

$$0 \leq M_i^{\beta^{LL}} z_i^{\beta^{LL}} + \sum_{t \in T} W_t g_{it} - E_i \quad , \quad 0 \leq \overline{\sigma}_{ic} \leq M_i^{\overline{\sigma}}(1 - z_i^{\beta^{LL}}) \quad \forall i,c \in G,C \tag{B.3n}$$

$$0 \leq M_i^{\beta^{LL}}(1 - z_i^{\beta^{LL}}) - \beta_i^{LL} \quad , \quad 0 \leq \tau_{ic} \leq M_i^{\tau} z_i^{\beta^{LL}} \quad \forall i,c \in G,C \tag{B.3o}$$

$$0 \leq -f_{bt} + (F_b^0 + y_b^{cap}) \quad , \quad 0 \leq \underline{\phi}_{btc} \leq M_{bt}^{\underline{\phi}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{B.3p}$$

$$0 \leq M_{bt}^{\overline{\gamma}^{LL}} z_{bt}^{\overline{\gamma}^{LL}} + f_{bt} - (F_b^0 + y_b^{cap}) \quad , \quad 0 \leq \overline{\phi}_{btc} \leq M_{bt}^{\overline{\phi}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{B.3q}$$

$$0 \leq M_{bt}^{\overline{\gamma}^{LL}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) - \overline{\gamma}_{bt}^{LL} \quad , \quad 0 \leq \chi_{btc} \leq M_{bt}^{\chi} z_{bt}^{\overline{\gamma}^{LL}} \quad \forall b,t,c \in B,T,C \tag{B.3r}$$

$$0 \leq (F_b^0 + y_b^{cap}) + f_{bt} \quad , \quad 0 \leq \underline{\psi}_{btc} \leq M_{bt}^{\underline{\psi}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{B.3s}$$

$$0 \leq M_{bt}^{\underline{\gamma}^{LL}} z_{bt}^{\underline{\gamma}^{LL}} - (F_b^0 + y_b^{cap}) - f_{bt} \quad , \quad 0 \leq \overline{\psi}_{btc} \leq M_{bt}^{\overline{\psi}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) \quad \forall b,t,c \in B,T,C \tag{B.3t}$$

$$0 \leq M_{bt}^{\underline{\gamma}^{LL}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) - \underline{\gamma}_{bt}^{LL} \quad , \quad 0 \leq \omega_{btc} \leq M_{bt}^{\omega} z_{bt}^{\underline{\gamma}^{LL}} \quad \forall b,t,c \in B,T,C \tag{B.3u}$$

Appendix C

Detailed results

Table C.1: Capacity investments from strategic and centrally planned model for increased generation CAPEX.

	Centrally planned new capacity [MW]				Strategic new capacity [MW]			
CAPEX multipl.	Non RES	RES	Sum gen.	Transm.	Non RES	RES	Sum gen.	Transm.
1.0	0	5000	5000	15248	8908	21802	30710	0
2.0	0	0	0	15248	8417	14898	23315	0
3.0	0	0	0	15248	2764	19674	22438	0
4.0	0	0	0	15248	9034	11445	20479	0
5.0	0	0	0	15248	1791	15252	17043	4456

Table C.2: Investment and operational costs from strategic and centrally planned model for increased generation CAPEX.

	Centrally planned expenses [$bEUR$]				Strategic expenses [$bEUR$]			
CAPEX multipl.	Transm.	Gen.	OPEX	Total	Transm.	Gen.	OPEX	Total
1.0	26383.0	5242.3	309640.3	341265.6	0	50731.2	351378.4	402109.6
2.0	26383.0	0	318753.7	345136.7	0	67427.3	363112.1	430539.4
3.0	26383.0	0	318753.7	345136.7	0	104941.8	356812.4	461754.2
4.0	26383.0	0	318753.7	345136.7	0	119411.6	364387.0	483798.6
5.0	26383.0	0	318753.7	345136.7	10511.9	141888.6	331980.1	484380.6

Table C.3: Capacity investments from strategic and centrally planned model for increased CO_2 price.

CO_2 multipl.	Centrally planned new capacity [MW] Non RES	RES	Sum gen.	Transm.	Strategic new capacity [MW] Non RES	RES	Sum gen.	Transm.
1.0	0	5000	5000	15248	8908	21802	30710	0
1.25	0	10000	10000	15248	0	21766	21766	0
1.5	0	12242	12242	16248	0	19795	19795	0
1.75	0	13504	13504	17248	0	23581	23581	0
2.0	0	14472	14472	17248	0	15968	15968	0

Table C.4: Investment and operational costs from strategic and centrally planned model for increased CO_2 price.

CO_2 multipl.	Centrally planned expenses [$bEUR$] Transm.	Gen.	OPEX	Total	Strategic expenses [$bEUR$] Transm.	Gen.	OPEX	Total
1.0	26383.0	5242.3	309640.3	341265.6	0	50731.2	351378.4	402109.6
1.25	26383.0	13992.3	318897.5	359272.8	0	31480.4	386967.6	418447.9
1.5	33327.0	17916.3	321746.9	372990.3	0	32420.0	409797.5	442217.5
1.75	35441.8	20125.2	325425.5	380992.5	0	34892.6	416905.1	451797.7
2.0	35962.2	21817.8	330792.5	388572.6	24034.4	141888.6	448803.3	472837.8

Appendix D

Paper 1

The following paper was written concurrent with the Master thesis and is based on a specialisation project prior to the thesis. It was accepted to the *IAEE International Conference 2018* in Groningen, the Netherlands. The paper will be presented at 12 June 2018 and appear in the conference proceedings. The title is *Assessing incentives for multinational cooperation towards a North Sea Offshore Grid using allocation methods from coalitional game theory*, and the authors are Simon Risanger, Martin Kristiansen, Francisco Muñoz, and Magnus Korpås.

Assessing incentives for multinational cooperation towards a North Sea Offshore Grid using allocation methods from coalitional game theory

Simon Risanger, Martin Kristiansen**, Francisco Muñoz***, and Magnus Korpås***

ABSTRACT

The North Sea Offshore Grid (NSOG) has been recognized as a beneficial infrastructure project with respect to both economic and environmental concerns. Because of the absence of a supra-national planner, system optimal investments are dependent on cooperation among the surrounding countries. The most valuable expansion plans at system level tend to represent a high degree of uncertainty regarding the distribution of costs and benefits to the individual countries and, consequently, their incentives to cooperate. In order to better understand fair and stable cooperative solutions for multinational infrastructure projects, we present an analytic framework based on coalitional game theory. In combination with an expansion planning model, we are able to assess different allocation schemes for costs and benefits. Each represents different targets of fairness. Allocation schemes include the natural outcome without any side-payments, in addition to two other methods where side-payments are required, namely the Shapley value and the nucleolus. The resulting allocations are demonstrated with a NSOG case study with varying outcomes reflecting their properties and axioms. This could be a useful tool for decision support.

Keywords: Cost-benefit analysis, Cooperative game theory, Multinational infrastructure projects, North Sea Offshore Grid, Nucleolus, Power system planning, Shapley value

1. INTRODUCTION

The North Sea Offshore Grid (NSOG) has been identified as a priority project by the European Commission (The Council of the European Union 2013). The project possess a twofold purpose of integrating both renewable resources and regional markets, resulting in environmental and economic benefits. Despite the benefits, there are challenges regarding the investments. Among others, there is no supra-national authority to facilitate the process (Lumbreras and Ramos 2016) and outcomes can become unevenly distributed (Egerer, Kunz, and Hirschhausen 2013). As a result, it can be difficult for countries to reach a system-optimal plan through a standard bargaining process. A framework for cooperation can be a valuable tool in order to realize the NSOG and achieve its potential benefits.

Both the EU (The European Commission 2014), the network of transmission system operators (TSOs) in Europe (ENTSO-E 2016) and academic studies (Gorenstein Dedecca and Hakvoort 2016) agree that the NSOG adds significant value to the European power system with regard to security of supply, economic and environmental metrics. Hence, incentives should be developed to promote and facilitate a cost-efficient development from a multinational perspective. Concerning the issue

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of cooperation, frameworks and negotiations can be established to provide a fair treatment to all involved parties. Konstantelos et al. (2017) explore the issue of uneven distributions of outcomes from NSOG investments and propose a positive net benefit differential (PNBD) mechanism for allocations where countries experiencing negative outcomes are compensated by those that receive benefits. The latter group provides compensations proportionally to their gained benefits. However, as argued by Kristiansen, Munoz, et al. (2017), although the PNBD may properly represent an allocation where parties receive what they pay, it does not necessarily express the actual *value* a member adds to the coalition[1]. The authors exemplify this argument by how, e.g., Norwegian hydropower adds significant value to the NSOG due to its highly flexible characteristics that could balance out variable power generation elsewhere in the system. Consequently, they propose using the Shapley value from cooperative game theory to calculate allocations with the purpose of making marginal contributions from each country more transparent.

This paper extends the current literature on cooperative game theory in the context of power system expansion planning. Methods for establishing a game, checking distribution stability and solution mechanisms are explored. The latter includes a standard allocation of outcomes from new transmission projects from a conventional 50/50 cost split; an application of the Shapley value to distribute outcomes among all countries based on their marginal contributions to the grand coaltions; and an application of the nucleolus, which considers bargaining power instead of contributions to distribute outcomes. Hence, the contributions of this paper are i) the application of cooperative game theory in combination with Transmission Expansion Planning (TEP) and ii) a comparison of three prominent methods that could help increasing knowledge and intuition about outcomes from multinational and cooperative infrastructure projects.

2. METHODOLOGY

2.1 Establish a cooperative game from a TEP problem

A cooperative game consists of a set of players, their potential coalitions and the corresponding characteristic function. The latter can be interpreted as the total payoff achieved by the cooperation. For the NSOG case study, the bordering countries are chosen as players. This include Belgium (BE), Germany (DE), Denmark (DK), Great Britain (GB), the Netherlands (NL) and Norway (NO). We assume a central planner performing TEP with a system welfare maximizing objective. Under the assumption of perfect competition and inelastic demand, this becomes a co-optimization problem minimizing both expansion and market operation costs (Samuelson 1952). Three possible interconnectors are available for investment. These include the planned, but not yet constructed, corridors of Great Britain to Norway (North Sea Link), Germany to Norway (NordLink) and Denmark to Great Britain (Viking Link). The projects are chosen for our case study due to their real-life relevance. Moreover, by limiting the investment possibilities, causalities in the result become clearer to analyze. The corridors are assumed to be available at the start of the time period if employed[2].

The game is established by solving the TEP problem for the different coalitions. If both countries included in an interconnector project are present in a coalition, investment in that particular corridor becomes possible. Whether it is beneficiary to expand, and to what extent, is decided by the optimization program. Existing connections in the NSOG are already present in the grid representation, displayed as solid lines in Figure 1. The dashed lines portray the candidate projects. For more information regarding the TEP model, see section 5.1.

[1] A coalition is a temporary agreement to cooperate in order to achieve a common goal.

[2] The consequence of this simplification also extends to the game establishment. A more realistic sequential investment scenario for multiple corridors can influence the order and timing of when countries join coalitions, and thus their payoff. This effect should be noted, but is outside the scope of this paper to investigate further.

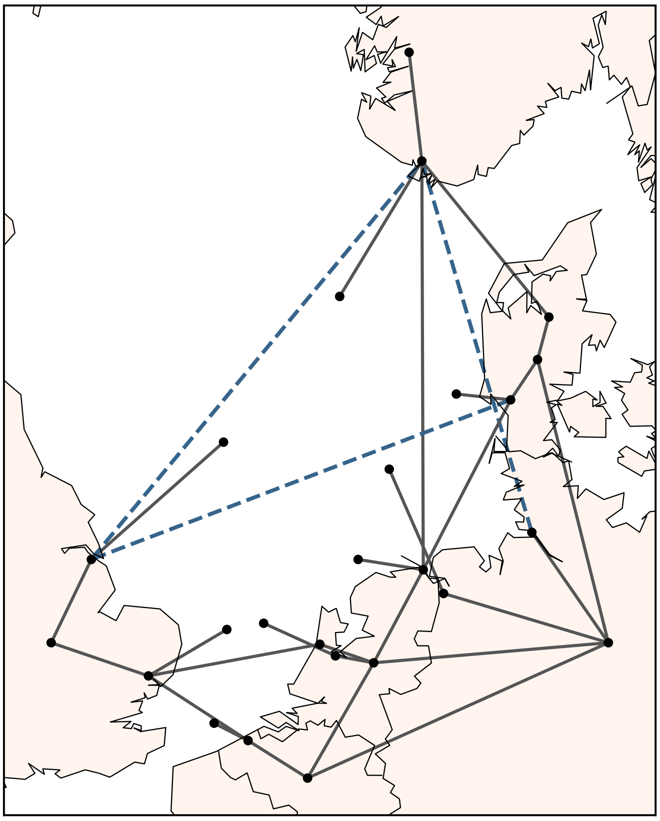


Figure 1: Representation of the North Sea Offshore Grid (NSOG) infrastructure and nodes for the case study. Solid lines are given exogenously in the TEP model, while dotted lines are candidate expansion projects determined endogenously.

