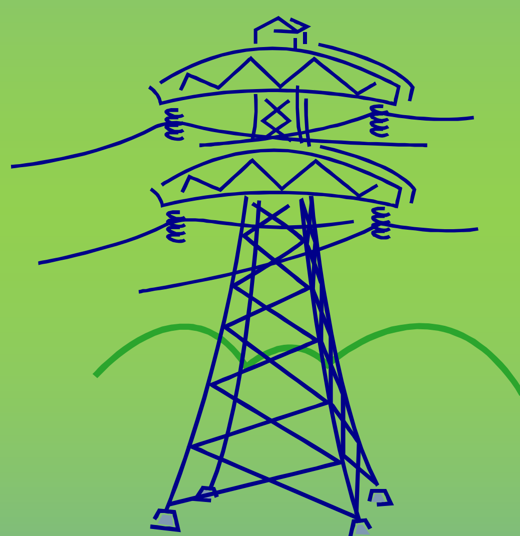
TRANSMISSION EXPANSION PLANNING UNDER INCREASED UNCERTAINTIES

TOWARDS EFFICIENT AND SUSTAINABLE POWER SYSTEMS



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Transmission expansion planning under increased uncertainties

towards efficient and sustainable power systems

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Proefschrift

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Summary

The ongoing liberalization process around the world has led to the emergence of energy markets, facilitating more international trade between countries making the best use of energy resources and optimizing overall power systems. Consequently, inter-area power exchanges have significantly increased and further growth can be foreseen. In Europe, the planning of large energy infrastructures has entered a new dimension, namely the trans-European one. The way of thinking is gradually switching from national to regional (European) interests, as this is the most efficient way to attain a sustainable energy future. This brings many new challenges. Europe finds itself at the beginning of a transition towards a low carbon and sustainable electricity supply system, which is guided by the European Union (EU) Energy Policy core objectives: competitiveness, reliability and sustainability.

This thesis looks at transmission expansion planning approaches under increased uncertainties. The liberalization of the electricity sector, the emergence of international electricity markets and increased penetration of renewable energy sources introduce many new challenges to transmission system operators. This is mainly because the complexity and related uncertainties in the power system have very much increased. These uncertainties are around the transmission scheduling and operation, and are especially related to the future needs for transmission capacity. Consequently, more advanced and robust methods for planning the transmission grid are needed. In addition, the building of new transmission lines is usually a lengthy process because of the authorization process duration. This process needs to become shorter in order to match the fast pace of changes in generation capacity and location.

The main contributions of this thesis are as follows:

New method and new criteria for assessing the bottlenecks in the grid. As novelty, this thesis proposed to use a round-the-year approach for assessing the security of the transmission grid, that is adequate for (multi-area) power systems with high RES penetration. Market simulations are combined with detailed load flow calculations for getting a complete picture of the congestions in the transmission grid. The consideration of the chronological aspect and the correlation of load and wind speed and solar radiation time series are enabled by the use of the market simulations. In addition, new criteria for prioritizing bottlenecks are developed in this thesis together with a method for ranking them according to a risk-based severity index. The new method allows detailed and insightful results, can be used on a real size grid, and can also be applied for analyzing both HVAC and HVDC grids.

Security-based iterative method for proposing network reinforcements. For finding the right (i.e. most effective) grid reinforcements, a round-the-year reinforcement solution generator was developed in this thesis which follows the reduction of grid congestion. As novelty, the solution generator makes use of the proposed round-the-year bottleneck assessment method. This allows a robust evaluation of the overloads in the grid for different reinforcement candidates as all the hours of the year are considered. New criteria for assessing the grid congestion level are defined and used in the assessment of candidates. The decrease of the grid severity index is used to measure the effectiveness of each reinforcement candidate. Consequently, the method gives also a good indication regarding the status of grid congestion at each reinforcement step.

Investigating the potential development of a transnational offshore grid in the North Sea and its effects on the onshore system. This thesis also provided as an additional contribution and as proof of principle an analysis of a combined planning of a possible offshore grid in the North Sea together with the onshore grid, for a high renewables scenario in the year 2030. The round-the-year bottleneck assessment is used in the analysis and detailed time-series for wind and solar generation were developed (considering thousands of locations) and served to the market simulations. As novelty, the relationship between grid design and offshore grid capacity that can be used securely by the market is investigated for different types of grid structures. A set of recommendations for planning of offshore and onshore grids together is made and factors that might help renewable generation integration in the studied scenario are highlighted.

Proposing an approach for streamlining approval procedures of transmission lines and fostering societal acceptance of transmission lines. In order to make the planning process of transmission lines more robust and effective, this thesis argued that actions have to be taken on two fronts, namely societal and regulatory. On the societal level, a bottom-up approach is proposed, that supports an effective decision making process targeting the increase of societal acceptance by a good information flow from and to the stakeholders and affected population. On the regulatory front, a clear regulatory (top-down) framework should be created, harmonized as much as possible especially when interconnections are involved. With respect to societal acceptance, this work highlights the role of dialogue in fostering acceptance of transmission lines with the help of an in-depth case study analysis, and proposes a new holistic approach to stakeholder engagement with transmission lines which embraces instrumental, substantive and normative notions.

Samenvatting

Het actuele proces van liberalisering in de wereld heeft geleid tot de opkomst van energiemarkten en meer internationale energiehandel om beter gebruik te kunnen maken van energiebronnen en om het elektriciteitssysteem te optimaliseren. Als gevolg daarvan is grensoverschrijdende elektriciteitsuitwisseling aanzienlijk toegenomen en verdere groei kan worden verwacht. In Europa is de planning van grote energie-infrastructuren in een nieuwe, trans-Europese dimensie gekomen. De manier van denken gaat langzaam over van nationale naar regionale (Europese) belangen, omdat dit de weg naar een duurzame toekomst in de energie is. Dit brengt echter wel veel nieuwe uitdagingen met zich mee. Europa bevindt zich aan het begin van een transitie naar een koolstofarme en duurzame elektriciteitsvoorziening, geleid door de (energie) beleidsdoelen van de Europese Unie: concurrentievermogen, betrouwbaarheid en duurzaamheid.

Dit proefschrift kijkt naar de methoden voor de planning van de uitbreiding van het elektriciteitstransportnet onder verhoogde onzekerheid. De liberalisering van de elekticiteitssector, de opkomst van de internationale elektriciteitsmarkt en een verhoogde penetratie van hernieuwbare energiebronnen leveren vele nieuwe uitdagingen voor de beheerders van het elektriciteitsnet op. Dit wordt voornamelijk veroorzaakt door de toename van complexiteit en bijkomende onzekerheden in het transportnet. Deze onzekerheden bestaan rond de dagelijkse transportplanning en uitvoering maar vooral rond de toekomstige behoeften aan transportcapaciteit. Als gevolg hiervan zijn meer geavanceerde en robuuste methoden voor het plannen van het transportnet nodig. Daarnaast is de bouw van nieuwe transportlijnen meestal een langdurig proces dat moet worden verkort om de snelle veranderingen in productiecapaciteit aan te kunnen.

De belangrijkste bijdragen van dit proefschrift zijn als volgt:

Een nieuwe methode en nieuwe criteria voor het beoordelen van knelpunten in het net. Als innovatie, stelt dit proefschrift voor om een jaar-rond aanpak te gebruiken voor de beoordeling van de veiligheid van het transportnet, dat geschikt is voor meerdere met elkaar verbonden energienetten met veel duurzame energiebronnen. Marktsimulaties worden gecombineerd met gedetailleerde berekeningen van de netbelastingen om een compleet beeld te krijgen van de congesties in het transportnet. Het chronologische aspect en de correlatie van belasting, windsnelheid en zoninstraling kunnen worden overwogen door het gebruik van marktsimulaties. Daarnaast zijn nieuwe criteria voor de rangschikking van knelpunten ontwikkeld, samen met een methode voor het rangschikken volgens een risico-gebaseerde ernstheid index. De nieuwe methode levert gedetailleerde en inzichtrijke resultaten op. Het kan gebruikt worden voor een volledig formaat net, én toegepast worden voor het analyseren van zowel HVAC als HVDC netten.

Op veiligheid gebaseerde iteratieve methode om netversterkingen te vinden. Om de juiste (meest effectieve) netversterking te vinden is in dit proefschrift een jaar-rond oplossingsgenerator voor netversterking ontwikkeld welke uitgaat van de reductie van netcongestie. Als noviteit gebruikt deze oplossingsgenerator de voorgestelde methode voor jaar-rond knelpunt beoordeling. De methode geeft een robuuste beoordeling van de overbelasting van het net voor verschillende versterkingkandidaten omdat alle uren van het jaar worden beschouwd. Nieuwe criteria om de overbelasting van het net te bepalen worden gedefineerd en gebruikt in de beoordeling van kandidaten. De daling van de net-ernstheidindex wordt gebruikt om de doeltreffendheid van elke versterkingkandidaat te meten. Als gevolg daarvan levert de methode ook een goed indicatie van de mate van netcongestie bij elke versterkingstap.

Onderzoek naar de mogelijke ontwikkeling van een transnationaal offshore-net in de Noordzee en de invloed op het onshore-net. Dit proefschrift biedt, als extra contributie en als “proof of principle”, ook een gecombineerde planninganalyse van een mogelijk offshore-transportnet in de Noordzee samen met het onshore-net aan. Het betreft een scenario met een groot aandeel hernieuwbare energiebronnen in 2030. De jaar-rond beoordeling is gebruikt in de analyse en gedetailleerde tijdreeksen voor wind- en zonne-energie generatie zijn ontwikkeld (waarbij duizenden locaties worden beschouwd) en ingevoerd in de markt simulaties. Als noviteit wordt het voor verschillende types netstructuur het verband onderzocht tussen netontwerp en offshore netcapaciteit, die veilig door de markt kan worden gebruikt. Een lijst met aanbevelingen voor het plannen van offshore- en onshore-netten is gemaakt waarbij factoren worden aangeduid die kunnen bijdragen aan de integratie van hernieuwbare energiebronnen in het onderzochte scenario.

Voorstel van een aanpak om de goedkeuringsprocedures voor transportlijnen te stroomlijnen en maatschappelijke acceptatie (van transportlijnen) te stimuleren. Teneinde het planningsproces van transportlijnen robuuster en effectiever te maken, stelt dit proefschrift dat maatregelen dienen te worden genomen op twee fronten, namelijk maatschappelijk en regelgeving. Op maatschappelijk niveau wordt een bottom-up aanpak voorgesteld, die ondersteuning biedt voor een effectieve besluitvorming gericht op een verhoging van de maatschappelijke acceptatie door een goede informatiestroom van en naar de belanghebbende en getroffen bevolking. Op regelgeving niveau zou een duidelijk regelgevende (top-down) aanpak ontwikkeld moeten worden, zo veel mogelijk geharmoniseerd, zeker bij grensoverschrijdende verbindingen. Met betrekking tot de maatschappelijke acceptatie, wordt de rol van de dialoog bij het bevorderen van acceptatie van transportlijnen benadrukt en wordt een holistische benadering voorgesteld door te kiezen voor instrumentale, inhoudelijke en normatieve begrippen.

Contents

Chapter 1

Introduction

1.1 Motivation

The ongoing liberalization process around the world has led to the emergence of energy markets, facilitating more international trade between countries making the best use of energy resources and optimizing overall power systems. Consequently, inter-area power exchanges have significantly increased and further growth can be foreseen. In Europe, the planning of large energy infrastructures has entered a new dimension, namely the trans-European one. The way of thinking is gradually switching from national to regional (European) interests, as this is the most effective way to attain a sustainable energy future. This brings many new challenges [1]. Europe finds itself at the beginning of a transition towards a low carbon and sustainable electricity supply system, which is guided by the European Union (EU) Energy Policy core objectives: competitiveness, reliability and sustainability [2].

The increased penetration of variable renewable energy sources in the European power system has been impressive in recent years and further grid-connections of large-scale onshore and offshore wind power installations are planned in order to meet Europe's environmental targets for 2020 and further. Moreover, the EU prognosis is that also the solar power penetration will increase dramatically, reaching 80 GW by 2020, and it will continue to grow after 2020. By issuing the Directives on Renewable Energy [3] including national renewable targets modified according to economic status, the EU aims towards the 20-20-20 goals presented in the Energy and Climate Package (2008). Among those goals is the 20% share of renewables in the European energy consumption within 2020. As we are approaching 2020, attention starts to shift beyond 2020, towards 2030 and even 2050. According to EWEA's forecast [4], in 2030 30% of EU's electricity will be produced by wind power. The European Commission (EC) has published in 2011 a roadmap leading to a competitive low carbon economy in 2050 [5]. There are recent studies that suggest that Renewable Energy Sources (RES) could have by 2050 a share in the electricity generation varying between 40% and 100% [6].

An essential prerequisite for the RES integration and international market facilitation is a robust transmission grid. The planning and development of grid infrastructures is extremely urgent since Europe needs to expand its extra high voltage electricity grid for ensuring a secure and sustainable future power system [7]. To that purpose more adequate planning methods are needed. The unbundling of the electricity sector and the high RES penetration increase the variability of the power flows in the system, which leads to congestions and inefficiency, and require a more international orientation and coordination of the planning process. Furthermore, increased uncertainties (trade, location of generation and output of renewables) must be incorporated during the planning process. Most of the existing transmissions planning methods make use of a worst-case approach [8]: an adequacy analysis is performed for one or a small number of cases, which should stand for all possible combinations of load, generation and interchange. With the increased uncertainty and the many assumptions necessary for the analysis, a large number of "worst cases" is likely to exist, which must be captured in order to achieve a robust planning under a variety of possible scenarios.

The European Network of Transmission System Operators for Electricity (ENTSO-E) [9, 10] together with the EC according to its energy infrastructure package are searching for solutions on how to be able to integrate in the European power systems all the new renewable energy sources. Large-scale RES are usually remotely located and require new transmission facilities for transporting the generated electricity to the consumers. With respect to large-scale wind power, the attention is oriented towards the North Sea area where there is a great potential for offshore wind power plants developments. That is why the North Seas Countries Offshore Grid Initiative was born, where Transmission System Operators (TSOs) examine the feasibility of having an offshore grid in the North Sea and also in other northern seas [11]. Moreover, other non-TSO organizations investigate such issues [12–14]. With the challenge of transporting electricity over long distances offshore and also onshore, the option of using High Voltage Direct Current (HVDC) becomes more of a reality. Many point to point HVDC lines are already operating in Europe. The idea of building and operating multiterminal HVDC grids is a new challenge. Research has oriented its attention towards the control, operation and planning of such grids, which has to be considered together with the control, operation and planning of the alternating current (AC) grids with whom they are interconnected.

Since liberalization and unbundling took place, coordination of generation and transmission infrastructures is difficult to attain, as generation facilities are build at a much higher pace than transmission infrastructures. One reason for that is that approval procedures of new transmission lines are very lengthy. In Europe, the authorization process of transmission line projects takes on average 5-10 years, going up to 20 years in extreme situations. Reducing the time needed for infrastructure realization is an objective clearly stated by the EC [15]. The achievement of societal acceptance for the new infrastructure development is one of the key factors that could help speeding up the approval process. However, improving this aspect is a complex process that requires simultaneous action on several fronts (e.g. political, cultural, regulatory, informative). In [16] the main difficulties with authorization procedures are discussed and grouped as: complicated and un-harmonised legal framework for the approval procedures, lack of political involvement and accountability on these issues, lack of reasonable time limits for authorization procedures, reduced social acceptance of projects, lack of balance between the environmental impact analysis and the necessity of the project.

1.2 Problem definition

This thesis deals with transmission expansion planning under increased uncertainty, motivated by the need for shaping the way towards efficient and sustainable future power systems. It was shown in the previous section that transmission expansion planning faces many new challenges. In the quest for adequate transmission infrastructures, the growing uncertainties (i.e. introduced by renewables, and electricity markets) have to be dealt with in an appropriate manner. Moreover getting approval for building new transmission infrastructures in itself is a difficult task due to lack of societal acceptance on the matter and complicated authorization procedures.

Consequently the following specific topics have been investigated and research questions have been answered.

How to assess the grid bottlenecks? Due to the increasing uncertainties in transmission expansion planning, the worst case scenario approach is no longer sufficient for assessing the adequacy of the transmission grid. Many combinations of load and generation need to be generated and analyzed in order to get a more realistic evaluation of the bottlenecks in the grid. In this process it is important to model adequately the generation park including RES-based generation. Moreover, due to the large amount of information a new approach for interpreting the results is needed.

How to make decisions on the proper network reinforcements? Transmission grid reinforcements cannot be justified anymore just by looking at a small number of worst case scenarios. Consequently, the search for proper network reinforcements has to be done by looking at a large number of situations, and by systematically evaluating the reduction of grid congestion. Indices defining the overall grid congestion level might be useful.

What would be the optimal design of an offshore HVDC grid and what is the impact on the onshore grids? Offshore HVDC grids is a subject that needs attention, especially because of the ongoing discussion of building such a grid in the North Sea. On the one hand, research is needed for assessing various offshore grid designs and their advantages and disadvantages. On the other hand, the effects of the offshore grid on the adequacy of the onshore transmission grids should be investigated.

What are the challenges in the approval process of new transmission lines? Approval procedures of new transmission lines are lengthy. It is important to investigate what are the delaying factors in the current procedures and what can be done in order to overcome them. As societal acceptance is a critical issue it is important to investigate improved ways of engaging with stakeholders during the authorization process (or even earlier in the planning process).

1.3 Research objectives

The research objectives of this thesis can be divided into objectives for the technical and policy domains of transmission expansion planning.

Objectives for the technical domain. At technical level this thesis focuses on grid security and the corresponding objectives can be summarized as follows:

- To review the state-of-the art in transmission expansion research and currently used approaches, with a focus on treatment of uncertainties.
- To develop a robust method for assessing the bottlenecks in the (multi-area) power system that accounts for the challenges introduced by electricity generated by renewable energy sources. To this purpose many combinations of load and generation should be analyzed.
- To develop a method for proposing network reinforcements by using the previous bottleneck assessment method.
- To investigate the development of an offshore grid in the North Sea and its impact on the onshore grid with the help of the bottleneck assessment method.

Objectives for the policy domain. The objectives of this research at policy level refer to authorization procedures of transmission projects. They can be detailed as follows:

- To analyze authorization procedures in different European countries and make recommendations on how to speed up approval procedures.
- To make suggestions on how to engage with stakeholders in the planning process in order to foster societal acceptance of new transmission lines.

1.4 Research approach

The research approach follows the previously defined problems and objectives. First, a literature study is performed and method is developed for assessing the bottlenecks in the grid that is adequate for power systems with high RES penetration. The method is tested and compared to the classical worst case snapshot method. Second, a method is developed for proposing network reinforcements that makes use of the round-the-year security analysis. The round-the-year security analysis can be used iteratively for finding network reinforcements. The method is tested and its advantages are emphasized. Next, the potential development of a transnational offshore grid in the North Sea and its effects on the onshore system are investigated. In this thesis the focus is on the effects of such a North Sea offshore grid for a 2030 scenario. Last, it is researched how to speed-up approval procedures of transmission lines. Both strengths and weaknesses of current approval procedures are emphasized in order to propose a general set of actions. A detailed analysis of a real case is performed.

The research for this thesis was performed within two projects, namely the European FP7 research project REALISEGRID and the Dutch research project NSTG (North Sea Transnational Grid).

1.4.1 The REALISEGRID project

The REALISEGRID [17] project targeted to develop a set of criteria, metrics, methods and tools to assess how the transmission infrastructure should be optimally developed to support the achievement of a reliable, competitive and sustainable electricity supply in the EU. The project went along three axes: identification of performances and costs of new technologies aimed at increasing capacity, reliability and flexibility of the transmission infrastructure and preparation of a roadmap for the incorporation of new transmission technologies into the electricity networks; definition of long term scenarios for the EU power sector, characterized by different evolutions of demand and supply, with the goal to assess the impact on future electricity exchanges among European countries; and implementation of a framework to facilitate harmonisation of pan-European approaches to electricity infrastructure evolution and to evaluate the overall benefits of transmission expansion investments. A cost-benefit analysis framework was applied to test specific transmission projects listed in the EC “Priority interconnection plan”.

The project REALISEGRID encompassed 30 months of activities, carried out by 20 partners from 9 countries. The consortium featured the presence of four major European TSOs, an important manufacturer of transmission hardware and software, and several international research centers and universities, out of which one was Delft University of Technology.

The project consisted out of three main work packages as shown in Figure 1.1. WP 1 reviewed the most recent transmission technology developments by assessing their performances and costs, and finally making a roadmap for their integration in the transmission grids. WP 2 developed and analyzed long term scenarios for the European power systems using The Integrated Markal Efom System (TIMES) energy system model. Both electricity and natural gas infrastructures were considered, and sensitivity analyses were performed to policy and socio-economic scenarios in order to see how energy exchanges in Europe are influenced. The largest work package was WP 3 which focused on developing a pan-European

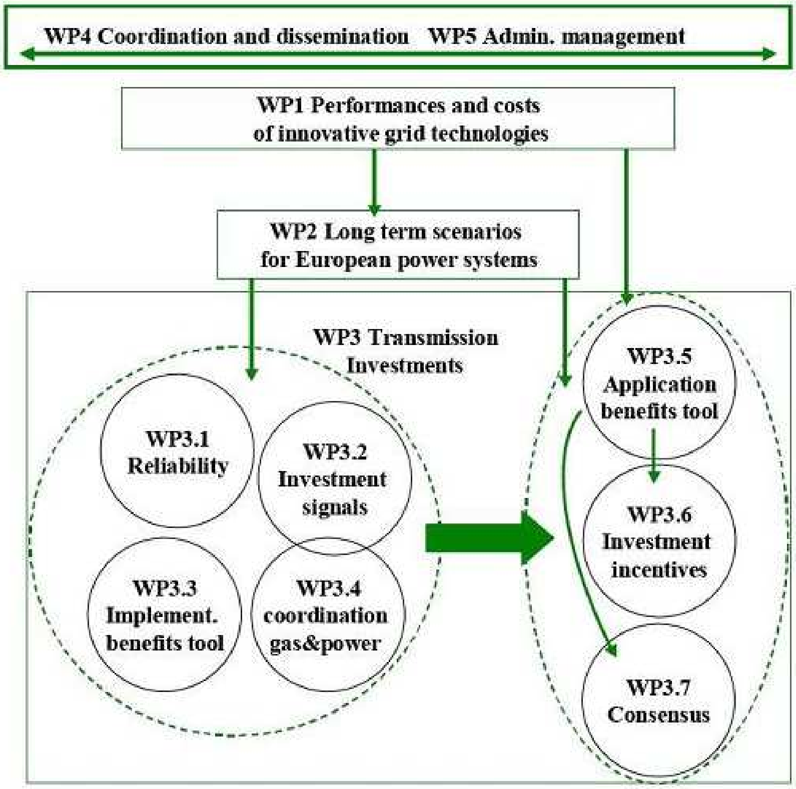


Figure 1.1: Structure of the REALISEGRID EU FP7 project (source [17]).

framework (i.e. methodologies and a set of tools) for assessing the costs and benefits of transmission expansion alternatives at European level. The purpose of this framework is to enable the achievement of a reliable transmission grid and at the same time to facilitate large scale renewable energy sources integration and pan-European electricity market.

For developing such a framework, WP 3 was further divided into 7 sub-work packages (see Figure 1.1). The work performed by Delft University of Technology is related to review and extension of transmission expansion planning methods (WP 3.1), sustainability benefits of transmission expansion projects (WP 3.3), and consensus on new infrastructures (WP 3.7). In this thesis results of this work related to WPs 3.1 and 3.7 are presented.

WP 3.1 summarised existing studies and experiences of methods for transmission planning particularly in the EU countries. Further it aimed to develop a robust set of criteria for the planning of transmission systems in an international context, characterised by a liberalized environment and increasing penetration of renewable energy sources. The criteria should be suited to the European transmission network in order to define reinforcement and extension priorities according to the EU energy policy.

WP 3.7 contributed to the objective of the European Commission to set up national procedures under which planning and approval processes for infrastructure projects should be completed in a maximum time span of five years. To this purpose, existing methods adopted in Europe to overcome the barriers to transmission system development were reviewed, by analysing real case studies based on experience of TSO partners. Further, the WP developed an integral process-approach in order to foster consensus between stakeholders of specific priority transmission system projects, allowing a speed-up of planning and approval procedures.

1.4.2 The North Sea Transnational Grid research project

The objective of the North Sea Transnational Grid research project (NSTG) [14] was to determine the optimal (modular, flexible, most cost effective) high capacity transnational offshore grid, connecting all future wind farms in the northern part of the North Sea to the Netherlands, UK, Norway, Denmark and Germany. Different technical solutions for a Transnational Grid were investigated. For the most promising solution a multi-terminal HVDC system control was developed and tested. A second objective was to determine the effects of the Transnational Grid on the national grids: the operating strategy of the Transnational Grid should be developed to regulate power exchange correctly and avoid congestion and the effect of the Transnational Grid on national grid stability was investigated. The costs, benefits, policies and regulations related to the realisation of such a North Sea Transnational Grid are investigated and compared to alternative scenarios.

Delft University of Technology was involved in assessing the possible topologies and determining the effects of the offshore grid on the onshore system. In this thesis the static security analysis part of the NSTG research project is presented and both onshore and offshore grids are examined.

1.5 Outline of the thesis

This section presents the outline of this thesis.

Chapter 2 - This chapter reviews transmission expansion planning practices. First, a classification of the various practices is done according to some specific features. Furthermore the attention is focused on the state-of-the art in transmission expansion planning with consideration of uncertainties. Scientific papers, actual European TSOs practices, and approaches used by relevant European studies are presented.

Chapter 3 - A round-the-year approach is developed by combining market simulations with static security analysis. Many combinations of load and generation (including RES) are created and analyzed, using unit dispatch based on cost optimization. For each combination, the branch loadings are determined for normal and contingency situations. A new statistical risk-based approach for ranking the most severe bottlenecks is developed. The method is illustrated on a modified New England test system where wind power was added at several buses. The risks of overload versus amount of installed wind power is also assessed. Furthermore, the method is applied in cooperation with TenneT TSO on a practical case study for a 2020 demand and supply scenario for North-Western Europe, focusing on the Dutch power system.

Chapter 4 - In this chapter a solution generator for the transmission expansion planning problem is developed. The method makes use of the round-the-year network security analysis introduced in Chapter 3 and it iterates sequentially over various possible reinforcements until no more overloads occur. A robust assessment of expected overloads in the grid for different reinforcement candidates is performed, as all the hours of the year are considered. The decrease of the so-called grid severity index is used to measure the goodness of each reinforcement candidate. The New England test system is used again for testing the method.

Chapter 5 - This chapter provides as proof of principle an analysis of a combined planning of a possible offshore grid in the North Sea together with the onshore grid, for a high renewables scenario in the year 2030. The round-the-year security analysis introduced in Chapter 3 is used to analyze on the one hand different possible structures of the offshore grid and the interdependencies that exist between grid structure and available capacity for market transactions. On the other hand, the same round-the-year security analysis is used to investigate the effects of the offshore grid structure on the security of the onshore grid. Zooming into critical hours is done for both the offshore and onshore grids for a better understanding of the results. A set of recommendations for planning of offshore and onshore grids together is made.

Chapter 6 - This chapter examines a new approach for speeding up approval procedures for building transmission infrastructure. First the experiences of Transmission System Operators from some European countries are studied in order to generalize and pinpoint the main weaknesses and strengths of current approval procedures. Recommendations concerning how to reduce the time needed for authorization procedures are made. The problem of societal acceptance of transmission lines is analysed further. Suggestions for better structuring of the decision process in transmission planning, with high involvement of stakeholders, are made.

Chapter 7 - This chapter presents the main conclusions, contributions, and recommendations for further research.

Chapter 2

Transmission expansion planning

This chapter reviews transmission expansion planning methods (in theory and practice). First, a classification of the various practices is done. Furthermore the attention is focused on the state-of-the art in transmission expansion planning methods that consider uncertainties especially those introduced by deregulation and renewable energy sources. Both scientific methods that have not yet been embraced by the industry as well as actual methods employed by European TSOs and various case studies are presented. At the end a discussion is made about transmission expansion planning approaches.

2.1 Introduction

Electrical power systems consist of generation plants, consumers and electricity grids for connecting generation to consumption. Following the liberalization of the energy sector, the operation and development of the grids is the responsibility of Transmission System Operators (TSOs) and Distribution System Operators (DSOs). The TSO operates at the transmission level which is normally performed at Extra High Voltages (EHV) of minimum 220 kV, while the DSO is in charge of the grids with voltages below 220 kV. However there can be cases when "subtransmission" grids (for example the Dutch TSO TenneT is since 2008 also in charge of the 110 and 150 kV grids), and even "distribution" grids (such as the 63 kV and 30 kV grids in France and Belgium respectively) are owned by the TSO. The grids at different voltage levels are coupled between each other via transformers. The transmission grid constitutes the backbone of the electrical power system and ensures electricity transmission over long distances, connecting (centralized) large power plants to consumers and ensuring international electricity exchanges.

The basic tasks for the transmission network planners (working for the TSO) are: to forecast the power flows in the power grid over a long-term horizon; to check whether or not the acceptable limits are exceeded (security analysis); to devise a set of possible solutions to overcome the problems found and to select the solutions with the best cost-benefit performance [18]. In order to do that, TSOs rely on future scenarios of generation and consumption for their service-area and areas of neighbouring TSOs. The purpose of security analysis in the transmission planning process [8] is to check whether the transmission network can be operated in a secure way under a variety of worst-case circumstances. To this end it is checked if the branch loadings with N, N-1 and N-2 branches in operation do not exceed a certain percentage of the rated capacity as defined by the TSO. This percentage varies from country to country and can be below or above the rated (thermal) capacity depending on the security margins (or risks) adopted. Also it is checked if the voltage at all nodes is within the required limits. The planning criteria traditionally employed by industry are deterministic: N, N-1 and N-2.

In the last years, the way power systems are planned changed due to the unbundling of the electricity sector and the emergence of (international) electricity markets. In the past, there was only one entity who owned the generation and the transmission grid of a given region. Consequently, long-term power system planning was done by considering generation and transmission assets together. Nowadays however, in many countries this is no longer the case. More precisely, generation units are owned by different market parties who follow their own interests. In Europe, the liberalization process led to growth of international electricity exchange. Moreover, generation from renewable energy sources (RES) (wind and solar especially) has experienced an incredible boom and will continue to grow in order to meet the targets of the European Commission, of a reliable, competitive and sustainable European interconnected power system.

All these changes have made the tasks of the TSOs more difficult due to an increased number of uncertainties that have to be considered in both the operation and planning of the power system. With respect to transmission expansion planning, most of the current planning methods are not appropriate anymore as they do not take into account the above mentioned uncertainties. Consequently, new approaches are being researched. These aspects will be discussed in this chapter.

In this thesis, the terms reliability, security and adequacy of power systems can be encountered. Power system security is related to a moment in time (which is defined by a set of conditions) and measures the ability of the system to withstand unplanned disturbances (called also contingencies) without interruption of electricity supply [19]. Power system reliability is defined over a longer period of time and expresses the probability of appropriate power system operation [19, 20]. Therefore a system is reliable if the likelihood of good operation is very high (i.e. only a few interruptions in the investigated period), or in other words, if it is secure most of the time. Power system security can be divided in two, namely static and dynamic security [19]. Static security analysis targets steady-state post disturbance conditions, namely it is assumed that the system reaches operating equilibrium after a disturbance and it is checked whether system limits are violated. Dynamic security analysis targets system stability after a disturbance, and therefore it is investigated whether the system can reach a new state of operating equilibrium after a disturbance. Sometimes static security reliability assessment can be referred by literature as adequacy assessment, and dynamic security reliability assessment can be met simply as security reliability assessment [20, 21]. Furthermore, an adequate power system implies both adequate generation and transmission systems, and generation adequacy assessment and transmission adequacy assessment can be distinguished.

The chapter is structured as follows. Section 2.2 proposes a classification of transmission expansion approaches. In Section 2.3 state-of-the art of transmission expansion planning methods that consider various sources of uncertainty in future generation and demand are reviewed. Section 2.4 summarizes the findings of the chapter.

2.2 Classification of transmission expansion planning approaches

As seen in the previous section, solving the transmission expansion planning problem means to develop future load and generation scenarios, to check if grid security violations occur under these scenarios, and, if needed, to determine the optimal grid reinforcements and also when in the planning horizon they should be built. This may sound easy, but it is not as many aspects have to be considered. Consequently, the transmission expansion planning problem has a high degree of complexity as it is a mixed integer, non linear, non convex, multi stage optimization problem. It is difficult to devise a planning approach that captures all the complexity. In literature mostly two type of approaches to transmission expansion planning can be identified. Some approaches try to identify and propose reinforcements based on predefined criteria. These criteria can be just grid security or also other such as investment cost, and, depending on the used criteria, further assessment of reinforcements might still be needed. That is why, other planning approaches assume that a set of possible reinforcements is already proposed and try to assess these reinforcements and select the most adequate ones (according to a larger set of criteria).

Transmission expansion planning (TEP) approaches can be divided considering criteria related to power system uncertainty, horizon, regulatory structure, and solution method [22–24]. Therefore these methods can be deterministic/non-deterministic, static/dynamic, for regulated/deregulated power systems, and adopting as solution method heuristics, mathematical optimization or meta-heuristics (the later combine the features of the previous two methods). One transmission planning method can have features from all four classification groups (for example a deterministic, static, for deregulated power systems planning method that uses mathematical optimization as solution method). The classification is briefly presented in the next paragraphs.