The following assumptions are necessary to establish a transferable utility (TU) cooperative game:

1. Sufficient motivation exist to promote cooperation.
2. Transferable utility, implying that payoff is transferable between the players without losses.
3. The characteristic function is obtainable and cannot be prevented by the other players.

With respect to the first assumption, agents acting in self-interest can find motivation to cooperate if it is more beneficial than individual operation. A profit maximizing player will join a coalition as long as it yields additional payoff compared to individual operation. The characteristic where the coalition payoff is larger than the sum of the individual payoffs is known as *superadditivity*. If a game fulfills this property, the full cooperation among all players, termed the *grand coalition*, will be desired by all members because of its superior payoff[3]. Other factors, such as environmental concerns, can also provide additional motivation for cooperation beyond pure profits.

Regarding the second assumption, some challenges arises. Mainly how to treat externalities and the intangible nature of total welfare as a measure of payoff. We choose to include externalities,

[3]Do note that our model assumes system optimal market operation and only centralized expansion. Strategic operation or decentralized grid investments would likely alter this in the objective of individual profit maximization. However, compared to our centralized approach, such methods will render lower total system outcome due to imperfect market conditions. See for instance Murphy and Smeers (2005) and Huppmann and Egerer (2015) for more information.

both positive and negative in this paper[4]. This is done on the basis of respecting potential negative outcomes and acknowledging indirect contribution to welfare. Externalities are exemplified by Belgium and the Netherlands who have no direct participation in the investments, but their market operations are altered. The challenge regarding intangible total welfare is discussed when the calculations of metric factors are introduced in section 2.3.

Finally, the third assumption ensures that the characteristic functions are representative and attainable. A characteristic function simply denote the payoff achieved by a coalition. Because the payoffs are calculated by an optimization model, each characteristic function is represented by a single value representing the optimal result within the given circumstances. This assumption prevents abuse of market power or other deviations from optimal results. Neither other players nor internal actors, most notably producers, must be able to restrict the optimal characteristic function. Some kind of *transaction costs* are likely to apply when forming a coalition[5]. However, they are both difficult to estimate and assumed to be relatively small compared to other costs, such as investment expenses. Transfers, and thus side-payments, are therefore considered as lossless.

2.2 Data input

An aggregated representation of the NSOG and countries is utilized to attain a computationally tractable TEP model. Most open source data are also presented as national values. Consequently, each country is represented with an aggregated node of total demand and onshore generation as summarized in Table 1. The other nodes function as hub stations between nodes of offshore wind farms or interconnectors. Vision 4 from ENTSO-E (2015b) is primarily used as data source, with the exception of offshore wind production obtained from WindEurope (2017). Note that generation expansion is not performed by the model, but is implicitly considered by the ENTSO-E scenarios[6]. Wind and solar profiles are obtained from the *renewable.ninja* project (Pfenninger and Staffell 2016a; Pfenninger and Staffell 2016b). Due to the seasonal characteristics and dominant position of hydropower in Norway (IEA 2017), hourly prices from 2015 (Nord Pool AS 2017) are used as a water value approximation under the assumption of marginal cost pricing[7]. To maintain an acceptable computational time, a random sample of 500 hours is used to represent a full operational year[8].

2.3 Calculating welfare metrics

The optimization problem yield system optimal results, but we are interested in coalition payoff to determine its characteristic function. Single node welfare calculations are thus necessary, and performed according to the equations in Table 2. For each node i and means of generation g, p_i

[4]The treatment of externalities are a complex challenge for electricity markets (Hogan 1999). Joining the grand coalition is likely when experiencing negative externalities in order to be compensated. However, it is unlikely when experiencing positive due to the possibility of a more beneficial situation outside the grand coalition, this is known as the free-rider problem (Yi 1997). ENTSO-E and Agency for the Cooperation of Energy Regulators (ACER) advise for negative externalities to be compensated (ACER 2013; ENTSO-E 2015a). Our paper shows how the framework deals with included externalities and provide no further discussion regarding ideal treatment of externalities. If other approaches are chosen with regards to externalities, these will simply be implemented in the establishment of the game. Hence, the methodology utilizing an existing game is unaffected.

[5]Transaction costs include all expenses connected to market participation. In addition to the actual transfer fee, this include cost of obtaining information, bargaining expenses, legal fees and more.

[6]It is important to recognize that generation and transmission expansion have strong inter-dependencies (Alayo, Rider, and Contreras 2017). How generation expansion is treated will influence the results, but it is out of scope to discuss optimal modeling techniques. If interested, see Hemmati, Hooshmand, and Khodabakhshian (2013). Regardless of approach, our framework is still valid because it only considers outcomes.

[7]A water value can be interpreted as a marginal opportunity cost. That is, the value is determined based on expectations about future electricity prices, demand, and water inflow.

[8]Random samples contain uncertainties, however, according to Trötscher and Korpås (2011) convergence is shown to be reached at about 200 random samples for a similar optimization problem. Additionally, Härtel, Kristiansen, and Korpås (2017) and Kristiansen, Korpås, and Härtel (2017) demonstrate that the performance of random samples is satisfactory compared to more sophisticated clustering and sampling methods, such as for instance k-means.

Table 1: Supply, demand and fuel price data from ENTSO-E Vision 4 (ENTSO-E 2015b). Onshore and offshore wind capacities are divided according to data from WindEurope (2017). CO_2 price is 76€/tonCO_2 and VOLL 1000€/MWh.

Supply/ Demand	Fuel price [€/MWh_e]	BE	DE	DK	GB	NL	NO
		Capacity [MW]					
Bio	50	2500	9340	1720	8420	5080	0
Gas	65	10040	45059	3746	40726	14438	855
Hard coal	21	0	14940	410	0	0	0
Hydro	10	2226	14505	9	5470	38	48700
Lignite	10	0	9026	0	0	0	0
Nuclear	5	0	0	0	9022	486	0
Oil	140	0	871	735	75	0	0
Solar PV	0	4925	58990	1405	11915	9700	0
Onshore wind	0	3518	76967	6695	27901	5495	1771
Offshore wind	0	4000	20000	6130	30000	4500	724
Total supply	-	27209	249698	20850	133529	39739	52050
Peak demand	-	13486	81369	6623	59578	18751	24468

denotes electricity price, q_i and q_g quantities, c_g cost of generation, EF_g the emission factor, p_{CO_2} the price of CO_2 emission, $VOLL$ the value of lost load, d_i the demand and f_{ij} the flow between two nodes. The coalition characteristic function is defined as the sum of welfare for the countries present in the coalition. A notable consideration by using this approach is its negligence of cost from transmission losses. While this is included in the optimization solution process, results from the welfare calculations in Table 2 do not entirely represent all costs.

Table 2: Equations used for welfare calculations. A standard 50/50 split is used to share congestion rents from an interconnector.

Metric	**Notation**	**For single node i**
Producer surplus [EUR]	PS	$p_i q_i - \sum_{g\in G_i} q_g(c_g + EF_g p_{CO_2})$
Consumer surplus [EUR]	CS	$(VOLL - p_i)d_i$
Congestion rent [EUR]	CR	$\sum_{j\in I\setminus\{i\}} \frac{1}{2}(p_j - p_i)f_{ij}$
Total Welfare [EUR]	TW	$PS_i + CS_i + CR_i$

Total welfare includes congestion rent, consumer and producer surplus, as defined in Table 2. While congestion rent and producer surplus are defined as economic profit, the consumer surplus is expressed relative to the value of lost load. Although this may represent the utility of a consumer, it cannot be utilized in direct monetary terms. As a result, some of the total welfare is intangible and cannot be transferred. The agent representing a country in the negotiations must have sufficient economic profit accessible to perform the necessary side-payments.

2.4 The allocation schemes

The grand coalition is the set of all players, $N = \{BE, DE, DK, GB, NL, NO\}$, where $n = 6$. The characteristic function, $v(S)$, is calculated with the TEP model for each coalition, $S \subseteq N$. A total of $2^6 = 64$ coalitions are possible and three different solution concepts for finding allocations are investigated:

1. The natural allocation, $\boldsymbol{x}_{nat}$: Markets will themselves achieve an optimal equilibrium without any side-payments.

2. The nucleolus, $\boldsymbol{x}_{nu}$: Based on minimizing the maximum dissatisfaction the coalitions experience.

3. The Shapley value, $\boldsymbol{x}_{sh}$: The allocation occurs when each agents receive according to the average value of their marginal contributions.

2.4.1 Stability and the core

An allocation or payoff vector, $\boldsymbol{x} = (x_1, ..., x_n)$, is the proposed payoff for the different members. To be an *imputation*, an allocation has to fulfill the requirement of individual and group rationality given in (1) and (2), respectively. These ensure that each player receive more in the cooperation than individually and that all payoff is distributed. The set of imputations is denoted X.

$$x_i \geq v(\{i\}) \tag{1}$$

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

Stability of an allocation can be determined by core presence. If an allocation is within the core, there are no incentives for any player to form any other subcoalition because it is not possible to improve the current situation. The core is the set mathematically expressed in (3).

$$C(N, v) = \left\{ \boldsymbol{x} \in X \mid \sum_{i \in S} x_i \geq v(S) \text{ for all } S \subset N \right\} \tag{3}$$

2.4.2 The nucleolus

The goal of the nucleolus, introduced by Schmeidler (1969), is to minimize the largest dissatisfaction the players experiences from an allocation. Dissatisfaction is measured by the notion of *excess*. If some members of the current coalition wants to exit and create their own subcoalition, the excess is the difference between the payoff of the new coalition compared to the sum of what the members are obtaining in the current allocation. Excess is mathematically expressed as $e(\boldsymbol{x}, S) = v(S) - \sum_{i \in S} x_i$. An allocation will give rise to an excess vector containing the excesses with respect to all the subcoalitions. The excess vectors can be ordered lexicographically, a concept similar to how words are alphabetically sorted. Consequently, the nucleolus is the payoff vector resulting in the lexicographically smallest excess vector.

An efficient method of finding the nucleolus is to utilize least cores to generate the minimal excess vector directly. This operation will gradually cut the core down to a single point, which is the nucleolus. By inserting the excess expression into the core formulation in (3), an expression for the ε-core, $C_\varepsilon(N, v)$, is given in (4). Instead of only satisfying the minimum of negative dissatisfaction, i.e. satisfaction, the ε-core restricts the dissatisfaction by amount ε.

$$C_\varepsilon(N, v) = \{\boldsymbol{x} \in X \mid e(S, \boldsymbol{x}) \leq \varepsilon \text{ for all } S \subset N\} \tag{4}$$

The largest possible ε before the ε-core becomes empty is called the least core, ε_0. This will also represent the first element of the minimum excess vector. It is not guaranteed that a unique allocation will produce the least core. Hence, the possible payoff vectors needs to be further reduced to a single allocation. This is done by utilizing the allocations satisfying the least core and find the second least core, i.e. the second element of the minimum excess vector, among them. The process is continued until a single allocation is found. Our paper solve this by the lexocigraphically extended minmax problem approach proposed by Fromen (1997).

In economic terms, the nucleolus can also be interpreted through bargaining. Notably, the nucleolus is a point within the kernel and consequently in the bargaining set of the game. See for instance Osborne and Rubinstein (1994) for additional information.

2.4.3 The Shapley value

While the nucleolus consider fairness as minimizing the maximum dissatisfaction, the Shapley value, ϕ, considers contributions. Shapley (1953) introduced a value that obey a set of axioms generally considered simple and intuitive interpretations of fairness:

1. *Symmetry*: Any agents who contribute the same amount to each contribution are substitutes and thus should receive equal treatment, $v(S \cup \{i\}) = v(S \cup \{j\})$.
2. *Efficiency*: All utility obtained should be allocated. This is equivalent to the group rationality statement in (2).
3. *Law of aggregation*: The value of combining two independent TU games is the sum of the allocated value to its agents, $\phi[v + w] = \phi[v] + \phi[w]$.
4. *Dummy*: If an agent contributes nothing it should receive nothing. This is called a dummy or null player, and has the property of $v(S \cup \{i\}) = v(S)$.

All the axioms are fulfilled by the expression for the Shapley value in (5). This represent the average marginal contribution a player provides. Intuitively, the Shapley value can be considered as an allocation according to the value an agent contributes. The formula will render a single solution, but in contrast to the nucleolus, the Shapley value is not guaranteed to be in the core. Hence its stability has to be determined by checking for core presence.

$$\phi_i(N, v) = \sum_{S, i \in S} \frac{(|S| - 1)!(n - |S|)!}{n!} [v(S) - v(S \setminus \{i\})] \tag{5}$$

3. RESULTS

3.1 Expansion results without side-payments

The solution of different investment options are presented in Table 3. Combinations are given as boolean statements in the following sequence of transmission corridors (GB-NO, DE-NO, DK-GB). All investment opportunities are utilized if possible. More interconnection generally increases the total welfare because of an increase in market efficiency from the expansion of congested corridors. Furthermore, the corridors connected to Norway tend to be more beneficial than the link between Denmark and Great Britain. All results are presented relative to the case of no investment because the absolute results are highly dependent on the value of lost load defined at a high rate of $1000 EUR/MWh$. This is an arbitrarily chosen value, but have no consequences for relative values.

The natural allocation is the distribution of the grand coalition solution shown in Table 4, i.e. metrics from combination (1, 1, 1) in Table 3. No side-payments are performed for this allocation. An important observation is the extensive negative producer surplus which jeopardize internal stability. All countries, except Norway, experience this. If no compensation or regulation are applied to the producers, they may start behaving strategically to prevent the current situation and obtain a better result for themselves. Another notable result is the considerable congestion rents obtained by the new projects. This is economic profit directly obtained by the TSO, which can be used for side-payments to obtain appropriate allocations. Such an outcome is favorable for the assumption of transferable utility. Congestion rents are flexible and can also be applied to internal compensations, for instance to the producers.

Table 3: An overview of the possible outcomes for the NSOG expansion game. Each combination of projects are given in the ordering of (GB-NO, DE-NO, DK-GB).

Combination	Objective $[bEUR]$	CAPEX $[bEUR]$	OPEX $[bEUR]$	Annual system welfare $[bEUR/year]$
(0, 0, 0)	547.856	0	547.856	1168.56
(0, 0, 0)	0	0	0	0
(0, 0, 1)	-1.42235	3.69822	-5.12057	0.39154
(0, 1, 0)	-29.1012	9.13644	-38.2377	2.72141
(0, 1, 1)	-30.5287	12.8347	-43.3634	2.99027
(1, 0, 0)	-13.7178	12.0818	-25.7996	1.74323
(1, 0, 1)	-17.6398	19.6427	-37.2826	2.52439
(1, 1, 0)	-37.4058	14.0480	-51.4538	3.71705
(1, 1, 1)	-39.1144	17.7462	-56.8606	4.09135

Table 4: Differences in welfare metrics between base case and investments under the grand coalition.

Welfare metric $[bEUR]$	BE	DE	DK	GB	NL	NO	System
Consumer surplus	0.243	1.513	0.204	1.579	0.241	0.003	3.783
Producer surplus	-0.148	-1.464	-0.208	-0.983	-0.152	0	-2.956
Congestion rent	0	1.288	0.070	0.298	0.015	1.593	3.264
Total welfare	0.095	1.337	0.066	0.894	0.104	1.596	4.091

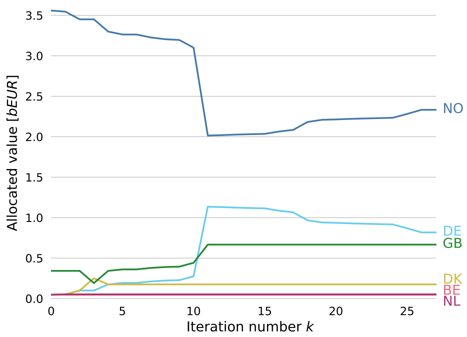
3.2 Comparing the three allocation methods

The natural allocation is the system optimal solution from full cooperation, as presented in Table 4, without any side-payments. Calculations leading to the nucleolus and Shapley value are presented in Figure 2. The nucleolus is found after 27 cut-iterations, as shown in Figure 2a. This means that previous iterations yielded solutions that are not unique. The largest dissatisfaction is always maximized, which reduces the core and consequently the amount of stable solutions. Before the distinct change in allocation at iteration 11, all the most beneficial coalitions containing Germany, Great Britain and Norway have been binding. These will contain a similar payoff, but when forced to split coalitions, their dependencies for each other become more apparent and lead to a considerable change in the solution space. Belgium and the Netherlands have no direct influence on the outcomes, and consequently their allocations remain more or less constant throughout the iterations.

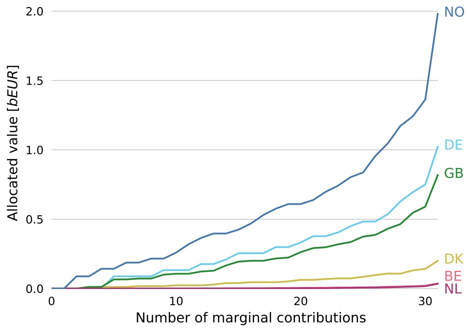
Figure 2b depicts the development of the Shapley value. In contrast to the nucleolus, it is gradually developed by additional marginal contributions. The contributions are added according to an arrangement considering the increasing size of coalitions[9]. Hence, the larger coalitions, and consequently the most beneficial, are the last ones to be evaluated. Countries are able to contribute more because of the opportunities more cooperation offer. In turn, the average value of marginal contributions becomes larger at the end of the plot.

A final comparison of the resulting allocations are presented in Figure 3. All three were found to be within the core, and hence provide stable distributions. However, the allocations do differ significantly. For instance, Belgium, Germany, Great Britain and the Netherlands receive more from the natural outcome, than what both the nucleolus and Shapley value deem to be fair. Germany and Norway present two interesting contrasting cases. Due to Norway's flexible and moderately priced generation capacity, she becomes a major exporter. This contributes significantly to the system because it provides a higher utilization of variable renewable generation. A fact the Shapley value

[9] Any input arrangement of the coalitions will lead to an equal final outcome because the Shapley value considers *average* marginal contributions.



(a) The nucleolus



(b) The Shapley value

Figure 2: Illustrations of how the Nucleolus and Shapley Value is calculated with respect to (a) number of cut-iterations and (b) the marginal contribution of different countries increasing the number of considered coalitions.

recognizes. Moreover, the nucleolus values Norway even more because of her important role in the most beneficial transmission projects. Although Germany and Great Britain are also present, they are both dependent on Norway who, in turn, have two profitable alternatives. These alternatives are taken into consideration in the calculation of the nucleolus, which allocate a considerable amount to Norway. The reverse is the case of Germany and Great Britain. Their dependency cause the nucleolus to assign them even less than what they contribute according to the Shapley value.

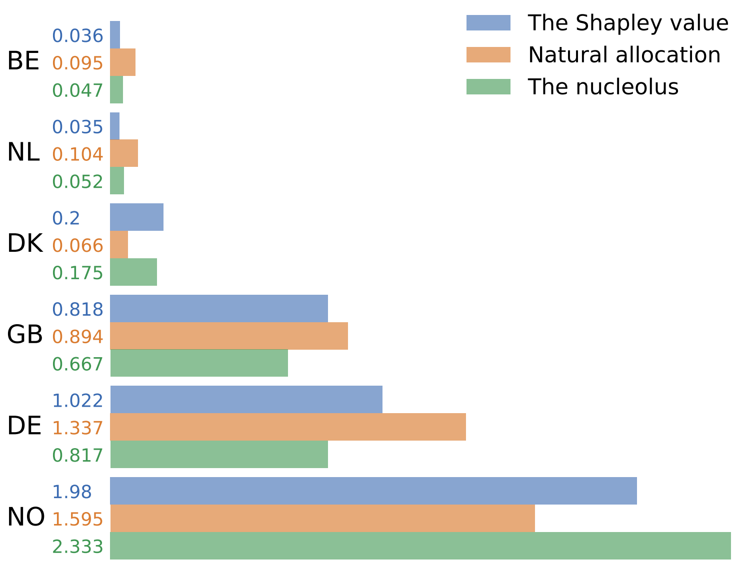


Figure 3: Comparison of the three different allocation methods.

Belgium and the Netherlands are not involved in the expenses of the grid investments, but achieve positive externalities. According to Figure 3, the natural allocation is the most beneficial outcome for them. Neither country are a necessary participant in any of the corridors and Table 3 show that full investments are expected to occur even in a situation without Belgium and the Netherlands due to its superior outcome. With respect to self-interest, the duo are better off as free-riders obtaining the larger share of positive externalities than the value assigned through the nucleolus or Shapley value.

Naturally, the proposed allocations are sensitive to our data assumptions and will likely change if other expansions or generation investment were included. Nevertheless, they do provide interesting insight regarding cooperation. The solution mechanisms provide valuable information regarding the countries' position in a negotiation situation. Another valuable ability is the possibility to determine the stability of allocation proposals. All the suggested distributions are stable, but provide different features. The natural allocation provide an acceptable outcome without being dependent on side-payments, while the nucleolus provide a notion about bargaining power. Norway is in a stronger negotiating position than the other countries, and is granted accordingly. The Shapley value, on the other hand, provides a benchmark signifying contributions.

4. CONCLUSION

Systems without any supra-national authority could be facing weak incentives for system-optimal infrastructure investments. This paper presents two methods from cooperative game theory, the Shapley value and nucleolus, that calculate fair and stable allocations of costs and benefits in the context of multinational transmission projects. In combination with a transmission expansion planning (TEP) model, we are able to demonstrate their properties and impact on a case study of grid expansion in the North Sea area. Both methods assume side-payments and are compared to a traditional 50/50 split allocation without side-payments.

A thorough description of methods and approach is provided, including a presentation of relevant input data from ENTSO-E Vision 4 for year 2030. All three allocation methods are compared with each other, and distinctive characteristics are identified and discussed in light of the underlying properties concerning fairness and stability.

The results portray how cooperative game theory can be used to create a decision support framework for cooperation. Such an approach contribute to better understanding of the negotiation position and provide insight in the contributions and features different actors provide. Notable features are the possibility to determine stability, benchmarks of contributions from the Shapley value and the notion of bargaining power provided by the nucleolus.

Further work should extend to non-cooperative games in order to quantify the estimated value of fully functioning allocation schemes for cooperative solutions. In addition, a comparison with allocation schemes suggested by officials, such as ENTSO-E, would be an interesting extension.

5. APPENDIX

5.1 TEP model

The model used to solve the TEP problem is the Power Grid Investment Model (PowerGIM) presented in Kristiansen, Munoz, et al. (2017). It is a modification of the open source Python package Power Grid and Market Analysis (PowerGAMA) (Svendsen and Spro 2016; Svendsen 2017). Both utilize the optimization modelling package Pyomo (Hart, Watson, and Woodruff 2011; Hart, Laird, et al. 2017) for Python. The notations for the model is presented in Table 5.

The problem is formulated in (6), where (6a) represent the objective of minimizing both investment and operational costs. These are formulated in (6b) and (6c), respectively. Investment cost include both fixed cost and variable cost, (6d) and (6e), to give a realistic representation and the opportunity to utilize economies of scale. The annuity factor a transforms future cash flows into present values. This is included because the operation cost only include a single year of market operation. Investment costs, on the other hand, depend upon the financial lifetime. The annuity factor represents the operational costs for the financial lifetime in net present value. Consequently, the total

Table 5: Notation for the generation and transmission planning model (PowerGIM).

Sets and mappings	
$n \in N$	: nodes
$i \in G$	: generators
$b \in B$	: branches
$l \in L$	: loads, demand, consumers
$t \in T$	: time steps, hour
$i \in G_n, l \in L_n$	: generators/load at node n
$n \in B_n^{in}, B_n^{out}$	: branch in/out at node n
$n(i), n(l)$	: node mapping to generator i/load unit l
Parameters	
a	: annuity factor
ω_t	: weighting factor for hour t (number of hours in a sample/cluster) $[h]$
$VOLL$	: value of lost load (cost of load shedding) $[EUR/MWh]$
MC_i	: marginal cost of generation, generator i $[EUR/MWh]$
$CO2_i$	: CO_2 emission costs, generator i $[EUR/MWh]$
D_{lt}	: demand at load l, hour t $[MW]$
B, B^d, B^{dp}	: branch mobilization $[EUR]$, fixed cost $[EUR/km]$ and variable cost $[EUR/kmMW]$
CS_b, CS_b^p	: fixed cost [EUR] and variable cost $[EUR/MW]$ of onshore/offshore switchgear, branch b
CX_i	: capital cost for generator capacity, generator i $[EUR/MW]$
CZ_n	: onshore/offshore node costs (e.g. platform costs), node n $[EUR]$
P_i^e	: existing generation capacity, generator i $[MW]$
γ_{it}	: factor for available generator capacity, generator i, hour t
P_b^e	: existing branch capacity, branch b $[MW]$
$P_b^{n,max}$	: maximum new branch capacity, branch b $[MW]$
D_b	: distance/length, branch b $[km]$
l_b	: transmission losses (fixed and variable w.r.t. distance), branch b
E_i	: yearly disposable energy (e.g. energy storage), generator i $[MWh]$
M	: a sufficiently large number
Primal variables	
y_b^{num}	: number of new transmission lines/cables, branch b
y_b^{cap}	: new transmission capacity, branch b $[MW]$
z_n	: new platform/station, node n
x_i	: new generation capacity, generator i $[MW]$
g_{it}	: power generation dispatch, generator i, hour t $[MW]$
f_{bt}	: power flow, branch b, hour t $[MW]$
s_{nt}	: load shedding, node n, hour t $[MW]$

system is under consideration.