2.2.1 Static/dynamic methods

Transmission expansion planning approaches can be static or dynamic, depending on how they treat the planning horizon. The static TEP (i.e. [25]) has as a goal to find the optimal transmission expansion solution for a given year in the planning horizon, without determining the specific moments in time when the circuit additions/modifications are to be made [23], [24]. In dynamic planning (i.e. [26]), the entire planning horizon is considered and therefore, the optimal expansion strategy is outlined for multiple years. To this purpose time restrictions must be included in the mathematical model for considering the temporal continuity [23]. Such type of methods are usually limited due to their increased complexity [24], that makes them computationally speaking non-applicable for large power systems. That is why hybrid static-dynamic models have been also developed (i.e. [27]). These methods solve the TEP problem by analyzing separately different time steps (years), without having any time restrictions included. Basically they perform static planning for more different various horizons.

As shown in [8]-[18], the European TSOs adopt such a hybrid static-dynamic model. There are typically three time horizons for network planning studies [28]:

- long-term studies which are characterized by a high degree of uncertainty as the planning horizon may be up to twenty years.

- medium-term studies where the uncertainties are reduced as the planning horizon may be up to ten years.
- short-term studies where the uncertainties are even more reduced as the planning horizon may be up to five years.

The 10-year time (medium-term) horizon is the most adopted by the European TSOs [8]. With respect to longer term analyses, there are several examples of countries conducting and publishing such kind of strategic studies, as for example Ireland and The Netherlands [18].

2.2.2 Methods for regulated/deregulated power systems

The liberalization of the electricity sector led to a shift from regulated to deregulated power systems. In regulated environments the whole planning process is centralized and generation and transmission are planned together with the purpose of minimizing the overall system cost. The planners have full access to important information such as generation cost, availability, location. The obligation of vertically integrated utilities is to serve their customers as economically as possible, while respecting certain levels of quality and security of supply [24].

On the other hand, in deregulated environments, the ownership of transmission and generation assets is separated. Generation owners are interested in maximizing their own profit rather than the social welfare, while TSOs must maintain a secure and reliable transmission grid, allow non-discriminatory access to the electricity market to different market players (consumers and producers), and finally also to support efficient and sustainable power systems. Uncertainties have become more numerous, and TSOs have only limited access to information regarding the development of new generation [24]. An example of TEP for a deregulated environment is introduced in [29]. The method utilizes the level of congestion in the transmission network as the indicator for the need of additional transmission lines. A combination between congestion cost and investment cost was utilized for determining the optimal expansion plan.

Cost-benefit analysis is an approach normally used for comparing and assessing different expansion alternatives. Usually an optimal power flow[1] tool is used for assessing the expansion alternatives for different planning years. The expansion alternatives for which the difference between benefits and costs is the highest are chosen as the best. There are many examples in the literature, and some try to capture most of the costs (i.e. investment cost, operation and maintenance cost, costs of possible dismantling works) and benefits (i.e. network losses reduction, grid congestion relief, reduction of generation costs, increase of system adequacy to cover demand and operation security, value of expected energy not supplied, avoided investments, CO_2 emissions reduction, higher integration of renewable energy sources, etc.) related to an expansion alternative, while other focus only on certain aspects. For example [30] proposed a cost-benefit analysis for coordinated transmission and generation planning, focusing on environmental benefits (internalization of external

[1] In optimal power flow, the power system operation is optimized with consideration of network-related constraints.

costs of conventional energy sources is also included). It is assumed that for reaching sustainable power systems such a coordination is needed; such an approach is therefore more adequate for regulated power systems. A more complex approach, suitable for deregulated environments, was proposed by the REALISEGRID project which adopts a multi-criteria cost-benefit analysis [31]. A wide range of benefits is considered with respect to security of supply, competitiveness and sustainability.

2.2.3 Deterministic/non-deterministic methods

In order to fulfill their tasks, the TSOs rely on scenarios of forecasted consumption, generation development, and power exchanges evolution. For each scenario, the stochastic aspects of the phenomena must be taken into account: load varies with human activity and weather conditions; generating units may produce or not, depending not only on economics but also upon external factors such as wind or hydro conditions and forced outages; the scenarios should reflect the asset and bidding strategies of the generation companies and other market players; cross-border exchanges may largely vary also depending on the behaviour of the different market players [8]. All these factors are uncertainties which can be divided in two-types [32]: random, which can be statistically represented by using historical data, and non-random, which cannot be estimated from previous experience. Some sources of random uncertainties are for example load, variable renewable energy sources such as wind and solar generation, the cost of generation and the implicit bid of generators, availability of power system components [32, 33]. Non-random uncertainties can be identified with the expansion, closure or replacement of power system assets (power plants, consumers, transmission grid components), by the evolution of transmission expansion costs and by changes in market rules and subsidy regimes [32]. In addition, power systems evolution is also influenced by vague data that cannot be clearly quantified. Such data are the importance of stakeholders in decision making on the one hand, and of planning criteria from the viewpoint of different stakeholders on the other hand, and also the probability of possible future scenarios [32].

By looking at how planning methods deal with uncertainties, there can be deterministic and non-deterministic methods. The classic deterministic approaches select a reduced number of worst cases for the target year, usually at system peak load, and perform contingency analysis (by checking if the branch loadings are exceeded with N, N-1 branches or even N-2 branches in operation) in order to discover the weak points in the network and suggesting reinforcements. Such an approach has clear disadvantages [34] as no uncertainties are considered in solving the problem. By looking only at a few snapshots a future scenario can be misrepresented as the probability of occurrence of line overloads for example is ignored, failing in integrating also the uncertainty factors introduced by future load-generation scenarios. Hence, it is very likely to miss the whole picture by looking only at some limited aspects. While focusing on system peak load only, other major system problems might happen at non-peak load points, hence the system's reliability is not being covered by the worst case assumption. Consequently the risk level associated to the N, N-1 and N-2 criteria is not captured.

In contrast, non-deterministic planning approaches consider many snapshots (situations) to which a probability of occurrence or a degree of importance is assigned. The purpose of that is to better model the uncertainties. These methods can be divided in [22]: probabilistic load flow [35], probabilistic reliability criteria [36], scenario techniques [37], decision analysis [38], fuzzy decision making [39], and combinations of the previous. For example, in [32] a market-based approach in unbundled power systems was created. For considering all the uncertainties and vagueness, optimal power flow, scenario technique and fuzzy decision making were combined. The latter was used for measuring the goodness of a plan by defining a fuzzy appropriateness index that takes into account the vagueness sources. Fuzzy risk assessment was applied for determining the best solution. Furthermore [40] proposed a risk-based approach for transmission expansion planning considering uncertainties in load forecasting and generator sitting. The focus is on the decision making process considering some given alternatives. The planner must minimize the regret according to risk acceptability levels, and finally select the most robust plan.

2.2.4 Solution methods for solving the TEP problem

According to the way the search for the TEP solution is performed, solution methods can be divided into mathematical optimization, heuristics and meta-heuristics.

The mathematical optimization solution methods use a mathematical model for the TEP problem. The method searches for the optimum solution for the TEP problem, by solving the mathematical formulation of the problem which is given by the objective function and a set of constraints. The goodness of various expansion options is measured with the help of the objective function. Generally the used constraints are limited and refer to technical, reliability and economic issues. Consequently, the TEP solution is optimal only under those conditions. The most common approaches used in mathematical optimization are Linear Programming [41], Non linear Programming [42], Dynamic Programming [43], Mixed integer Programming [44]. Further, decomposition techniques (Benders [45], Hierarchical [46]) and the Branch and Bound [47] are also used. Such methods decompose the TEP problem in several different subproblems.

Another way of solving the TEP problem is by using heuristics. Heuristic methods are as the name says creative methods that use the human experience. The experience is used for defining a set of rules (logical, empirical, sensitivities) to be used for finding in a step-by-step process the TEP solution. The search stops when no better solution can be found anymore giving the considered criteria (i.e. overload, investment cost, energy not served). Heuristic methods have a better performance than mathematical models in terms of computation time and convergence rate [24], and they provide good solutions but however not proven to be optimal. One of the most used heuristic approaches is to select the reinforcement solutions with the help of sensitivity analysis, with respect to reducing overloads [48], reducing energy not served or increasing the load supplying capability [49], or other criteria measuring the goodness of the plan [50].

Meta-heuristic methods combine heuristics with mathematical optimization. There are e.g. algorithms inspired from the theory of evolution (such as genetic algorithms [51], differential evolution [52]), algorithms inspired from animal collective behaviour (e.g. Ant Colony Optimization [53], Particle Swarm Optimization [54]), algorithms inspired from processes and phenomena (Simulated Annealing [55], Tabu Search [56]).

2.3 Transmission expansion planning with consideration of uncertainties

Because this thesis is focused on transmission expansion planning under increased uncertainties towards sustainable power systems, the following section will examine the state of the art in non-deterministic TEP approaches with a focus on how uncertainties of RES generation and of power systems with RES generation in general are modelled. The section is divided in two parts. One is the state-of-the-art in research and the other are the existing European TSOs' TEP practices and various studies for RES integration.

2.3.1 Research state of the art

Recent non-deterministic TEP approaches proposed by the scientific world, try to address the various uncertainties related to the TEP problem on the one hand, and/or consider some of the TSOs planning targets in deregulated environments. However, due to the increased complexity it would bring to the TEP problem, they do not model separately the uncertainties related to variable RES-based generation. For example, in [56], the authors propose a meta-heuristic planning approach which considers several generation dispatch snapshots. The solution is searched with the help of a Multi-Objective Tabu Search approach, which has as objectives to minimize investment cost and to maximize the number of snapshots satisfied by the solution. The different generation snapshots are generated with the help of a Beta probability density function. Moreover, in [52] a differential evolution (DE) algorithm is used for searching the TEP solution. The analysis is performed using a few planning scenarios. For each scenario DE is run and a solution is found. Then the adaptation cost of each solution under other scenario is calculated. At the end the most flexible plan is chosen (sum of investment and adaptation costs considered). The fact that only a small number of snapshots is analysed is a limitation of this method.

The work in [57] introduces a multi-stage stochastic multi-objective optimization framework, which has a steady-state voltage security management feature which is performed with the help of an optimal AC power flow. The method considers system load uncertainties and produces scenarios with the help of Monte Carlo simulations. Scenario tree construction and scenario reduction techniques for the load scenarios are used for reducing the number of scenarios to only a few, which are basically snapshots which have a certain associated probability. The multiple stages are considered chronologically starting from step 1 and considering the reinforcements at step 1 in step 2. The four objective functions considered are the investment cost, the expected operating cost, expected load shedding cost and expected loading factor (or loading margin, used for evaluating the voltage stability margin). This method has the advantages that it looks at more stages in the planning horizon and it considers several criteria in the choice of the solution. Its downside is that it does not model at all the uncertainties introduced by RES generation and it analyses a reduced number of snapshots (even though with a probability attached). Furthermore, branch overloadings are not monitored.

A TEP approach based on dependent chance programming was introduced in [58]. In dependent chance programming, the objective function is formed by a weighted sum of the chance measures that uncertain indices fulfil deterministic conditions. Three types of uncertainties are modelled, namely generator output, load and line investment cost. These uncertainties are merged into fuzzy random variables within the optimization model. Using tabu search, the model tries to find the solutions having the highest chance in meeting the objectives related to investment cost, transmission losses and circuit load factor (ratio between the loading and the rated capacity of a circuit). Again the uncertainties related to RES-based energy are not modelled.

Only a few recent papers tried to address the uncertainties related to variable RES, with a focus mainly on wind energy. [59] made a review of some of the probabilistic problems introduced by variable generation integration for both operation and planning of power systems. Research in the field on how to model these resources and how to integrate the resulting models in power system operations and planning is still not mature enough. One of the main challenges is due to the need of modelling dependencies in the primary resources (wind, solar) among various locations in the power systems. Moreover modelling such resources increases tremendously the complexity of the TEP problem. A Monte-Carlo approach was proposed in [60] for modelling stochastic generation for power systems studies. Copula theory is used for modelling the correlated random variables, and model reduction techniques were proposed for making the method applicable for real power systems. This method could be applied for example in a probabilistic load flow based TEP approach. However, probabilistic load flow has the disadvantage that unrealistic snapshots are also included in the analysis and inter-temporal constraints (such as generation minimum up and down times and ramp rate constraints) are not considered.

Going back to TEP literature, a mixed-integer linear programming model was proposed in [25]. The model considers the variability of wind power and the wind power impact on system security and on the reserve market. However, wind generation is modelled in a very simple way by considering a few peak and off-peak scenarios where wind generation contribution is changed.

A reliability-based TEP approach was proposed in [61], using a sequential Monte-Carlo simulation for examining transmission reinforcement alternatives when connecting new wind farms. Wind power variability is modelled (for each site separately) with the help of the auto-regressive moving average (ARMA) model. Furthermore, [62] proposed a security value based method for comparing power system planning schemes. Both generation and transmission planning are considered in this approach. Unit commitment simulation is used for assessing security related costs (for preventive and emergency control, and social losses) due to uncertainties in load and wind power. Hourly load and wind data are used for the unit commitment. The various planning schemes can at the end be compared through their security costs. This method has the advantage that it maintains chronology throughout the simulation, it generates realistic generation and load combinations, and it models the uncertainties related to load and wind generation through the use of load and wind power time series. This method however does not propose reinforcement solutions, as these are served as an input.

A risk based probabilistic multi-objective TEP approach which also models wind power was recently proposed in [63]. The ability of the power system to integrate wind power is evaluated with the help of risk of overload indices. Three risk strategies are modelled and combined in one risk of overload index, namely the branch non-overload probability, system non-overload probability and margin of non-overload probability for the system. The model uses Genetic Algorithms for searching for the expansion solution and runs probabilistic load flow for each solution, while trying to maximize the ratio between the overload risk index and the investment cost of the system. For speeding up the calculation, for the probabilistic load flow combined cumulants and Gram-Charlier series (which approximate a probability distribution in terms of its cumulants) are used, instead of the Monte Carlo simulations. A Weibull distribution is assumed for wind speed, and the cumulative distribution function and probability distribution function for the wind generation output are derived from the ones of the wind speed. It is assumed that the load demand at the system's buses as well as the wind generation output at different locations are statistically independent. This method is very interesting, however some important aspects are not modelled such as the actual severity of the overloads, and also the wind and load correlations.

2.3.2 Recent steps towards application of non-deterministic transmission planning in Europe

2.3.2.1 TSO practices

Within the REALISEGRID project a thorough comparison of various transmission expansion practices in Europe was performed in [8]. Some interesting results from that work are presented in this section.

In Europe, TSOs have two main objectives when planning the development of the transmission grid. The first one is to maintain an adequate level of reliability and security of supply, and the second objective is to facilitate electricity markets. Consequently transmission planning has to target the specific connection of a new generation unit to the grid and the general development of the main transmission grid for allowing secure and efficient use of the whole generating system. While the analysis of the connection to the transmission grid is a case-by-case process, the general planning process takes place regularly at certain intervals of usually 2 years. The planning is generally hybrid static-dynamic focusing on a future target year and one or more intermediate years for which scenarios are being developed and the security of supply is checked. For assessing the network security, for each of the developed scenarios the network design must be verified with a security analysis. Generally, load flow analyses are performed for normal operation of the network (N), and contingency situations (N-1 and sometimes even N-2 security criteria). The load flow analyses allow the identification of bottlenecks in the existing transmission network, and, in addition, they are a means to verify if possible grid reinforcements will solve these issues.

The following are the most common measures used for grid reinforcement:

- Adding transformers in existing substations in order to be generally able to feed higher load and/or evacuate higher power.
- Upgrading some assets, for example by replacing the conductors of a line with ones of a higher ampacity, or adding new circuits in parallel to an existing line.
- Installing new equipment in some grid substations, for facilitating a better grid operation (e.g. shunt and series reactive compensation devices, phases shifting transformers, FACTS).
- Replacing existing transmission lines with ones operating at a higher voltage and implicitly having a higher transmission capacity (for example new 400 kV line in the place of an existing 220 kV line).

- Building new high voltage lines or substations.

Alternatively, if possible, congestion management can be used for solving grid bottlenecks. When managing congestion, generators in the power systems are redispatched in order to relieve congested corridors. Congestion management is an operational measure and results in a sub-optimal dispatch as compared to the unconstrained market equilibrium. Congestion management cannot always relieve congestion completely and it is generally not considered as a long-term solution.

All the TSOs rely on scenarios of forecasted consumption, generation development and power exchanges and they have to consider their stochastic nature. In addition the methods used by the TSOs in making their assumptions largely differ. In the current competitive environment the role of generation adequacy criteria is not clear anymore. The practices are different as some countries prefer to rely on such criteria when planning their system, while others regard the evolution of supply and demand in a more general way. The TSOs practices vary with the time horizons, used analysis methods and the investment criteria. Regarding planning approaches, most European TSOs still make use of deterministic planning criteria, and the consideration of uncertainties is rather limited. However there is a slow trend towards more non-deterministic approaches as it is recognized that better consideration of uncertainties for example by using probabilistic risk-based planning standards are needed [64]. While many of the European countries already consider to a certain level uncertainties introduced by the market, only a few countries adopted some probabilistic items within their planning practices. This will be discussed in detail bellow.

The planning process in Italy, in the responsibility of the TSO Terna, starts with data collection and analysis. Consequently one or more likely operational scenarios are developed for the target year and specific snapshots are created for the grid analysis. The power dispatching assumptions for each scenario are based on estimations of production cost and market simulation results. The static security of the grid is analyzed for each snapshot, using the N-1 criterion, and possible grid problems with corresponding grid reinforcement solutions are identified. The necessary grid reinforcements are defined in order to maintain N-1 grid security, reduce grid congestion and reduce restrictions on constrained generation units. During the N-1 security analysis the uncertainty related to wind generation units is considered by estimating their probable production level. The main drivers for grid planning are reliability and security of supply. However, at the end also the economic benefit each project brings is considered. This is done using a cost-benefit analysis. Only projects bringing an overall economic benefit larger than their costs are included in the Transmission Development Plan.

In France (TSO RTE France) [8], transmission expansion planning also covers several steps. First scenarios are developed and constraints are detected in N and N-1 operating conditions. Next several reinforcements strategies are developed considering technical, environmental, legal and also sometimes contextual issues (presence of influent political actors in the considered area; the area history of societal acceptance of new transmission infrastructure). These strategies are compared (considering investment cost of a strategy, the operating cost and the cost of unsupplied energy) and the best one is chosen. Last step is to find the optimal date for the first investment. For the grid analysis part, load flow analyses performed via probabilistic methods are mainly used for the 400 kV network as in those cases the network is quite influenced by the generation plan and the cross-border flows. Different load situations are forecasted (winter peak, winter off-peak, summer peak, summer off-peak, inter-season peak), different scenarios are also established for exchanges on interconnectors, thousands of generation scenarios playing on availability of the different units and on wind level on French wind areas are sampled and constraints are detected in all load flow situations and summarized statistically. This on the one hand, better considers the uncertainties in the planning process, but on the other hand it complicates the analysis and brings extra difficulties such as estimating the probability of a given situation.

The transmission planning approach used by the Spanish TSO REE [65] is more adequate for competitive environments and has a better treatment of uncertainties than the French practice, by trying to look at a high number of plausible operating conditions. The main criteria used are minimization of investment and grid operation costs, secure and efficient static and dynamic grid operation, and complying with specific environmental, administrative and social requirements. The TEP approach has four steps: multiple scenario generation covering the whole planning horizon and detailed analysis of these scenarios, information structuring and index calculation, identification of competitive and necessary network reinforcements and finally decision making. For the first step, about 400 scenarios are generated trying to cover all plausible operating conditions of the target year, including extreme scenarios. An operating condition is given by load conditions, generation profile and network status. A probability of occurrence is associated to each scenario. For the target year, the scenarios must cover the expected demand range, to capture all the technical constraint violations in the system (overloads and high and low voltage bounds) and to consider also the uncertainty of fuel prices, hydro conditions (wet and dry), wind conditions (high and low), international exchanges etc. Both static and dynamic analyses are performed. For the static analysis an optimal power flow (OPF) tool is used and N-1 criterion is tested for generating units, lines and transformers and N-2 criterion is tested on double-circuit lines, substations with a high level of generation or transit, and substations with very short fault-clearing times. For dynamic analyses a transient stability tool is used for the related studies. The results of the analysis are summarized with the help of criteria (grid element criticality[2] and sensitivity[3]) and indices (extreme values, probability-weighted RMS values, probability-weighted deviations over limits). Using his experience, the planner proposes reinforcement alternatives considering the degree of criticality and sensitivity in each transmission corridor. The target is to achieve a network that works without limit violation for (most of) all the investigated scenarios. At the end a cost-benefit analysis is performed on the proposed reinforcements and the most competitive ones are chosen. Finally, these solutions together with well structured information are presented to the decision maker, who will define the most appropriate expansion plan.

Even though the Spanish planning approach has a better treatment of uncertainties than the French practice, it should be noted that both French and Spanish approaches do not consider the chronological aspect, i.e. inter-temporal constraints when scheduling generation resources over a given time horizon and temporal correlations between load and wind power inputs. In addition, it is not clear whether the spatial correlations of load and wind power were taken into account to some extent by the Spanish TSO when generating the scenarios.

[2]Criticality is the impact that the failure of a given element has on other elements.

[3]Sensitivity is the impact on a given element as a result of the failure of other elements in the system.

2.3.2.2 European studies and initiatives for wind integration

In the last years many studies have been focusing on integration of large-scale wind energy in the European power system. To this purpose these studies had to consider the variability of the wind energy resources within their calculations.

The European Wind Integration Study (EWIS) [66] adopted a round-the-year approach using a market simulations tool that considers transmission constraints via a Power Transfer Distribution Factor (PTDF) matrix[4]. However, while here the chronological and correlation aspects are considered in the market study, the grid security analysis was performed only on a small number of critical cases at European level, selected after analysing the output of the market simulations.

A similar approach was taken by the TradeWind study [67] which furthermore considered the European transmission grid only by its interconnectors. Generation capacity forecast for one year was an input and the tool determined the optimum power output of all generators subject to interconnector transmission constraints. The power flow on all lines was also computed. The findings of this study indicate that higher wind power penetration will result in increased cross-border exchanges, and consequently more (onshore but also offshore) transmission reinforcements will be needed for reducing grid congestion. As an additional remark, the approaches used by both EWIS and TradeWind studies are one of the first examples of using large multi-area market based models. Such models produce more realistic generation and international exchange profiles.

The idea of a possible offshore grid started contouring, and next the OffshoreGrid Study [12] looked at the feasibility of building an offshore grid in the North and Baltic Seas to connect both offshore wind farms and coastal countries to each other. Different offshore grid development strategies are proposed and optimal power flow is used for comparing the resulting grid topologies. Both AC and DC reinforcement options are considered. A limitation of the model is that the optimization does not model inter-temporal constraints when scheduling conventional generation. Furthermore, availability of both wind and solar generation is modelled, but the latter is modelled in a very simplified way as constant generation (meaning that solar generation is available also at night). In addition, the impact on the onshore grid security is not analyzed.

The Irish TSO Eirgrid also performed a study for a possible offshore grid in the Irish Sea [13]. More precisely it looked at what the best options for connecting future offshore generation are. The software used in the study provides the optimum network expansion plan, which minimises the combined cost of network development capital costs, the costs of resulting electrical losses from the network and the cost of production for a future year. A higher cost generation selection may prove ultimately to be a lower cost solution if the cost of grid development or losses can be reduced. DC optimal power flow was used for estimating the impact of a certain grid reinforcement on the overall system, and branch and bound techniques were used for choosing the best reinforcement solutions. The TSOs of some North European countries have created the North Seas Countries Offshore Grid Initiative (NSCOGI) [11]. They also look at the feasibility of building offshore grids in the North Seas. Cost-benefit analysis is used for assessing together offshore and onshore grids reinforcements.

[4] The PTDF matrix holds the relationship between inter-zonal power transfer and the distribution of the transfer on the different flowgates (which can be borders but also transmission elements).

Moreover, the Friends of the Supergrid initiative supports the development of an European Supergrid. Such a supergrid is a European transnational (possibly HVDC) transmission grid which would play an essential role in future integration of large-scale renewable energy sources and as well in the general secure operation of the European power system. The first steps towards such a Supergrid have been announced by the German TSOs as several high capacity HVDC corridors between the North and South of Germany are planned to be build in the next 20 years.

With the new challenge of transporting electricity over long distances offshore and also onshore, the option of using HVDC (Current Source Converter (CSC) or Voltage Source Converter (VSC) based) becomes more of a reality. Many point to point HVDC lines are already operating in Europe. The idea of building and operating multiterminal HVDC grids is a new challenge. The existence of such a grid is at this moment hampered by the development of DC circuit breakers. However it is believed that such breakers will be on the market in a few years (see press releases ABB, Alstom). Assuming the existence of HVDC breakers, research (i.e. [68–72]) has oriented towards the control, operation and planning of such grids, which has to be considered together with the AC grids with whom they are interconnected.

2.4 Discussion on transmission expansion planning approaches

Transmission expansion planning is a complex problem for which a solution that is a global optimum seems impossible to find. TEP approaches can be classified according to criteria related to power system uncertainty, horizon, regulatory structure, and solution method.

Due to the recent changes in power systems, planners have to account for more and more uncertainties when searching for good reinforcement solutions. Planning methods can look only at technical aspects (e.g. branch overloads, voltage excursions) or at more aspects (i.e. social welfare, environmental issues, reliability). Consequently planning methods, before presented to decision makers, can propose reinforcements which have to be further analysed on multiple criteria, or can assess the costs and benefits of various proposed reinforcements. There are also methods which try to do both (propose reinforcements and also analyse them with i.e. cost-benefit analysis), but this increases the difficulty of the problem and limits the treatment of more complex uncertainties (such as output of variable RES generation).

The approaches used by TSOs usually solve the transmission expansion problem in steps and also with the help of expert knowledge. First, scenarios are developed. Next, security analysis is performed on the grid and problems are identified. Using expert knowledge several solutions for overcoming the problems are found. The solutions are further analysed and compared typically with the help of cost-benefit analysis. At the end decision-makers decide what the actual reinforcements will be. Giving the complexity of the TEP problem, maintaining certain steps (i.e. testing the grid security and finding solutions for the found problems; comparing the solutions with cost-benefit analysis) in the transmission expansion process seems like a good idea. In this way, uncertainties can be better considered at each step.

With respect to consideration of variable renewable energy sources within the transmission expansion planning problem, there is not very much experience available. Some

European TSOs approaches and studies try to model RES-based generation, introducing non-deterministic elements in the planning process. However, the treatment of RES based generation in transmission expansion planning has a lot of room for improvement. The spatial and temporal correlations between load of different market areas and RES power inputs for different production locations, are important aspects that should be considered when assessing the security of the grid and transmission expansion alternatives. Moreover, the output of conventional generation should also be modelled more realistically by considering inter-temporal constraints such as minimum up and down times and ramp rate constraints. In this way more realistic combinations of load and generation can be achieved. A few European studies [12, 66, 67] considered the wind and load correlations by serving as input hourly load and wind power time series to market simulations or to the optimal power flow. These multi-area optimization models produce also more realistic international-exchange profiles. Recent scientific papers [61–63] also try to better model RES-based generation when trying to solve the TEP problem. The most common approach is to use probability distributions for wind power, but no correlations are considered (even though models for this exist e.g. [60]). Such methods have also the disadvantage that they do not model inter-temporal constraints. On the other hand, the approach proposed in [62] uses a unit-commitment based assessment of transmission expansion solutions, where wind power time series were served as input. The approach has the advantage that it can consider correlation of wind and load at different locations (by using adequate time series) and also it maintains chronology when scheduling conventional generation (inter-temporal constraints). This method is used for comparing already proposed solutions. By contrast, in this thesis unit-commitment and economic dispatch simulations together with load flow calculations will be used for identifying bottlenecks and proposing reinforcement solutions.

Recent studies and research also focus on the development of offshore and/or onshore HVDC multiterminal grids [11–13, 68–70]. In Europe this is mostly with respect to offshore grids in the Northern seas and to a so called onshore pan-European “supergrid” connecting multiple countries and remote large-scale generation sites to consumer centers. The HVDC and HVAC grids are interlinked. Consequently planning methods need to be adapted for considering this new type of mixed HVAC - HVDC grids.

Chapter 3

Round-the-year network security analysis

The ongoing liberalization process together with the growing penetration of renewable energy sources (RES), e.g. wind power, require an internationally oriented transmission planning approach that considers the increased uncertainties in terms of trade, location of generation and output of (variable) generation. This chapter introduces a method for identifying and ranking bottlenecks, which is the first step of the transmission planning process for interconnected high-voltage grids. A round-the-year approach is proposed, by combining market simulations with static security analysis (introduced in Chapter 2). Many combinations of load and generation (including RES) are created and analyzed, using unit dispatch based on cost optimization. For each combination, the branch loadings are determined for normal and contingency situations. A statistical risk-based approach for ranking the most severe bottlenecks is developed. The method is illustrated on a modified New England test system where wind power was added at several buses. The risk of overload versus amount of installed wind power is also assessed. Furthermore, the method is applied in cooperation with TenneT TSO on a practical case study for a 2020 demand and supply scenario for north-western Europe, focusing on the Dutch power system.

3.1 Introduction

The ongoing liberalization process around the world has led to the emergence of energy markets, facilitating international trade between countries. Consequently, inter-area power exchanges have significantly increased and further growth can be foreseen. At the same time, the increased penetration of variable renewable energy sources in the European grid has been impressive in recent years and further grid-connections of large-scale onshore and offshore wind power installations are planned in order to meet Europe's environmental targets for 2020 and further.

Both developments increase the variability of the power flows in the system and require a more international orientation and coordination of the planning process. Furthermore, increased uncertainties (trade, location of generation and output of renewables) must be incorporated during the planning process. Most of the existing transmissions planning methods make use of a worst-case approach [8]: a security analysis is performed for one or a small number of cases, which should stand for all possible combinations of load, generation and interchange.

With the increased uncertainty and the many assumptions necessary for the analysis, a large number of "worst cases" is likely to exist, which must be captured in order to achieve a robust planning under a variety of possible scenarios. Hence in Europe some TSOs (in France and Spain [65]) and projects of European interest (the EWIS [66] and TRADEWIND [67] studies) have started to adopt more probabilistic methods for assessing the transmission grid, as surveyed in [8]. Especially the large-scale wind power integration is a driver for this.

The US Midwest Independent System Operator (ISO) also considers the relationship between wind integration and transmission expansion in its value-based transmission planning. The expansion plans are economically driven and are tested in parallel during their development with traditional reliability calculations to ensure system security. Wind power is considered within the market simulations, which are performed for one or more years within the planning horizon ([73]) and which are used for providing the necessary information for designing the grid. At the inter-regional level in the US, a coordinated joint planning effort between more ISOs has adopted the same value-based approach [74]. It should be emphasised that the security analysis is based on snapshots in both [73]-[74].

At international (or inter-regional) level, when there are many load and wind power variations for the different countries (areas) that participate in a regional transmission expansion, chronology (inter-temporal – between different time steps– constraints when scheduling resources over a given time horizon such as ramp up and ramp down rates of generators) and correlation between load and wind power based on measurement data, become even more important than at national level. To this purpose, a probabilistic approach combining chronological market simulations and static security analysis to deal with uncertainties was introduced in [75] and is proposed and further developed in this work. In order to handle the increased variability of power flows in the system many combinations of load, conventional generation and renewables are created and analyzed, using unit dispatch based on operational cost optimization. The correlation aspect is also considered by using simultaneous load profiles and wind speed measurements. For each combination of load and generation the branch loadings are determined for normal and contingency situations via load flow analysis. Subsequently, criteria are developed to rank the most severe bottlenecks which will become the main problems to be solved. This approach does not consider voltage constraints in the first place. As for speeding up the calculations a linearised (DC) load flow for contingency analysis is used, where the voltage issues are neglected. Moreover, the target of this approach is the interconnected transmission grid, and it is assumed that each TSO solves locally its own internal voltage problems.

In contrast to the other approaches, the proposed method has the advantage of considering both chronological and correlation aspects within the market simulations and performing after that security analysis for all the simulated time steps (hours). Thus, this method is also adequate for security analysis at regional level.

The chapter is structured in three main parts. First, the round-the-year security analysis and the bottleneck identification method are explained together with the proposed ranking criteria. Secondly the method is tested on a modified New England test system. Furthermore, the method is applied on a practical case study of the Dutch grid for a scenario for the year 2020. At the end the main findings of the chapter are summarized.

3.2 Method formulation

3.2.1 Round-the-year approach

Figure 3.1 shows the proposed round-the-year approach within the network planning process, underlining the need to also consider the uncertainties introduced by wind power. The methodology is focused on the first steps of the planning process, namely on the power system security analysis part which refers to finding transmission grid bottlenecks and deciding which are the most constrained grid elements. In particular, a round-the-year approach is adopted by combining market simulations (where wind integration is considered) with hourly load flow analyses (which constitute the round-the-year security analysis) as illustrated in Figure 3.1.

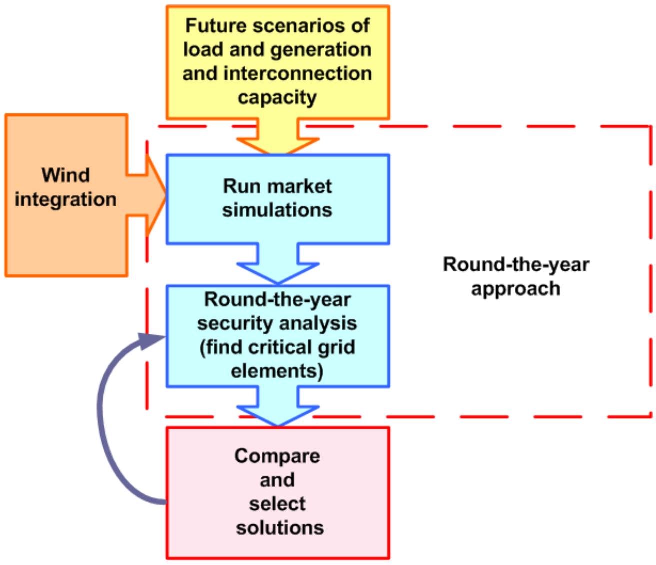


Figure 3.1: Round-the-year security analysis within the planning process.