Restrictions are represented by (6f) to (6k). Energy balance is preserved by (6f). The demand at a node is equal to its own production, imports, exports and load shedding. Note that the importer pays for transmission losses. (6g) ensures that a generation technology is producing within its minimum and maximum limits. Both existing and potential newly invested capacity from previous time steps are included. The availability factor γ_{it} represent intermittent variable production. It is provided by input data of available production, given as a range from zero to 100%, for different nodes and time stages. Inequality (6h) enforce a restriction of yearly disposable energy. This is mainly relevant for generation methods requiring storage, such as hydro power. Flow limits, from both original and new capacity, are fulfilled by (6i). For the same corridor, upper and lower limit is the same. The designated sign is just a matter of how directions are defined. (6j) restricts new branch capacity by a maximum limit. Finally, restriction (6k) ensures that a new node facility is employed if corridors wishes to use it. For a more detailed presentation of the model, the reader is referred to Kristiansen, Munoz, et al. (2017).

$$\min_{x,y,z,g,f,s} \quad IC + a \cdot OC \tag{6a}$$

where

$$IC = \sum_{b \in B} (C_b^{fix} y_b^{num} + C_b^{var} y_b^{cap}) + \sum_{n \in N} CZ_n z_n + \sum_{i \in G} CX_i x_i \tag{6b}$$

$$OC = \sum_{t \in T} \omega_t (\sum_{i \in G} (MC_i + CO2_i) g_{it} + \sum_{n \in N} VOLL s_{nt}) \tag{6c}$$

$$C_b^{fix} = B + B^d D_b + 2CS_b \qquad \forall b \in B \tag{6d}$$

$$C_b^{var} = B^{dp} D_b + 2CS_b^p \qquad \forall b \in B \tag{6e}$$

subject to

$$\sum_{l \in L_n} D_{lt} = \sum_{i \in G_n} g_{it} + \sum_{b \in B_n^{in}} f_{bt}(1 - l_b) - \sum_{b \in B_n^{out}} f_{bt} + s_{nt} \qquad \forall n, t \in N, T \tag{6f}$$

$$P_i^{min} \le g_{it} \le \gamma_{it}(P_i^e + x_i) \qquad \forall i, t \in G, T \tag{6g}$$

$$\sum_{t \in T} \omega_t g_{it} \le E_i \qquad \forall i \in G \tag{6h}$$

$$-(P_b^e + y_b^{cap}) \le f_{bt} \le (P_b^e + y_b^{cap}) \qquad \forall b, t \in B, T \tag{6i}$$

$$y_b^{cap} \le P_b^{n,max} y_b^{num} \qquad \forall b \in B \tag{6j}$$

$$\sum_{b \in B_n} y_b^{num} \le M z_n \qquad \forall n \in N \tag{6k}$$

$$x_i, y_b^{cap}, g_{it}, s_{nt} \in \mathbb{R}^+, \quad f_{bt} \in \mathbb{R}, \quad y_b^{num} \in \mathbb{Z}^+, \quad z_n \in \{0, 1\}$$

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Appendix E

Paper 2

The following paper is a working paper of the Master thesis made in connection with a presentation held at 31 May 2018 at the *Conference on Computational Management Science 2018* in Trondheim, Norway. The title is *A strategic investment model for multinational transmission expansion planning: Comparing competitive and cooperative solutions for a North Sea Offshore Grid*, and the authors are Simon Risanger and Martin Kristiansen. Paolo Pisciella will also be added as author in future drafts. The objective is to add producer surplus and congestion rents to the intermediate level problem before the paper is submitted.

A strategic investment model for multinational transmission expansion planning: Comparing competitive and cooperative solutions for a North Sea Offshore Grid

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Abstract

Market agents often have different objectives and ignoring this can lead to inefficient markets. To confront this challenge in a multinational transmission expansion setting, we propose a three-stage model. A lower level problem consists of a market operator optimizing short-term system welfare, strategic countries who maximizes their own welfare are in the intermediate problem, while transmission expansion is performed by a benevolent planner in the upper level. All problems anticipates the solutions of the other problems, and thus creates an equilibrium. We utilize Karush-Kuhn-Tucker conditions as optimality conditions for both the lower and intermediate problems. By exploiting relationships between binary variables from disjunctive constraints and dual variables, a mixed integer linear problem providing global optimum is formulated. The method is demonstrated on a case study of the North Sea Offshore Grid. In a strategic framework, the system resources are used in a less efficient way compared to cooperation. Consequences include over-investments in generation capacity, no transmission expansion, higher expenses and additional fossil fuel power plants.

Keywords: Transmission expansion planning, multilevel programming, hierarchical optimization, three-stage problems, MPEC, EPEC, North Sea Offshore Grid (NSOG)

1. Introduction

The North Sea Offshore Grid (NSOG) has been identified as a priority project by the European Commission (The Council of the European Union 2013). The project possess a twofold purpose of integrating both renewable resources and regional markets, resulting in environmental and economic benefits. Despite the benefits, there are challenges regarding investments. Among others, there is no supra-national authority to facilitate the process (Lumbreras and Ramos 2016) and outcomes can become unevenly distributed (Egerer, Kunz, and Hirschhausen 2013). A study of incentives for multinational transmission investments by Buijs, Bekaert, and Belmans (2010) concludes that the current frameworks are not sufficient to adapt a full system perspective for investments. This may motivate countries to act strategically in order to maximize their own benefits. If transmission expansion planning (TEP) do not consider strategic behavior, countries are able to exploit the

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expansions. According to David and Wen (2001), market power in electricity markets can be applied by influencing prices or exploiting import and export by strategic line congestion. Countries are able to strengthen their position by for instance generation investments.

Both the EU (The European Commission 2014), the network of transmission system operators (TSOs) in Europe (ENTSO-E 2016) and academic studies (Gorenstein Dedecca and Hakvoort 2016) agree that the NSOG adds significant value to the European power system with regard to security of supply, economic and environmental metrics. Hence, we should work towards a more interconnected grid. Konstantelos et al. (2017) and Kristiansen et al. (2017) suggest different allocation mechanisms to create a fair distribution among the countries affected by network extensions. Such approaches introduces the possibility of perfect system expansions, because the countries who are worse off are compensated. For allocation schemes to be valid they are dependent upon side payments and that no one exploit them by strategic operation. Both assumptions can be hard to accomplish in practical terms. An alternative is to perform TEP with the assumption of strategic behavior of countries.

Multilevel problem structures have several favourable features when including strategic behavior in electricity markets. Bilevel or three-stage models are hierarchical optimization problems where the solution at the different problems are dependent upon the other problems. A three-stage problem can thus consist of market operator, producers and transmission system operators with different objectives. The expansion planner will then anticipate the actions of other market agents. Consequently, the optimal expansion will not only consider expansions to remove contingencies, but also additional objectives such as reducing market power.

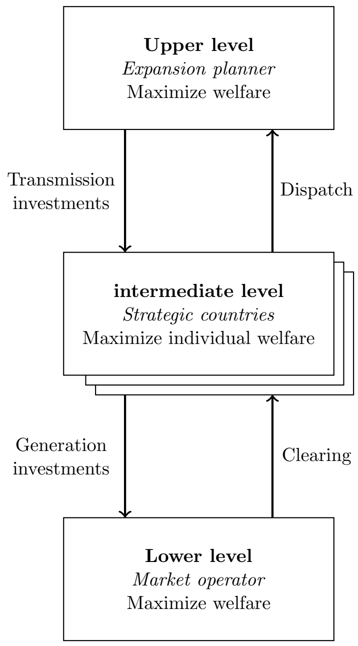
Strategic TEP problems have recently developed from bilevel to three-stage models. Because it is challenging to solve problems of multiple objective functions, multistage models are often reformulated by representing the lower level problems with optimality conditions. We then obtain a mathematical program with equilibrium constraints (MPEC) or an equilibrium program with equilibrium constraints (EPEC). Moreover, equilibrium constraints often takes the form of non-convex complementarity constraints. This is for instance the case of Karush-Kuhn-Tucker (KKT) conditions for optimality. For bilevel, we can use the linearization techniques of Fortuny-Amat and McCarl (1981) or the Siddiqui and Gabriel (2013) approach of SOS-1 variables and Schur's decomposition to solve the problem. For three-stage problems, however, we need to proceed one stage further. To solve this issue, algorithms or alternative formulations of optimality conditions have been utilized. Jin and Ryan (2014) propose hybrid iterative of solving three-stage problems using a diagonalization method. However, as stated in Ruiz, Conejo, and Smeers (2012), diagonalization methods have the major drawback of not guaranteeing global optimum. Instead, the authors propose using strong duality as an optimlity condition instead of KKT. While this prevents complemenentarity conditions, bilinear terms may still appear because of the inter-dependencies among the problems. Nevertheless, an advantage is that because no non-continuous variables are introduced it has more options of further reformulation. Huppmann and Egerer (2015) and Zerrahn and Huppmann (2017) use strong duality to move from lower to intermediate problems, and afterwards using the KKT conditions towards the upper level problem. Because of bilinearities in the intermediate problem, the KKT conditions are not necessary nor sufficient. Hence they need a scanning algorithm to search all KKT solutions to find the best one. Solutions may also exist outside the scanned points.

We extend upon current literature by presenting a novel approach of solving three-stage problems to global optimum as a standard mixed-integer linear programming (MILP) problem. When

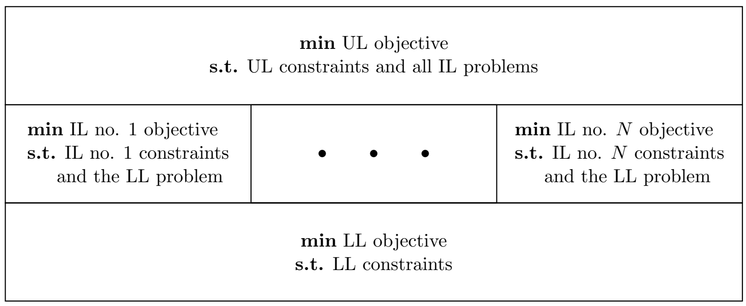
KKT conditions of the lower level problems are introduced into the intermediate level we linearize the complementarity conditions by the Fortuny-Amat and McCarl (1981) approach. To move the KKT conditions of the intermediate problem towards the upper level problem, we can exploit the relationship between binary and dual variables in the problem. The approach is presented after a general three-stage problem introduction. We will then reformulate a three-stage TEP model and demonstrate it on a case study considering an offshore grid between Germany, Great Britain and Norway.

2. Methodology

Three-stage problem structures have the favourable property of being able to represent the relationship between the different actors in a problem. Multinational TEP problems often contain decision makers of different goals, namely a market operator, countries and an expansion planner[1]. The market operator wants to maximize short-term total welfare by optimal market clearing. Strategic countries maximizes their own welfare by capacity investments, without considering the system consequences. We finally assume a benevolent expansion planner who maximizes long-term total welfare by investments in the transmission network. Because outcomes of the different problems are dependent upon each other, the optimal solution becomes an equilibrium among the agents. The TEP problem structure and dependencies is shown in Figure 1a.



(a) Multinational TEP problem in a three-stage structure



(b) General representation of a three-stage problem with multiple intermediate level problems

Figure 1: A TEP and general three-level problem structure.

[1] If we consider national TEP instead, a similar structure will occur between the market operator, producers and transmission system operator (TSO).

A general representation of a three-stage problem with multiple intermediate level problems are shown in Figure 1b. In the current form, all problems in Figure 1 have a standard representation of an objective function subject to constraints. If we want to solve the full three-level problem in its current form we need to consider multiple objective functions which can be challenging. An alternative is to represent a problem as optimality conditions. If optimality conditions are fulfilled, the outcome is equivalent to the optimal solution of the optimization problem they represent. Figure 2 shows the transition of the general three-stage problem in Figure 1b to a single problem.

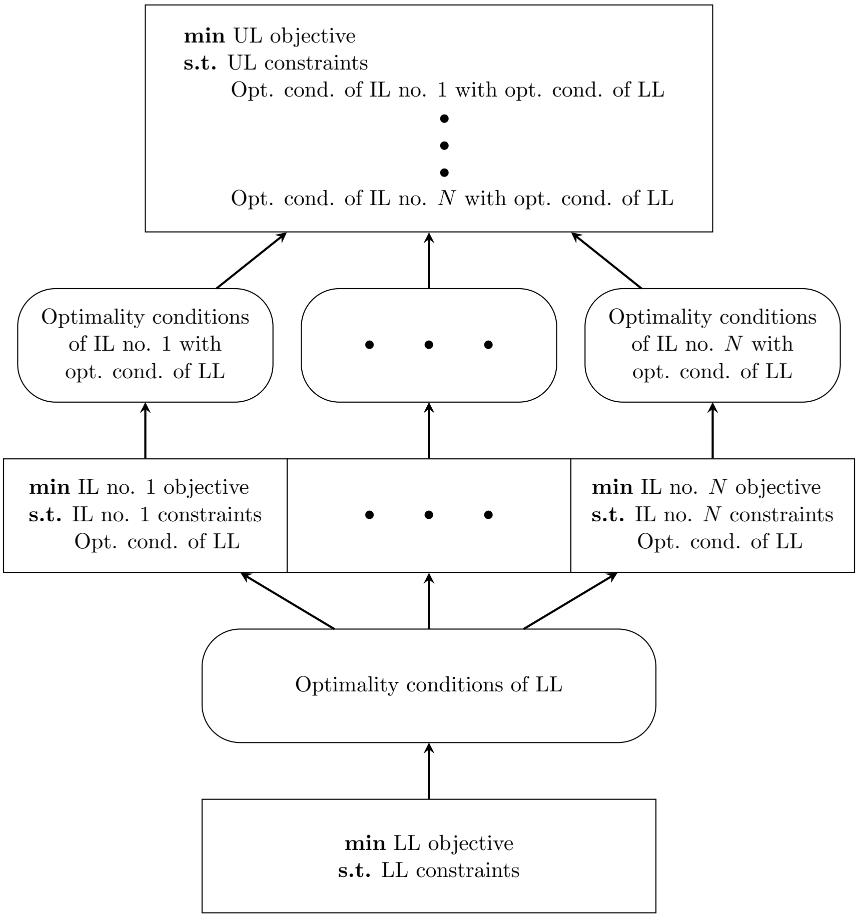


Figure 2: Transformation of a three-stage problem into a single EPEC

Two common optimality conditions are strong duality and KKT conditions, given that certain constraint qualification of the problem is met. The former introduces bilinear terms, i.e. multiplication of two different variables, because multilevel problems are dependent upon decision variables of other problems. KKT conditions, however, introduce complementarity conditions which is non-convex. In a bilevel problem, we can utilize methods to handle these challenges and solve the non-linear problems directly or linearize the complementarity conditions. For three-stage problems, we need to develop the optimality conditions of the intermediate problem as well. Because the lower level optimality conditions are non-convex, they violate the constraint qualifications that ensure necessary and sufficient KKT conditions. An algorithmic approach can be one way to handle this challenge. All solutions meeting the KKT conditions are then scanned through. For each iteration a new cut is added to prevent the same solution, while the point of best objective is chosen at the end. While this has been previously used in three-stage TEP models, it provides the challenge of how to efficiently perform the actual cutting. In addition, because the KKT conditions are unnecessary, there may exist solutions other than those the algorithm scans. We therefore introduce a new technique where the relationship between the binary variables of linearized complementarity constraints and their dual variables are exploited. As a result, the final problem becomes a MILP problem which can be implemented in commercial solvers.