Instead of performing load flow analysis for only a few worst cases, this method proposes to perform it for each hour of the year. Such a method has the advantage of clearly highlighting the structural rather than incidental bottlenecks. Moreover, since this method is based on prognoses of wind speed time series per location, it is expected that analyzing one year (or more if desired) of data will automatically capture a representative number of worst-cases, together with their probability of occurrence. The results can be used for comparing and selecting solutions which might be network reinforcements or congestion management measures (which means redispatching the generation in order to alleviate bottlenecks).

3.2.1.1 Market simulations

Establishing the balance between the production and demand of electricity depends on many parameters such as availability of primary energy sources, prices of fuel, bidding strategies, generation dispatch, etc. The way generation covers the demand from moment to moment can be modeled with the help of market simulations. The implicit assumption here is that the market operates perfectly: the system marginal price is set by the operating cost of the most expensive unit on-line during a given time period. For the implementation of the proposed method, a probabilistic multi-area, multi-fuel chronological simulation model is used that can handle technologies such as combined heat and power, energy storage, wind power and hydro power.

For the market simulations the tool called Powrsym3 [76] is used. Powrsym3 adopts a zonal market model, where the physical grid is not considered. Unit outages are modeled using a Monte Carlo method for a given time period. The power system operation is simulated by the means of a total generation system operational cost minimization (including fuel costs and emission penalties) in user-definable sequential time steps, while taking into account many technical constraints such as minimum up and down times of power plants, ramp rates of power plants, start-up costs, spinning reserves requirements, etc. In this thesis 1-hour time steps are adopted. The model is fully adapted to handle systems with large-scale wind power; multiple, chronological, correlated wind power time series can be input to the model. In addition, in order to accurately simulate production cost, unit maintenance can be scheduled and system reliability indices can be calculated.

The presented method does not depend on a specific software tool, which means that also tools with similar characteristics can produce a valid output to be further used in the security-analysis approach. In the market calculations only the inter-area transmission capacities allocated to the market are considered, while the networks of different areas are seen as a "copper-plate". For the European power system, such a consideration is correct as the electricity market adopts a zonal operating model that neglects the internal grid. But for the network security analysis it is necessary to see what the real power flows in the grid are using a detailed network model. Hence, for every hour considered in the market calculations, it is investigated what the effects of the generation and load distribution on the network security are. Because it considers all the hours of the year, this analysis is called round-the-year security analysis and is performed as explained in section 3.2.1.2.

3.2.1.2 Round-the-year security analysis

The real power flows that may occur in the network as a result of the generation and load patterns obtained from the market simulations are determined via load flow and security analysis. Given the load demand at all buses of the electric power system and the generation of each power plant, the power flow through each line and transformer of the interconnected network can be determined for different network situations. The flows in the network are determined for operation of the grid with all N elements, with N-1 or, for some specific cases, with N-2 elements in service. For each hour simulated by the market calculations, the load flow analyses are repeated. Hence every hour of the year is analysed, each with its own operating point with different values for load and generation at the nodes of the network.

This round-the-year network security analysis process implies a large number of calculations to be performed with specialized load flow analysis software (such as PSS/e). The results are also numerous and it is important to be able to process them in a structured manner. Hence, there is a need to make a compromise between precision and computation time. A combined AC-DC calculation approach is used, by performing an AC load flow for the normal operating situations (with all N elements in service) and DC load flow contingency analysis for the N-1 and N-2 states. It is also possible to use a DC-DC approach (where a DC load flow is run for the N situations and also for N-1 and N-2 situations), in cases when convergence is an issue. For better results, it is recommended to adopt an AC-DC approach. In this thesis the software PSS/e version 32 is used for the load flow calculations.

3.2.1.3 Coupling market simulations and load flow analysis

In order to be able to perform the load flow calculations for a given moment in time, first generation and load must be specified at the nodes of the specific grid. It should be mentioned that when one examines a distant year in the future, many uncertainties regarding the location of power plants and of loads arise. Hence a set of assumptions must be made in the process of attributing load and generation to the network nodes. These assumptions may differ from case to case depending of the data availability [75], [77], [78] but they are not the subject of this work. The nodal distribution has to be done repeatedly, for all the hours in the year. For each hour, load and generation are attributed to the grid nodes and then the security analysis is performed and finalized with an output report. Therefore an automated process must be created for allowing a rapid and continuous execution of all the steps.

Figure 3.2 illustrates the implementation of the proposed method, showing the interaction between market simulations and load flow analysis. The market simulations have two inputs, 1a and 1b. Input 1a contains the generating units database (generation technology, heat rates, emission penalties, ramp up and ramp down rates, start-up costs, fuel costs, forced outage rates, maintenance outage rates, etc), wind series (average hourly wind power

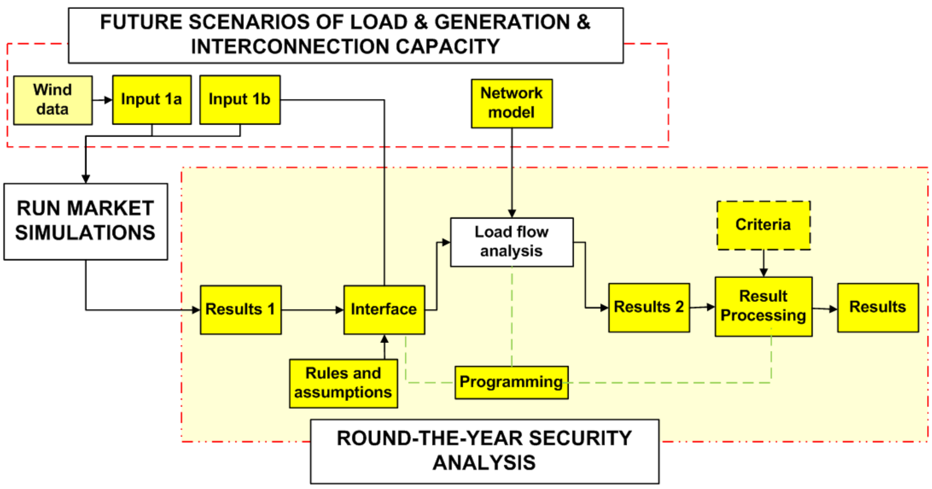


Figure 3.2: Block diagram of the round-the-year approach.

production) and inter-area flow constraints. Input 1b is the load data for the study period, as average hourly values; the load data is also an input for the security analysis.

The output of the market simulations (Results 1) is the hourly status and production of each generation unit (including wind power production) as well as the hourly programmed interchange between different areas. Results 1 together with Input 1b are further processed via an interface where specific assumptions for attributing load and generation to the nodes of the grid are made and sent as an input to the load flow analysis tool together with the model of the network (topology, transformer and line parameters). This process is repeated for each hour of the study period and the output is Results 2 consisting of hourly loadings of the grid elements for the normal situation and contingency situations.

Because of the large amount of data these results have to be post-processed using ranking criteria for indicating the weakest links in the network in order to present results that can contribute effectively to the decision-making process. The ranking criteria will be described in section 3.2.2.

The process of exporting the hourly market simulation results into the load flow model is automated using Python 2.5. Python is an open-source powerful dynamic programming language that can be used to interact with the load flow tool PSS/e via an application programme interface (API). An additional advantage is that interfacing with Microsoft Excel and ASCII files is a default capability. The numerous ASCII files with the hourly reports of load flow calculations can be easily processed with Python. Excel templates are used for providing the input to the load flow calculations, and the results of the processed results of the security analysis are saved in Excel format also. This provides both transparency in the generated cases and capabilities to visualise the results. In the analysis of the aggregated results, specific cases can be easily reproduced and can be used for further analysis and validation.

3.2.2 Bottleneck ranking process

The criteria for choosing the weakest links in the network are developed based on a statistical analysis of the results. Whereas the time dimension is absent in the classical snapshot method, in the proposed method it plays an important role within the severity ranking process. Moreover, since more aspects determine the results regarding the severity of a bottleneck, a multi-criteria ranking method as shown in Figure 3.3 is adopted.

For each generation and load scenario, bottlenecks are ranked firstly per network status situation (N, N-1 and N-2). Then they are further ranked per scenario, and finally aggregated for more scenarios according to their likelihood. The ranking is done according to certain calculated severity indices.

In subsection 3.2.2.1, the criteria to be considered in the decision-making process are illustrated. After that, the multi-criteria ranking method is explained more in detail in subsection 3.2.2.2 including the calculation of the severity indices.

3.2.2.1 Bottleneck ranking criteria

In this section the criteria that can be used in the bottleneck ranking process are defined. These criteria are formulated for the N, N-1 and the N-2 situations.

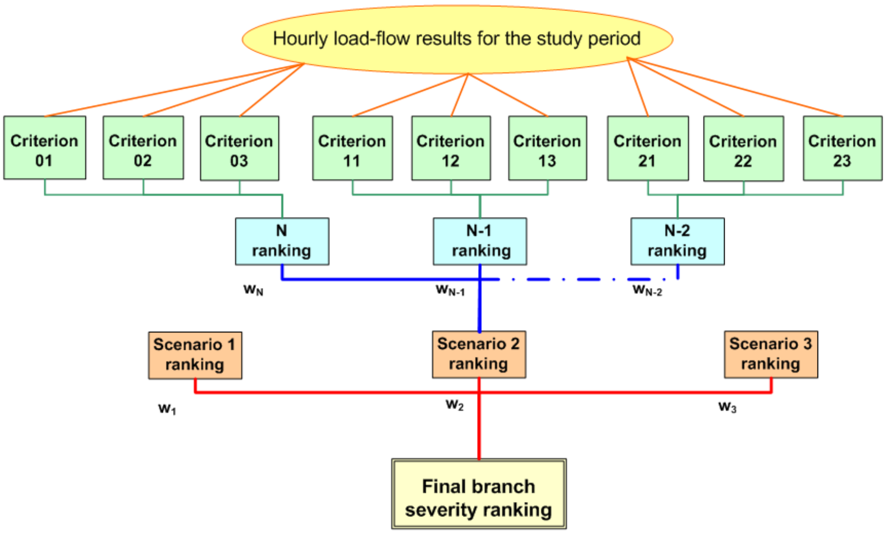


Figure 3.3: Multi-criteria bottleneck ranking.

a) The normal (N) situation The examined criteria are:

- C01: branch loading median for the overloaded hours,
- C02: total number of overloaded hours,
- C03: maximum loading of overloaded equipment.

Figure 3.4 a) shows an example of a loading-duration curve for a given branch. A loading-duration curve is similar to a loading curve but the data is ordered in descending order of magnitude, instead of chronologically. With such a curve it can be easily visualized how often values are very high or very low. Of interest here are the overloads that occur when the loading is higher than a percentage of the elements rated capacity as agreed by the involved TSOs. It is assumed here that an overload occurs above 100% rated capacity. Hence from the previous curve only the first part with loadings over 100% rated capacity is extracted. The resulting curve can be named overload-duration curve of a branch, as illustrated in Figure 3.4 b). The three criteria are also depicted in this figure.

a) The N-1 situation The examined criteria are:

- C11: branch loading median for the overloaded hours,
- C12: total number of overloaded hours,
- C13: maximum loading of overloaded equipment,
- C14: the total number of branches that can be congested due to a given branch being off service,

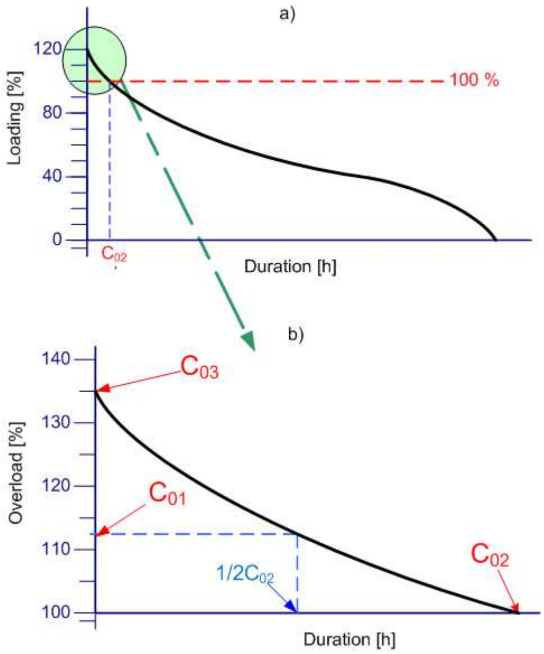


Figure 3.4: a) Loading-duration curve for a branch; b) Overload-duration curve for a branch with indication of the criteria.

- C15: the total number of branches that if taken out cause the congestion of a given branch.

For each simulated hour there are many N-1 contingency situations and therefore the same number of loading values for each transmission element. Hence it is important to decide on how the results are to be interpreted. For this reason only the maximum (hourly) loading for each transmission element during an arbitrary N-1 contingency is considered.

$$MaxLoading_{i,t} = Max\{\text{load branch } i \text{ in hour } t\text{, during N-1}\}, t \in \text{study period} \qquad (3.1)$$

Using this value, the *maximum N-1 loading - duration curve* and furthermore the *maximum N-1 overload - duration curve* can be obtained for each branch. Using this curve, criteria C11, C12 and C13 can be identified similarly to C01, C02 and C03 in Figure 3.4 b). Criterion C14 is calculated as the sum of all the branches that were congested in the study period while branch *i* was absent. Similarly, C15 is calculated as the total number of N-1 situations in which congestion on branch *i* occurs in the study period.

c) The N-2 situation The examined criteria are:

- C21: branch loading median for the overloaded hours,
- C22: total number of overloaded hours,
- C23: maximum loading of overloaded equipment.

These criteria are defined similarly to C11, C12 and C13 by considering the maximum loading-duration curves for N-2 situations.

3.2.2.2 Risk of overload and severity ranking of bottlenecks

For each of the three situations (N, N-1, N-2) the same procedure is applied. The severity ranking index of a branch for a situation is given by the risk of overload for that branch. The risk of overload is computed as the product of the total overloaded hours and the branch loading median for the overloaded hours minus the 100% overload threshold. Hence the risk of overload for branch i during the N situation ($RO_{N,i}$) is:

$$RO_{N,i} = (C01_i - 100) \cdot C02_i \text{ [\% of rated capacity} \cdot \text{hours]}, \; i = 1..N_B \tag{3.2}$$

Similarly the risk of overload for a branch during the N-1 situations is illustrated in Figure 3.5 and given by the formula:

$$RO_{N-1,i} = (C11_i - 100) \cdot C12_i \text{ [\% of rated capacity} \cdot \text{hours]}, \; i = 1..N_B \tag{3.3}$$

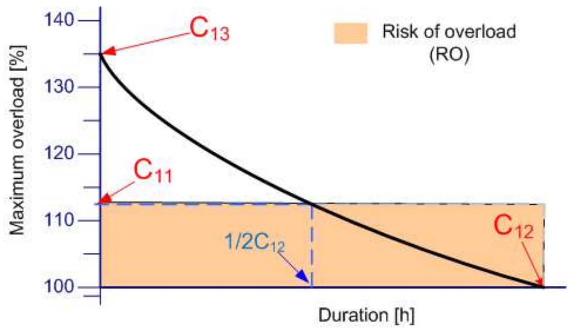


Figure 3.5: Maximum overload-duration curve for a branch and the calculated risk of overload.

The risk of overload during the N-2 contingency situations is:

$$RO_{N-2,i} = (C21_i - 100) \cdot C22_i \text{ [\% of rated capacity} \cdot \text{hours]}, \; i = 1..N_B \tag{3.4}$$

In planning, a scenario describes a possible future of load and conventional and renewable generation (including wind power) development. If N_s is the total number of future scenarios and N_B the total number of branches in the system analyzed, then the severity index for each scenario and each branch can be computed as a weighted sum:

$$SI_{s,i} = [w_N \overline{RO}_{N,i} + w_{N-1}\overline{RO}_{N-1,i} + w_{N-2}\overline{RO}_{N-2,i}]_s \tag{3.5}$$

where $w_N + w_{N-1} + w_{N-2} = 1$, $s = 1..N_s$, $i = 1..N_B$. $SI_{s,i}$ is the severity index for scenario s and branch i; w_N, w_{N-1}, w_{N-2} are the weighting factors for the N, N-1 and N-2 situations respectively; $\overline{RO}_{N,i}$, $\overline{RO}_{N-1,i}$, and $\overline{RO}_{N-2,i}$ are the normalized values of the risks of overload computed in Eq. 3.2, 3.3, and 3.4. The normalized risks of overload are calculated according to Eq. 3.6, where $maxRO_{sit}$ is the maximum risk of overload during situation *sit* for all N_B branches and all N_s scenarios.

$$\overline{RO}_{sit,i,s} = \frac{RO_{sit,i,s}}{maxRO_{sit}} \tag{3.6}$$

where $sit = \{N, N-1, N-2\}$, $i = 1..N_B$, and $s = 1..N_s$.

At very little overloads during N situation with respect to N-1 situations the normalization can distort the results. In order to prevent that, for cases when the number of overloaded hours during N-1 situation (C12) of the top N-1 situation bottleneck (which has $maxRO_{N-1}$) is at least 100 times higher than the number of overloaded hours during N situation (C02) of the top N situation bottleneck (which has $maxRO_N$), the first term of Eq. 3.5 corresponding to $\overline{RO}_{N,i}$ is ignored.

The values of the above mentioned weights should be set according to the preferences of the decision-maker and based on the requirement for the TSO to ensure the security of electricity supply in the area under its responsibility. After consulting with transmission planning experts [79], values in the range of w_N= 0.6-0.5, w_{N-1} = 0.3-0.4 and w_{N-2} = 0.1 were chosen. Note that the choice of weights is influencing the values of the severity indices and maybe also the ranking order of the various bottlenecks. However all detected overloads are presented to the decision-maker, ordered from most to least severe, together with their bottleneck ranking criteria for each scenario.

For an overall view, an aggregated severity index for all studied scenarios can be obtained (see Figure 3.3), with higher weights assigned to the more likely scenarios. The final severity index of branch *i* can be computed as:

$$SI_i = \sum_{j=1}^{N_s} w_j SI_{j,i},\ i = 1..N_B,\ \sum_{j=1}^{N_s} w_j = 1 \tag{3.7}$$

where w_j are assigned to individual future scenarios j.

The aggregation can be performed if an overall ranking for more scenarios is needed. However, scenarios are usually compared instead of being aggregated. This is the normal practice of TSOs. In this way the differences between various scenarios can be compared and analysed. In this case Eq. 3.7 is not needed.

An observation is that the severity indices are always a relative measure which depends on the set of scenarios analysed. The severity indices help to present the information in an aggregated way for all situations (N, N-1 and N-2). For absolute measures of overloading in N, N-1 and N-2 situations, the risks of overload should be used.

The remaining criteria (C03, C13, C14, C15 and C23) can be further used by the decision makers if more information is needed for prioritizing bottlenecks and recommending solutions for eliminating them. After obtaining the final bottleneck ranking for all elements in the system, further investigations can be also done. For observing if the voltage is within limits, AC contingency analysis can be performed on some identified critical moments in time. System stability issues can be also investigated if needed for the most critical cases.

3.2.2.3 Risk of overload related to installed wind power

For assessing the risk of overload in the system related to the exploitation of renewables (in terms of installed capacity), different scenarios of installed wind power can be studied, and separately, with the proposed method, the severity indices per scenario for all the branches in the system can be compared. Conclusions can be formulated regarding the influence of the installed wind power capacities level on the congestion in the grid and consequently on the need of grid reinforcement. The focus in this work is on a multi-area analysis where the risk of tie-line congestion is quantified.

3.3 Method testing

In this section the method proposed in the previous section is tested.

3.3.1 The New England test system

As a case study, the 39-bus New England test system is used [80]. This system consists of 46 branches (lines and transformers), 10 generators and 39 buses (see Figure 3.6). The system is modified in order to fit the needs of this study. It is assumed that bus 31 connects a wind power plant. Two more buses (40 and 41) are added to the system, and they connect wind power generation to the rest of the system via two new branches (transformers) between buses 41 and 25 and between buses 40 and 21. Therefore the system becomes a 41-bus system with 12 generators, 41 buses and 48 transmission branches. All branches are assumed to have a rated capacity of 900 MVA.

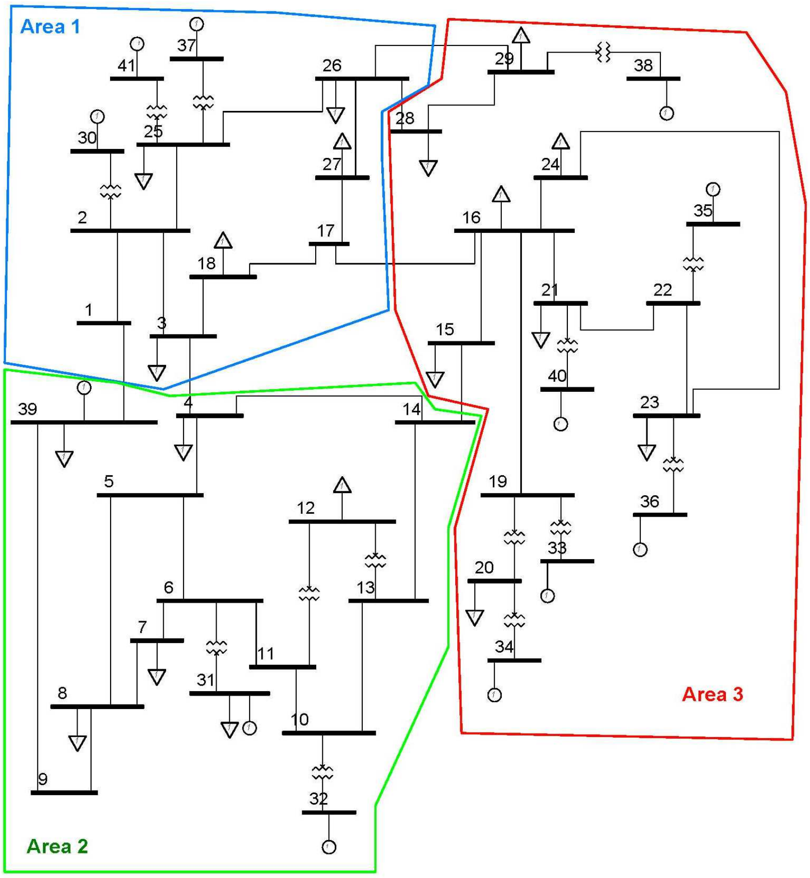


Figure 3.6: New England test system.

Furthermore, the system is split up into three interconnected areas: Area 1, Area 2 and Area 3. The three areas are connected by the branches illustrated in Table 3.1.

Table 3.1: New England interconnectors.

Areas	**Branches [bus no. - bus no.]**
Area 1 - Area 2	1 - 39; 3 - 4
Area 1 - Area 3	26 - 29; 26 - 28; 16 - 17
Area 2 - Area 3	14 - 15

The loads are not fixed to the values given in the original system. Instead, three load curves for one year (hourly values) are taken from a real system and are scaled relative to the peak load values of these time series. These relative values (between 0 and 1) are multiplied by the area total load values specified for the original New England system.

Also, the data for the generators is enhanced and made consistent with current conversion technologies and fuel prices. The types of generators used in the test system are given in Table 3.2. In this table also the installed wind capacity is given. This example is used for the method validation. Wind power time series based on measured wind speed data are scaled to the installed wind capacity considered for the studied scenario. It is important to mention that the load and wind input data are chronological and correlated, and span one year of hourly averages. A perfect forecast is assumed for both wind and load. After running the market simulations, the output of each generating unit is obtained together with other information as exchanges between areas. Within the market simulation the transmission capacity limits between the three areas are enforced.

Table 3.2: Types of generation in the New England test system.

Area	**Plant type**	**Installed capacity [MW]**	**Utilization factor [%]**
Area 1	Lignite bus 37	965	85
	Gas bus 30	640	22
	Wind bus 41	300	41
Area 2	Coal bus 39	1100	59
	Gas bus 32	$185 \cdot 2$	33
	Wind bus 31	400	24
Area 3	Coal bus 38	1050	82
	Gas bus 33	$200 \cdot 2$	4
	CCGT bus 35	790	79
	CCGT bus 34	625	33
	CCGT bus 36	699	40
	Wind bus 40	400	38

In Table 3.2 the resulting utilization factors of each power plant for the studied year are given, whereas Table 3.3 presents aggregated information at area level for load, total generation, imports and exports.

The time needed for the round-the-year security analysis together with the results processing is 1 hour in the case of the New England test system, for which 37 N-1 outages were used. The simulations were performed on an Intel(R) Core(TM)Duo CPU E6550 @2.33 Ghz, 2 GB of RAM.

Table 3.3: Generation, load and exchange data for New England.

Area	Total demand [GWh]	Total generation [GWh]	Imports [GWh]	Exports [GWh]
Area 1	7249	9497	750.7	3008.5
Area 2	13306	7545.7	5755.1	17.8
Area 3	15280	18759	194.9	3674.5

3.3.2 Detailed security analysis; comparison with the snapshot method for Area 1

In this section a comparison between the snapshot method and the proposed round-the-year method is made in order to show that the round-the-year method gives more in-depth results. For purposes of illustration this comparison is shown for Area 1. Two seasonal peaks (summer (hour 3804) and winter (hour 8466)) are identified from the load curve for Area 1 for the snapshot method.

In Figure 3.7 the loadings of the 13 branches belonging to Area 1 are shown for the snapshots related to the N and N-1 situations. It can be noticed that during the summer peak there are no overloads. The winter peak gives 9 overloaded branches for the N-1 contingency situations, and no overload for the N situation.

Figure 3.8 shows the aggregated results for the round-the-year security analysis. The risks of overload are computed as in Eq. 3.2 and 3.3 and then normalized relative to the maximum risk of overload during N and N-1 respectively. The aggregation is done according to Eq. 3.5 and with the weights for 0.67 for the N situation and 0.33 for the N-1 situation. All 11 branches in the figure are overloaded at least once in the study period. The other two branches of Area 1 (not shown in Figure 3.8) are never overloaded. Because in this example the maximum risks of overload for N and N-1 do not coincide for the same branch, the severity index for the top bottleneck (branch 2-3) is smaller than one.

Table 3.4 shows the most important results of the classic snapshot based security analysis and of the round-the-year security analysis. While in the snapshot a number of overloads were identified only at the winter peak during N-1 situations, by using the round-the-year analysis it was noticed that actually already in the normal situation 3 branches are overloaded and in the N-1 situation 11, in comparison to 0 and respectively 9 overloaded branches in the snapshots. It can be concluded that the snapshot method misses a number of overloaded situations.

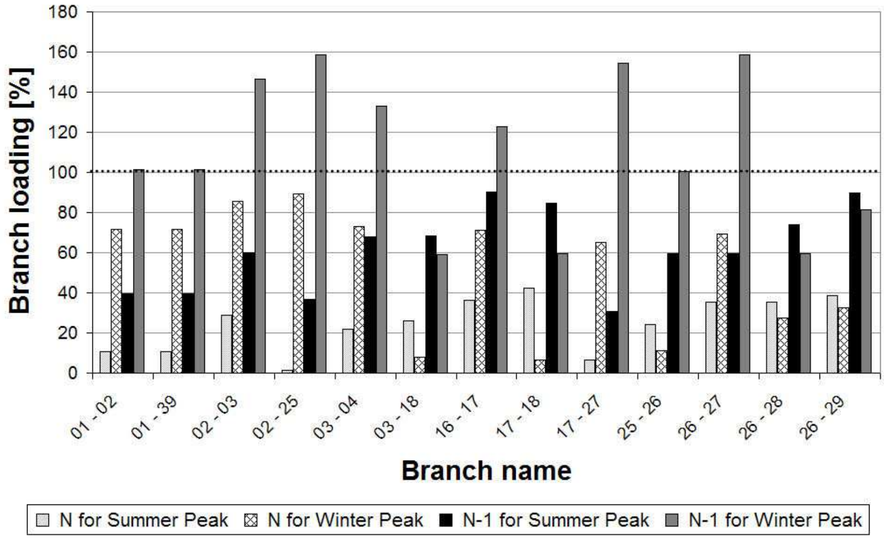


Figure 3.7: Area 1 branch loadings for the winter and summer peaks.

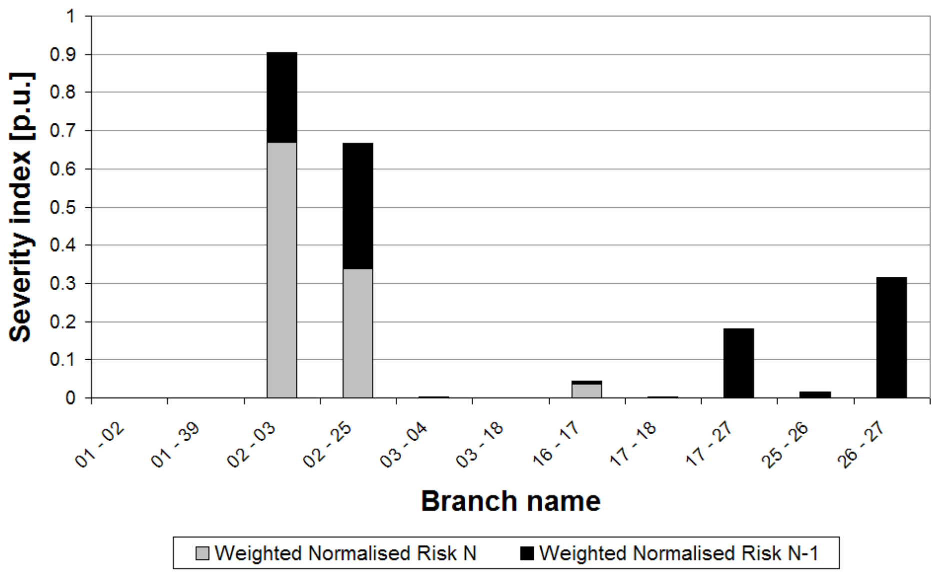


Figure 3.8: Bottleneck ranking for Area 1.

Table 3.4: *Security analysis results: round-the-year versus snapshot.*

Branch	Snapshot	Round-the-year					
	Winter Peak N-1 max loading [%]	C01 [%]	C02 [h]	C03 [%]	C11 [%]	C12 [h]	C13 [%]
01 - 02	101.6	0	0	0	120.6	8	129.3
01 - 39	101.6	0	0	0	120.6	8	129.3
02 - 03	146.3	109.6	246	135.4	137.5	7302	219.7
02 - 25	158.7	102.6	464	109.8	153.8	7139	185.6
03 - 04	132.9	0	0	0	106.0	671	142.3
03 - 18	59.1	0	0	0	103.4	131	131.1
16 - 17	122.9	104.2	31	115.9	111.0	583	180.2
17 - 18	59.5	0	0	0	108.2	536	127.5
17 - 27	154.5	0	0	0	132.3	6495	166.9
25 - 26	100.6	0	0	0	106.6	2794	140.2
26 - 27	158.8	0	0	0	155.3	6637	185.6

Table 3.5: *Bottleneck ranking for Area1: snapshot versus round-the-year security analysis.*

Rank	Snapshot		Round-the-year	
	Branch name	Winter Peak N-1 Max Loading[%]	Branch name	Severity Index [p.u.]
1	26 - 27	158.8	02 - 03	0.905270
2	02 - 25	158.7	02 - 25	0.667438
3	17 - 27	154.5	26 - 27	0.315349
4	02 - 03	146.3	17 - 27	0.180250
5	03 - 04	132.9	16 - 17	0.042642
6	16 - 17	122.9	25 - 26	0.015844
7	01 - 02, 01 - 39	101.6	17 - 18	0.003753
8	–	–	03 - 04	0.003459
9	25 - 26	100.6	03 - 18	0.000383
10	–	–	01 - 02, 01 - 39	0.000141

Moreover the round-the-year approach gives more relevant results as it captures better the severity of the bottlenecks. Table 3.4 illustrates that for example line 16-17 in the snapshot is not overloaded for the normal situation and during N-1 it is overloaded with a loading of 122.9% of rated capacity. The round-the-year approach shows that actually there are hours when the line is more heavily loaded in both N and N-1 situations, in N-1 reaching a maximum of 180.2%.

As a consequence of all the above mentioned, the ranking of the bottlenecks is different for the snapshot and the round-the-year method. Table 3.5 illustrates the changing in ranking together with the ranking values. It can be noticed that the differences between ranks are clearer with the round-the-year approach.

3.3.3 New England tie-lines overview

In actual regional studies with more interconnected areas, where individual areas are modeled possibly in a more simplified way, the focus could be on interconnectors only. Consequently, in this section an overview of the bottleneck ranking results for the tie-lines in the New England system is made.

Table 3.6 shows the main criteria and the normalized risks of overload for the normal situation and for the N-1 situations respectively. The bottleneck ranking according to the severity index is shown in Figure 3.9. The aggregation is done according to Eq. 3.5 and with the weights for N and N-1 situations, of 0.67 and 0.33 respectively.

Table 3.6: Tie-lines: main criteria and risks of overload.