2.1. Exploitation of binary and dual variables

We consider a general complementary constraint containing a function $g(x)$ and a variable λ, as shown in (1). It simply express how the product of two or more decision variables or functions of decision variables must be zero (Billups and Murty 2000). Hence, the problem is non-convex. The *perp* operator $\perp$ states that the inner product of two vectors is equal to zero. Consequently, either $g(x) = 0$ and $\lambda \geq 0$ or $g(x) \geq 0$ and $\lambda = 0$.

$$0 \leq -g(x) \quad \perp \quad \lambda \geq 0 \tag{1}$$

By using the Fortuny-Amat and McCarl (1981) approach, we linearize (1) into disjunctive constraints (2). The either $g(x) = 0$ and $\lambda \geq 0$ or $g(x) \geq 0$ and $\lambda = 0$ statement is now replaced by binary variable z and the sufficiently big parameter M. Dual variables of the constraints are given in parentheses.

$$g(x) \leq 0 \qquad (\overline{\theta}) \tag{2a}$$
$$-g(x) \leq Mz \qquad (\underline{\theta}) \tag{2b}$$
$$\lambda \leq M^{\lambda}(1-z) \qquad (\phi) \tag{2c}$$
$$z \in \{0,1\} \tag{2d}$$

Binary variables in (2b) and (2c) make the representation non-linear, and consequently the KKT conditions become not necessary nor sufficient. However, if we currently assume that z is a parameter, the KKT conditions of (2) become (3).

$$g(x) \leq 0 \tag{3a}$$
$$-g(x) \leq Mz \tag{3b}$$
$$\lambda \leq M^{\lambda}(1-z) \tag{3c}$$
$$\overline{\theta}\,(-g(x)) = 0 \tag{3d}$$
$$\underline{\theta}\,(g(x) + Mz) = 0 \tag{3e}$$
$$\phi\,(M(1-z) - \lambda) = 0 \tag{3f}$$
$$\overline{\theta}, \underline{\theta}, \phi, \lambda \geq 0 \tag{3g}$$

We know that z can only take two values, either 0 or 1. First, let us consider the KKT conditions if $z = 0$:

- $g(x) = 0$ by (3a) and (3b).
- $\overline{\theta} \geq 0$ by (3d) when $g(x) = 0$.

- $\underline{\theta} \geq 0$ by (3e) when $g(x) = 0$ and $z = 0$.
- $\lambda \geq 0$ by (3c).
- $\phi = 0$ by (3f) when $z = 0$.

For the situation when $z = 1$, (3b) do not enforce anything on (3a). $g(x)$ can be both zero or non-negative if it chooses. Consequently, $\overline{\theta}$ is not decided a priori and (3d) may hold for either $\overline{\theta}$ or $g(x)$ set to zero. Let us consider if $g(x)$ was forced to zero. This means that (3a) is restricted to equality, but its corresponding variable λ is also forced to zero already, just to provide $\overline{\theta} \geq 0$. However, we could achieve the same by $z = 0$, where we also would have $\lambda \geq 0$, and thus a less restricted problem. The effect of $z = 1$ then becomes:

- $g(x) \geq 0$ by (3a), (3b) and argument above.
- $\overline{\theta} = 0$ by (3d) when $g(x) \geq 0$.
- $\underline{\theta} = 0$ by (3e) when $z = 1$.
- $\lambda = 0$ by (3c).
- $\phi \geq 0$ by (3f) when $\lambda = 0$ and $z = 1$.

From the discussion above, we observe how the KKT conditions of complementarity conditions as disjunctive constraints depend upon the binary variables. Expressed mathematically, the KKT conditions of (2) become (4).

$$g(x) \leq 0 \tag{4a}$$
$$-g(x) \leq Mz \tag{4b}$$
$$\lambda \leq M^{\lambda}(1 - z) \tag{4c}$$
$$\overline{\theta} \leq M^{\overline{\theta}}(1 - z) \tag{4d}$$
$$\underline{\theta} \leq M^{\underline{\theta}}(1 - z) \tag{4e}$$
$$\phi \leq M^{\phi} z \tag{4f}$$
$$z \in \{0, 1\} \tag{4g}$$

2.2. Three-stage TEP model to MILP problem

We now consider the three-stage TEP problem presented in Figure 1a. All nomenclature is presented in Table 1.

2.2.1. The lower level problem: Market clearing

Problem (5) represent a traditional market clearing problem in its simplest form. The market operator tries to minimize the cost of dispatch at an hourly basis. Expenses in the objective function (5a) are marginal costs, MC_i, CO_2 emission cost, $CO2_i$, and value of lost load, $VOLL$, if shedding is necessary[2]. The objective is multiplied by a samplefactor, W_t, to make the time steps representative for a full year and an annuity factor A to compare operating expenses throughout

[2]Load shedding occurs if load cannot be met and it is thus cut off.

Table 1: Notation for the three-stage model

Sets and mappings	
$n \in N$	: nodes
$i \in G$	: generators
$b \in B$	: branches
$t \in T$	: time steps, hour
$n \in B_n^{in}, B_n^{out}$	: branch in/out at node n
$c \in C$	: countries
$n(i)$	: node mapping to generator i
Parameters	
A	: annuity factor
W_t	: weighting factor for hour t (number of hours in a sample/cluster) $[h]$
$VOLL$	: value of lost load (cost of load shedding) $[EUR/MWh]$
MC_i	: marginal cost of generation, generator i $[EUR/MWh]$
$CO2_i$	: CO_2 emission costs, generator i $[EUR/MWh]$
D_{nt}	: demand at node n, hour t $[MW]$
B, B^d, B^{dp}	: branch mobilization $[EUR]$, fixed cost $[EUR/km]$ and variable cost $[EUR/kmMW]$
CS_b, CS_b^p	: fixed cost [EUR] and variable cost $[EUR/MW]$ of onshore/offshore switchgear, branch b
CX_i	: capital cost for generator capacity, generator i $[EUR/MW]$
CZ_n	: onshore/offshore node costs (e.g. platform costs), node n $[EUR]$
P_i^0	: existing generation capacity, generator i $[MW]$
$P_i^{max\ new}$	: Maximum new generation capacity, generator i $[MW]$
η_{it}	: factor for available generator capacity, generator i, hour t
F_b^0	: existing branch capacity, branch b $[MW]$
$F_b^{max\ line}$	: maximum new capacity for a line, branch b $[MW]$
$F_b^{max\ new}$	: maximum new branch capacity, branch b $[MW]$
L_b^{km}	: distance/length, branch b $[km]$
F_b^{loss}	: transmission losses (fixed and variable w.r.t. distance), branch b
M	: a sufficiently large number
Primal variables	
y_b^{num}	: number of new transmission lines/cables, branch b
y_b^{cap}	: new transmission capacity, branch b $[MW]$
x_i	: new generation capacity, generator i $[MW]$
g_{it}	: power generation dispatch, generator i, hour t $[MW]$
f_{bt}	: power flow, branch b, hour t $[MW]$
s_{nt}	: load shedding, node n, hour t $[MW]$
z	: binary variable connected to disjunctive constraints

the financial lifetime of investments. Demand, D_{nt}, at a node must be met at all times, either by production, g_{it}, load shedding, s_{nt}, import or export, as shown in (5b). Constraint (5c) ensures that generation do not exceed existing capacity, P_i^0 and new capacity investments, x_i. Available generation capacity, η_{it}, represent profiles of intermittent production, such as solar and wind. Keep in mind that x_i is a decision variable in the intermediate problem. However, because the market operator has no control over it, we treat it as a parameter in the lower level problem. Restrictions (5d) and (5e) enforce the flow, f_{bt}, to be within the capacity limits of existing capacity, F_b^0, and expansions, y_b^{cap}, performed by the upper level problem. Dual variables are given in parentheses. Pay especially attention to the price p_{nt} given endogenously by the model through constraint (5b).

$$\min_{g_{it},s_{nt},f_{bt}} \quad \sum_{t\in T} A \cdot W_t \Bigg(\sum_{i\in G} (MC_i + CO2_i) g_{it} + \sum_{n\in N} VOLL \cdot s_{nt} \Bigg) \tag{5a}$$

subject to

$$D_{nt} - \sum_{i\in G_n} g_{it} - s_{nt} - \sum_{b\in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b\in B_n^{out}} f_{bt} = 0 \qquad (p_{nt}) \quad \forall n,t \in N,T \tag{5b}$$

$$g_{it} - \eta_{it}(P_i^0 + x_i) \leq 0 \qquad (\overline{\alpha}_{it}^{LL}) \quad \forall i,t \in G,T \tag{5c}$$

$$f_{bt} - (F_b^0 + y_b^{cap}) \leq 0 \qquad (\overline{\gamma}_{bt}^{LL}) \quad \forall b,t \in B,T \tag{5d}$$

$$-(F_b^0 + y_b^{cap}) - f_{bt} \leq 0 \qquad \left(\underline{\gamma}_{bt}^{LL}\right) \quad \forall b,t \in B,T \tag{5e}$$

$$g_{it} \geq 0 \qquad \forall i,t \in G,T \tag{5f}$$

$$s_{nt} \geq 0 \qquad \forall n,t \in N,T \tag{5g}$$

$$f_{bt} \in \mathbb{R} \qquad \forall b,t \in B,T \tag{5h}$$

The KKT conditions of (5) become (6). Because the lower level problem is linear, it fulfills the *linearity constraint qualification* (LCQ). Consequently, the KKT conditions are necessary and sufficient and (6) are valid optimality conditions of (5).

Stationary conditions of free variables:

$$0 = -p_{n(b^{in})t}(1 - F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} \quad , \quad f_{bt} \text{ (free)} \qquad \forall b,t \in B,T \tag{6a}$$

Stationary conditions of non-free variables:

$$0 \leq A \cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}_{it}^{LL} \quad \perp \quad g_{it} \geq 0 \qquad \forall i,t \in G,T \tag{6b}$$

$$0 \leq A \cdot W_t \cdot VOLL - p_{nt} \quad \perp \quad s_{nt} \geq 0 \qquad \forall n,t \in N,T \tag{6c}$$

Primal equality constraints:

$$0 = D_{nt} - \sum_{i\in G_n} g_{it} - s_{nt} - \sum_{b\in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b\in B_n^{out}} f_{bt} \quad , \quad p_{nt} \text{ (free)} \qquad \forall n,t \in N,T \tag{6d}$$

Complementarity conditions:

$$0 \leq -g_{it} + \eta_{it}(P_i^0 + x_i) \quad \perp \quad \overline{\alpha}_{it}^{LL} \geq 0 \qquad \forall i,t \in G,T \tag{6e}$$

$$0 \leq -f_{bt} + (F_b^0 + y_b^{cap}) \quad \perp \quad \overline{\gamma}_{bt}^{LL} \geq 0 \qquad \forall b,t \in B,T \tag{6f}$$

$$0 \leq (F_b^0 + y_b^{cap}) + f_{bt} \quad \perp \quad \underline{\gamma}_{bt}^{LL} \geq 0 \qquad \forall b,t \in B,T \tag{6g}$$

2.2.2. The intermediate level problem: Strategic countries

The intermediate level problem consist of strategic countries trying to maximize their own welfare by congestion rent, CR, producer surplus, PS, and consumer surplus, CS while minimizing investment costs. (7) provide a representation of the different welfare functions for a country. Both the producer surplus and the congestion rent have bilinear terms in their expression. If they are included in their current form in the objective function, the KKT conditions will become unnecessary and insufficient. We therefore only include the linear consumer surplus in the objective function. While this reduces realistic behaviour of the countries, especially with respect to strategic trade, it is outside the scope of this paper to perform more advanced linearization techniques[3]. The methodology of adapting the three-stage problem to a MILP by our methodology will be valid for all problems where KKT conditions are necessary and sufficient.

$$PS_c = \sum_{t \in T} \sum_{i \in G_c} A \cdot W_t \left(p_{n(i)t} - MC_i - CO2_i \right) g_{it} \tag{7a}$$

$$CS_c = \sum_{t \in T} \sum_{n \in N_c} A \cdot W_t \left(VOLL - p_{nt} \right) D_{nt} \tag{7b}$$

$$CR_c = \frac{1}{2} \sum_{t \in T} A \cdot W_t \Bigg(\sum_{b \in B_c^{in}} \left(p_{n^{from}(b)t} - p_{n^{to}(b)t} \right) f_{bt} + \sum_{b \in B_c^{out}} \left(p_{n^{to}(b)t} - p_{n^{from}(b)t} \right) f_{bt} \Bigg) \tag{7c}$$

Problem (8) presents the intermediate level problem with the optimality conditions of the lower level problem. The complementarity conditions in (6) are linearized into disjunctive constraints. Objective (8a) minimizes the negative consumer surplus and investment cost of new generation capacity. New investments are restricted by a maximum limit of $P_i^{max\ new}$ in (8b) and KKT conditions of the lower level problem from (8d) to (8o). All primal and dual variables of the lower level problem are now decision variables of the intermediate problem, in addition to new generation capacity in the country and binary variables z. KKT conditions of (8) are given by (A.1) in Appendix A.

$$\min_{x_{i \in G_c}, \text{all } z, g_{it}, s_{nt}, f_{bt}, p_{nt}, \overline{\alpha}_{it}^{LL}, \overline{\gamma}_{bt}^{LL}, \underline{\gamma}_{bt}^{LL}} \quad - \sum_{t \in T} \sum_{n \in N_c} A \cdot W_t \left(VOLL - p_{nt} \right) D_{nt} + \sum_{i \in G_c} CX_i x_i \tag{8a}$$

Subject to

$$x_i - P_i^{max\ new} \leq 0 \quad (\delta_i) \quad \forall i \in G_c \tag{8b}$$

$$x_i \geq 0 \quad \forall i \in G_c \tag{8c}$$

Non-complementarity KKT conditions of lower level problem

$$D_{nt} - \sum_{i \in G_n} g_{it} - s_{nt} - \sum_{b \in B_n^{in}} f_{bt}(1 - F_b^{loss}) + \sum_{b \in B_n^{out}} f_{bt} = 0 \quad (\epsilon_{ntc}) \quad \forall n, t \in N, T \tag{8d}$$

$$-p_{n(b^{in})t}(1 - F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} = 0 \quad (\zeta_{btc}) \quad \forall b, t \in B, T \tag{8e}$$

[3] We performed some experiments of linearization by using the lower level KKT conditions in (6). This would be valid if only one country is considered. However, for multiple countries, only nodes, branches and generators included in their country is considered. Hence, the KKT conditions in (6) which considers all nodes, branches and generators cannot be used.

Complementarity KKT conditions of lower level problem as disjunctive constraints

$$0 \leq A \cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}_{it}^{LL} \leq M_{it}^{g} z_{it}^{g} \qquad (\theta_{itc}) \quad \forall i,t \in G,T \tag{8f}$$

$$0 \leq g_{it} \leq M_{it}^{g}(1 - z_{it}^{g}) \qquad (\kappa_{itc}) \quad \forall i,t \in G,T \tag{8g}$$

$$0 \leq A \cdot W_t \cdot VOLL - p_{nt} \leq M_{nt}^{s} z_{nt}^{s} \qquad (\lambda_{ntc}) \quad \forall n,t \in N,T \tag{8h}$$

$$0 \leq s_{nt} \leq M_{nt}^{s}(1 - z_{nt}^{s}) \qquad (\mu_{ntc}) \quad \forall n,t \in N,T \tag{8i}$$

$$0 \leq -g_{it} + \eta_{it}(P_i^0 + x_i) \leq M_{it}^{\overline{\alpha}^{LL}} z_{it}^{\overline{\alpha}^{LL}} \qquad (\nu_{itc}) \quad \forall i,t \in G,T \tag{8j}$$

$$0 \leq \overline{\alpha}_{it}^{LL} \leq M_{it}^{\overline{\alpha}^{LL}}(1 - z_{it}^{\overline{\alpha}^{LL}}) \qquad (\xi_{itc}) \quad \forall i,t \in G,T \tag{8k}$$

$$0 \leq -f_{bt} + (F_b^0 + y_b^{cap}) \leq M_{bt}^{\overline{\gamma}^{LL}} z_{bt}^{\overline{\gamma}^{LL}} \qquad (\phi_{btc}) \quad \forall b,t \in B,T \tag{8l}$$

$$0 \leq \overline{\gamma}_{bt}^{LL} \leq M_{bt}^{\overline{\gamma}^{LL}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) \qquad (\chi_{btc}) \quad \forall b,t \in B,T \tag{8m}$$

$$0 \leq (F_b^0 + y_b^{cap}) + f_{bt} \leq M_{bt}^{\underline{\gamma}^{LL}} z_{bt}^{\underline{\gamma}^{LL}} \qquad (\psi_{btc}) \quad \forall b,t \in B,T \tag{8n}$$

$$0 \leq \underline{\gamma}_{bt}^{LL} \leq M_{bt}^{\underline{\gamma}^{LL}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) \qquad (\omega_{btc}) \quad \forall b,t \in B,T \tag{8o}$$

2.2.3. The upper level problem: System optimal transmission expansion

A benevolent system planner performs transmission expansion in the upper level problem (9) and (10). The objective is to reduce cost of investments, as shown in (9a). Expenses are dependent both upon the number of new lines, y_b^{num}, and capacity, y_b^{cap}. Costs are divided into a branch mobilization cost, B, a fixed cost per unit length, B^d and B^{dp}, in addition to the cost of switch-gear for moving from onshore to offshore branches, CS_b and CS_b^p. New branch capacity is dependent upon the number of new lines, where each has a maximum capacity of $F_b^{max\ line}$. Moreover, the total capacity of a branch cannot exceed the total maximum limit of F_b^{max}, as enforced by (9b).

Optimality conditions of the intermediate level problem are the KKT conditions in (A.1). For the disjunctive constraints in (8) from the lower level problem, we utilize the approach of exploiting the relationship between the binary and dual variables from section 2.1, as shown in (10). The intermediate problem is linear, except for binary variables z. However, the z variables are considered as parameters when developing the KKT conditions by our approach, and do not become decision variables until they reach the upper level problem. The KKT conditions are consequently necessary and sufficient. This makes the solution of upper level problem (9) and (10) a global optimum.

$$\min_{y_b^{num}, y_b^{cap}, \text{all } z, \text{primal and dual variables of (8)}} \sum_{b \in B} \Big((B + B^d L_b^{km} + 2CS_b) y_b^{num} + (B^{dp} L_b^{km} + 2CS_b^p) y_b^{cap} \Big) \tag{9a}$$

Subject to

$$y_b^{cap} \leq F_b^{max\ line} y_b^{num} \leq F_b^{max} \qquad \forall b \in B \tag{9b}$$

$$y_b^{cap} \geq 0 \qquad \forall b \in B \tag{9c}$$

$$y_b^{num} \in \mathbb{Z}_{\geq 0} \qquad \forall b \in B \tag{9d}$$

Equality KKT conditions of intermediate problem:

$$-(1 - F_b^{loss}) \epsilon_{n(b^{in})tc} + \epsilon_{n(b^{out})tc} + \underline{\phi}_{btc} - \overline{\phi}_{btc} - \underline{\psi}_{btc} + \overline{\psi}_{btc} = 0 \qquad \forall b, t, c \in B, T, C \tag{9e}$$

$$\begin{aligned} A \cdot W_t \cdot D_{nt} - \sum_{b \in B_n^{in}} (1 - F_b^{loss}) \zeta_{btc} + \sum_{b \in B_n^{out}} \zeta_{btc} \\ + \sum_{i \in G_n} \underline{\theta}_{itc} - \sum_{i \in G_n} \overline{\theta}_{itc} + \underline{\lambda}_{ntc} - \overline{\lambda}_{ntc} = 0 \qquad \forall n, t, c \in N, T, C \end{aligned} \tag{9f}$$

$$D_{nt} - \sum_{i \in G_n} g_{it} - s_{nt} - \sum_{b \in B_n^{in}} f_{bt} (1 - F_b^{loss}) + \sum_{b \in B_n^{out}} f_{bt} = 0 \qquad \forall n, t, c \in N, T, C \tag{9g}$$

$$-p_{n(b^{in})t} (1 - F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} = 0 \qquad \forall b, t, c \in B, T, C \tag{9h}$$

KKT conditions (A.1c) to (A.1h) and (A.1k) as disjunctive constraints:

$$0 \leq CX_i + \delta_i - \sum_{t \in T} \eta_{it} \underline{\nu}_{itc(i)} + \sum_{t \in T} \eta_{it} \overline{\nu}_{itc(i)} \leq M_i^x z_i^x \qquad \forall i \in G \tag{9i}$$

$$0 \leq x_i \leq M_i^x (1 - z_i^x) \qquad \forall i \in G \tag{9j}$$

$$0 \leq -\epsilon_{n(i)tc} + \kappa_{itc} + \underline{\nu}_{itc} - \overline{\nu}_{itc} \leq M_{itc}^{g^{IL}} z_{itc}^{g^{IL}} \qquad \forall i, t, c \in G, T, C \tag{9k}$$

$$0 \leq g_{it} \leq M_{itc}^{g^{IL}} (1 - z_{itc}^{g^{IL}}) \qquad \forall i, t \in G, T \tag{9l}$$

$$0 \leq -\epsilon_{ntc} + \mu_{ntc} \leq M_{ntc}^{s^{IL}} z_{ntc}^{s^{IL}} \qquad \forall n, t, c \in N, T, C \tag{9m}$$

$$0 \leq s_{nt} \leq M_{ntc}^{s^{IL}} (1 - z_{ntc}^{s^{IL}}) \qquad \forall n, t, c \in N, T, C \tag{9n}$$

$$0 \leq -\underline{\theta}_{itc} + \overline{\theta}_{itc} + \xi_{itc} \leq M_{itc}^{\overline{\alpha}^{IL}} z_{itc}^{\overline{\alpha}^{IL}} \qquad \forall i, t, c \in G, T, C \tag{9o}$$

$$0 \leq \overline{\alpha}_{it}^{LL} \leq M_{itc}^{\overline{\alpha}^{IL}} (1 - z_{itc}^{\overline{\alpha}^{IL}}) \qquad \forall i, t, c \in G, T, C \tag{9p}$$

$$0 \leq \zeta_{btc} + \chi_{btc} \leq M_{btc}^{\overline{\gamma}^{IL}} z_{btc}^{\overline{\gamma}^{IL}} \qquad \forall b, t, c \in B, T, C \tag{9q}$$

$$0 \leq \overline{\gamma}_{bt}^{LL} \leq M_{btc}^{\overline{\gamma}^{IL}} (1 - z_{btc}^{\overline{\gamma}^{IL}}) \qquad \forall b, t, c \in B, T, C \tag{9r}$$

$$0 \leq -\zeta_{btc} + \omega_{btc} \leq M_{btc}^{\underline{\gamma}^{IL}} z_{btc}^{\underline{\gamma}^{IL}} \qquad \forall b, t, c \in B, T, C \tag{9s}$$

$$0 \leq \underline{\gamma}_{bt}^{LL} \leq M_{btc}^{\underline{\gamma}^{IL}} (1 - z_{btc}^{\underline{\gamma}^{IL}}) \qquad \forall b, t, c \in B, T, C \tag{9t}$$

$$0 \leq -x_i + P_i^{max\ new} \leq M_i^{\delta} z_i^{\delta} \qquad \forall i \in G \tag{9u}$$

$$0 \leq \delta_i \leq M_i^{\delta} (1 - z_i^{\delta}) \qquad \forall i \in G \tag{9v}$$