Border	Branch	C01 [%]	C02 [h]	$\overline{\mathrm{RO}}_{\mathrm{N}}$	C11 [%]	C12 [h]	$\overline{\mathrm{RO}}_{\mathrm{N-1}}$
A 1 - A 2	01 - 39	0	0	0	120.6	8	0.025635
	03 - 04	0	0	0	106.0	671	0.627787
A 1 - A 3	16 - 17	104.2	31	1	111.0	583	1
A 2 - A 3	14 - 15	0	0	0	118.8	211	0.618556

The tie-lines that appear in Figure 3.9 have a severity index SI>0, and therefore they are congested. The top 3 bottlenecks are branch 16-17, followed by 3-4, and 14-15. Last in line is branch 1-39. By analyzing this together with the information shown in Table 3.3 it can be noticed that probably the reason for tie-lines 16-17, 3-4, 14-15 being the most congested ones, is the structure of the grid and the limited available interconnection capacity, in

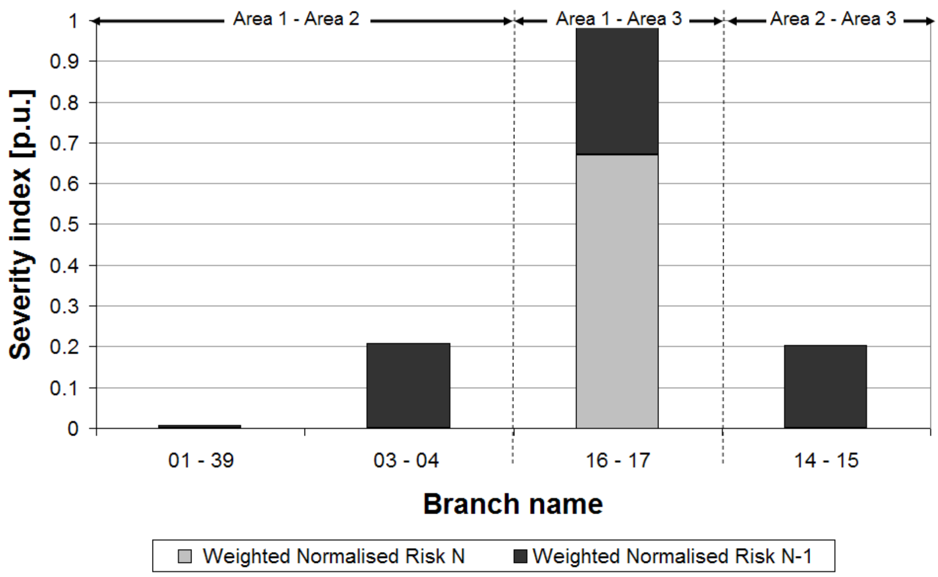


Figure 3.9: Bottleneck ranking for all the tie-lines.

combination with the high exports from Area 3 to Areas 1 and 2, and from Area 1 to Area 2. The subsystem formed by buses 28, 29 and 38 in Area 3 is not directly connected with the rest of the Area 3 buses (where most of the generation and load are concentrated), this leading to having only line 16-17 overloaded between areas 1 and 3.

3.3.4 Risk of overload with increasing wind power

An example of evaluating the risk of overload versus exploitation of renewables is presented in this section. The generation park is the same as in Table 3.2 except for the wind power. Three scenarios of installed wind power are considered as illustrated in Table 3.7. The tie-lines of the New England system are monitored. The purpose of this example is to see what

Table 3.7: Scenarios of installed wind power.

Area	**Installed Wind Power [MW]**		
	Scenario 1	**Scenario 2**	**Scenario 3**
Area 1	300	300	300
Area 2	400	800	1600
Area 3	400	800	1600

happens in the grid when the installed wind power is increased in Areas 2 and 3 (while in Area 1 it is constant). The three scenarios differ only through the wind power capacities. The load time series and other generation data are the same. New market simulations are run for the scenarios 2 and 3.

The comparison of the final severity indices is shown in Figure 3.10. The aggregation is done according to Eq. 3.5 and with the weights 0.67 for the N case and 0.33 for the N-1 case. The risks of overload are computed according to Eq. 3.2 and 3.3 and then normalized relative to the maximum risk of overload during N and N-1 respectively for all three scenarios.

It can be noticed that with the increase of installed wind capacities in Areas 2 and 3, the severity of the bottlenecks changes due to the shifting of generation output between the three areas. Figure 3.11 illustrates the generation mix for each of the three scenarios. In Areas 2 and 3 the conventional units decrease their production and more wind energy is produced. In Area 1 the lignite power plant maintains constant output in all three scenarios, due to its inflexibility, while the gas and wind power plants reduce their output as Areas 2 and 3 have to accommodate much more wind power.

Furthermore, Table 3.8 shows the total generation, imports and exports for the three areas under scenarios 2 and 3, while the same data for Scenario 1 was presented earlier in Table 3.3.

The total generation in Area 1 is decreasing while in Area 2 it is increasing. In Area 3 the generation slightly increases in Scenario 2, while in Scenario 3 it dramatically decreases. Consequently, the imports and exports change. Figure 3.12 gives a more detailed image of the area-to-area total energy transports under the three scenarios.

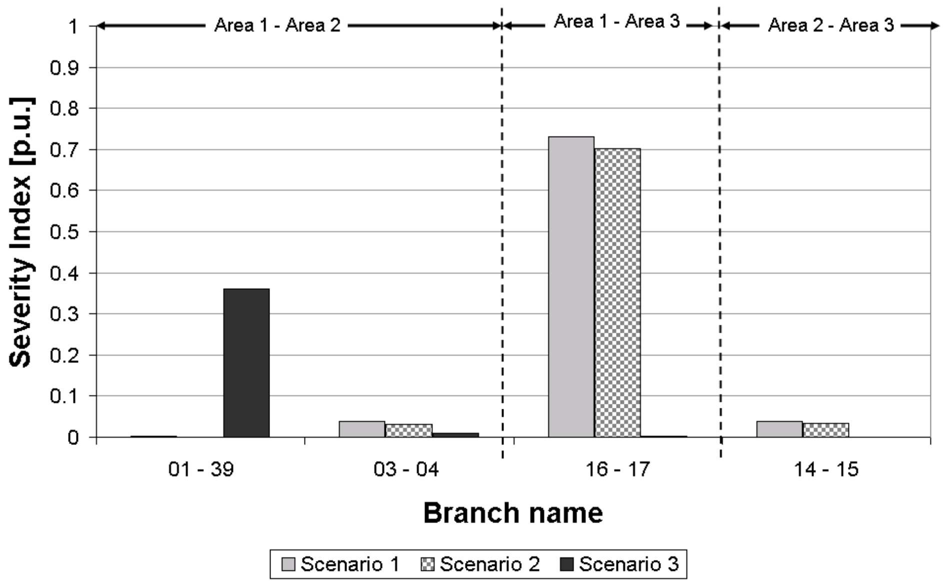


Figure 3.10: Comparison of severity indices for three scenarios of installed wind power.

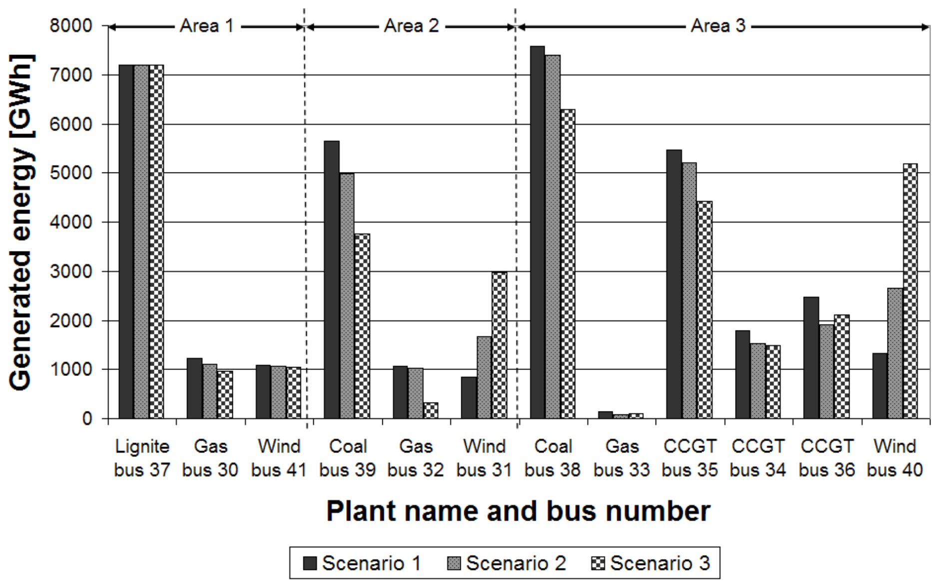


Figure 3.11: Generation mix for the three scenarios.

Table 3.8: Generation and exchange data - Scenarios 2 and 3.

Area	Scenario 2			Scenario 3		
	Generation	Imports	Exports	Generation	Imports	Exports
	[GWh]					
1	9367.3	766.5	2890.3	9187.4	621.6	2561.2
2	7664.1	5661.5	29	13343.7	1510	1547.8
3	18790.5	185.6	3694.3	13301.3	2511.2	533.8

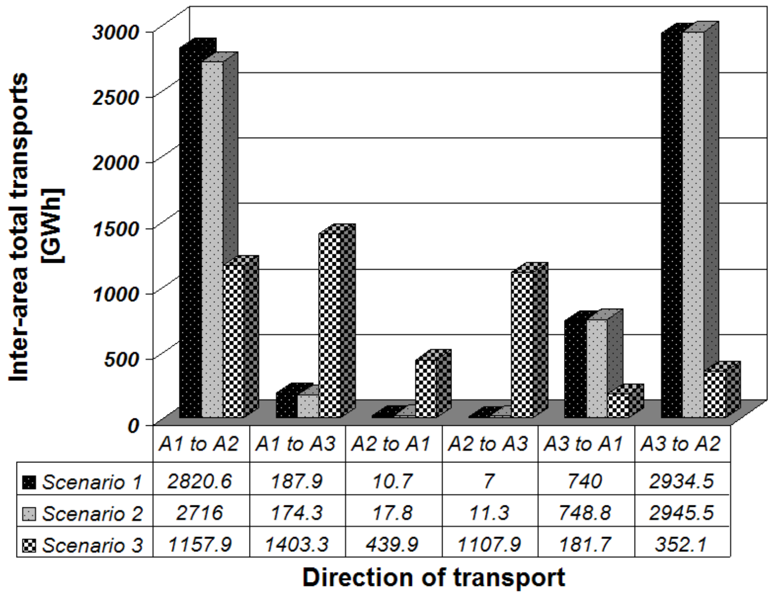


Figure 3.12: Inter-area total transports for the three scenarios.

3.4 Dutch power system case study

This section illustrates the method further by implementing it on a practical case study for a 2020 demand and supply scenario for North-Western Europe, focusing on the Dutch power system. The implementation has been done in collaboration with TenneT TSO. The market model has a larger perimeter (10 countries) than the grid model (5 countries) in order to more accurately reflect influences of generation, i.e. RES, and demand in the area outside the transmission grid planning focus area. Of course such an implementation brings many challenges in terms of coupling the market and the grid models, but this is not the purpose of the current section. More details can be found in [78] and in Appendix C. Running this method of combined market simulations and load flow calculations for a real system on a regular office computer is demonstrated. The results that are obtained with the round-the-year approach are compared to an analysis based on two snapshots of moments chosen in transmission grid planning for the same future scenario by TenneT, the Dutch TSO, in their 2011 Quality and Capacity Plan [81].

3.4.1 Case study description

3.4.1.1 Market model

The zonal market model is formed by detailed models of ten countries in Northwest Europe: Belgium, Netherlands, Luxembourg, France, Germany, Denmark, Sweden, Norway, Great-Britain, and Ireland. The model is split into 14 market nodes related to grid design while neglecting the internal bottlenecks. These market nodes are connected with each other by links of limited cross-border transfer capacities. Thermal power plants are clustered into 126 different categories. Furthermore in total 54 non-thermal generation categories are modelled. The hourly output of the market simulations constitutes the hourly planning cases for the studied year (2020). The underlying scenario is the EU 2020 scenario which has been used in [81].

3.4.1.2 Grid model

Loadings of selected branches in normal and contingency situations are determined using PSS/E version 32. A DC-DC contingency analysis is used. The grid model that is used to perform the calculations for the analysis, consists of a representation of the Dutch EHV grid (380 kV and 220 kV) and a small part of the HV grid (150 kV and 110 kV) where appropriate. Similarly a significant part of the HV and EHV of the neighbouring grids of Belgium, Luxemburg, Germany and France have been included. There are many interconnections between the modelled countries (38 tie-lines modelled), but also between the modelled area and the rest of the interconnected system (71 tie-lines modelled). Table 3.9 gives an overview of the elements within the grid model. The contingency analysis is performed only on the Dutch part of the grid. The surrounding countries are modelled to obtain realistic cross-border flows. Phase shifting transformers are set to their neutral position in all cases and no post-contingency generation re-dispatch is taken into account. A diagram of the Dutch EHV grid is given in Figure 3.13.

Figure 3.13: Map of the Dutch EHV grid (planned for 2020).

Table 3.9: Characteristics of the used grid model.

Element	Buses	Machines	Loads	Lines	Transformers
Total System	4876	2582	3711	5157	1713
The Netherlands	250	80	39	122	93

3.4.2 Results

3.4.2.1 Computational aspects

For this study case, N-1 and N-2 contingency analyses on the Dutch grid for a complete year are performed. The analyses are carried out on a regular computer with an Intel Core2 Duo P8700 processor at 2.53 GHz with 2.9 GB of RAM and a 320 GB hard disk. The computational characteristics are presented in Table 3.10. The vast amount of produced data exists partly due to the fact that for each hour a full contingency report is stored in a plain ASCII file which can be compressed at a later stage.

Table 3.10: Calculation reference.

Type	Contingencies [no.]	Monitored lines [no.]	Comp. time [h]	Storage [GB]	Compressed [GB]
N-1	133	119	5	9.4	0.6
N-2	1789	119	24	154.6	5.2

3.4.2.2 Overall results

Table 3.11 illustrates the main results of the round-the-year security analysis. All branches reported in the first column were congested at a certain moment under N, N-1 or N-2 condition.[1] For each of them the criteria C01, C02 and C03 (for the N situation), C11 to C15 (for N-1 situation) and C21, C22 and C23 (for N-2 situation) are computed. Using the criteria the risks of overload are computed, and ultimately the severity index is determined for each branch using the weights 0.6 for N, 0.3 for N-1, and 0.1 for N-2 situations. The results of the bottleneck ranking are shown in Figure 3.14 and Table 3.11. In Table E.1 from Appendix E, the link between node full name and node abbreviation can be found.

It can be noticed that the branch between MEE and DRT (connecting the substation of Meeden to the phase shifter in Meeden) is overloaded in N, N-1, and N-2 situations and is the most frequent occurring bottleneck. The next most frequently occurring bottleneck is given by the branch EHV-MBT (Eindhoven-Maasbracht), followed by the lines GT-KIJ (Gertruidenberg-Krimpen) and DIM-OZN (Diemen-Oostzaan). In addition, by looking at the C15 values it can be noticed that the most frequently occurring bottleneck (between MEE and DRT) is sensitive to 125 N-1 outages (almost all N-1 outages). Also the branch DIM-OZN is sensitive to 107 outages. The same line DIM-OZN is the most critical from the perspective of C14, meaning that 9 branches are affected by the outage of this line.

[1]Note: for the branches that have more identical parallel circuits, only the results for one circuit are presented because the results are the same for these circuits. Hence, the branch names refer to one circuit only.

Table 3.11: Results of the round-the-year contingency analysis.

Branch	C01 [%]	C02 [h]	C03 [%]	C11 [%]	C12 [h]	C13 [%]	C14 [br.]	C15 [out.]	C21 [%]	C22 [h]	C23 [%]
EOS-EEM	0	0	0	108	57	130.1	6	1	107.1	134	134.1
DIM-OZN	102.2	1	102.2	110.35	114	130.7	9	107	110.9	645	162.6
DIM-BKL	0	0	0	105.25	88	134.3	3	1	110.7	148	139.2
EHV-MBT	0	0	0	112.2	719	148.1	6	2	118.5	1067	169.9
GT-KIJ	0	0	0	107.45	252	132.6	6	1	112.6	690	152.4
HGL-ZL	0	0	0	103.3	71	118.3	3	1	105.7	342	128.7
KIJ-BKL	0	0	0	107.7	97	129.9	5	1	109.9	181	140.5
MEE-DRT	107.1	92	139.4	122.05	1190	224.3	3	125	123.2	1652	225.3
ENS-ZL	0	0	0	0	0	0	0	0	103.9	15	111.9
BVW-OZN	0	0	0	0	0	0	0	0	104.2	43	116.1
TBG-GT	0	0	0	0	0	0	0	0	105.7	388	127
TBG-EHV	0	0	0	0	0	0	0	0	113.6	1066	152

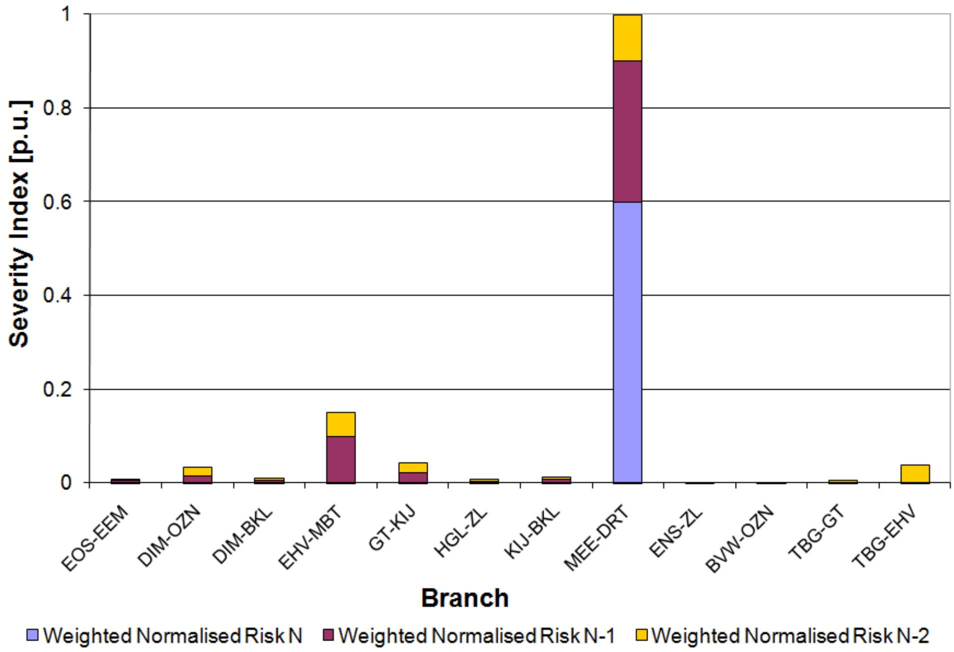


Figure 3.14: Bottleneck ranking for the normal, N-1 and N-2 situations in the Dutch EHV grid.

For getting a better picture of the cause-effect relationships between bottlenecks and outages, the relationship between them is analysed by means of a matrix containing the number of overload instances per outage. Table 3.12 shows such a matrix for the top 5 N-1 outages (in terms of number of overload instances). On the first row the outage names are listed and on the first column the bottleneck names. At the intersection of each row and column the number of instances of branch overload due to that outage can be found. The last row sums all the number instances of branch overloading per outage for the whole year.

Table 3.12: Top 5 N-1 outages measured in instances of overload on the 380kV grid.

Outage / Branch	MEE-DRT	EHV-MBT	GT-KIJ1	DIM-OZN	KIJ-BKL
EOS-EEM	0	0	0	0	0
DIM-OZN	1	7	3	0	109
DIM-BKL	0	0	0	88	0
EHV-MBT	0	*719*	0	1	0
GT-KIJ	0	0	*252*	0	0
HGL-ZL	0	0	0	0	0
KIJ-BKL	0	0	0	97	0
MEE-DRT	*1190*	82	80	79	76
Total no. of overloads	**1191**	**808**	**335**	**265**	**185**

3.4.2.3 Zooming into a specific bottleneck

From the results in the previous subsection it can be seen that the severity index of the branch MEE-DRT is the highest. When looking at the actual situation in the grid, this branch appears to be fully controllable due to a series phase shifting transformer in the substation of Meeden [82]. As stated before, in the current analysis the phase shifter settings have not been optimised hence it is assumed that the setting of phase shifters would resolve this issue in most of the cases. Therefore in this chapter the line with the second largest risk of overload (EHV-MBT) is zoomed into. This line is connecting the substations of Eindhoven and Maasbracht. The line EHV-MBT has been identified by TenneT in [81] as a bottleneck presenting N-1 and N-2 risks. One of the scenarios in that document is comparable to the underlying scenario for the results in this work, namely the EU2020 scenario. The results of the N-1 assessments on a high onshore wind situation and a high offshore wind situation, both in conjunction with high load are given in Figure 3.15.

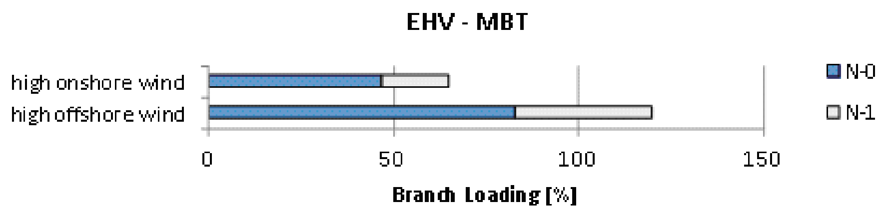


Figure 3.15: Results of the snapshot analysis for two high wind - high load situations [81].

One of the options for reducing this bottleneck is the increase of the rated capacity of the line itself. The line EHV-MBT currently has a rated capacity of 2.5 kA (1645 MVA at 380kV). The effect of increasing the rated capacity of the line to 3.0 kA (1975 MVA at 380kV) has been assessed. According to the conventional planning analysis, by increasing the line's capacity to 3.0 kA, the EHV-MBT line becomes N-1 safe. However, the round-the-year analysis gives different results as shown in Table 3.13. It can be seen that C12, the number of overloaded hours under N-1, decreased but settled at 205 hours. The risk of overload of line EHV-MBT reduces more than ten times because of the capacity increase, but does not disappear. Hence more or other grid reinforcement measures should probably be taken. For the other lines, the risks of overload do not change and are not reported in the table.

Table 3.13: Effect of increasing the rated capacity of the EHV-MBT line.

Case	Ampacity	C01	C02	C03	C11	C12	C13	RO_{N-1}
Current capacity	2.5 kA	0	0	0	112.2	719	148.1	8771.8
Increased capacity	3.0 kA	0	0	0	104.1	205	125.2	840.5

3.5 Scalability of the round-the-year security analysis

It was shown in this thesis that the round-the-year security analysis method is scalable for different power system sizes and thus can be used for both small and large power systems. Table 3.14 sums up the grid models on which the round-the-year security analysis is applied in this work (model 2 is used later in Chapter 5). Furthermore, Table 3.15 shows the total round-the-year security analysis computation time for the three grid models. For performing the calculations, regular computers were used: for models 1 and 2 an Intel(R)Core(TM)Duo E6550 CPU @2.33 Ghz, and for model 3 an Intel Core2 Duo P8700 CPU @2.53 GHz.

The time needed for the round-the-year security analysis together with the results processing was 1 hour in the case of the 41-bus New England test system (model 1), for which 37 N-1 contingencies were performed and 37 branches were monitored. In the case of the 316 bus EHV Dutch transmission grid with simplified representation of the Belgian and German grids (model 2), with 139 N-1 contingencies and 96 monitored lines, the security analysis together with the data processing took about 2.5 hours. For both models 1 and 2 an AC-DC approach was used (AC for the N situations and DC for the N-1 contingency situations). For grid model 2, due to convergence issues, multiple AC load flows had to be run in some cases. A third of the 2.5 h was taken by the data processing. In model 3 the transmission grids of the neighbouring systems were represented with a higher level of detail. In total 4876 buses can be found in the interconnected system. The analysis for 133 N-1 contingencies and 119 monitored lines, using a DC-DC approach, took 5 hours. Here also N-2 contingency analysis was performed separately from the N-1, using again a DC-DC approach (DC for the N situations and DC for the N-2 situations). This process took 24 h for 1789 contingencies and 119 monitored lines.

Table 3.14: The three AC grid models used in this thesis and their characteristics.

No.	Model	Buses	Generators	Loads	Branches
1	New England	41	12	19	48
2	NL + simplified BE, DE	316	209	87	421
3	NL + detailed BE, DE, LUX, FR	4876	2582	3711	6870

Table 3.15: Computation time comparison.

Model no.	Approach	Contingencies	Monitored elements	Computation time
1	AC-DC	37 N-1	37	1 h
2	AC-DC	139 N-1	96	2.5 h
3	DC-DC	133 N-1	119	5 h
3	DC-DC	1789 N-2	119	24 h

The computation time is determined by several factors which are discussed in the following.

- **Computer performance and parallel processing.** The computer used has a great impact on the speed of the calculation. However even on the regular computers used for the study cases investigated in this thesis, the computation time is acceptable. With computers having multiple processors parallel computing is possible, this leading to a significant reduction of the total computation time. The option of using multiple processors in parallel during the calculation has been added recently to some of the commercial power system analysis software.

- **Used load flow approach and case difficulty**. The load flow approach, namely AC or DC load flow, for the base case (N situation) and the contingencies situations (N-1, N-2) influences the computation time. The power flow problem of an AC power system is a non linear problem and therefore it should be solved by using an iterative solution method (AC load flow). Finding a solution is not guaranteed, as convergence may not necessarily be reached. As a simplifying alternative the so called DC load flow or better said linearised load flow method can be used, which adopts a simplified linear model of the AC system and is not iterative, therefore always providing a solution. Summing up, DC load flow is faster but less accurate, while AC load flow gives more accurate results but is slower than the DC load flow, and in addition it may not converge. In this thesis AC-DC and DC-DC approaches are used. For solving the convergence issues of the AC calculations, in Chapter 5 subsequent load flow calculations are performed, and this is also increasing the computation time. If an AC-AC approach was to be used, an automated method for solving as many as possible of the convergence issues should be developed. There are different AC load flow methods, which bring their own advantages and disadvantages with respect to computation speed and ease of reaching convergence. In this thesis the Newton-Raphson method was used (when AC load flow was performed), which generally has a good convergence rate no matter the size of the system [83]. Another aspect to be noted here is the complexity of the load flow cases. If there are many difficult cases with respect to reaching convergence when using AC load flow methods, this will add to the computation time.

- **Data processing efficiency.** The efficiency of the approach used for reading and writing files during the data processing phase also plays an important role, as if programmed poorly could result in very high computation time. In this work the data processing has been already optimized, but further optimization is still possible and could probably make the process even more efficient.

- **Size of the grid model** The size of the grid model will also impact the computation time largely. By comparing models 2 and 3 for N and N-1 contingency analysis, it can be noticed that the computation time is double in the case of model 3 (5 h for model 3 and 2.5 h for model 2). Although the number of contingencies and monitored lines is comparable, the grid model 3 is much bigger than model 2 (i.e. 15 times more buses and 16 times more branches in model 3).

- **Number of contingencies and number of monitored elements.** The number of contingencies to be performed and the number of monitored elements will also influence strongly the total duration of the computation. First, the number of contingencies determines the number of load flow calculations that have to be performed for every hourly snapshot. Moreover the number of contingencies will also increase the amount of data to be processed, leading to a further increase in computation time. By comparing the analysis for N and N-1 situations to the one for N and N-2 situations in the case of grid model 3, we can see that the only parameter that changed was the number of contingencies (139 N-1 versus 1789 N-2). The high number of contingencies in the N-2 contingency analysis leads to a total computation time of 24 h in comparison to the 5 h needed for the N-1 contingency analysis. This means that for an increase of 13.5 times in the number of contingencies, the computation time is almost 5 times longer for a DC-DC approach. Similarly, the number of monitored lines will impact the simulation time from the point of view of data processing. This is due to more load flow results having to be written on the hard-disk and further processed.

3.6 Summary

In this chapter a statistical method for bottleneck ranking to be used in transmission expansion planning has been presented. The method uses a round-the-year approach and is adequate for large interconnected power systems having a mix of generation technologies including a high penetration of wind power. Market simulations are combined with detailed load flow calculations for getting a complete picture of the congestions in the transmission grid, while considering the chronological aspect and the correlation of load and wind speed time series. Criteria for prioritizing bottlenecks were developed together with a method for ranking them according to a risk-based severity index.

The method is tested on a modified New England test system that includes wind power plants, using one year of load and wind data. The results of the traditional snapshot method and of the proposed round-the-year method are compared for a specific area. It was shown that the new method gives more detailed and insightful results, identifying bottlenecks that the snapshot method missed and also giving a reliable bottleneck ranking based on the risk of overload calculation. In addition, an analysis for all the tie-lines of the New England system split up in three areas is made via the proposed method. The round-the-year security analysis pinpoints which physical transmission lines are affected by a given scenario and the top bottlenecks are identified. The structure of the grid, the limited interconnection capacity and the market simulation results regarding the optimal energy exchanges between the three areas lead to presence of congestion in these corridors. A comparison between different wind penetration scenarios reveals the relationship between the tie lines severity indices and the increase in installed wind power. The subsequent changes in the generation mix cause changes in the grid power flows, and therefore in the severity indices of the tie-lines as well.

The method is also applied on the Dutch transmission grid for a scenario for the year 2020. With an up-to-date standard computer, using the presented methodology proves to be feasible for the hourly one year evaluation of a large system where 133 N-1 outages and 1789 N-2 outages were performed. The results were compared again with the traditional snapshot planning method where only a few planning cases that represent a whole year are analysed. In a comprehensive way the presented method provides additional information with respect to the risk of overload of transmission branches and assessing the severity of each bottleneck. Furthermore, with the help of the ranking criteria the relationships between outages and bottlenecks are emphasized, revealing the most critical sensitivities in the grid. The method can also be used for testing grid reinforcements in order to get insight into the effect of grid modifications aimed at reducing specific bottlenecks. The case of increasing the rated capacity of one of the main bottlenecks is checked against the bottleneck ranking criteria by using the same market simulation results. It is observed that the risk of overload is dramatically reduced but not completely eliminated in this example, while in the classical planning (snapshot) method the bottleneck would disappear. The used grid model is representative for the study area of the Dutch EHV grid. More reliable results can be obtained on the one hand by having better grid models of the neighbouring countries, and on the other hand by using Power Transfer Distribution Factors (PTDFs) established jointly by responsible TSOs i.e. by ENTSO-E. Over the last decades the controllability of cross-border flows in the Dutch and Belgian grids has been improved by installing phase shifters on several tie-lines. In the DC load flow model the phase shifting capabilities are not considered. A more accurate modelling of the control capabilities of phase shifters should be adopted in future research.

Chapter 4

Round-the-year reinforcement solution generator

In this chapter a solution generator for the transmission expansion planning problem is proposed. The method makes use of the round-the-year network security analysis introduced in Chapter 3 and it iterates sequentially over various possible reinforcements until no more overloads occur. A robust assessment of overloads in the grid for different reinforcement candidates is performed, as all the hours of the year are considered. The decrease of the so-called grid severity index is used to measure the goodness of each reinforcement candidate. The reinforcement candidates are formed by doubling existing lines and by building new lines. The existing lines candidates are limited with the help of the round-the-year security analysis to the most serious bottlenecks and the most serious contingencies. The set of new lines candidates is chosen by expert judgement and served as input to the solution generator. The New England test system is used again for testing the method.

4.1 The need for a reinforcement solution generator

The round-the-year security analysis is meant to be used in the transmission expansion planning (TEP) process. For that, bottleneck ranking is not enough, as the result should be an assessment of the reinforcement candidates. Indeed, the goal of transmission expansion planning is to determine what reinforcements are needed for a future scenario in order to maintain a reliable, efficient and sustainable power system.

Because of the deregulation of the electricity sector, the emergence of regional electricity markets and continuously increasing penetration of variable renewable energy sources, it was already shown in Chapters 2 and 3 that transmission expansion planning is facing new challenges and has to deal with a lot of uncertainties. The research in the transmission expansion field has to keep up with these uncertainties, and at the same time offer solutions that are optimal from as many viewpoints as possible (such as reliability, economics, sustainability). However due to the complexity of the TEP problem, finding the global optimum solution seems an impossible, even arbitrary task. Moreover, it should be noted that no matter how advanced a method is, in the end decision makers always determine the reinforcement plans on the basis of the regulatory framework, transmission companies strategies and policies, and the need and opportunities for reinforcements. Hence it could be useful to give the decision makers robust and intuitive information.

To this purpose, in this chapter a round-the-year reinforcement solution generator is developed, which has as goal to reduce the overloads in the grid in an efficient way based on a priority list until complete elimination (if desired). The solution generator makes use of the round-the-year security analysis for assessing the effectiveness of reinforcement candidates at each reinforcement step. In this way a robust result can be obtained by considering a large set of realistic generation (including renewables) and load combinations provided by the initial market simulations. Criteria for measuring the total risks of overload in the grid are developed (in addition to the bottleneck ranking criteria introduced in Chapter 3) and used in the assessment. At the end of the process, the ordered list of reinforcements is given together with the grid overloading indices for each reinforcement step. Additionally, detailed information for each step and the results of the round-the-year analyses at each step are made available for allowing further in-depth analysis of results and efficient decision making.

The chapter is structured as follows. In section 4.2 the round-the-year reinforcement solution generator is introduced. Further in section 4.3 the method is applied on the New England test system and a few sensitivity analyses are performed for investigating how stable and robust the reinforcement solution is. At the end the main conclusions of the chapter are summarised.

4.2 Method description

After having determined the bottlenecks (the overloaded branches) in the grid and their severity, the next step is to find solutions for reinforcing the grid in order to solve these bottlenecks. It was already shown in the Chapter 3 (section 3.4.2.3) that the round-the-year network security analysis can be used for testing reinforcements. Consequently, in the current chapter a solution generator that makes use of the round-the-year network security analysis is introduced. Candidates for the transmission expansion problem are tested and selected iteratively (sequentially) until all bottlenecks in the grid are removed (see Figure 4.1). During this process, the same initial market simulations results are used, while the grid topology is changed. By using the proposed method more reinforcements solutions can be proposed. The method stops here. The different reinforcement solutions can be better defined and further assessed in a (multi-criteria) cost-benefit analysis such as the one introduced in [31].

4.2.1 Grid risks of overload and grid severity index

In this chapter the grid structure prior to adding any reinforcement is referred to as the base case. It is assumed that in the solution generator only N and N-1 situations are investigated, due to computation time. In case overloads are discovered during the base case round-the-year security analysis (see Figure 4.1) the solution generator is initiated. In order to

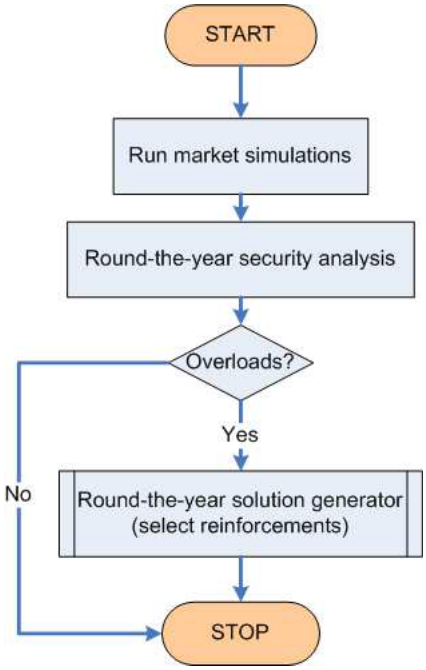


Figure 4.1: Round-the-year security analysis and reinforcement solution generator.

assess the reinforcement candidates some new criteria have to be introduced and these new quantities to be used in the proposed method are defined in Table 4.1.

In Chapter 3 the risks of overload for the N and N-1 situations and the severity index are defined for each branch and so also for each bottleneck. In this chapter indices defining the overall grid risks of overload are introduced.

For a certain grid structure *str* (including the base case), the grid risks of overload for N and N-1 situations are computed by summing up the risks of overload for each bottleneck during N and N-1 situations respectively (see Eq. 4.1).

$$[RO_{grid,sit}]_{str} = [\sum_{i=1}^{N_B} RO_{sit,i}]_{str} \tag{4.1}$$

where $sit = \{N, N-1\}$, N_B is the number of branches. Consequently, the grid risks of overload for the base case are :$[RO_{grid,N}]_{base}$, $[RO_{grid,N-1}]_{base}$.

Further the grid severity index for a certain grid structure *str* (different than the base case) can be calculated by a weighted sum, as in Eq. 4.2. Because the grid severity indices are computed with respect to the base case, in this equation the grid risks of overload of the structure *str* are normalized with respect to the risks of overload of the base case.

$$[SI_{grid}]_{str} = w_N \frac{[RO_{grid,N}]_{str}}{[RO_{grid,N}]_{base}} + w_{N-1} \frac{[RO_{grid,N-1}]_{str}}{[RO_{grid,N-1}]_{base}} \tag{4.2}$$

If Eq. 4.2 is applied for the base case then it can be noticed that the grid severity index for the base case is always $[SI_{grid}]_{base} = 1$.

Table 4.1: Relevant quantities

Name	Symbol	Definition
Top bottleneck	TB	The bottleneck that has the highest severity index (SI)
Top contingency	TC	The contingency that causes the highest number of branch overloading occurences for the whole study period (multiple overload occurences per hour are counted)
New possible lines	NPL	New lines that connect nodes that are not directly connected in the base case
List of candidates	LC	Contains the candidates (new lines or upgrades of existing corridors) to be tested during a certain step of the reinforcement solution search
N grid risk of overload	$RO_{grid,N}$	A measure of the overload in the grid during the normal (N) situation
N-1 grid risk of overload	$RO_{grid,N-1}$	A measure of the overload in the grid during single contingency (N-1) situations
Grid severity index	SI_{grid}	A measure of the overload level in the grid
Top reinforcement candidate(s)	TRC	The candidate(s) that brings the highest decrease in the grid severity index
Reinforcement	r	The chosen reinforcement, where $r \in TRC$; in case more candidates are in TRC, then r is the one of shortest length (lowest cost approximation)

At very little overloads during N situation with respect to N-1 situations the normalization can distort the results. In order to prevent that (in accordance to section 3.2.2.2), in cases when the number of overloaded hours for a grid structure *str* during the N-1 situations (C12) of the top N-1 situation bottleneck (having $maxRO_{N-1}$) is at least 100 times higher than the number of overloaded hours during the N situation (C02) for the top N situation bottleneck (which has $maxRO_N$), the first term of Eq. 4.2 is ignored.

4.2.2 Choosing the reinforcement

4.2.2.1 The list of candidates

Let G_0 be the set of branches in the base case grid. Let G_k be the set of branches in a reinforced grid with k reinforcements with respect to G_0.

If in the base case G_0 overloads are found, a list of candidates for reinforcement (LC_0) is made, providing the candidates to be tested in the first step of the reinforcement solution search. The list consists of the top bottlenecks (TB_0) and top contingencies (TC_0) branches from the round-the-year security analysis which can be upgraded (here implemented as adding another circuit to an existing line), together with a list of new possible lines (NPL_0) which are lines that do not exist in the initial grid. It is assumed that other existing lines than the top bottlenecks or the top contingencies bring less grid overload reduction, as the TB is the most sensitive branch and the TC is the most critical (in analogy with the criticality and sensitivity network theory concepts used in TEP for example in Spain [65]). Consequently computational time is saved by limiting to TB and TC the list of existing lines that can be upgraded. It should be noted that in this work the criticality of a contingency is measured by the total number of branch overloading occurrences caused in the system during the whole study period; for a given hour of the study period multiple overload occurrences can exist.

The base case grid risks of overload for N and N-1 situations are computed according to Eq. 4.1. In the base case there is an initial NPL_0 chosen by expert judgement, which during the search process, is reduced each time the grid is reinforced with a line $l \in NPL_0$, as this line might become a top bottleneck or a top contingency.

For a certain step k in the reinforcements search, a list of candidates LC_k is used. The list of candidates for reinforcement is given by the reunion of three sets as shown in Eq. 4.3.

$$LC_k = TB_{k-1} \cup TC_{k-1} \cup NPL_{k-1} \tag{4.3}$$

TB_{k-1} is the set of top bottlenecks for step $k-1$, namely the top bottlenecks (with maximum severity index) for grid configuration G_{k-1}. The top contingencies for step $k-1$ are TC_{k-1} which are the contingencies that cause the highest number of overloads in the study period. Last but not least, NPL_{k-1} is the set of new possible lines. (These lines do not exist in G_{k-1}.) The list of candidates is updated at each reinforcement step according to Eq.4.3.

It should be kept in mind that NPL_0 is an input data set for the solution generator and has impact on the final solution. The more options the better the solutions. However, more options means also an increase in the total computation time. Hence a large NPL_0 should be carefully selected by expert judgement before serving as an input to the simulation and possibly reduced in the first 2-3 steps of the solution generator by eliminating the lines that do not bring enough grid overload reduction or that increase the grid overloads.

4.2.2.2 Selection of reinforcements

As mentioned previously, LC_k is the set of candidates for reinforcement for adding reinforcement k (in step k) to grid G_{k-1}. Each candidate $l \in LC_k$ is added to the grid G_{k-1}, and the round-the-year security analysis is performed. Consequently the grid risks of overload ($[RO_{grid,N}]_{G_{k-1}\cup\{l\}}$, $[RO_{grid,N-1}]_{G_{k-1}\cup\{l\}}$) and the grid severity index $[SI_{grid}]_{G_{k-1}\cup\{l\}}$ are estimated for each reinforcement option $G_{k-1} \cup \{l\}$ separately, according to Eq. 4.1 and 4.2.

The impact of different reinforcement options $G_{k-1} \cup \{l\}$ with respect to the G_{k-1} case in terms of reduction of overloads in the grid is measured via the decrease in grid severity index ΔSI_{grid}. For each reinforcement case $G_{k-1} \cup \{l\}$, the decrease in grid severity index is calculated as the difference between the grid severity index of the G_{k-1} case and the grid severity index of the reinforcement case with line l added to G_{k-1} (Eq. 4.4).

$$[\Delta SI_{grid}]_{G_{k-1} \cup \{l\}} = [SI_{grid}]_{G_{k-1}} - [SI_{grid}]_{G_{k-1} \cup \{l\}}, \forall l \in LC_k \tag{4.4}$$

From all the lines $l \in LC_k$, the ones which bring the highest decrease in grid severity index are selected. Hence, the set of top reinforcement candidates TRC_k is calculated as the set of candidates that cause the highest decrease in grid severity index (see Eq. 4.5).

$$TRC_k = \{l \in LC_{k-1} : [\Delta SI_{grid}]_{G_{k-1} \cup \{l\}} = \max \text{ and } [\Delta SI_{grid}]_{G_{k-1} \cup \{l\}} > 0\} \tag{4.5}$$

Most likely, TRC_k has only one element, and then $\{r_k\} = TRC_k$, where r_k is the k^{th} reinforcement. If $TRC_k = \emptyset$ then there is no reinforcement candidate found. Assuming that more than one top reinforcement candidates are found (which is not very likely but might happen), then the line with the smaller length is chosen as the reinforcement r_k (as an approximation for least investment cost). A similar approach could be used if the top 2 reinforcement candidates are very close in terms of the decrease in grid severity index. This option is not considered in this work.

After selecting reinforcement r_k, the grid G_{k-1} is updated and becomes grid G_k (Eq. 4.6). The grid severity index for grid G_k is assigned according to Eq. 4.7.

$$G_k = G_{k-1} \cup \{r_k\} \tag{4.6}$$

$$[SI_{grid}]_{G_k} = [SI_{grid}]_{G_{k-1} \cup \{r_k\}} \tag{4.7}$$

If $[SI_{grid}]_{G_k} = 0$ there are no more overloadings in the grid. Consequently, the search can stop as no more reinforcements are needed. Otherwise the search continues to next step.

4.2.3 Execution procedure

Figure 4.2 shows the flow chart for the execution of the solution generator, which summarizes the procedure described in the previous section. The procedure starts from the base case which is step (iteration) 0.

For each step k the procedure is the following. First the list of candidates for reinforcement for step k (LC_k) is formed considering the top bottlenecks (TB_{k-1}), top contingencies (TC_{k-1}) and the new possible lines (NPL_{k-1}) that result from the previous step $k-1$, according to Eq. 4.3.

Next, all the lines from LC_k are tested one by one. This is done by adding separately each line to the initial grid and performing the round-the-year security analysis. For each tested line l added to the grid of the previous step G_{k-1}, the grid risks of overload during N and N-1 situation (Eq. 4.1), together with the grid severity index (Eq. 4.2) are computed.

The lines that bring the highest decrease in the grid severity index (ΔSI_{grid}) are chosen to be the top reinforcement candidates for step k (TRC_k). If TRC_k is not void then the reinforcement r_k is selected from TRC_k. In case there are more equal top reinforcement candidates, the reinforcement is the one with the smallest length. The grid G_{k-1} is updated with the reinforcement r_k and becomes grid G_k. If the grid severity index is zero then the search has finished. If the grid severity index is still different from 0, then the TB, TC and NPL are calculated for step k (in case r_k was part of NPL_{k-1} then it is removed from NPL_k). LC_{k+1} is calculated and the procedure repeats until no more overloadings occur or an early stop condition is met.

Because after a certain number of steps the grid risks of overload become very small, adding new lines is not the most logical thing to do as it is no longer economically desirable. In such cases congestion management could be used to solve the overloadings. Hence it is possible to stop the solution generator earlier by indicating a certain threshold of grid risks of overload and maximum overloading during N-1 situation (C13) for example. This is the early stop condition. In this way valuable computation time is saved by avoiding unnecessary simulations.

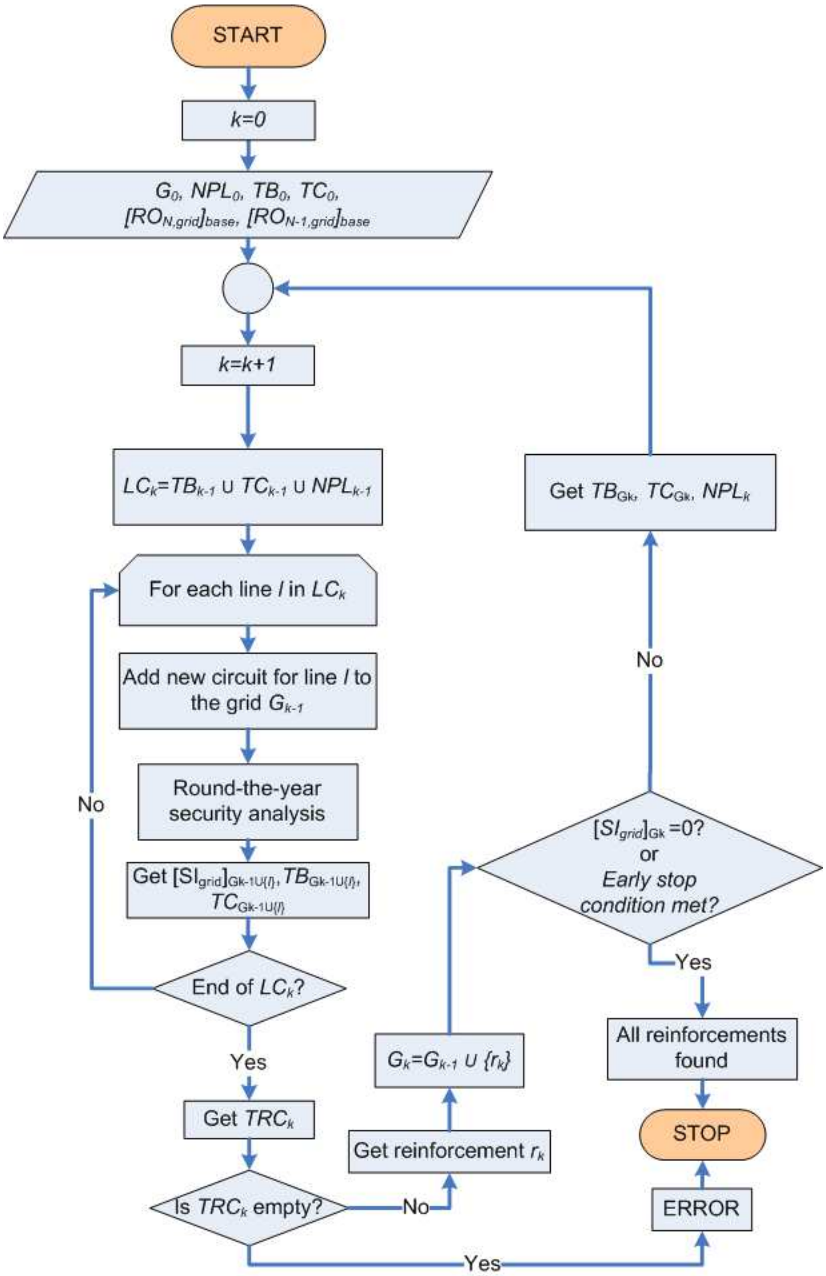


Figure 4.2: Round-the-year solution generator execution flowchart.

4.3 Application to the New England test system

In this section, the solution generator is applied to the New England test system introduced in Chapter 3, section 3.3.1. It is assumed that the reinforcement of the grid is computed for all three areas simultaneously. Consequently, the bottleneck ranking is done this time for the whole New England test system.

4.3.1 The base case

In this section the main results of the round-the-year network security analysis for the base case are presented. Table 4.2 illustrates the main bottleneck ranking criteria and risks of overload during N and N-1 situations for the New England test system. The security analysis indicates the presence of 22 bottlenecks. Figure 4.3 shows the bottlenecks on the grid map, sorted according to C12.

Table 4.2: The base case for the New England test system: bottleneck ranking criteria and risks of overload.

Branch	**C01 [%]**	**C02 [h]**	**C03 [%]**	**C03 hour**	**$\mathbf{RO_N}$ [% * h]**	**C11 [%]**	**C12 [h]**	**C13 [%]**	**C13 hour**	**$\mathbf{RO_{N-1}}$ [% * h]**
1 - 2	0	0	0	n.a.	0	120.55	8	129.3	1188	164.4
1 - 39	0	0	0	n.a.	0	120.55	8	129.3	1188	164.4
2 - 25	102.55	464	109.8	5419	1183.2	153.8	7139	185.6	6003	***384078.2**
2 - 3	109.55	246	135.4	6764	***2349.3**	137.5	7302	219.7	6932	273825
3 - 4	0	0	0	n.a.	0	106	671	142.3	6920	4026
3 - 18	0	0	0	n.a.	0	103.4	131	131.1	6920	445.4
4 - 14	0	0	0	n.a.	0	106.1	39	118.3	5131	237.9
8 - 9	0	0	0	n.a.	0	112.55	12	128	1188	150.6
9 - 39	0	0	0	n.a.	0	113.4	13	129.3	1188	174.2
14 - 15	0	0	0	n.a.	0	118.8	211	159.5	5442	3966.8
15 - 16	0	0	0	n.a.	0	110	553	180.2	5135	5530
16 - 17	104.2	31	115.9	6920	130.2	111	583	180.2	5135	6413
16 - 21	0	0	0	n.a.	0	122.7	2812	159.5	5298	63832.4
16 - 24	0	0	0	n.a.	0	115	1846	142.2	5118	27690
17 - 18	0	0	0	n.a.	0	108.15	536	127.5	6957	4368.4
17 - 27	0	0	0	n.a.	0	132.3	6495	166.9	2189	209788.5
21 - 22	0	0	0	n.a.	0	133.9	2516	147	5432	85292.4
22 - 23	0	0	0	n.a.	0	101.7	264	107.1	7289	448.8
23 - 24	0	0	0	n.a.	0	134	2852	159.5	5298	96968
25 - 26	0	0	0	n.a.	0	106.6	2794	140.2	1242	18440.4
26 - 27	0	0	0	n.a.	0	155.3	6637	185.6	6003	367026.1

Next the ranking of bottlenecks is performed according to the method in Chapter 3. The risks of overload are normalized for N and N-1 situations respectively to the maximum risk of overload values emphasized in italics in Table 4.2. The weights used for calculating the severity index are $w_N = 0.67$ and $w_{N-1} = 0.33$, which were chosen by expert judgement as specified in Chapter 3 (a sensitivity analysis to the choice of weights will follow in section 4.3.3). The top 5 bottlenecks according to the value of their severity index are shown in Table 4.3. It can be noticed that the top bottleneck is line 2-3, followed by line 2 - 25. Hence $TB_0 = \{2-3\}$. In the same table, the top 5 contingencies are also shown. The ranking of

Table 4.3: Top 5 bottlenecks and contingencies for the base case.

Rank	Bottleneck	SI [%*h]	Rank	Contingency	Total # of overloading occurences
1	2 - 3	0.90527	1	2 - 25	16217
2	2 - 25	0.66744	2	26 - 27	13375
3	26 - 27	0.31535	3	17 - 27	12265
4	17 - 27	0.18025	4	2 - 3	8962
5	23 - 24	0.08331	5	23 - 24	5919

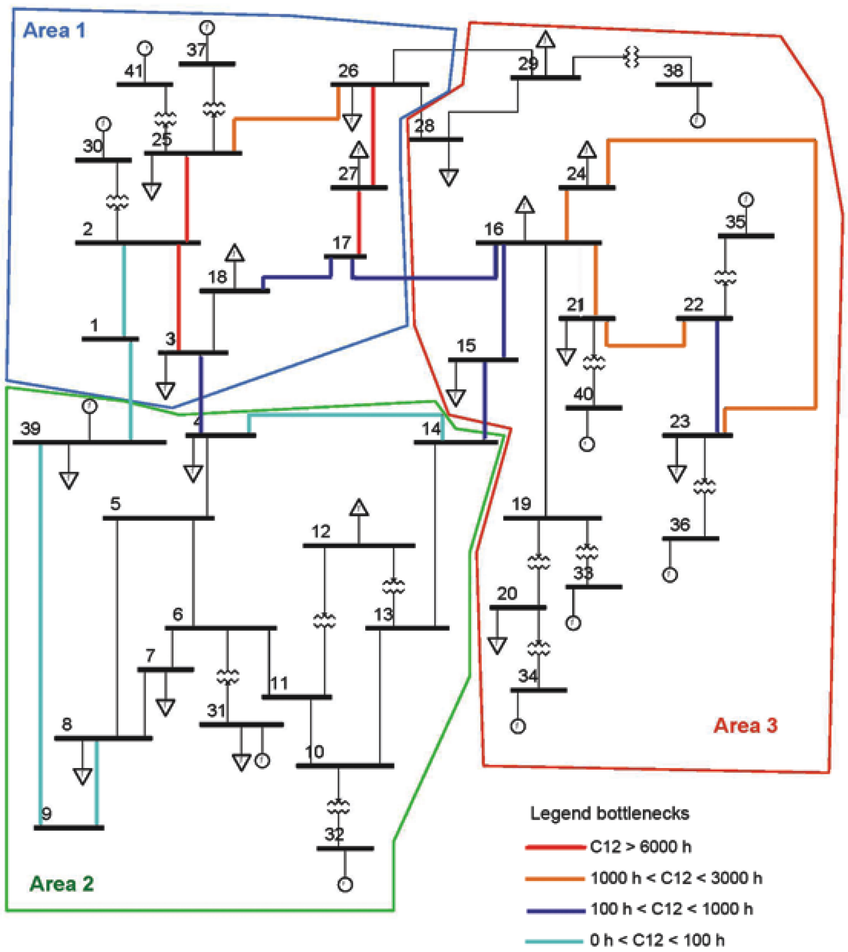


Figure 4.3: Base case bottlenecks ranked according to C12.

contingencies is done according to the total number of branch overloading occurrences each contingency causes in the study period. The top contingency is the outage of line 2 - 25, followed by line 26 - 27. It results that $TC_0 = \{2-25\}$. It can be noticed that the top 5 bottlenecks are also the top 5 contingencies.

A set of 7 new possible lines is proposed (based on expert judgement) for the further search of solutions $NPL_0 = \{24-29, 16-28, 15-28, 1-5, 5-39, 13-19, 2-18\}$. As there is no information on the actual distances in the New England test system, it was assumed that the parameters of the NPL_0 lines are similar to those of other lines in the New England test system, and each new line has a rated capacity of 900 MVA. In Appendix A the line parameters of both initial New England lines (Table A.1) as well of the proposed NPL_0 lines (Table A.2) are given.

4.3.2 Finding reinforcements

As in the previous section bottlenecks were found, the solution generator can be applied for finding grid reinforcements. The weights that are used for calculating the grid severity index are the same as the ones used for the branch severity index calculation, namely $w_N = 0.67$ and $w_{N-1} = 0.33$. The simulation stops when $SI_{grid} = 0$ and no early stop conditions are taken.

4.3.2.1 The first two steps

For a better understanding of the solution generator, the first two steps are detailed in the following paragraphs and illustrated in Table 4.4[1].

Step 0. Step 0 is the base case with the grid G_0. The base case grid risks of overload ($[RO_{grid,N}]_{base}$, $[RO_{grid,N-1}]_{base}$) are calculated with the help of Eq. 4.1 and the grid severity index for the base case is 1. The top bottleneck is $TB_0 = \{2-3\}$, the top contingency is $TC_0 = \{2-25\}$ and the set of new possible lines proposed in the previous section is $NPL_0 = \{24-29, 16-28, 15-28, 1-5, 5-39, 13-19, 2-18\}$.

Step 1. The list of candidates for reinforcement at step 1 (LC_1) is calculated with Eq. 4.3. Hence $LC_1 = TB_0 \cup TC_0 \cup NPL_0$. Consequently, each of the candidates $l \in LC_1$ is tested by adding it to the grid G_0 and performing round-the-year security analysis. For each reinforcement case $G_0 \cup \{l\}$, the grid risks of overload are calculated with Eq. 4.1, and then the grid severity index is determined according to Eq. 4.2, where the normalization is done with respect to the base case grid risks of overload. The reinforcement candidate l with the highest decrease in grid severity index with respect to step 0 is line 15 - 28. Hence, line 15 - 28 is chosen as the reinforcement r_1. The grid is updated with r_1: $G_1 = G_0 \cup \{15-28\}$. The set of new possible lines is also updated and because line 15 - 28 belongs to NPL_0, $NPL_1 = NPL_0 \setminus \{15-28\}$. The new top bottleneck is $TB_1 = \{2-3\}$ and the new top contingency is $TC_1 = \{25-26\}$. From Table 4.4 it can be noticed that sometimes (here when testing candidate { 2 - 3}) a reinforcement can result in an increase of the grid severity index. This is caused by power flow shifts in the meshed grid.

[1] If the $RO_{grid,N}$ value is in brackets, then the exception is applied and $RO_{grid,N}$ is ignored. This is because there are very little overloads in the N situation in comparison to the N-1 situation.

Table 4.4: First two steps of the solution generator.

Step k	Sub step	Grid	$\mathbf{SI_{grid}}$ [p.u.]	$\mathbf{\Delta SI_{grid}}$ [p.u.]	$\mathbf{RO_{grid,N}}$ [%*h]	$\mathbf{RO_{grid,N-1}}$ [%*h]	TB (for reinf. $\mathbf{r_k}$)	TC (for reinf. $\mathbf{r_k}$)
0	n.a.	G_0	1.00000	n.a.	3662.7	1553030.9	2 - 3	2 - 25
	1	$G_0 \cup \{2-3\}$	1.03536	-0.03536	4190.2	1265343.3		
	2	$G_0 \cup \{2-25\}$	0.63151	0.36849	2601.5	732432.5		
	3	$G_0 \cup \{24-29\}$	0.14854	0.85146	262.0	473507.8		
	4	$G_0 \cup \{16-28\}$	0.13704	0.86296	329.6	361193.6		
1	5	$G_0 \cup \{15-28\}$	***0.12618**	***0.87382**	270.9	360602.0	2 - 3	25 - 26
	6	$G_0 \cup \{1-5\}$	0.65086	0.34914	1952.6	1382082.1		
	7	$G_0 \cup \{5-39\}$	0.59054	0.40946	1538.6	1454621.5		
	8	$G_0 \cup \{13-19\}$	0.95384	0.04616	3444.9	1523288.8		
	9	$G_0 \cup \{2-18\}$	1.36892	-0.36892	6016.5	1262882.4		
	r_1=15 - 28, $G_1 = G_0 \cup \{15-28\}$, $NPL_1 = NPL_0 \setminus \{15-28\}$							
	1	$G_1 \cup \{2-3\}$	0.07011	0.05607	0.0	329930.0		
	2	$G_1 \cup \{25-26\}$	***0.06204**	***0.06416**	(8.0)	291954.9	23 - 24	23 - 24
	3	$G_1 \cup \{24-29\}$	0.11291	0.01326	184.8	372300.2		
2	4	$G_1 \cup \{16-28\}$	0.12075	0.00543	252.0	351313.0		
	5	$G_1 \cup \{1-5\}$	0.07132	0.05486	0.0	335625.1		
	6	$G_1 \cup \{5-39\}$	0.07245	0.05373	0.0	340964.4		
	7	$G_1 \cup \{13-19\}$	0.12635	-0.00017	287.1	347449.6		
	8	$G_1 \cup \{2-18\}$	0.07006	0.05612	0.0	329712.9		
	r_2=25 - 26, $G_2 = G_1 \cup \{25-26\}$, $NPL_2 = NPL_1$							

Step 2. The list of reinforcement candidates for step 2 LC_2 is calculated $LC_2 = TB_1 \cup TC_1 \cup NPL_1$. Consequently, each of the candidates $l \in LC_2$ is tested by adding it to the grid G_1 and performing round-the-year security analysis. For each reinforcement case $G_1 \cup \{l\}$, the grid risks of overload are calculated with Eq. 4.1, and then the grid severity index is determined according to Eq. 4.2, where the normalization is done with respect to the base case grid risks of overload. The reinforcement candidate l with the highest decrease in grid severity index with respect to step 1 is line 25 - 26 which is the top contingency TC_1. Hence, line 25 - 26 is chosen as the reinforcement r_2. The grid is updated: $G_2 = G_1 \cup \{25-26\}$. The set of new possible lines is also updated and $NPL_2 = NPL_1$. The new top bottleneck is $TB_2 = \{23-24\}$ and the new top contingency is $TC_2 = \{23-24\}$. And then step 3 begins. For all the detailed solution generator steps please consult Table B.1 from Appendix B.

4.3.2.2 The final result

The solution generator needs 13 steps to find a list of reinforcements for which no grid overloads occur. Table 4.5 [1] summarizes the reinforcement found at each step together with the new grid structure grid severity index and grid risks of overload.

As mentioned in section 4.2.3, by targeting 0 overloads in the grid, the risks of overload in the last steps (here after step 6 or 7) become very small and adding new lines may no longer be justified.

For getting a better insight into the iterative process, Table 4.6 illustrates the bottleneck ranking criteria and risks of overload for the reinforced grid at step 6 and step 7. In both cases there are no overloads in the N situation and the corresponding criteria are all 0 and not reported in the table. It can be noticed that the number and severity of the bottlenecks is very much reduced in comparison to the base case. If at step 6 there are still some overloads going up to 121% of rated capacity (line 16-17), at step 7 all overloads are under 110% of rated capacity. Hence the reinforcements after step 7 can be ignored and step 7 reinforcement remains a possible solution that is not highly necessary. This will depend on the operating philosophy of the grid operator and the level of security mandated by grid codes.

Giving all the afore mentioned, Figure 4.4 illustrates the proposed reinforcements which are 4 new lines (3 important and 1 optional) and 3 cases of doubling of existing lines.

Table 4.5: The list of reinforcements.

Step k	**Added r_k**	**SI_{grid} [p.u.]**	**$RO_{grid,N}$ [%*h]**	**$RO_{grid,N-1}$ [%*h]**
0	n.a.	1.0	3662.7	1553030.9
1	15 - 28	1.262E-01	270.9	360602.0
2	25 - 26	6.204E-02	(8.0)	291954.9
3	23 - 24	1.757E-02	(8.0)	82698.8
4	16 - 24	3.959E-03	(8.0)	18633.4
5	16 - 28	1.318E-03	(0.1)	6204.0
6	5 - 39	5.652E-04	0.0	2659.7
7	13 - 19	2.505E-04	0.0	1178.8
8	22 - 23	3.332E-05	0.0	156.8
9	4 - 14	8.691E-06	0.0	40.9
10	24 - 29	3.272E-06	0.0	15.4
11	1 - 5	4.675E-07	0.0	2.2
12	2 - 18	1.487E-07	0.0	0.7
13	6 - 11	0.0	0.0	0.0

Table 4.6: Bottleneck ranking criteria and risks of overload for the reinforced grid at steps 6 and 7.

Branch	**C11 [%]**	**C12 [h]**	**C13 [%]**	**RO_{N-1} [%*h]**
Step 6 reinforced grid G_6				
2 - 3	101.8	89	106.2	160.2
2 - 25	102.05	112	112.9	229.6
3 - 4	102.45	108	113.8	264.6
5 - 39	104.25	6	108.5	25.5
14 - 15	102	88	110.3	176
15 - 16	103.4	21	107.9	71.4
16 - 17	105.4	124	121.6	669.6
16 - 21	101.7	292	107.2	496.4
17 - 18	103.5	20	108.6	70
22 - 23	101.7	292	107.2	496.4
Step 7 reinforced grid G_7				
2 - 3	101.35	18	105.1	24.3
2 - 25	100.8	14	102.1	11.2
4 - 14	101.55	14	104.2	21.7
5 - 39	101.2	2	101.9	2.4
6 - 11	103.3	29	107.5	95.7
10 - 11	100.5	3	100.5	1.5
16 - 21	101.75	292	107.2	511
22 - 23	101.75	292	107.2	511

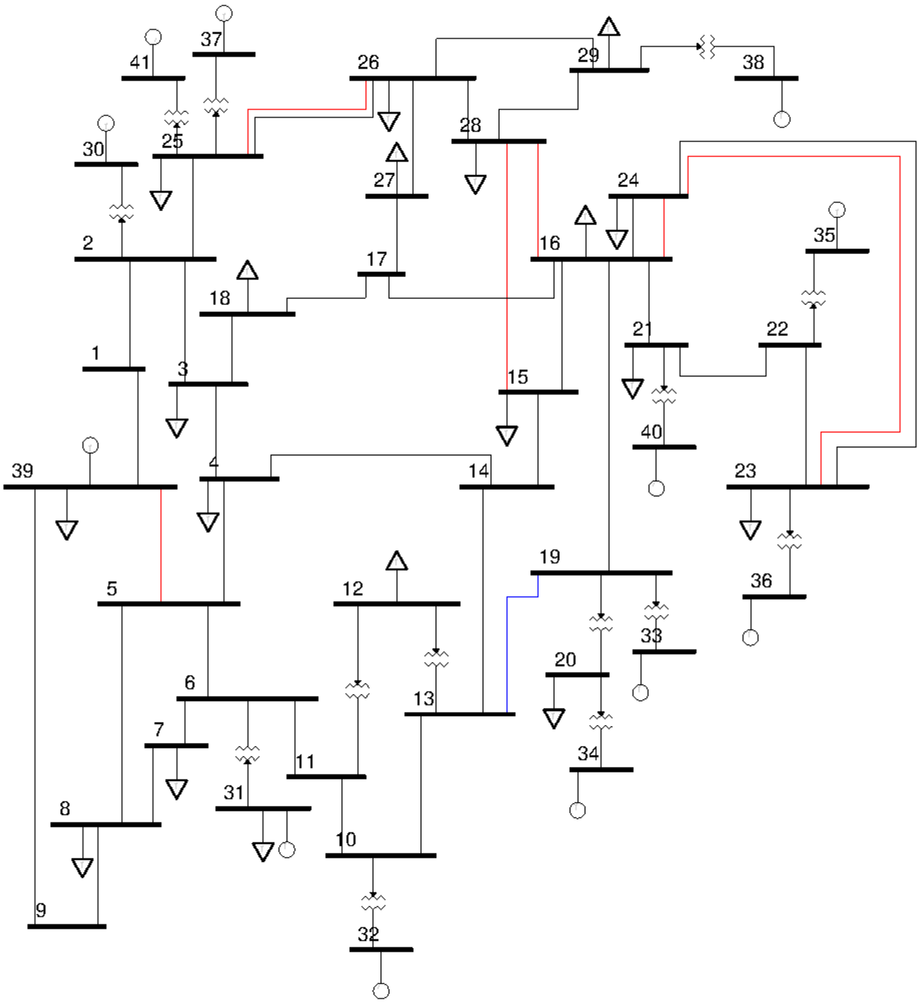


Figure 4.4: Proposed reinforcements: red line - important, blue line - optional.