KKT conditions (A.1l) to (A.1z) where binary and dual variables are exploited:

$$0 \leq A \cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}^{LL}_{it} \quad , \quad 0 \leq \underline{\theta}_{itc} \leq M^{\underline{\theta}}_{it}(1 - z^g_{it}) \quad \forall i, t, c \in G, T, C \tag{10a}$$

$$0 \leq M^g_{it} z^g_{it} - A \cdot W_t(MC_i + CO2_i) + p_{n(i)t} - \overline{\alpha}^{LL}_{it} \quad , \quad 0 \leq \overline{\theta}_{itc} \leq M^{\overline{\theta}}_{it}(1 - z^g_{it}) \quad \forall i, t, c \in G, T, C \tag{10b}$$

$$0 \leq M^g_{it}(1 - z^g_{it}) - g_{it} \quad , \quad 0 \leq \kappa_{itc} \leq M^{\kappa}_{it} z^g_{it} \quad \forall i, t, c \in G, T, C \tag{10c}$$

$$0 \leq A \cdot W_t \cdot VOLL - p_{nt} \quad , \quad 0 \leq \underline{\lambda}_{ntc} \leq M^{\underline{\lambda}}_{nt}(1 - z^s_{nt}) \quad \forall n, t, c \in N, T, C \tag{10d}$$

$$0 \leq M^s_{nt} z^s_{nt} - A \cdot W_t \cdot VOLL + p_{nt} \quad , \quad 0 \leq \overline{\lambda}_{ntc} \leq M^{\overline{\lambda}}_{nt}(1 - z^s_{nt}) \quad \forall n, t, c \in N, T, C \tag{10e}$$

$$0 \leq M^s_{nt}(1 - z^s_{nt}) - s_{nt} \quad , \quad 0 \leq \mu_{ntc} \leq M^{\mu}_{nt} z^s_{nt} \quad \forall n, t, c \in N, T, C \tag{10f}$$

$$0 \leq -g_{it} + \eta_{it}(P^0_i + x_i) \quad , \quad 0 \leq \underline{\nu}_{itc} \leq M^{\underline{\nu}}_{it}(1 - z^{\overline{\alpha}^{LL}}_{it}) \quad \forall i, t, c \in G, T, C \tag{10g}$$

$$0 \leq M^{\overline{\alpha}^{LL}}_{it} z^{\overline{\alpha}^{LL}}_{it} + g_{it} - \eta_{it}(P^0_i + x_i) \quad , \quad 0 \leq \overline{\nu}_{itc} \leq M^{\overline{\nu}}_{it}(1 - z^{\overline{\alpha}^{LL}}_{it}) \quad \forall i, t, c \in G, T, C \tag{10h}$$

$$0 \leq M^{\overline{\alpha}^{LL}}_{it}(1 - z^{\overline{\alpha}^{LL}}_{it}) - \overline{\alpha}^{LL}_{it} \quad , \quad 0 \leq \xi_{itc} \leq M^{\xi}_{it} z^{\overline{\alpha}^{LL}}_{it} \quad \forall i, t, c \in G, T, C \tag{10i}$$

$$0 \leq -f_{bt} + (F^0_b + y^{cap}_b) \quad , \quad 0 \leq \underline{\phi}_{btc} \leq M^{\underline{\phi}}_{bt}(1 - z^{\overline{\gamma}^{LL}}_{bt}) \quad \forall b, t, c \in B, T, C \tag{10j}$$

$$0 \leq M^{\overline{\gamma}^{LL}}_{bt} z^{\overline{\gamma}^{LL}}_{bt} + f_{bt} - (F^0_b + y^{cap}_b) \quad , \quad 0 \leq \overline{\phi}_{btc} \leq M^{\overline{\phi}}_{bt}(1 - z^{\overline{\gamma}^{LL}}_{bt}) \quad \forall b, t, c \in B, T, C \tag{10k}$$

$$0 \leq M^{\overline{\gamma}^{LL}}_{bt}(1 - z^{\overline{\gamma}^{LL}}_{bt}) - \overline{\gamma}^{LL}_{bt} \quad , \quad 0 \leq \chi_{btc} \leq M^{\chi}_{bt} z^{\overline{\gamma}^{LL}}_{bt} \quad \forall b, t, c \in B, T, C \tag{10l}$$

$$0 \leq (F^0_b + y^{cap}_b) + f_{bt} \quad , \quad 0 \leq \underline{\psi}_{btc} \leq M^{\underline{\psi}}_{bt}(1 - z^{\underline{\gamma}^{LL}}_{bt}) \quad \forall b, t, c \in B, T, C \tag{10m}$$

$$0 \leq M^{\underline{\gamma}^{LL}}_{bt} z^{\underline{\gamma}^{LL}}_{bt} - (F^0_b + y^{cap}_b) - f_{bt} \quad , \quad 0 \leq \overline{\psi}_{btc} \leq M^{\overline{\psi}}_{bt}(1 - z^{\underline{\gamma}^{LL}}_{bt}) \quad \forall b, t, c \in B, T, C \tag{10n}$$

$$0 \leq M^{\underline{\gamma}^{LL}}_{bt}(1 - z^{\underline{\gamma}^{LL}}_{bt}) - \underline{\gamma}^{LL}_{bt} \quad , \quad 0 \leq \omega_{btc} \leq M^{\omega}_{bt} z^{\underline{\gamma}^{LL}}_{bt} \quad \forall b, t, c \in B, T, C \tag{10o}$$

2.3. Cooperative TEP model

We want to compare our strategic model against a framework where all countries cooperate to achieve system optimal results. A benevolent system planer are expected to perform investments in both transmission and generation on behalf of the countries. The problem is presented in (11). It contains all the objectives and restrictions of the three-stage problem, but all decisions are taken by a system authority to achieve system optimal results.

The objective is to minimize both investment and operational costs, as shown in (11a). Investment cost in (11b) consist of transmission and generation investment costs. Operating costs in (11c) are equivalent to the short-term market clearing of the lower level problem. Restrictions (11f) to (11j) are the same as those enforced at the different levels of the three-stage problem.

$$\min_{x_i, y_b^{num}, y_b^{cap}, g_{it}, f_{bt}, s_{nt}} \quad IC + A \cdot OC \tag{11a}$$

where

$$IC = \sum_{b \in B} (C_b^{fix} y_b^{num} + C_b^{var} y_b^{cap}) + \sum_{i \in G} CX_i x_i \tag{11b}$$

$$OC = \sum_{t \in T} W_t (\sum_{i \in G} (MC_i + CO2_i) g_{it} + \sum_{n \in N} VOLL s_{nt}) \tag{11c}$$

$$C_b^{fix} = B + B^d L_b^{km} + 2CS_b \qquad \forall b \in B \tag{11d}$$

$$C_b^{var} = B^{dp} L_b^{km} + 2CS_b^p \qquad \forall b \in B \tag{11e}$$

subject to

$$\sum_{l \in L_n} D_{lt} = \sum_{i \in G_n} g_{it} + \sum_{b \in B_n^{in}} f_{bt}(1 - F_b^{loss}) - \sum_{b \in B_n^{out}} f_{bt} + s_{nt} \qquad \forall n, t \in N, T \tag{11f}$$

$$g_{it} \leq \eta_{it}(P_i^0 + x_i) \qquad \forall i, t \in G, T \tag{11g}$$

$$x_i \leq P_i^{max\ new} \qquad \forall i \in G \tag{11h}$$

$$-(F_b^0 + y_b^{cap}) \leq f_{bt} \leq (F_b^0 + y_b^{cap}) \qquad \forall b, t \in B, T \tag{11i}$$

$$y_b^{cap} \leq F_b^{max\ line} y_b^{num} \leq F_b^{max} \qquad \forall b \in B \tag{11j}$$

$$x_i, y_b^{cap}, g_{it}, s_{nt} \geq 0, \quad f_{bt} \in \mathbb{R}, \quad y_b^{num} \in \mathbb{Z}^+$$

2.4. Data input

We perform a case study of Germany, Great Britain and Norway because they represent the largest players in the NSOG. An aggregated representation of the countries is used to attain a computationally tractable TEP model and for being able to use open source national values. Each country is represented by an aggregated node of total demand and onshore generation. The other nodes function as hub stations between nodes of offshore wind farms or interconnectors, as shown in Figure 3.

Vision 4 from ENTSO-E (2015) is primarily used as data source, with the exception of offshore wind production obtained from WindEurope (2017). The roadmap 2050 of European Climate Foundation (2010) provides investment costs for new generation capacity. Wind and solar profiles are obtained from the *renewable.ninja* project (Pfenninger and Staffell 2016a; Pfenninger and Staffell 2016b). Due to the seasonal characteristics and dominant position of hydro power in Norway (IEA 2017), hourly prices from 2015 (Nord Pool AS 2017) are used as a water value approximation under the assumption of marginal cost pricing[4]. To maintain an acceptable computational time, a random sample of 50 hours is used to represent a full operational year. Moreover, we assume a financial lifetime of 30 years with a discount rate of 5%. No line losses are included, and a max

[4] A water value can be interpreted as a marginal opportunity cost. That is, the value is determined based on expectations about future electricity prices, demand, and water inflow.

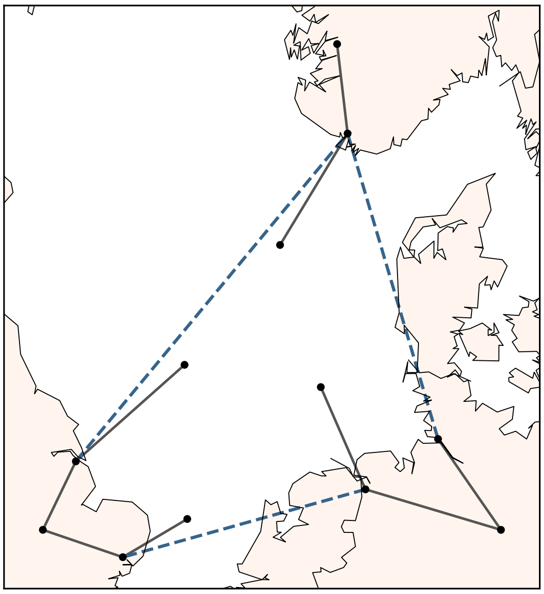


Figure 3: Representation of the NSOG case study of Germany, Great Britain and Norway. Dashed lines are candidate expansion projects determined endogenously.

limit of 5000MW new capacity is chosen. We also assume that there are no more hydro power investment opportunities and that nuclear power investments are being phased out. The value of lost load is set to 1000EUR and the CO_2 price is 76EUR/tonCO_2 (International Energy Agency 2016). The most important input data is summarized in Table 2.

Table 2: Supply, demand and fuel price data from ENTSO-E Vision 4 (ENTSO-E 2015). Onshore and offshore wind capacities are divided according to data from WindEurope (2017). CO_2 price is 76EUR/tonCO_2 and VOLL 1000EUR/MWh. Capital expenditure (CAPEX) given by ECF Roadmap 2050 (European Climate Foundation 2010)

Supply/ Demand	Fuel price $[EUR/MWh_e]$	Capacity $[MW]$ DE	GB	NO	Max new cap $[MW]$	CAPEX $[EUR/(MWh\ yr)]$
Bio	50	9340	8420	0	5000	113840
Gas	65	45059	40726	855	5000	48789
Hard coal	21	14940	0	0	5000	97577
Hydro	10	14505	5470	48700	0	121971
Lignite	10	9026	0	0	5000	97577
Nuclear	5	0	9022	0	0	195154
Oil	140	871	75	0	5000	48789
Solar PV	0	58990	11915	0	5000	78062
Onshore wind	0	76967	27901	1771	5000	68204
Offshore wind	0	20000	30000	724	5000	143113
Total supply	-	249698	133529	52050	-	-
Peak demand	-	81369	59578	24468	-	-

3. Results and discussion

Both the three-stage model as a MILP problem and the cooperative model is implemented in Pyomo (Hart, Watson, and Woodruff 2011; Hart, Laird, et al. 2017) and solved by the Gurobi solver.

3.1. Case study of Germany, Great Britain and Norway

New generation capacity for both strategic and cooperative TEP are shown in Table 3, while new transmission capacities are presented in Table 4. We observe two quite contrasting scenarios. The strategic countries invest in much more generation capacity than the cooperative countries. As a result, all countries become self-sufficient, and it is not necessary for the expansion planner to invest. Cooperation presents a completely contrasting case, where the transmission expansion planer expands all lines significantly and generation investments are sparse.

Table 3: Generation investments from strategic and cooperative model.

	Strategic new capacity $[MW]$			Cooperative new capacity $[MW]$		
	DE	GB	NO	DE	GB	NO
Bio	5000	1277	0	0	0	0
Gas	0	0	0	0	0	0
Hard coal	2038	1662	0	0	0	0
Hydro	0	0	0	0	0	0
Lignite	965	1253	0	0	0	0
Nuclear	0	0	0	0	0	0
Oil	0	0	0	0	0	0
Solar PV	0	1078	0	0	0	0
Onshore wind	3141	3140	0	0	5000	0
Offshore wind	4456	1561	0	0	0	0
Average price $[EUR]$	72.8	57.8	19.1	71.3	55.2	19.2

Table 4: Generation investments from strategic and cooperative model.

Corridor	Strategic new capacity $[MW]$	Cooperative new capacity $[MW]$
DE - GB	0	5000
DE - NO	0	5248
GB - NO	0	4993

Cooperation enables the countries to deploy the generation assets in the system more efficiently. The variable nature of renewable production is an example of this. To be only dependent upon one large source of intermittent renewable production is risky for a single country. However, in the cooperative case the risk is diversified through several generation units and locations. The efficient use of network expansions makes more generation investments redundant.

Strategic countries do only consider maximizing consumer surplus while minimizing generation investments in our model. They only consider their own prices and not the system. The large generation investments leads to self-sufficiency and hence the expansion planner does not invest in any expansion to save the expenses. However, as seen in Table 3, the prices do in fact become slightly lower if the countries would cooperate. This is due to a larger exploitation of renewable resources with low marginal costs. Norway is mainly unaffected because their large hydro power capacity. Although countries invest in renewable production, they also have to protect themselves of the intermittent production by investing in fossil fuels, such as hard coal and lignite. Not only is this more expensive for the countries, but is also has negative consequences for the environment.