4.3.3 Sensitivity analyses

4.3.3.1 Sensitivity analysis to the weights used

In Chapter 3 no sensitivity analysis was performed on the influence the weights w_N and w_{N-1} have on the results of the bottleneck ranking. As in the current chapter the weights might affect both the bottleneck ranking and the final reinforcement solution, a sensitivity analysis is needed.

Hence, four sensitivity scenarios to the used weights are studied, in addition to the original pair of weights $w_N = 0.67$ and $w_{N-1} = 0.33$. Two of the sensitivity scenarios have small variation of the weights, namely the pairs $w_N = 0.64$, $w_{N-1} = 0.36$, and $w_N = 0.7$,$w_{N-1} = 0.3$. The other two sensitivity scenarios have a bigger variation of the weights: $w_N = 0.5$, $w_{N-1} = 0.5$, and $w_N = 0.8$, $w_{N-1} = 0.2$. Other scenarios having a more than 50% weight for the N-1 situation are not considered in this analysis as they are not logical from both researcher's and system operator's points of view(see section 3.2.2.2) since it is reasonable to give higher weight to the risk of overload in the N situation.

First the effects the choice of weight has on the base case bottleneck ranking are studied. The results show that the ranking of bottlenecks is not affected by the weights. The weights only influence values of the severity indices in such a way that the difference between different ranks is increased or decreased, generally without changing the ranking order (Table 4.7). This is a positive finding. There is only one exception: for the set of weights $w_N = 0.8$, $w_{N-1} = 0.2$, branch { 21 - 22} becomes the 8^{th} instead of the 6^{th} and branch { 16 - 17} vice versa. In cases when N-1 situation is not highly dominant for a certain branch, the ranking order might change if extreme priority is given to w_N. This is the only ranking order change. The top 5 bottlenecks remain unchanged, as well as the other ranks.

Further, the effect of the weights on the final reinforcement solution given by the solution generator is investigated. Again the results show that even though the values of grid severity indices change, there is no effect on the reinforcement solution. This is again a robustness signal. The changes in grid severity indices only increase/decrease the differences between reinforcement steps and between the candidates that are tested. Table 4.8 shows the grid severity indices at each reinforcement step for the base case and for all sensitivity scenarios.

Summing up, it was shown that varying the weights given for N and N-1 situation (while keeping the weight for the N situation at least equal to 50%) does not influence the bottleneck ranking nor the solution generator, although it affects the severity index and grid severity index values. This can separate better both bottlenecks and reinforcement candidates. The results are stable and the weights used in this thesis are a good choice. If desired, equal weights for N and N-1 situation can be also used.

Table 4.7: Base case bottleneck ranking comparison for 5 weights scenarios.

Rank	Branch	$w_N = 0.5$ $w_{N-1} = 0.5$	$w_N = 0.64$ $w_{N-1} = 0.36$	$w_N = 0.67$ $w_{N-1} = 0.33$	$w_N = 0.7$ $w_{N-1} = 0.3$	New rank	$w_N = 0.8$ $w_{N-1} = 0.2$
		SI [p.u.]					SI [p.u.]
1	2 - 3	0.856470	0.896659	0.905270	0.913882	1	0.942588
2	2 - 25	0.751820	0.682329	0.667438	0.652548	2	0.602912
3	26 - 27	0.477801	0.344017	0.315349	0.286681	3	0.191121
4	17 - 27	0.273106	0.196637	0.180250	0.163864	4	0.109243
5	23 - 24	0.126235	0.090889	0.083315	0.075741	5	0.050494
6	21 - 22	0.111035	0.079945	0.073283	0.066621	*8*	*0.044414*
7	16 - 21	0.083098	0.059831	0.054845	0.049859	7	0.033239
8	16 - 17	0.036059	0.041480	0.042642	0.043804	*6*	*0.047676*
9	16 - 24	0.036047	0.025954	0.023791	0.021628	9	0.014419
10	25 - 26	0.024006	0.017284	0.015844	0.014404	10	0.009602
11	15 - 16	0.007199	0.005183	0.004751	0.004319	11	0.002880
12	17 - 18	0.005687	0.004095	0.003753	0.003412	12	0.002275
13	3 - 4	0.005241	0.003774	0.003459	0.003145	13	0.002096
14	14 - 15	0.005164	0.003718	0.003408	0.003098	14	0.002066
15	22 - 23	0.000584	0.000421	0.000386	0.000351	15	0.000234
16	3 - 18	0.000580	0.000417	0.000383	0.000348	16	0.000232
17	4 - 14	0.000310	0.000223	0.000204	0.000186	17	0.000124
18	9 - 39	0.000227	0.000163	0.000150	0.000136	18	0.000091
19	1 - 39	0.000214	0.000154	0.000141	0.000128	19	0.000086
	1 - 2	0.000214	0.000154	0.000141	0.000128		0.000086
21	8 - 9	0.000196	0.000141	0.000129	0.000118	21	0.000078

Table 4.8: List of reinforcements for 5 weights scenarios.

Step	Added r	$w_N = 0.5$ $w_{N-1} = 0.5$	$w_N = 0.64$ $w_{N-1} = 0.36$	$w_N = 0.67$ $w_{N-1} = 0.33$	$w_N = 0.7$ $w_{N-1} = 0.3$	$w_N = 0.8$ $w_{N-1} = 0.2$
		SI_{grid} [p.u.]				
0	n.a.	1.0	1.0	1.0	1.0	1.0
1	15 - 28	1.531E-01	1.309E-01	1.262E-01	1.214E-01	1.056E-01
2	25 - 26	9.400E-02	6.768E-02	6.204E-02	5.640E-02	3.760E-02
3	23 - 24	2.662E-02	1.917E-02	1.757E-02	1.597E-02	1.065E-02
4	16 - 24	5.999E-03	4.319E-03	3.959E-03	3.599E-03	2.400E-03
5	16 - 28	1.997E-03	1.438E-03	1.318E-03	1.198E-03	7.990E-04
6	5 - 39	8.563E-04	6.165E-04	5.652E-04	5.138E-04	3.425E-04
7	13 - 19	3.795E-04	2.733E-04	2.505E-04	2.277E-04	1.518E-04
8	22 - 23	5.048E-05	3.635E-05	3.332E-05	3.029E-05	2.019E-05
9	4 - 14	1.317E-05	9.481E-06	8.691E-06	7.901E-06	5.267E-06
10	24 - 29	4.958E-06	3.570E-06	3.272E-06	2.975E-06	1.983E-06
11	1 - 5	7.083E-07	5.100E-07	4.675E-07	4.250E-07	2.833E-07
12	2 - 18	2.254E-07	1.623E-07	1.487E-07	1.352E-07	9.015E-08
13	6 - 11	0.0	0.0	0.0	0.0	0.0

4.3.3.2 Sensitivity analysis to the hours considered

As running the solution generator for the whole year is time consuming, an investigation of what happens when the solution generator is ran only for a set of critical hours is performed.

Here, the solution generator is ran for the 16 critical hours from the base case (see Table 4.2). The computational time is very short. These critical hours (C03 hour and C13 hour) are the hours when the maximum branch overloadings during N and respectively N-1 situations occurred. However, the solution is different from the round-the-year solution generator. The critical-hours solution generator needs 12 steps to converge to a SI_{grid} of zero. Table 4.9 shows the reinforcement selected at each step by the critical-hours solution generator.

Table 4.9: Solution generator for critical hours:list of reinforcements.

Step k	Added r_k	SI_{grid} [p.u.]	$RO_{grid,N}$ [%*h]	$RO_{grid,N-1}$ [%*h]
0	n.a.	1	166.7	5490
1	24 - 29	3.016E-01	42.8	2156
2	1 - 5	1.117E-01	1	1791.6
3	16 - 21	7.841E-02	0	1304.4
4	21 - 22	3.583E-02	0	596
5	13 - 19	2.069E-02	0	344.2
6	25 - 26	1.132E-02	0	188.4
7	15 - 28	6.336E-03	0	105.4
8	5 - 39	2.020E-03	0	33.6
9	6 - 11	1.767E-03	0	29.4
10	16 - 21	5.049E-04	0	8.4
11	10 - 11	2.404E-05	0	0.4
12	5 - 39	0	0	0

In order to see if indeed there are no more overloadings in the grid proposed at step 12 (G_{12}) by the critical-hours solution generator (Table 4.9), the round-the-year security analysis is ran on this grid. The results of the round-the-year security analysis reveal that the grid risk of overload during N-1 situation is $RO_{grid,N-1} = 14.2$ [%*h], which is still pretty small but not 0 as in Table 4.9.

Further, the grid reinforced at step 6 (G_6) in Table 4.9 is also tested with the round-the-year security analysis. The results show that the N-1 grid risk of overload is $RO_{grid,N-1} = 7155.9$ [%*h]. This value is higher than the $RO_{grid,N-1}$ at step 6 in Table 4.5, when running the solution generator round-the-year, and even higher than the $RO_{grid,N-1}$ at step 5 from the same table.

Table 4.10 shows the results of the round-the-year security analysis ran on the grids G_6 and G_{12} from steps 6 and respectively 12 of Table 4.9.

It can be concluded that by considering only a few critical hours for the analysis, the big picture is missed. Even though the round-the-year solution generator is time consuming, its advantages are obvious as it gives a good insight of how each reinforcement influences the overloadings in the grid and considers this in the solution search process.

Table 4.10: Round-the-year bottleneck ranking criteria and risks of overload for the reinforced grid obtained at steps 6 and 12 of the solution generator ran for 16 critical hours. Note the presence of overloads in the (N-1) situations.

Branch	**C11 [%]**	**C12 [h]**	**C13 [%]**	**RO_{N-1} [%*h]**
Round-the-year results for G_6				
1 - 39	115.6	9	126	140.4
2 - 25	104.3	1149	114.3	4940.7
2 - 3	101.05	46	107.1	48.3
6 - 11	103.7	12	105.3	44.4
8 - 9	118.9	7	125.5	132.3
9 - 39	119.3	7	126	135.1
16 - 19	102.3	3	103.7	6.9
16 - 21	102.1	62	110.1	130.2
16 - 24	101.45	68	110.2	98.6
24 - 29	102.4	562	109.9	1348.8
Round-the-year results for G_{12}				
2 - 3	101.6	1	101.6	1.6
5 - 6	101.8	7	107	12.6

4.4 Summary

In this chapter a round-the-year reinforcement solution generator is proposed. The solution generator solves the transmission expansion problem sequentially while following at each reinforcement step the maximum reduction of the grid overloadings in a future year. The method makes use of the round-the-year security analysis and bottleneck ranking method introduced in Chapter 3. This allows a robust assessment of overloadings in the grid for different reinforcement candidates, as all the hours in the future year scenario are considered. New criteria for defining the grid overload level are defined and used in the assessment of candidates where the decrease of the so called grid severity index is used to measure the effectiveness of each reinforcement candidate. The reinforcement that brings the highest decrease in the grid severity index with respect to the previous step is chosen. The process stops when no more overloadings occur or when an early stop condition that satisfies the grid planners is met. The reinforcement candidates are formed by doubling of existing circuits and by building new lines. The existing lines candidates are limited with the help of the round-the-year security analysis to the most serious bottlenecks and most serious contingencies. The set of new possible lines is selected by expert judgement and served as input to the solution generator. After each reinforcement step the list of reinforcement candidates is updated since the top contingency and top bottleneck may change for the new grid configuration. At the end of the process an ordered list of reinforcements is given together with the grid risks of overloads and severity indices at each reinforcement step. Regarding computation time, on a regular computer (PC) the process is time consuming and it is proportional to the total number of times the round-the-year security analysis is run. However with the help of powerful computers and parallel programming the process duration can be easily reduced (the algorithm can be easily parallelized).

The method is applied on the same New England test system used in Chapter 3, in this case focusing on the whole system. A reduced set of new possible lines is given as input and the solution generator stops when no more overloadings occur.

Next, a sensitivity analysis to the set of weights for the N and N-1 situations is performed in order to see whether the bottleneck ranking and the reinforcement solution are robust with the change of the weights. The sensitivity scenarios show that the solution is stable as both the bottleneck ranking and the list of reinforcements found by the solution generator are generally not affected. The values of the branch and grid severity indices change indeed, but this hardly influences the final ranking result.

Because the round-the-year solution generator is time consuming as it is run for all the hours in the year, it is checked whether by running the solution generator only for some critical hours identified in the base case round-the-year security analysis, the same solution can be obtained. However, the results show that the critical-hours solution is different from the one obtained when the solution generator is run round-the-year. Moreover, by testing the final reinforced grid with the round-the-year security analysis it is shown that some overloadings still remain. Step 6 is also tested, and the resulting grid severity index is higher than the one which was obtained for step 5 of the round-the-year solution generator. It is concluded that using only a set of critical hours does not represent well the whole set of load and generation combinations provided by the market simulations for the study year and the big picture is missed. Running the solution generator for all the hours in the year gives robustness to the solution and also good indication to the grid planners regarding the status of the overload in the grid at each reinforcement step.

The result of the solution generator is dependent on the initial set of new possible lines that is served as input. It is recommended that a more extensive set is carefully selected. As more candidates means increased computation time, this set can already be reduced after the first steps of the solution generator by eliminating the lines that show not to improve (much) the overloadings in the grid. Also for reducing computation time, early stop conditions can be defined for stopping the solution generator when a certain low and manageable overloading level in the grid is reached.

Furthermore, in the presented example only one capacity option for line doubling or for building a new line was considered. It is possible to use more line capacity options as well as upgrading of lines by increasing the capacity of an existing circuit instead of adding an extra circuit to it. As all these increase computation time it is recommended that not too many such options are used. Details of reinforcements can be decided later.

Chapter 5

North Sea transnational offshore grid case study

This chapter provides as proof of principle an analysis of a combined planning of a possible offshore grid in the North Sea together with the onshore grid, for a high renewables scenario in the year 2030. The round-the-year security analysis introduced in this thesis in Chapter 3 is used to analyze on the one hand different possible offshore grid structures and the interdependencies that exist between grid structure and available capacity for market transactions. On the other hand, the same round-the-year security analysis is used to investigate the effects of the offshore grid structure on the security of the onshore grid. Zooming into critical hours is performed for both the offshore and onshore grids for a better understanding of the results. A set of recommendations for planning the offshore and onshore grids together is made.

5.1 Introduction

The planning of large energy infrastructures in Europe has entered a new dimension, namely the trans-European one. The way of thinking is slowly switching from national to regional (European) interests, as this is the most efficient way to attain a sustainable energy future. Europe finds itself at the beginning of a transition towards a low carbon and sustainable electricity system, which is guided by the European Union (EU) Energy Policy core objectives: competitiveness, reliability and sustainability [2].

By issuing the Directives on Renewable Energy [3] including national renewable targets modified according to economic status, the EU aims towards the 20-20-20 goals presented in the Energy and Climate Package (2008). Among those goals is the 20% share of renewables in the European energy consumption within 2020. As we are approaching 2020, attention starts to shift beyond 2020, towards 2030 and even 2050. According to EWEA's forecast [4], in 2030 30% of EU's electricity will be produced by wind power. Moreover, the EU prognosis is that the solar power penetration will increase dramatically to 80 GW by 2020, and it will continue to grow after 2020. The European Commission (EC) has published in 2011 a roadmap leading to a competitive low carbon economy in 2050 [5]. There are recent studies that suggest that Renewable Energy Sources (RES) could have by 2050 a share in the electricity generation varying between 40% and 100% [6].

ENTSO-E [9, 10] together with the EC according to its energy infrastructure package are searching for solutions on how to be able to integrate in the European power systems all the new renewable energy. With respect to large-scale wind power, the attention is oriented towards the North Sea area where there is a great potential for offshore wind power plant developments. That is why the North Seas Countries Offshore Grid Initiative (NSCOGI) was born, where TSOs together look at the the feasibility of having offshore grid in the North Sea and also in other northern seas [11].

It is of main interest whether a transnational grid connecting both wind farms and countries amongst each other is worth building. For such a transnational grid, VSC-HVDC power transmission technology is most likely to be used because of the large distances over which cables would span, for which HVAC undersea cables cannot be used. This is because the capacitive charging of AC cables limits the length that can actually be used to maximum 100km [84] per section without reactive power compensation. Moreover, VSC-HVDC technology is compatible with a multi-terminal grid due to its flexibility. The only condition needed for having such grids is the existence of DC circuit breakers which at the moment are still under development. Next to ENSTO-E, many others [12–14, 67, 85] have set up studies for the integration of large-scale wind in the future European power systems. The OffshoreGrid Study [12] has investigated the development of offshore grids in the North Western European seas and the North Sea Transnational Grid study [14] specifically focuses on a transnational grid in the North Sea. Furthermore, [13] has investigated the option of building an offshore grid for integrating Irish wind farms mostly located in the Irish Sea. These studies have in common the fact that they look at potential wind power developments and the modalities of transporting to shore and integrating the large amounts of RES, together with also allowing international electricity trade via the offshore grid. All these studies took into account at least North Western European power systems for an adequate assessment of the offshore grid development.

The focus of this chapter is on studying the development of a transnational offshore grid in the North Sea and assessing its impact on the onshore grid, for a future 2030 high renewables scenario. Consequently models for North Western European power systems are developed and used. As a general approach the round-the-year security analysis introduced in Chapter 3 is used for both offshore and onshore grids. Consequently both market and grid models are developed. The chapter is structured as follows. In section 5.2 the Base Scenario is presented and the market simulation results for the Base Scenario. This is the starting point of the analyses in the next sections, and no transnational offshore grid is considered yet. Next, section 5.3 looks at at the relationship between offshore grid topology and interconnection capacity that can be given to the market, and using the findings a more suitable offshore grid topology is chosen. Furthermore, in section 5.4 the security of the onshore grid is assessed. This is done first for a Reference Scenario where the previously chosen offshore grid is assumed, and next sensitivity analyses are performed to both different structures of the onshore and offshore grids. At the end, the main findings of the chapter are summarized.

5.2 Base Scenario for North-Western Europe in the year 2030

The development of a North Sea transnational offshore grid (NSTG) which will be assessed in this thesis work, cannot be separated from the power systems developments in the surrounding countries. Hence, a Base Scenario for the North Sea offshore grid-related countries has to be considered for a 2030 scenario of load, generation and interconnection capacities [86]. Furthermore, hourly wind and solar power time series are developed and serve as an input to the market simulation tool (chronological unit commitment and economic dispatch (UC-ED)), which is run for a whole year with hourly resolution. The market simulation is run for the Base Scenario. The ability of the modeled power system to cope with a high RES penetration level is examined. The development of temporally- and spatially-correlated time series for RES production enable accurate assessment of constraints related to the flexibility of fossil-fuel resources, as well as of the positive smoothing effects when RES are traded across large geographical areas.

5.2.1 The market model

The Base Scenario is a future scenario for the year 2030 of load, generation and interconnection capacities for North-Western Europe (Figure 5.1). The considered countries are Belgium, Denmark, France, Germany, Great Britain, Netherlands, Norway and Sweden. For the

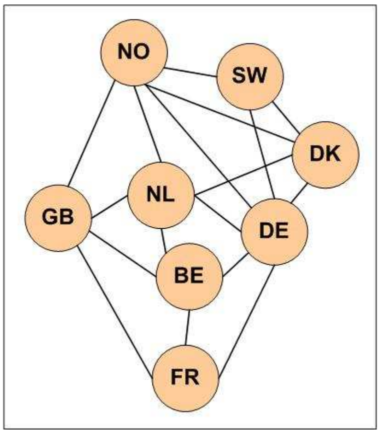


Figure 5.1: Transmission corridors in North-Western Europe.

market simulations the commercially available PowrSym4 tool was used [76]. PowrSym4 is a probabilistic, chronological, multi-area, multi-fuel electricity and heat unit commitment and economic dispatch simulation tool. The market model is optimized considering sequential hourly time steps (within each weekly horizon), with the purpose of obtaining the minimum operating cost (including fuel, emission and start-up costs) at the system level while the technical constraints for generating units and interconnection capacities are met at all times. The model is run in zonal mode, where only the inter-area transmission capacities allocated to the market are considered, while the networks of the different areas are seen as a “copper-plate”, hence the underlying physical grid is neglected. The modeling of different types of power plant technologies for the 8 countries is taken from [87, 88]. Biomass was considered only in Germany, and only a part of it was considered to be flexible.

Weekly hydro energy schedules for the different countries are served as input to the market simulation. For Norway and Sweden the schedules are elaborated considering amongst others also wind power availability. For details about the hydro schedules consult Appendix D. The hydro power stations are scheduled in the weekly optimization using a price levelling algorithm, which refers to time-related constraints in the system. Consequently, the hydro schedule is optimized based on the system’s marginal cost, while taking into account reservoir size limits, load prediction and wind power and solar power forecasts. Wind and solar generation are scheduled before hydro generation since they are usually taken as they occur while hydro generation hourly scheduling usually has some flexibility. In the event that more energy is available than needed in a given week, all other resources (including wind) will be curtailed before hydro. This is because there may be physical consequences for curtailing the hydro generation and there are no consequences other than economic opportunity for curtailing wind generation and other resources. Both hydro and RES generation are modeled as having zero generation cost. The total pumped storage capacity in the system is assumed to be 21.88 GW, and no other storage technology is modelled.

Scenario B (“most likely” scenario) from the System Adequacy Forecast 2011-2025 report (SAF) from ENTSO-E [9] is used as a reference for sizing the conventional generation parks of each country per technology and also for scaling historical load series from 2011 to the year 2030. One exception is Germany, for which the recently announced nuclear shut-down was considered, resulting in no installed nuclear capacity in Germany in the year 2030. To compensate this, some increases in the forecasted capacities of other conventional generation are assumed. The installed capacities for each country per technology can be found in Appendix D. The fuel prices are based on the World Energy Outlook 2010 [89] published by the International Energy Agency, scenario New Policies. The CO_2 price is taken from the same scenario and it is 46 Euro/ton CO2.

To ensure a uniform model, combined heat and power plants are not specifically modeled as data availability for such modeling was only available for the Netherlands. Instead of this, heat delivery obligations are translated in minimum generation obligations. Assumptions of minimum operating requirements are made for thermal and nuclear power plants. Moreover, it is assumed that in order to accommodate more RES the conventional generating park will be more flexible than at present, meaning that the minimum output requirements for some conventional thermal power plants were reduced.

When simulating, there might be situations where dumped energy and/or energy not served are reported indicating that there is an operational problem. On the one hand, energy is dumped as a last resort when there is excess generated energy due to the flexibility constraints of the system. On the other hand, energy not served (ENS) appears as a consequence of a deficit in generated energy with respect to the load demand. In reality dump energy and energy not served do not occur as the Transmission System Operators (TSOs) take operational security measures to prevent this from happening.

The Net Transfer Capacities (NTCs) between countries are approximated for the year 2020. This is done based on TenneT and ENTSO-E data [9, 90] regarding the current NTC values, and rough estimates of an increase of the current NTCs based on the Ten-Year Network Development Plan for the next decade (2020) (see Figure D.3 of Appendix D for the values). The rest of the continental European system and Ireland are not modelled. A perfect forecast is considered for both load and wind power. Within the market simulation, it is assumed that all wind power can be curtailed, while solar and part of the biomass generation categories are assumed to be uncurtailable. The curtailed wind energy is reported separately in the market simulation output.

The installed capacities for onshore wind power per country are taken from the TradeWind high wind scenario [67] for Denmark and from the Offshore Grid project for the rest of the countries [12], and for the offshore wind power from the offshore wind from the Global Offshore Wind Portal [91]. The resulting capacities are illustrated in Table 5.1. Detailed wind power time series are developed for both onshore and offshore wind farms as detailed in Appendix D. Moreover, solar power time series are also developed for France and for Germany. The installed capacities in 2030 are 13 GW for France [9] and 66 GW for Germany (German government's target for 2030) (see Appendix D).

Table 5.1: Scenario of installed wind capacities for 2030

Country	Country abbreviation	Wind onshore [GW]	Wind offshore [GW]
Belgium	BE	2.5	3.8
Denmark	DK	4.7	3.8
France	FR	38	7
Germany	DE	47	31.6
Great Britain	GB	19.4	43
Netherlands	NL	6	10.3
Norway	NO	5.8	11.9
Sweden	SW	7	7.5
Totals	-	130.4	118.8

5.2.2 Market simulation results

Table 5.2 illustrates the generated energy per technology type in the Base Scenario for 2030 North-Western Europe. It should be reminded here that the interconnection capacity in the Base Scenario was kept at the values for the year 2020. From the table, it can be noticed that the wind generation sums up at 30.7% of the total generated electrical energy (in line with EWEA's forecast), and all together the RES (biomass, solar and wind) constitute about 38% of the whole generation mix. If hydro is also added, the total percentage of more or less "clean" electricity production is almost 52.4%. Then nuclear plants deliver 24.5% of the energy share, and the rest of 23.1% is represented by fossil-fuel generated electricity. It may be noted that the minimum output requirements for conventional thermal power plants sum up to a total of 27.1 % of the system's minimum load.

Table 5.3 shows other main results of the Base Scenario market simulation. It can be noticed that the wasted wind energy (because of system and interconnection constraints) sums up to 115 TWh, representing 14.7% of the total available wind energy of 781.3 TWh. Besides wasting of wind power, there still are some flexibility problems in the system as there 1.35 TWh of dump energy and 0.6 TWh of energy not served. This means that the system – even though able to integrate almost all available solar energy – still faces some operational problems due to inflexible generating units and transmission constraints.

Table 5.2: Base Scenario: generated energy per technology

Technology	**Generated electricity [TWh]**	**% total generation**
Biomass	50.53	2.33
Coal	184.07	8.48
Gas	230.30	10.61
Hydro	310.79	14.32
Lignite	84.35	3.89
Mix fuel	0.99	0.05
Nuclear	531.71	24.50
Oil	1.9	0.09
Solar	108.95	5.02
Wind onshore	369.18	17.01
Wind offshore	297.18	13.69
System	2169.96	100

Table 5.3: Base Scenario: main market simulation results

Pumped Storage Load	[TWh]	25
Curtailed Wind Energy	[TWh]	115
Dump Energy	[TWh]	1.35
Energy Not Served	[TWh]	0.6
CO_2 Emissions	[kton]	345676
CO_2 Cost	[M€]	15900
Fuel Cost	[M€]	30522.1
Start-up Cost	[M€]	2202
Operation & Maintenance Cost	[M€]	6798
Energy Not Served Cost	[M€]	130
Total System Operating Cost	[M€]	55553

In the Base Scenario there are already point-to-point HVDC offshore connections between various countries around the North Sea. Table 5.4 shows these links and the Base Scenario market simulation results regarding their annual usage. It can be noticed that all links have quite high usages, all of them being more than 80% of the time used and more than 50% of the time used at maximum capacity. This is an indication that additional interconnection capacity within the North Sea might be beneficial.

5.3 Offshore grid topologies analysis

In this section an analysis of various offshore grid topologies is performed. The investigated topologies are introduced as well as the approach used for the assessment. Further, the results of the analysis are presented. A discussion on offshore grid structure and security is made.

Table 5.4: Base Scenario market simulation results: offshore links between countries in the North Sea and their usage statistics.

Link	Capacity [MW]	% hours at max	% hours used
NL-NO	1400	76.8	84.4
GB-NO	1400	74.5	88.9
DK-NO	1600	67.7	80.3
NL-GB	1000	66.5	93.8
BE-GB	1000	88.3	99.8
NL-DK	700	50.7	83.4
NO-DE	1400	80.7	91.5

5.3.1 Topologies

For a given set of onshore nodes and offshore generation nodes, there are more ways of connecting the nodes to each other. Each way of connecting the nodes is called a grid structure or a grid topology. When talking about offshore wind, the wind farms (or at an aggregated level the offshore wind hubs) can be either connected radially to shore only, or they can also be interconnected to other wind farms (or hubs) and to more than one onshore system. These interconnections allow for increased trading capacity and enhance the reliability of the offshore grid.

In this thesis three types of offshore grid structures are defined and used as reference, as shown in Figure 5.2: radial, looped and meshed grid structures. In a radial grid topology there is no loop in the offshore grid, in a looped grid structure there is one loop in the grid, and in a meshed grid structure there are multiple loops in the grid.

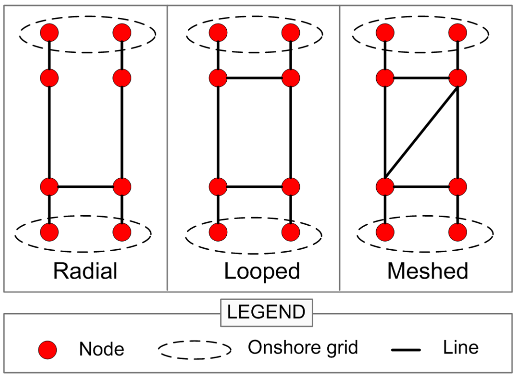
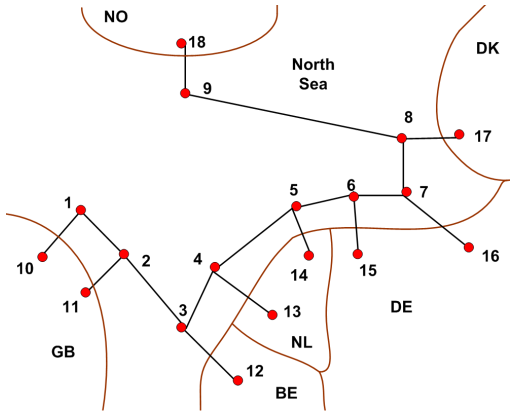


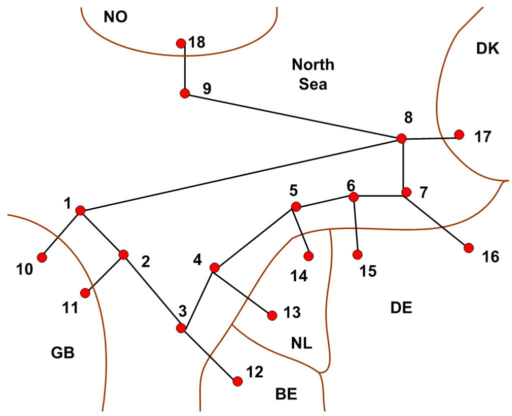
Figure 5.2: Different offshore grid structures.

In the development phases of the offshore HVDC grid proposed by the NSTG study [14], the radial, looped and meshed topologies are encountered as illustrated in Figure 5.3. In this section each of the three topologies is studied starting from the same 2030 Base Scenario (which was introduced in Section 5.2).

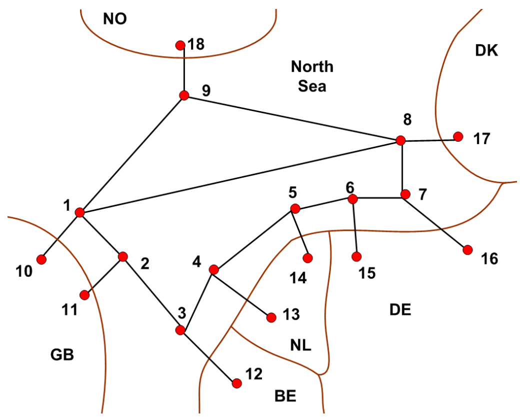
In total there are 18 nodes in the offshore grid, that can be connected by different combinations of lines. The lines that appear in Figure 5.3 are detailed in Table 5.5, together with



(a) Radial



(b) Looped



(c) Meshed

Figure 5.3: Investigated offshore grid topologies, for country abbreviations see Table 5.1

an estimate of their length that corresponds to the geography of the North Sea area.

Table 5.5: Approximate lengths of the transnational offshore grid sections.

Line no.	**Line name**	**From Bus**	**To Bus**	**Length [km]**
		Hub-to-shore		
1	L1-10	1	10	40
4	L2-11	2	11	25
6	L3-12	3	12	80
9	L4-13	4	13	60
10	L5-14	5	14	40
12	L6-15	6	15	125
14	L7-16	7	16	150
16	L8-17	8	17	55
18	L9-18	9	18	120
		Hub-to-hub		
2	L1-9	1	9	600
3	L1-2	1	2	250
5	L2-3	2	3	100
7	L3-4	3	4	125
8	L4-5	4	5	260
11	L5-6	5	6	40
13	L6-7	6	7	75
15	L7-8	7	8	50
17	L8-9	8	9	225
19	L1-8	1	8	500

5.3.2 Approach for assessing offshore grid topologies

In order to assess the differences between the three offshore grid topologies, and finally choose a topology for studying the effect of the offshore grid on the onshore grid in section 5.4, both market and grid issues have to be considered. With the help of market simulations (performed with a zonal market model that uses net transfer capacities - NTCs) the market benefits of having an offshore grid can be assessed. With the help of load flow calculations the security of the grid for various combinations of load and generation coming from the market simulation can be assessed. Hence the round-the-year security analysis approach is used for the offshore grid but performed for the N situation only. With the round-the-year security analysis it is investigated how much offshore grid capacity can be given to the market. For a future offshore grid for which there is no net transfer capacity (NTC) history, it is important to have some NTC estimates.

Sections 5.3.2.1 and 5.3.2.2 explain how the offshore grid is modelled in both market and grid models. Furthermore, section 5.3.2.3 shows how the round-the-year security is used for the offshore grid.

5.3.2.1 Offshore grid and the market model

A market analysis is performed by using the market model introduced in section 5.2. The Base Scenario is used as a starting point for the offshore grid topology investigation.

For modelling the offshore grid, the market model is changed by assuming that part of the offshore wind in the North Sea (see Table 5.6) is connected to a transnational offshore grid. This is modelled by adding market areas with zero load, for the hub nodes 1 through 9 in Figure 5.3. It is assumed that each of the hub nodes is connected to the shore with sufficient transmission capacity (the closest multiple of 1256 MW to the installed wind capacity of the hub node). 1256 MW is the rated capacity per circuit for the chosen VSC-HVDC bipolar transmission lines. More details are given in the next section, where the grid model is described. For simplicity, only the multiple of 1200 MW is given to the wind area-to-country links in the market model. All this is illustrated in Table 5.6. Furthermore, connections between the hub areas are modelled according to the desired offshore grid topology using the same rated capacity (1256 MW) and as a starting point it is assumed that the capacity given to the market is also 1200 MW per circuit.

Table 5.6: Wind capacities and hub-to-shore links chosen for the DC offshore grid

DC node	Wind capacity [MW]	Line	Hub-to-shore links		
			No. of circuits	Rated capacity [MW]	Market capacity [MW]
1	13000	L1-10	11	13816	13200
2	7200	L2-11	6	7536	7200
3	2000	L3-12	2	2512	2400
4	2045	L4-13	2	2512	2400
5	875	L5-14	1	1256	1200
6	17418	L6-15	15	18840	18000
7	3523	L7-16	3	3768	3600
8	1200	L8-17	1	1256	1200
9	5200	L9-18	5	6280	6000

5.3.2.2 Offshore grid and DC load flow model

As mentioned in section 5.1, it is assumed that the offshore grid is based on VSC-HVDC technology. Load flows in the offshore DC grid are calculated with a simplified Newthon-Raphson load flow adapted for the DC grid [72], which was implemented in Python. In the DC grid we do not have phase angles and reactive power, hence the load flow can be written in a simplified way. The iteration process is given in Eq. 5.1 and 5.2, where k is the iteration index.

$$\mathbf{x}(k+1) = \mathbf{x}(k) + \Delta\mathbf{x}(k) \tag{5.1}$$

where

$$\Delta\mathbf{x}(k) = -\mathbf{J}(k)^{-1} \cdot \mathbf{F}(x(k)) \tag{5.2}$$

The state variables are the nodal voltages (Eq. 5.3), with the slack considered to be the last node (N), hence its voltage V_N is fixed. Moreover, the vector $\mathbf{F}$ holds the mismatch equation for the active power (Eq. 5.4 and 5.5). $\mathbf{J}^{-1}$ is the inverse Jacobian of the active power mismatch equations.

$$\mathbf{x} = [V_1, ..., V_{N-1}]^T \tag{5.3}$$

$$\mathbf{F}(\mathbf{x}) = [f_{P_1}, ..., f_{P_{N-1}}]^T \tag{5.4}$$

$$f_{P_i} = P_{Gi} - P_{Li} - \sum_{j \neq i} V_i V_j Y_{ij} - Y_{ii} V_i^2 \tag{5.5}$$

P_{Gi} and P_{Li} are the generation and the load injected at node i, values coming as input from the market model (no converter losses are assumed). Y_{ii} and Y_{ij} are terms of the $\mathbf{Y}_{bus}$ matrix. The $\mathbf{Y}_{bus}$ matrix can be expressed as the product between the incidence matrix $\mathbf{I_M}$ and the primitive diagonal $\mathbf{Y}$ matrix as in Eq. 5.6. The terms of the primitive $\mathbf{Y}$ matrix are calculated as in Eq. 5.7. For L being the number of lines in the grid and B the number of nodes, $\mathbf{Y}_{bus}$ is a matrix of size B x B, $\mathbf{Y}$ is an L x L matrix, and $\mathbf{I_M}$ is a L x B sparse oriented incidence matrix (having the value 1 or -1 when the nodes are connected and 0 otherwise).

$$\mathbf{Y}_{bus} = (\mathbf{I_M})^T \cdot \mathbf{Y} \cdot \mathbf{I_M} \tag{5.6}$$

$$Y_{ll} = \frac{1}{R_{DCline_l}} \text{and } Y_{lm} = 0 \tag{5.7}$$

The simplified Jacobian matrix **J**, which represents the variation of the mismatch equations 5.4 and 5.5 with respect to the state variables 5.3 can be written as in Eq. 5.8 and 5.9.

$$\mathbf{J} = \frac{\partial \mathbf{F}_P}{\partial \mathbf{V}} = \begin{pmatrix} \frac{\partial f_{P_1}}{\partial V_1} & \cdots & \frac{\partial f_{P_1}}{\partial V_{N-1}} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_{P_{N-1}}}{\partial V_1} & \cdots & \frac{\partial f_{P_{N-1}}}{\partial V_{N-1}} \end{pmatrix} \tag{5.8}$$

$$\frac{\partial f_{P_i}}{\partial V_n} = \begin{cases} -Y_{in}V_i & \text{if } n \neq i \\ -\sum_{j\neq i} V_j Y_{ij} - 2Y_{ii}V_i & \text{if } n = i \end{cases} \tag{5.9}$$

By replacing in Eq. 5.2 **x** with **V**, the difference between two consecutive load flow iterations can be expressed as in Eq. 5.10.

$$\triangle \mathbf{V}(k+1) = -\mathbf{J}(k)^{-1} \cdot \mathbf{F}(\mathbf{V}(k)) \tag{5.10}$$

In this thesis the case of a single slack node is used, which is chosen from the onshore converter nodes [1]. It is assumed that the voltage of the slack node is 1 p.u. The choice of the slack node voltage value mostly influences here the distribution of voltages in the offshore grid, and 1.p.u. should generally not cause voltage excursions outside the limits (as here it is assumed that all converters are operating). In this work the focus is on overloads and not on over/under voltages, but the voltage limits can be checked. Moreover, since the choice of the slack node has an effect on the flows in the offshore grid, for a certain distribution of load and generation, the slack node is chosen as the first node that does not cause overload in the DC grid or, as the node that causes the least overloads.

All the other nodes in the offshore grid act as fixed active power nodes. More precisely, the hourly generation and load for the DC grid nodes except the slack node are given by the output of the market simulations: for the wind hub nodes (1 to 9), the power generation of the corresponding wind farms for that particular hour, and for the onshore converter nodes (10 to 18) as the power transported through the corresponding wind hub-to-shore market link. Hence, load flows are run for every hour of the year, and for each hour the best slack node is chosen as described above. In this thesis for the offshore grid only the N situation is considered, and N-1 contingency analysis is not performed.

It is assumed that the transmission circuit is a bipole at ± 320 kV with 1400 mm^2 submarine cables with copper conductor, for moderate climate, in spaced laying, with a specific resistance (per phase) of 0.0126 ohm/km and an ampacity of 1962 A, as given by the manufacturer [92]. Consequently, a transmission circuit has a rated capacity of 1.256 GW and all transmission lines in the model are formed by 1.256 GW circuits. For accounting for the bipolar power transmission, the base DC voltage in the load flow is 640 kV (the voltage on the DC side).

[1] In general, it is also possible to use distributed slack bus, but this is not applicable for the used model, where the load and generation values from the market simulation have to be respected.

5.3.2.3 Offshore grid and round-the-year security analysis

There are two possibilities of assessing the consequences, in especially the market utilization of different offshore grid topologies. The ideal one would be to have a flow-based market model [93–95] (which is the target of ENTSO-E) for both offshore and onshore power systems. In such a model, the market optimization considers to some extent the physical limitations of the grid and tries to ensure that no overloads are caused. In such a model the resulting grid flows still have to be checked for being sure that no overloads occur, but the chances of having overloads are reduced.

The second approach, which is adopted in this thesis, is to use a zonal energy transportation market model (i.e. it has no underlying physical grid model) where only fixed Net Transfer Capacities (NTCs) between various market areas are defined. Normally these NTCs are chosen in order to respect system security conditions, thus having a certain reserve margin with respect to the actual installed inter-area grid capacity. It is important to see what the resulting flows in the grid are if the market outcome is to be implemented. This can be done with the help of the round-the-year security analysis introduced in Chapter 3; it is assumed that the security analysis is performed for the N situation only. As for the future offshore grid investigated in this work no history of NTCs exists, a set of "safe" NTCs has to be first determined. So for a certain offshore grid structure it is first assumed that for all the offshore grid links full NTC values are given to the market. Consequently, round-the-year security analysis for the offshore grid is performed in order to check if overloads occur. If that is the case the NTCs of the initially overloaded links are all reduced in equal steps in the market simulation, until almost no overloads occur anymore. When this is reached the set of "safe" NTCs is found and the effect of the offshore grid can be more accurately quantified.

5.3.3 Comparison of topologies

In order to make a comparison of the three different topologies introduced in subsection 5.3.1, each of the grid structures is modelled in the market simulation. It is assumed that all hub-to-hub connections have a rated capacity of 1256 MW. Moreover the hub-to-hub capacities given to the market are 1200 MW each as a starting point. For the offshore grid load flow calculations the DC grid model presented in subsection 5.3.2.2 is used and by running load flow calculations for each hour of the simulated year, the risks of overload are assessed according to the methodology presented in Chapter 3. Next, the Net Transfer Capacities (NTCs) given to the market model for all the overloaded hub-to-hub links are reduced in equal steps until no more overloads occur. Consequently, the capacity that can be given "safely" to the market for each grid topology is roughly estimated.

5.3.3.1 Market simulation results

Table 5.7 shows a comparison of the market simulation results for the radial, looped and meshed offshore grid topologies with 1.2 GW hub-to-hub capacities. This comparison is done with respect to the Base Scenario, where only the hub-to-shore links and the bilateral country interconnections are present. It can be noticed that increasing the interconnection capacity in the market model, by adding the hub-to-hub links, inherently brings benefits such as total operating cost reduction, decrease in CO_2 emissions and also reduction of wind energy curtailment. The reason of these benefits is the access to a more geographically diverse generation park.

Table 5.8 shows the usage results of the hub-to-hub links, for each of the three cases, as a result of the market simulation. The most used links are L1-9 between the Norwegian wind hub and the first British wind hub, and L8-9, between the Norwegian wind hub and the Danish wind hub. These are followed by L2-3, L1-8 and L7-8. For all these links there is a high number of hours when the market makes use of the whole transfer capacity. The least used links are the hub-to-hub links connecting wind hubs of the same country: L6-7, L4-5 and L1-2, but also L5-6 connecting the German and Dutch wind hubs. Links between hubs of different countries are much more used than the ones between hubs of the same country. This can be explained by the fact that these less used links connect hub-nodes that are connected to onshore nodes belonging to the same price zone. These aspects will be considered later in the final choice of an offshore grid.

Table 5.7: Comparison (with respect to the Base Scenario) of market simulation results for the three grid topologies with 1.2 GW NTCs for the hub-to-hub links.

Case	**Total System Operating Cost [M€]**	**CO_2 Emissions [ktons]**	**Curtailed Wind [TWh]**
Base Scenario	55553	345676	115
	Changes with respect to the Base Scenario		
Radial	-921	-4927	-8.4
Looped	-1074	-5779	-10
Meshed	-1457	-8548	-13.4

Table 5.8: Market simulations results: hub-to-hub link usage statistics (see Figure 5.3 for line labels).

Case	**Parameter**	**Line**									
		L1-9	**L1-2**	**L2-3**	**L3-4**	**L4-5**	**L5-6**	**L6-7**	**L7-8**	**L8-9**	**L1-8**
Meshed	**Mean power [MW]**	809	227	733	517	113	267	34	657	758	695
	% hours used	74.0	48.9	83.5	69.5	28.5	31.6	9.0	74.3	70.3	80.5
	% hours at NTC	62.0	1.3	42.0	18.9	0.6	16.6	0.03	38.7	55.4	31.8
	% hours > 0.5NTC	67.0	14.6	59.9	41.7	6.6	21.3	2.0	53.8	63.2	57.8
Looped	**Mean power [MW]**	n/a	133	685	536	118	273	34	634	784	725
	% hours used	n/a	35.9	81.0	70.4	29.2	32.3	9.0	75.1	72.0	81.1
	% hours at NTC	n/a	0.6	37.3	21.1	0.5	16.7	0.1	35.1	56.9	36.1
	% hours > 0.5NTC	n/a	6.4	55.6	43.0	7.4	21.9	2.0	50.7	66.1	60.6
Radial	**Mean power [MW]**	n/a	25	655	565	117	284	41	732	760	n/a
	% hours used	n/a	5.0	78.7	71.2	29.6	32.9	9.4	69.7	68.2	n/a
	% hours at NTC	n/a	0.2	35.4	24.8	0.5	17.6	0.1	40.0	58.4	n/a
	% hours > 0.5NTC	n/a	1.7	52.9	45.9	7.2	23.0	2.9	64.0	63.3	n/a

5.3.3.2 Load flow and risk of overload assessment results

Next, load flow calculations are performed with hourly resolution for each of the three topologies [2]. Only N situations were analyzed as it was assumed that the offshore grid does not have to be N-1 secure (see discussion later in paragraph 5.3.4). The risk of overload during N situation ($RO_{N,i}$) for each of the hub-to-hub links is determined under all cases using Eq. 3.2 as described in Chapter 3. For a branch i $RO_{N,i} = (C01_i - 100) \cdot C02_i$ [% of rated capacity $\cdot$ hours].

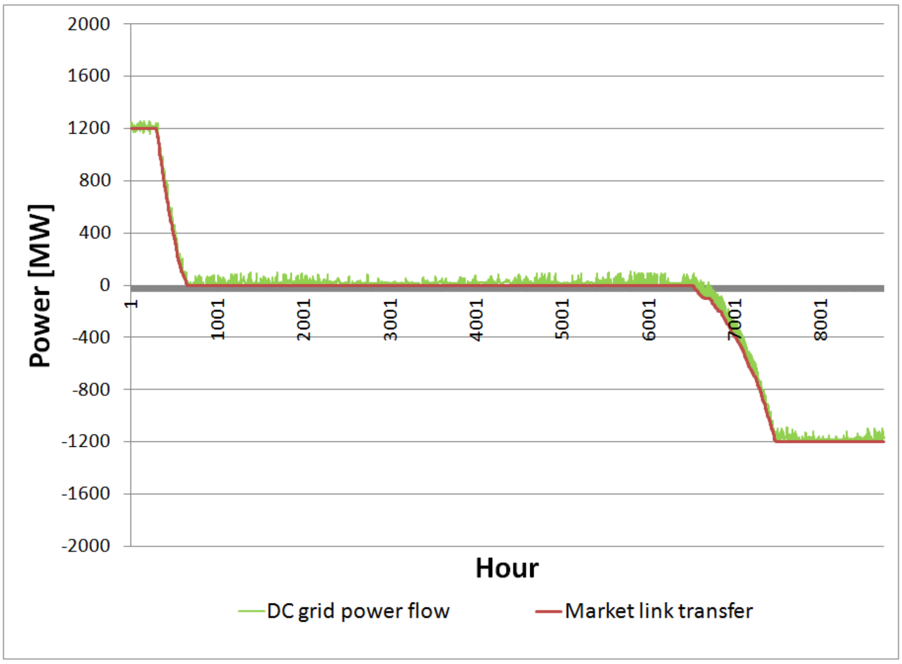
Table 5.9 illustrates the risks of overload and the criteria for the N situation for each of the three grid topologies. The criteria are C01: branch loading median for the overloaded hours; C02: total number of overloaded hours, and C03: maximum loading of overloaded equipment. It can be noticed that in the radial structure no overloads occur. By creating loops in the grid as is the case in the looped and meshed structures, the risks of overload increase dramatically, highlighting the differences between the NTC-based market transactions and the physical flows.

Table 5.9: Risks of overload and bottleneck ranking criteria for the three topologies.

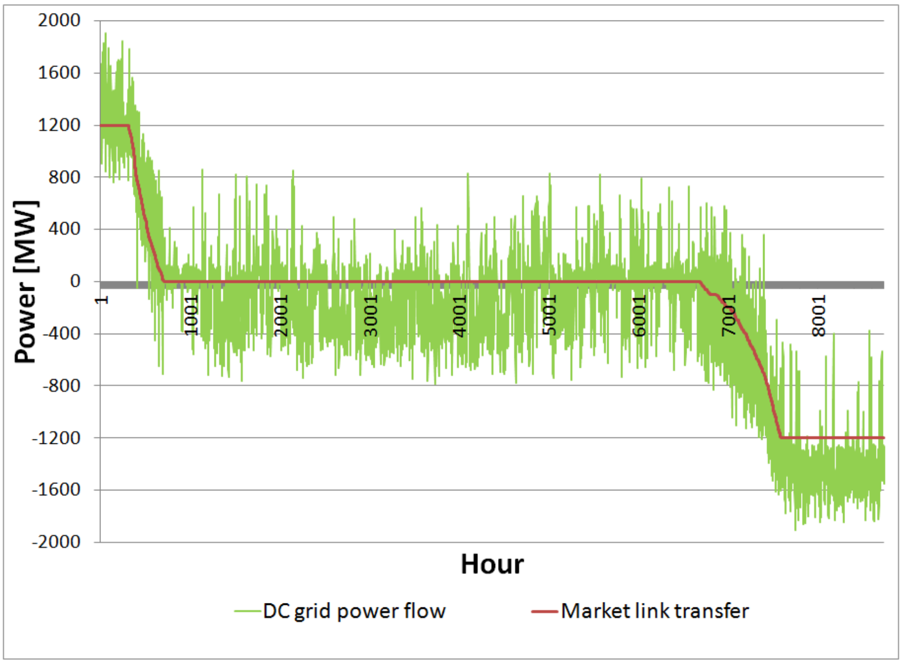
Line	Radial	Looped				Meshed			
	RO_N [%*h]	**RO_N [%*h]**	**C01 [%]**	**C02 [h]**	**C03 [%]**	**RO_N [%*h]**	**C01 [%]**	**C02 [h]**	**C03 [%]**
L1-9	n/a	n/a	n/a	n/a	n/a	664.6	102.6	258	108.0
L1-2	0	276.3	110.2	27	114.4	37.1	104.1	9	116.0
L2-3	0	40344.1	119.3	2085	150.7	19679.3	111.3	1745	175.7
L3-4	0	24901.8	114.3	1738	139.6	38338.6	121.3	1803	160.4
L4-5	0	237.9	106.8	35	117.9	680.7	108.0	85	139.4
L5-6	0	21270.1	115.7	1354	150.2	29469.7	121.7	1360	159.1
L6-7	0	109.1	107.8	14	125.2	137.2	108.1	17	145.7
L7-8	0	9588.4	113.7	700	144.9	19368.8	112.0	1612	162.9
L8-9	0	0.0	0.0	0	0.0	119782.1	129.2	4096	176.4
L1-8	n/a	0.0	0.0	0	0.0	16.6	101.3	13	105.7

In order to illustrate this aspect better, Figure 5.4 shows the load-duration curve of line 5-6, between the Dutch and German parts of the offshore grid, according to the market simulations, together with the corresponding DC grid computed power flow curve, for the radial and the meshed structures. It can be noticed that in the radial structure, the physical flows are close to the market flows, while in the meshed structure, the differences between the two are rather high.

[2] Note that no attempt was made to optimize the voltage profiles in the DC grid, since the focus is on the capacity of accommodating the market outcomes.



(a) Radial



(b) Meshed

Figure 5.4: L5-6 market transfers and actual DC grid flows: loading-duration curve ordered according to decreasing values of market transfers.

Furthermore, for getting a better insight into the differences between the market transactions and the physical flows one critical snapshot for the meshed grid structure is investigated. This snapshot is hour 1380, when line L5-6 is at its maximum overload with a loading of 159.1% (Table 5.9) and it is illustrated in Figure 5.5[3]. It can be noticed that the market makes use of the available NTC values. However, the physical flows take the path of least resistance (shortest path). Around 700 MW take the shorter way between nodes 7 and 3 (namely 7-6-5-4-3 which sums to 500 km), instead of 350 MW via 9-1-2-3 (950 km) and 350 MW via 7-8-1-2-3 (900 km) as it appears from the market simulation. As a consequence, in this hour line L5-6 is heavily overloaded.

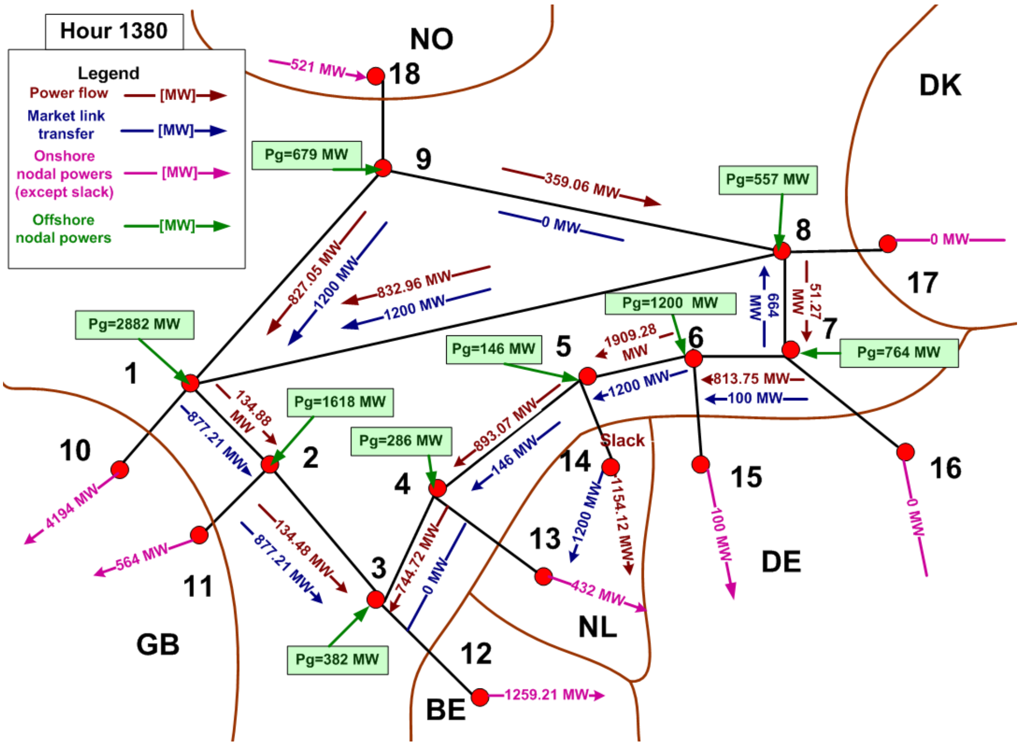


Figure 5.5: Snapshot of hour 1380: power flows versus market transfers in the offshore grid, meshed structure, 1.2 GW hub-to-hub links.

It can be concluded that the offshore grid structure is a limiting factor for the transfer capacities that can be given "safely" to the market. For roughly approximating this limitation in the looped and meshed cases, the net transfer capacities (NTCs) in the market model for the hub-to-hub links that are overloaded for NTC of 1200 MW, are reduced in steps of 120 MW simultaneously until (almost) no more overloads occur.

For the looped structure it can be seen in Table 5.9 that lines L8-9 and L1-8 are not overloaded hence the capacity given to the market for these links is kept the same, namely 1200 MW each. For the rest of the hub-to-hub links the market capacity is reduced in steps.

[3]Please note that the figure is not to scale, the grid representation does not reflect the real distances between different nodes in the North Sea. For the actual distances see Table 5.5.

At each step the round-the-year security analysis is performed and the overloads in the grid are checked. At a NTC value of 720 MW each, almost no overloads occur as shown in Table 5.10. By summing up all NTCs of the hub-to-hub links and dividing this number to the sum of the rated capacities of the same links, it results that only 65.8% of the total hub-to-hub rated capacity can be given to the market. This value is conservative because in the market model fixed NTC values for the whole year were defined. With a flow-based market coupling [93, 94] the total capacity that could be used by the market throughout the year would vary and would probably bring some increase in the yearly average total capacities, allowing a better interconnection capacity usage. In addition, novel control methods for the offshore grid power flow, such as a Distributed Direct Voltage Control Strategy [72] may also bring some improvement in the grid usage. As in the meshed case all lines are overloaded in Table 5.9 , all the hub-to-hub NTCs are reduced in steps from 1200 MW, to 720 MW each. As shown in Table 5.11, at a 720 MW NTC value, the risk of overload in the grid is negligible. Hence, 57.3% of the total offshore grid rated capacity can be safely given to the market.

Table 5.10: Risk of overload and bottleneck ranking criteria for the looped structure with safe NTCs.

Line	**Pn [MW]**	**NTC [MW]**	**RO_N [%*h]**	**C01 [%]**	**C02 [h]**	**C03 [%]**
L2-3	1256	720	33.6	101.6	21	110
L3-4	1256	720	7.6	101.3	6	102.2
L5-6	1256	720	0.7	100.7	1	100.7
L7-8	1256	720	4.9	100.8	6	102.3

Table 5.11: Risk of overload and bottleneck ranking criteria for the meshed structure with safe NTCs.

Line	**Pn [MW]**	**NTC [MW]**	**RO_N [% * h]**	**C01 [%]**	**C02 [h]**	**C03 [%]**
L2-3	1256	720	9.1	102.3	4	109.4
L8-9	1256	720	1.0	100.5	2	100.8

A new comparison of the market simulation results can be made now for a more accurate assessment of the different benefits (see Table 5.12). It can be noticed that when safe NTCs are used for the looped and meshed structures, the benefits are reduced in comparison to Table 5.7, and are comparable to the ones of the radial grid structure with 1.2 GW NTCs.

From the analysis in this section it can be concluded that the more meshed the structure of the DC grid, the less of its capacity can be safely used for market transactions. Hence interconnection capacity can be better used in radial grid structures. For a more accurate assessment of the effect of offshore grid design on how much of its capacity the market can use, and of the resulting changes in the generation mix of the modelled power systems, a flow-based market model is needed. In this thesis the model was simplified due to grid data

Table 5.12: Comparison of market simulation results for the three grid topologies with safe NTCs for the hub-to-hub links.

Case	**Total System Operating Cost [M€]**	**CO_2 Emissions [ktons]**	**Curtailed Wind [TWh]**
Base Scenario	55553	345676	115
	Changes with respect to the Base Scenario		
Radial	-921	-4927	-8.4
Looped	-901	-4857	-8.5
Meshed	-943	-5305	-9

availability for the countries in the market model, and the question of how a flow-based market coupling would operate in the North Sea is not treated.

5.3.4 Discussion on offshore grid structure

From the grid security and grid utilization perspectives, there is no blue print approach for choosing a most optimum configuration, and such a choice may depend from case to case. Assessing the security of a grid has to be done considering many combinations of load and generation. The round-the-year security analysis introduced in this thesis proved to be very effective for this, giving a much better overall picture of the overloads in the grid. It was moreover found that in a looped or meshed grid, issues such as the lengths of the offshore grid's links and the exchanged power at the grid nodes are very important in determining the physical flows in the grid. This is a well known fact for AC grids and becomes important also in multiterminal DC grids. The benefits of point-to-point VSC-HVDC connections are partially lost in a multiterminal looped or meshed VSC-HVDC grid. This is because it is not possible to fully control the grid flows for various combinations of load and generation at the grid's nodes. Control approaches such as optimization of converter voltage set-points could be used for having a certain degree of controllability in the grid, but the operation of the electricity market across the offshore grid area has to consider its physical structure. So, grid structure limits the capacity that can be ("safely") given to the market. More utilization of looped and meshed grids could be achieved by operating them as radial grids.

Offshore grid security can refer to more aspects, such as not exceeding rated capacities of DC lines and of converters, staying within the normal voltage limits during operation during N situation or also during cases when failure of elements is considered (N-1). In this thesis only security during N situation was tested. It is still a question whether an offshore grid should be N-1 secure in itself. The most simple way of achieving N-1 security is building redundant sections, but this would come with a high cost for a grid with very long undersea lines and expensive converter stations. In Germany they do not intend to make the North-South HVDC corridors redundant, but instead they want to plan the AC grid N-1 secure considering the loss of HVDC corridors circuits. However an offshore transnational grid connects different power systems out of which some are in not synchronous areas. Consequently losing an offshore grid link from the onshore grid side is comparable to losing an HVDC point-to-point interconnector such as NorNed. The solution would be then to adjust onshore power system reserves to the loss of individual offshore grid circuits ($\sim$ N-1), and consequently, the onshore grid has to accommodate the dispatch changes. For that, using reasonable circuit capacities for the offshore grid links is recommended as too big capacities may become problematic for the reserves of onshore systems.

5.3.5 Choice of an offshore grid configuration

In this paragraph, a suitable grid structure is determined in order to use it further in this chapter for the security analysis of the onshore grid. This work does not try to find the most optimum grid structure, as for this an adequate multi-criteria optimization model is required. In such a model a balance has to be found between congestion, overall grid utilization, investment cost, security (reliability), operating cost and wind integration [96, 97]. There can be moments when a hub-to-hub link cannot be used for power exchanges because of wind power being transported to shore, and/or because of too many hub-to-hub links being connected to the same hub-to-shore link, the hub-to-shore link being a limiting factor.

Regarding grid utilization, in Section 5.3.3 (see Table 5.8), it was noticed that some hub-to-hub links have low utilization factors, while some links have high ones. Installing new submarine cables is very costly, and it is desirable to have a reasonable degree of utilization of the assets in order to recover investments. The case of the NorNed classical HVDC link is considered [98] as a benchmark. For the yearly period between 1-07-2008 and 30-06-2009, the NorNed link was used 66.4% of the time. Moreover, 36.6% of the time it was used at maximum capacity. Hence, in this work it is required that the hub-to-hub links are used on average around 65% of the year and around 35% of the time at full NTC. This is also in line with the average link utilization factor of 63.7% used in the Offshore Grid EU project [12].

The choice of a suitable offshore grid configuration is done considering the criteria listed below and with the help of market simulation. Round-the-year security analysis is also used at the end for checking if any overloads occur in the offshore grid. The criteria are:

- The grid is operated without overloadings (in this work with no overloads in N situation).
- The grid has a radial structure for allowing maximum link utilization.
- A new circuit is added to a hub-to-hub link when it is used at least 72% of the year, and at least 55% of the year the link is used at full NTC.
- A hub-to-hub link is removed when it is used by the market less than 30% of the year.
- It is allowed to add new hub-to-hub links as long as they are used.

As the meshed grid structure brings the highest decrease in operating cost and wind curtailment (Table 5.7), this grid is chosen as a starting point. By looking at the hub-to-hub link utilization statistics for the meshed structure which were given previously in Table 5.8 and considering the criteria above the following can be noticed. Firstly, link L1-9 between the Norwegian and British hubs meets the criterion for adding a new circuit. Secondly, links L4-5 and L6-7 between the Dutch hubs and the German hubs respectively are not very much used and they are removed as they meet the criterion for link removal. Thirdly, a new link is added (L1-5) between the British wind hub 1 and the Dutch wind hub 5. Last but not least, for having a radial grid structure the loop 1-8-9 is opened by creating an extra onshore node (node 19) in Denmark. Consequently, link L1-8 is replaced with link L1-19 which is 555 km long.

The chosen offshore grid structure is shown in Figure 5.6. It can be noticed that a third circuit was added to Link 1-9. All other hub-to-hub links have only one circuit. The market simulation is run for this grid configuration, resulting in a total operating cost of 53349 M€ (i.e. -2204 M€ with respect to the Base Scenario) and total wind curtailment of 96.15 TWh (i.e. -18.85 TWh). The dump energy is 0.045 TWh and the energy not served is 0.36 TWh, both visibly reduced in comparison to the Base Scenario.

The offshore grid hub-to-hub and hub-to-foreign shore link usage statistics resulting from the market simulation are given in Table 5.13.

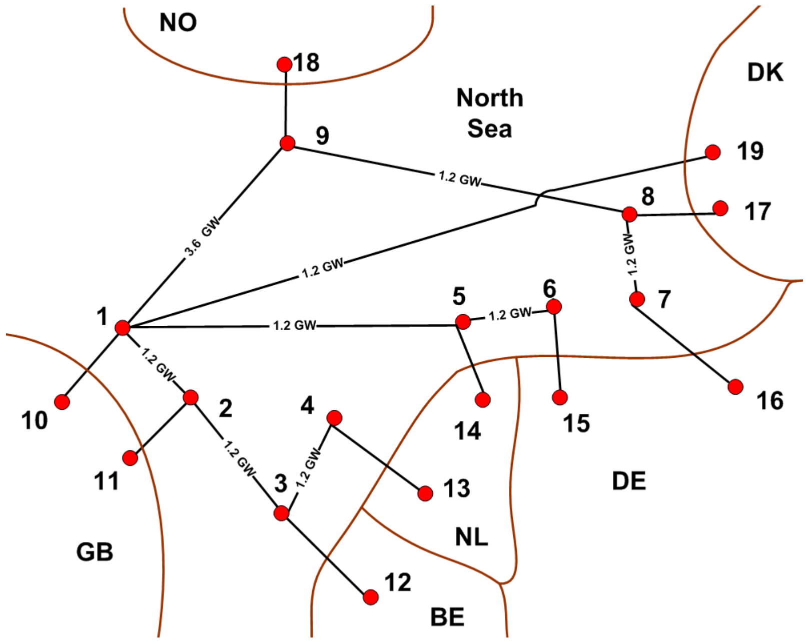


Figure 5.6: Chosen offshore grid configuration.