Table 5 shows the different expenses in the two models. Because cooperation assumes system optimal behaviour it can be considered a benchmark of perfectly efficient transmission and generation expansion. We see higher investment and operational cost for the strategic case. They are not able to utilize their generation asset as efficiently as the cooperation case. This will result in over-investments, and the use of more costly fossil fuels instead of low cost intermittent renewable production. The difference in total costs of $48113.2mEUR$ can be regarded as the cost of anarchy. Hence, the system has a potential of reducing costs by 11.62% by moving towards a cooperative scheme.

Table 5: Comparison of expenses in the models.

Model	Investment costs $[mEUR]$	Operational costs $[mEUR]$	Total costs $[mEUR]$
Strategic	40783.5	373399.8	414183.2
Cooperation	33232.0	332838.0	366070.0
Difference	7551.5	40561.8	48113.2

3.2. The approach and its limitations

Although the results from the NSOG case study is not fully realistic, our approach of solving three-stage problems to a global optimum show potential. The solver finds the global optimum solution, and we are not dependent upon further algorithmic scanning approaches or being concerned about other optimal solutions. The results are as expected from strategic actors who are only concerned by decreasing their own price. A more correct representation would of course be to include producer surplus as profit and congestion rent from trade activities. To achieve more realistic results from the TEP model, it is definitely worth considering how to alternatively express producer surplus and congestion rent in a manner where the KKT conditions are necessary and sufficient.

For our current case study of eleven nodes, twelve branches, 26 generation units and 50 time periods produce 48865 continuous 17652 integer variables. They are reduced to 14656 continuous and 3550 integer variables by the presolver. Gurobi solves the case study in approximately 200 seconds on a 2.2GHz quad-core Intel i7 processor and 16GB memory computer.

3.2.1. Computational difficulties

The MILP problem formulation in (9) and (10) has the advantage of being able to utilize commercial solvers. However, it still contains some computational difficulties. Using disjunctive constraints, and especially over two stages, produces lots of M parameters. Too large M can result in numerical errors, while too low can restrict the problem (Gabriel and Leuthold 2010). For primal variables it is often easy to estimate M because they have natural bounds. This is not the case for dual variables, which our model accumulate when moving up the stages. Moreover, investment cost and aggregated countries provide large input data, where the M parameters has to be even higher than.

While commercial solvers have powerful techniques of solving MILP problems, it is still a computationally hard class of problems. Our approach introduces a lot of binary variables, especially for larger case studies. The current 50 time periods of random samples are in our opinion too few and provide some deviation among different time steps. Although the majority of solved 50 random sample cases show no transmission expansions, a few did in fact contain small branch investments. More time periods are favourable, but the problem yield long computational time because of the increase in binary variables.

The final problem has the objective of minimizing transmission investments. However, start-up investments for a new line is high. Consequently, the relaxed problem at branch-and-bound nodes jumps from the no investment option of zero cost, and the large start-up cost. It is therefore challenging for the solver to find good bounds, and the algorithm has to enumerate through a lot of nodes, which is a time-consuming process. Running a full NSOG case study of six countries are too computationally time consuming for acceptable time periods at the present problem formulation.

3.2.2. Unrealistic strategic behavior

The strategic countries are in the current model not acting fully strategic, as discussed in section 2.2.2. When only consumer surplus is considered, they try to minimize their country price and not participate in strategic trade. As a result, we do not achieve the same amount of competitiveness expected in such a scenario. In fact, the current formulation give no incentives for countries to perform trade. Transmission expansions are likely to occur if trade is possible because countries can use it as a means of obtaining additional welfare. Another important consideration is producer surplus which concern itself with profits. Hence, they do not want to minimize price, but to maximize the difference between their marginal cost and the price. Countries would likely act differently if this behavior was included as well.

4. Conclusion

Proper transmission expansion planning (TEP) is important to create an efficient electricity market. However, if the expansion planner do not consider how the market agents act, situations may arise where market power can be exploited. To prevent this outcome, we propose a three-stage TEP problem where a market operator is in the lower level, multiple strategic countries trying to maximize their own welfare are in the intermediate and a benevolent system planner is in the upper level. Their actions will anticipate the behavior of the other market participants.

When transforming the three-stage problem to a mixed-integer liner program (MILP), we use Karush–Kuhn–Tucker (KKT) conditions as optimality conditions for the lower level problem. The complementarity conditions are linearized into disjunctive constraints. To move the intermediate problem optimality conditions, we again use KKT conditions, but exploit the relationship between the binary variables of the disjunctive constraints and the dual variables. We extend on current methodology by providing a method of solving the MILP problem directly to a global optimum.

The method is demonstrated on a case study consisting of Germany, Great Britain and Norway. Strategic countries are only trying to maximize their consumer surplus, because the bilinear expressions of producer surplus and congestion rents prevents necessity and sufficiency of KKT conditions. Compared to a perfect cooperative case, the strategic framework deploy their generation assets less efficiently. The countries are focused on their individual goals and over-invest in domestic production. Consequently, there is less need for transmission expansion because the countries become more self-sufficient. As a result, the countries cannot diversify the risk of intermittent renewable production among each other, and are still dependent on more expansive fossil fuel generation. The cooperative framework, on the other hand, invests in a lot of transmission capacity and little generation. They are able to use the system assets more efficiently and make a larger transition into renewable generation. Our case study show potential of decreasing expenses if a system moves from a strategic framework towards a cooperative one.

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Appendix A. KKT conditions of intermediate problem

The KKT conditions of the intermediate problem (8) are given in (A.1).

Stationary conditions of free variables:

$$0 = -(1-F_b^{loss})\epsilon_{n(b^{in})tc} + \epsilon_{n(b^{out})tc} + \underline{\phi}_{btc} - \overline{\phi}_{btc} - \underline{\psi}_{btc} + \overline{\psi}_{btc} \quad , \quad f_{bt} \text{ (free)} \quad \forall b,t \in B,T \tag{A.1a}$$

$$\begin{aligned} 0 = A \cdot W_t \cdot D_{nt} - \sum_{b\in B_n^{in}} (1-F_b^{loss})\zeta_{btc} + \sum_{b\in B_n^{out}} \zeta_{btc} \\ + \sum_{i\in G_n} \underline{\theta}_{itc} - \sum_{i\in G_n} \overline{\theta}_{itc} + \underline{\lambda}_{ntc} - \overline{\lambda}_{ntc} \quad , \quad p_{nt} \text{ (free)} \quad \forall n,t \in N,T \end{aligned} \tag{A.1b}$$

Stationary conditions of non-free variables:

$$0 \le CX_i + \delta_i - \sum_{t\in T} \eta_{it}\underline{\nu}_{itc} + \sum_{t\in T} \eta_{it}\overline{\nu}_{itc} \quad \perp \quad x_i \ge 0 \quad \forall i \in G_c \tag{A.1c}$$

$$0 \le -\epsilon_{n(i)tc} + \kappa_{itc} + \underline{\nu}_{itc} - \overline{\nu}_{itc} \quad \perp \quad g_{it} \ge 0 \quad \forall i,t \in G,T \tag{A.1d}$$

$$0 \le -\epsilon_{ntc} + \mu_{ntc} \quad \perp \quad s_{nt} \ge 0 \quad \forall n,t \in N,T \tag{A.1e}$$

$$0 \le -\underline{\theta}_{itc} + \overline{\theta}_{itc} + \xi_{itc} \quad \perp \quad \overline{\alpha}_{it}^{LL} \ge 0 \quad \forall i,t \in G,T \tag{A.1f}$$

$$0 \le \zeta_{btc} + \chi_{btc} \quad \perp \quad \overline{\gamma}_{bt}^{LL} \ge 0 \quad \forall b,t \in B,T \tag{A.1g}$$

$$0 \le -\zeta_{btc} + \omega_{btc} \quad \perp \quad \underline{\gamma}_{bt}^{LL} \ge 0 \quad \forall b,t \in B,T \tag{A.1h}$$

Equality constraints:

$$0 = D_{nt} - \sum_{i\in G_n} g_{it} - s_{nt} - \sum_{b\in B_n^{in}} f_{bt}(1-F_b^{loss}) + \sum_{b\in B_n^{out}} f_{bt} \quad , \quad \epsilon_{ntc} \text{ (free)} \quad \forall n,t \in N,T \tag{A.1i}$$

$$0 = -p_{n(b^{in})t}(1-F_b^{loss}) + p_{n(b^{out})t} + \overline{\gamma}_{bt}^{LL} - \underline{\gamma}_{bt}^{LL} \quad , \quad \zeta_{btc} \text{ (free)} \quad \forall b,t \in B,T \tag{A.1j}$$

Complementarity conditions from inequality constraints:

$$
\begin{aligned}
0 \leq -x_i + P_i^{max\ new} \quad &\perp \quad \delta_i \geq 0 \quad \forall i \in G_c && \text{(A.1k)}\\
0 \leq A \cdot W_t(MC_i + CO2_i) - p_{n(i)t} + \overline{\alpha}_{it}^{LL} \quad &\perp \quad \underline{\theta}_{itc} \geq 0 \quad \forall i, t \in G, T && \text{(A.1l)}\\
0 \leq M_{it}^{g} z_{it}^{g} - A \cdot W_t(MC_i + CO2_i) + p_{n(i)t} - \overline{\alpha}_{it}^{LL} \quad &\perp \quad \overline{\theta}_{itc} \geq 0 \quad \forall i, t \in G, T && \text{(A.1m)}\\
0 \leq M_{it}^{g}(1 - z_{it}^{g}) - g_{it} \quad &\perp \quad \kappa_{itc} \geq 0 \quad \forall i, t \in G, T && \text{(A.1n)}\\
0 \leq A \cdot W_t \cdot VOLL - p_{nt} \quad &\perp \quad \underline{\lambda}_{ntc} \geq 0 \quad \forall n, t \in N, T && \text{(A.1o)}\\
0 \leq M_{nt}^{s} z_{nt}^{s} - A \cdot W_t \cdot VOLL + p_{nt} \quad &\perp \quad \overline{\lambda}_{ntc} \geq 0 \quad \forall n, t \in N, T && \text{(A.1p)}\\
0 \leq M_{nt}^{s}(1 - z_{nt}^{s}) - s_{nt} \quad &\perp \quad \mu_{ntc} \geq 0 \quad \forall n, t \in N, T && \text{(A.1q)}\\
0 \leq -g_{it} + \eta_{it}(P_i^0 + x_i) \quad &\perp \quad \underline{\nu}_{itc} \geq 0 \quad \forall i, t \in G, T && \text{(A.1r)}\\
0 \leq M_{it}^{\overline{\alpha}^{LL}} z_{it}^{\overline{\alpha}^{LL}} + g_{it} - \eta_{it}(P_i^0 + x_i) \quad &\perp \quad \overline{\nu}_{itc} \geq 0 \quad \forall i, t \in G, T && \text{(A.1s)}\\
0 \leq M_{it}^{\overline{\alpha}^{LL}}(1 - z_{it}^{\overline{\alpha}^{LL}}) - \overline{\alpha}_{it}^{LL} \quad &\perp \quad \xi_{itc} \geq 0 \quad \forall i, t \in G, T && \text{(A.1t)}\\
0 \leq -f_{bt} + (F_b^0 + y_b^{cap}) \quad &\perp \quad \underline{\phi}_{btc} \geq 0 \quad \forall b, t \in B, T && \text{(A.1u)}\\
0 \leq M_{bt}^{\overline{\gamma}^{LL}} z_{bt}^{\overline{\gamma}^{LL}} + f_{bt} - (F_b^0 + y_b^{cap}) \quad &\perp \quad \overline{\phi}_{btc} \geq 0 \quad \forall b, t \in B, T && \text{(A.1v)}\\
0 \leq M_{bt}^{\overline{\gamma}^{LL}}(1 - z_{bt}^{\overline{\gamma}^{LL}}) - \overline{\gamma}_{bt}^{LL} \quad &\perp \quad \chi_{btc} \geq 0 \quad \forall b, t \in B, T && \text{(A.1w)}\\
0 \leq (F_b^0 + y_b^{cap}) + f_{bt} \quad &\perp \quad \underline{\psi}_{btc} \geq 0 \quad \forall b, t \in B, T && \text{(A.1x)}\\
0 \leq M_{bt}^{\underline{\gamma}^{LL}} z_{bt}^{\underline{\gamma}^{LL}} - (F_b^0 + y_b^{cap}) - f_{bt} \quad &\perp \quad \overline{\psi}_{btc} \geq 0 \quad \forall b, t \in B, T && \text{(A.1y)}\\
0 \leq M_{bt}^{\underline{\gamma}^{LL}}(1 - z_{bt}^{\underline{\gamma}^{LL}}) - \underline{\gamma}_{bt}^{LL} \quad &\perp \quad \omega_{btc} \geq 0 \quad \forall b, t \in B, T && \text{(A.1z)}
\end{aligned}
$$

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