Table 5.13: Market simulation results for the chosen offshore grid configuration: usage of the hub-to-hub and hub-to-foreign shore links.

Parameter	**Line**								
	L1-9	**L1-2**	**L2-3**	**L3-4**	**L5-6**	**L7-8**	**L8-9**	**L1-19**	**L1-5**
Mean power [MW]	2145	398	796	486	321	650	717	743	690
% hours used	75.2	62.1	87.0	67.0	52.3	68.2	68.9	83.4	75.3
% hours at NTC	45.9	6.6	45.6	13.2	17.3	34.9	50.6	45.9	38.8
% hours > 0.5NTC	59.3	31.3	66.0	39.8	23.9	55.4	59.4	60.7	57.2

It can be noticed that no more new circuits are needed for any of the links in the table as the criterion for adding new circuits is not met. Also no circuits have to be removed. On average the links are used 71.04% of the year and 33.2% of the year at full NTC, meeting the average link usage criteria. Last but not least, round-the-year security analysis is run and no overloads are found.

Without claiming that the offshore grid structure arrived at its optimum, it can be concluded that the solution achieves a reasonable balance between improved link utilization and decrease in operating cost. The load flow results indicate the offshore grid to be secure for the N situation.

In the offshore grid topology analysis the capacities of the hub-to-shore links were kept constant. For getting an overview of the changes in the usage of the hub-to-shore links, a comparison of their usage is done. The market simulation results for the Base Scenario (without a transnational grid, usage given just by the wind generation) and for the offshore grid structure chosen in this section are shown in Table 5.14. Several things can be noticed. First, in the Base Scenario, none of the hub-to-shore links is used at maximum NTC. Second, when the chosen transnational grid is added, the usage of the links generally increases (exception L2-11). Link L6-15 is used more hours in the year, but its mean power usage decreases from 4925 MW to 4419 MW. Last, even with the transnational grid, some of hub-to-shore links are very little used at full NTC. Link 6-15 connecting one of the German wind hubs to the Germany, is not used at all at full NTC. However there are also links that are benefiting a lot from the chosen offshore grid structure (L3-12, L5-14, L9-18). Given these findings, the dimensioning of hub-to-shore links should probably consider their potential usage.

Table 5.14: Market simulation results comparison: usage of the hub-to-shore links.

Parameter	Line								
	L1-10	**L2-11**	**L3-12**	**L4-13**	**L5-14**	**L6-15**	**L7-16**	**L8-17**	**L9-18**
Base Scenario									
Mean power [MW]	2798	1168	663	384	187	4925	696	228	590
% hours at NTC	0	0	0	0	0	0	0	0	0
% hours > 0.5NTC	12.6	8.5	20.9	7.3	6.3	15.7	10.9	11.4	6.2
% hours used	86.7	78.6	95.3	76.3	79.1	86.3	80.6	71.6	39.4
Chosen offshore grid									
Mean power [MW]	4349	998	1881	444	720	4419	1367	325	2106
% hours at NTC	1.37	0.1	47.6	0.18	39.1	0	2.91	0.94	0.05
% hours > 0.5NTC	25.5	7.5	86.5	5.2	58.8	17.9	29.8	22.1	37.5
% hours used	88.1	73.3	94.7	84.4	89.5	90.3	88.6	77.5	77.1

5.4 Security analysis for the onshore grid

In this section the structure of the offshore grid is fixed and attention is moved to the onshore grid. The effects of the offshore grid on the onshore grid are investigated with the help of the round-the-year security analysis method introduced in Chapter 3. First, the considered onshore grid model and its assumptions are presented. Further, a detailed investigation of the bottlenecks in the Dutch EHV grid is performed. Some possible reinforcements are also analysed. Last, more sensitivity analyses are performed, for shedding more light on the quality of the results, on important aspects that affect the onshore integration of the offshore wind in the North Sea, and on the effect of the presence/structure of the offshore grid on the onshore grid.

5.4.1 Grid model and analysis setup

5.4.1.1 The onshore grid model

The grid model that is used to perform the calculations for the analysis, consists of a representation of the Dutch, Belgian and German grids for the year 2020. For the Netherlands the EHV grid (380 kV and 220 kV) is modelled and a small part of the HV grid (for connections to lower voltages) [81, 99]. For Belgium and Germany a simplified model of the EHV grids is adopted and these countries are modelled to obtain more realistic cross-border flows [9, 100].

Figure 5.7 illustrates the EHV Dutch grid model and is complemented by Table E.2 of Appendix E where the number of circuits as well as the rated capacity of each circuit are given. Moreover, Table E.1 gives the relationship between the abbreviation of each 380 kV Dutch node and its full name (see Appendix E).

Figure 5.8 illustrates the models constructed in the work to represent the Belgian and German grids. Table E.3 gives an overview of the number of circuits and the assumed capacity per circuit of each 380 kV corridor. The announced plans in Germany to build HVDC corridors between North and South [101] are also considered by modelling such corridors similar to the ones in the leading scenario of the German Grid Development Plan, namely Scenario B 2032 (see Figure 5.8 and Table E.4). This is done in a simplified fashion by injection/withdrawal of power, namely withdrawal from the North and injection in the South in hours with excess generation in the North as shown in Algorithm E.1 (no losses in the HVDC corridors are modeled).

The connections to countries/areas which exist in the market model but are not represented in the grid model are also modelled via injection/withdrawal of power at the respective nodes. The same is done for the planned HVDC connection between Gramme in Belgium and Rommerskirchen in Germany.

There are 6 phase shifting transformers (PSTs) modelled at the border of the Dutch grid with its neighbours. Between the Netherlands and Germany, two PSTs are modelled at the Meeden substation. Furthermore, between the Netherlands and Belgium, four PSTs are modelled on the Belgian side as follows: two at the Zandvliet substation, and two at the Van Eyck substation.

In Figure 5.7 the landing points of the offshore grid (NSTG) and of the radially connected offshore wind are indicated for the Dutch grid. Furthermore, in Appendix E, for all three countries, the total installed capacity per onshore connection node for the radially connected wind (not connected to the offshore grid) is reported in Table E.6, and the NSTG onshore landing points are given in Table E.5. For ensuring sufficient connection capacity for the wind and offshore grid power flows at Oterleek, two double circuit lines between Oterleek and Beverwijk, and between Oterleek and Diemen were added to the Dutch grid model. These lines were proposed in TenneT's Vision2030 report [99].

The coupling between the market and the grid models is done with the method presented in [78] and explained in Appendix C. For the Belgian and German models, the load and generation were aggregated in the nodes of the simplified grid representations, according to their geographical distribution.

Loadings of selected branches in normal and contingency situations are determined using the commercial software PSS/E version 32.

5.4.1.2 Analysis setup

An AC-DC contingency analysis is adopted, for the N and respectively N-1 situations. The contingency analysis is performed only on the Dutch part of the grid including interconnections to neighbouring grids; there are 139 N-1 contingencies performed (only branch contingencies), and 96 monitored branches. The AC base case is calculated with a full Newton-Raphson method for the Dutch, Belgian and German interconnected system. The slack node is set far from the Dutch grid, in Neurott, for reducing its influence on the Dutch grid flows. The adjustment of phase shifting transformers is allowed only during the AC base case, and these adjustments are kept at current levels during the DC contingency analysis. Moreover, no generation re-dispatch is allowed. Multiple consecutive AC full Newton-Raphson load flows are allowed , in case convergence issues appear. As the neighbouring countries of the Dutch grid have simplified grid models, results might not be accurate. Hence, from the analysis in this chapter only general conclusions can be drawn, and specific recommendations about the Dutch grid cannot be made.

The round-the-year security analysis with all the data processing for the considered onshore grid, takes around 2.5 hours. Regarding the analysis of the results [4], the risks of overload defined in Chapter 3 are computed as in Eq. 3.2 and 3.3 and then normalized relative to the maximum risk of overload (for one scenario, or for more scenarios in case of sensitivity analysis) during N and N-1 situations respectively. The aggregation is done according to Eq. 3.5 and with the weights for 0.67 for the N situation and 0.33 for the N-1 situation.

[4] Note: for the branches that have more identical parallel circuits, only the results for one circuit are presented because the results are the same for all circuits. Hence, the branch names refer to one circuit only. Otherwise, if parallel circuits are not identical, the circuit number is mentioned after the branch name.

5.4.2 Security analysis for the "Reference Scenario"

Round-the-year security analysis is performed (according to the methodology in Chapter 3) for the Reference Scenario where the offshore grid as chosen in paragraph 5.3.5 is considered (Figure 5.6). The criteria and risks of overload for all the overloaded Dutch 380 kV

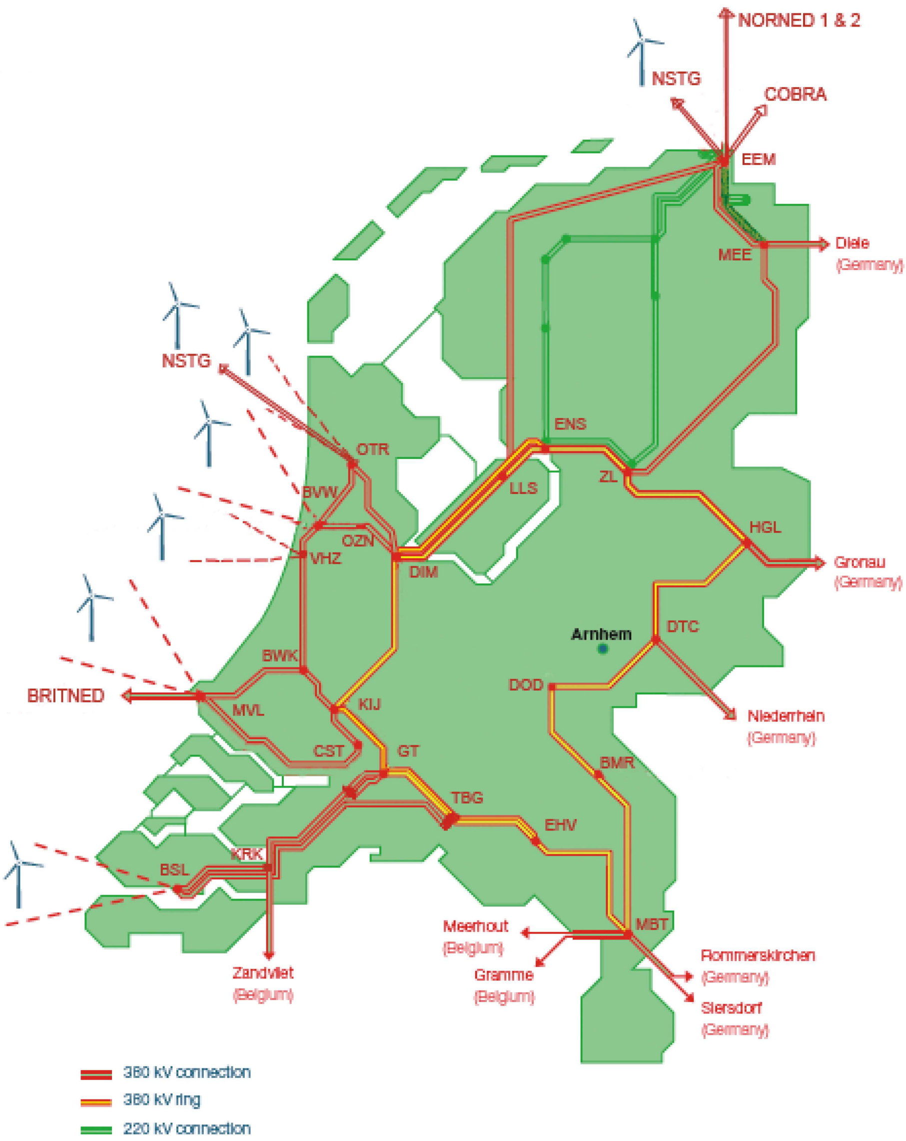


Figure 5.7: Dutch grid representation adapted from TenneT's Vision2030 report [99]. Landing points of the offshore grid (NSTG), of the radially connected offshore wind and of the HVDC interconnectors are indicated.

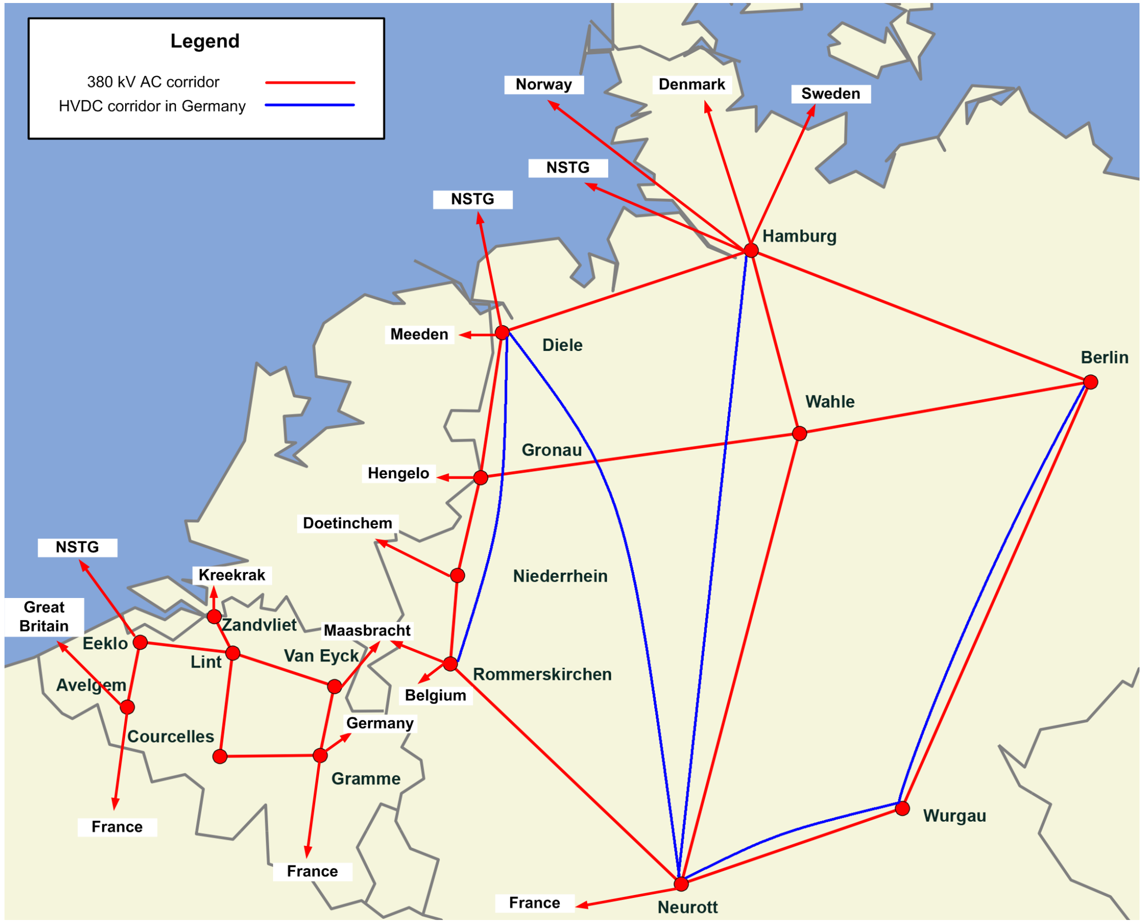


Figure 5.8: German and Belgian simplified grid representation

interior and border branches are illustrated in Table 5.15 [5] (the lines that are not overloaded in any situation are not indicated). It can be noticed that there are many bottlenecks in the grid. Figure 5.9 gives an illustration of the geographical spread of the bottlenecks during N-1 situations. There are three main bottleneck regions in the Dutch grid: in the North East (Eemschaven-Meeden-Diele), East (Ens-Zwolle-Hengelo-Gronau; Hengelo-Doetinchem-Dodewaard), and South and South East (Krimpen-Gertruidenberg-Tilburg-Eindhoven--Maasbracht-Rommerschirchen; Maasbracht-Van Eyck).

Table 5.15: Criteria and risks of overload for the overloaded 380 kV NL interior and border branches (highest values in Italics). For node abbreviations see Appendix E.

Branch	**C01 [%]**	**C02 [h]**	**C03 [%]**	**C03 hour**	**RO_N [% * h]**	**C11 [%]**	**C12 [h]**	**C13 [%]**	**C13 hour**	**RO_{N-1} [% * h]**
Interior branches										
DIM-BKL	0	0	0	n.a.	0	103.7	10	108.5	2364	37
DIM-OZN	0	0	0	n.a.	0	101.2	13	107.8	2364	15.6
DOD-DTC	0	0	0	n.a.	0	103.9	553	117.9	2364	2156.7
DTC-HGL;1	0	0	0	n.a.	0	102	11	105.5	325	22
DTC-HGL;2	0	0	0	n.a.	0	101.8	23	107.7	325	41.4
EEM-MEE;10	0	0	0	n.a.	0	109.9	746	156.4	8353	7385.4
EEM-MEE;11	0	0	0	n.a.	0	109.8	739	156.2	8353	7242.2
EHV-MBT	102.05	26	109.4	3310	53.3	123.6	1825	180.8	3310	***43070**
ENS-ZL	0	0	0	n.a.	0	107.35	250	131.5	1509	1837.5
GT-KIJ	100.9	5	104.3	8248	4.5	118.3	1675	188.9	8248	30652.5
HGL-ZL	105.8	63	130.1	8321	***365.4**	117.8	1848	195.2	8321	32894.4
MVL-SMH	0	0	0	n.a.	0	100.9	3	101.7	8249	2.7
TBG-EHV;1 and 2	0	0	0	n.a.	0	103.5	199	121.3	8248	696.5
TBG-EHV;3	0	0	0	n.a.	0	103.25	164	120.4	8248	533
TBG-GT	0	0	0	n.a.	0	102.3	1	102.3	8248	2.3
Border branches										
PST-XDI_ME	101.7	8	109.6	8498	13.6	111.8	510	170.1	8498	6018
HGL-XGR_HG	101.5	5	106.4	370	7.5	119.5	1413	182.4	370	27553.5
MBT-XRO_MB	0	0	0	n.a.	0	107.45	98	132.2	8073	730.1
MBT-XVY_MB;1	113.8	1802	154.2	7349	***24867.6**	114.7	2124	159.1	7349	31222.8
MEE-PST	107.7	253	152.3	8498	1948.1	125.3	1522	235.8	8498	***38506.6**

The bottleneck ranking is done separately for the interior branches and the border branches. The maximum risks of overload during N and N-1 situations with respect to which the normalization is performed are written in italics in Table 5.15.

Figures 5.10(a) and 5.10(b) show the normalized risks of overload and the severity indices for the most important bottlenecks. From both table and figures, it can be noticed that three of the interior branches and four of the border branches are congested in both N and N-1 situations. The most congested interior branch as indicated by the severity index, is the line HGL-ZL between Hengelo and Zwolle, followed by line EHV-MBT between Eindhoven and Maasbracht.

Similarly, the most congested border line is line MBT-XVY_MB;1 between Maasbracht and Van Eyck PST_1 (connected further in Belgium to Van Eyck and to Lint) which is

[5] Because the two PSTs at Meeden substation are on the Dutch side of the cross-border line Meeden-Diele, the branch MEE-PST is considered together with the border branches.

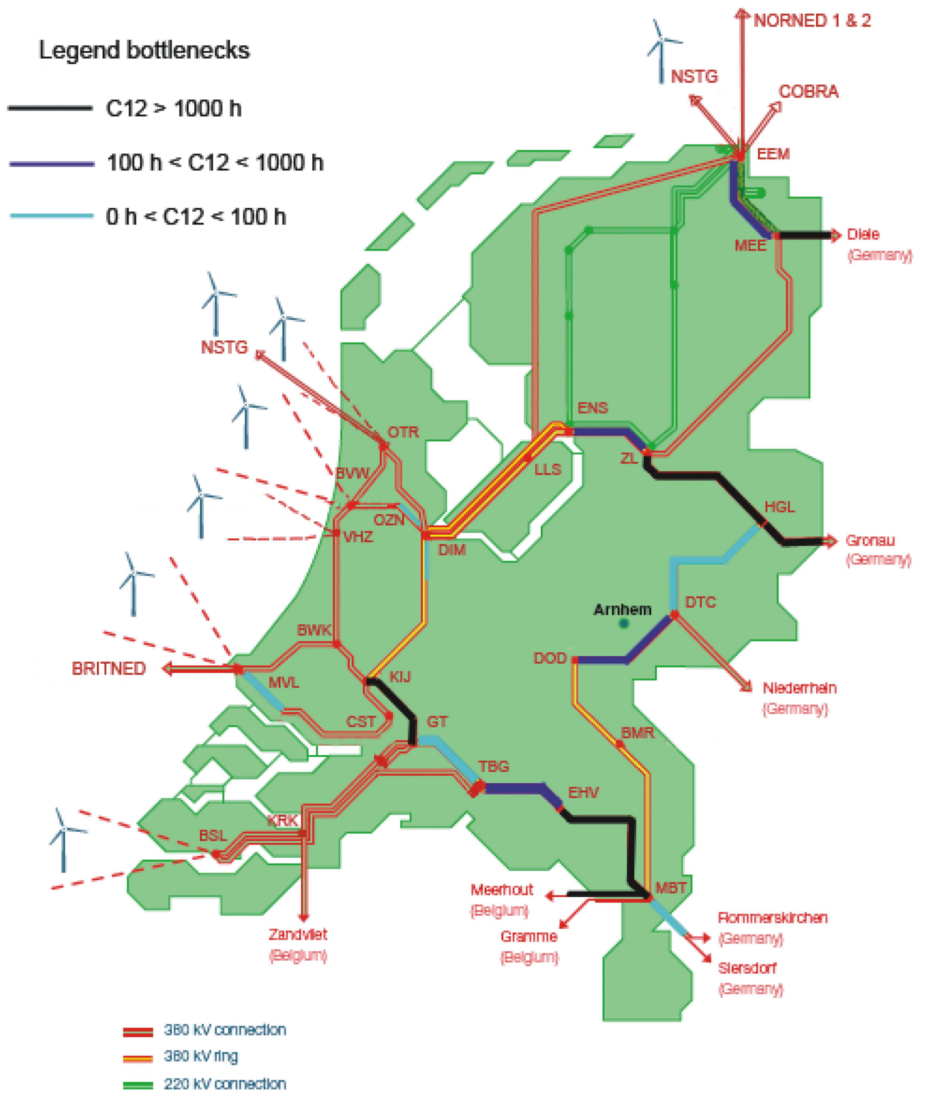
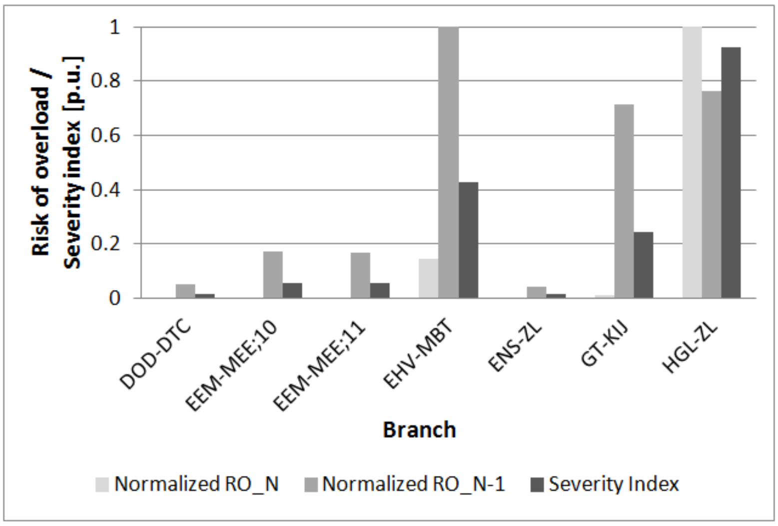


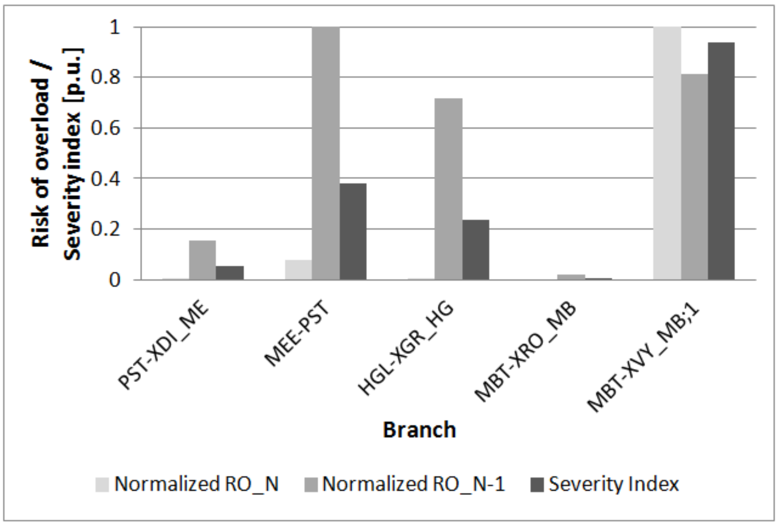
Figure 5.9: Reference Scenario: bottlenecks in the Dutch grid according to C12.

seriously overloaded even in the N situation. It is followed in ranking by the two PSTs MEE-PST at Meeden. [6]

[6] It can also be noticed that the branch between the Meeden PST and Diele (PST-XDI_ME) is less overloaded even though the same power flows through it; this is because its rating is higher.



(a) Interior branches



(b) Border branches

Figure 5.10: Most important bottlenecks in the Dutch grid, Reference Scenario.

5.4.2.1 Testing proposed reinforcements in the Dutch grid

Two reinforcements scenarios are assessed, by reinforcing the interior grid of the Netherlands with some of the TenneT Vision2030 [99] recommendations:

- **Reinf_1**: two circuits are added to the GT-KIJ branch, one circuit is added to the EEM-MEE branch and the capacity of branch HGL-ZL is increased from 1645 MVA to 2633 MVA per circuit.
- **Reinf_2**: to the reinforcements in Reinf_1, a new double circuit branch is added between DIM and DOD, with 2633 MVA per circuit.

Table 5.16 shows the comparison of the grid risks of overload for the interior grid and for the border grid. These risks were computed according to Eq. 4.1 from Chapter 4. According to this equation the grid risk of overload during N situation is the sum of the branch risks of overload during N situation, and the grid risk of overload during N-1 situations is the sum of the branch risks of overload during N-1 situations. The comparison of the branch risks of overload can be found in Table F.1 of Appendix F.

It can be noticed that by adding the reinforcements, the internal grid risks of overload are very much reduced as most of the interior bottlenecks can be eliminated/reduced. At the same time the border grid risks of overload are not very much affected as the severity of the border bottlenecks is not significantly changed. If by reinforcing GT-KIJ in Reinf_1, the EHV-MBT line is slightly more overloaded than in the Reference Scenario, by adding further the DIM-DOD line, the overloads of the EHV-MBT line are dramatically reduced.

For trying to solve both internal and border bottlenecks, the solution generator proposed in Chapter 4 could be used. The best approach would be to apply the solution generator for the interconnected grids of The Netherlands, Belgium and Germany where more detailed grid models of the latter two countries are used. In such an approach also reinforcements in the German and Belgian grids could be tested, as these might lead to a decrease in the power flows on the Dutch border branches.

Table 5.16: Grid risks of overload for the 380 kV NL interior and border grids. Comparison for two reinforcement scenarios.

Grid	Reference Scenario		Reinf_1		Reinf_2	
	$RO_{grid,N}$	$RO_{grid,N-1}$	$RO_{grid,N}$	$RO_{grid,N-1}$	$RO_{grid,N}$	$RO_{grid,N-1}$
	[%*h]					
Interior grid	432.2	126589.2	114	53315	0	5539.8
Border grid	26836.8	104031	27136.2	109835	29485.7	101842.1

5.4.3 Sensitivity analysis to the HVDC corridors in Germany

In this paragraph, a sensitivity analysis for the HVDC corridors in Germany as part of the onshore grid is made. Two scenarios are compared:

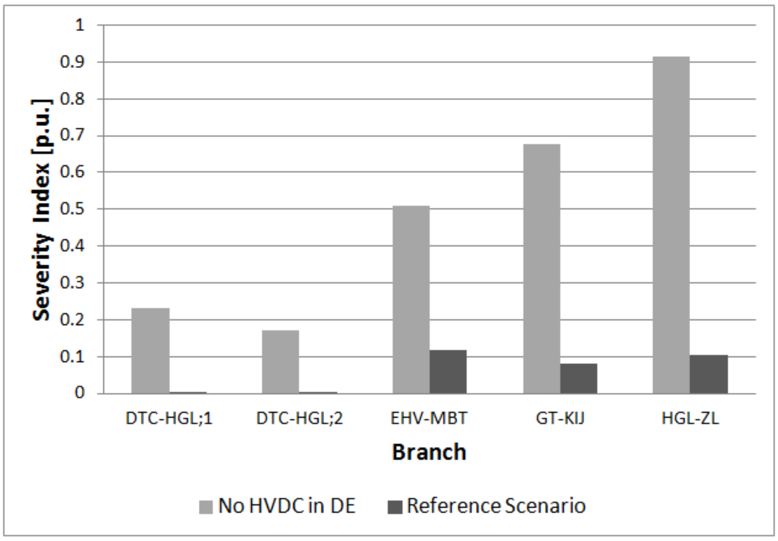
- **HVDC corridors in DE**. This is the **Reference Scenario** which was investigated in the previous section (5.4.2).
- **No HVDC corridors in DE**. In this scenario the North-South HVDC corridors in Germany are not modelled (not assumed to be built for the scenario year analyzed).

The round-the-year security analysis is performed for both scenarios. Furthermore, the bottleneck ranking is performed, again separate for the interior and border branches of the Dutch grid. This time, for comparison purpose, the risks of overload are normalized to the maximum risks of overload over both scenarios during N and N-1 situations. In Appendix F, Table F.3 gives a comparison of the risks of overload during N and N-1 situations, and the main bottleneck ranking criteria can be found in Table F.4. It can be noticed that most of the bottlenecks appear in both scenarios, but their severity is different.

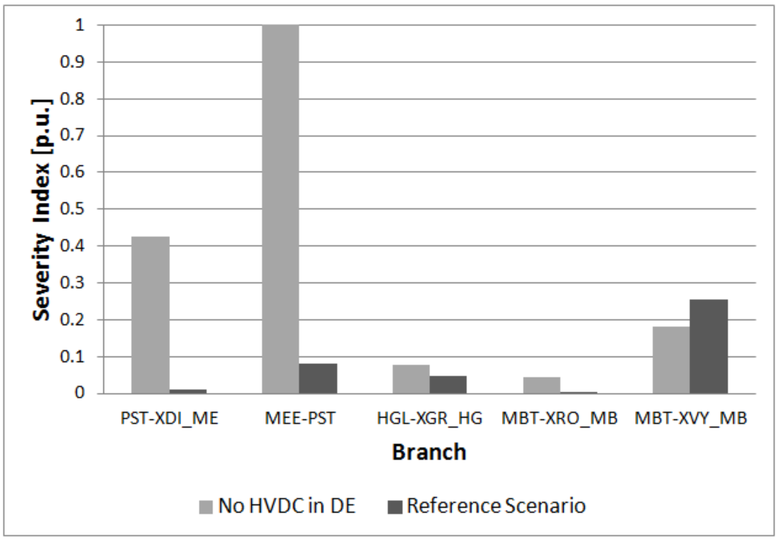
The severity index comparison for the main bottlenecks is illustrated in Figures 5.11(a) and 5.11(b). For the interior branches, it can be noticed that not having HVDC corridors in Germany results in much more severe overloads in the Dutch grid for most of the lines, due to more loop flows through the Dutch grid. For the border branches it can be noticed also that in the "No HVDC corridors in DE" scenario the severity of the overloads is higher, especially in the Meeden phase shifter MEE-PST. One exception is the MBT-XVY_MB;1 line, which is more overloaded in the Reference Scenario. This is because in the "No HVDC corridors in DE" scenario there are increased power flows on the Western side of the Dutch grid and consequently, in comparison to the Reference Scenario, more power goes to Belgium through the Kreekrak-Zandvliet cross-border branch and less through the Maasbracht-Van Eyck branch. Next, in order to understand better what happens in the grid one snapshot is chosen and a comparison for a critical hour during N situation is performed. The comparison is made for a critical hour in the "No HVDC corridors in DE" scenario: hour 8080 (according to Table F.4).

The hour 8080 comparison is illustrated in Figure 5.12 where a qualitative graphical representation of the flows in the Dutch grid is made for both scenarios. This is a high wind hour, with also high imports from the North Sea neighbouring areas. It can be observed that having no HVDC corridors in Germany results in high loop flows through the Netherlands, causing many severe bottlenecks even in the N situation. Approximate 6.7 GW of DE-NL-DE loop flow goes from North to South, creating severe overloads on the cross-border lines but also on the interior lines of the Dutch grid. Because of the highly congested situation in both Dutch and German grids, the adjustment of the phase shifting transformers fails in preventing this loop flow.

For the same hour, the presence of HVDC corridors eliminates almost completely the loop flow by sending the power from the North of Germany directly to the load centers in the South of Germany. Also the influence on the distribution of border flows between the Netherlands and Belgium can be noticed: when no HVDC corridors exist, more power flows through the Zandvliet border-lines than through the Van Eyck ones (Figure 5.12). It can be concluded that the HVDC corridors planned in Germany are key for wind integration and they have a major impact on the Dutch grid power flows. Hence, it is important to model



(a) Interior branches

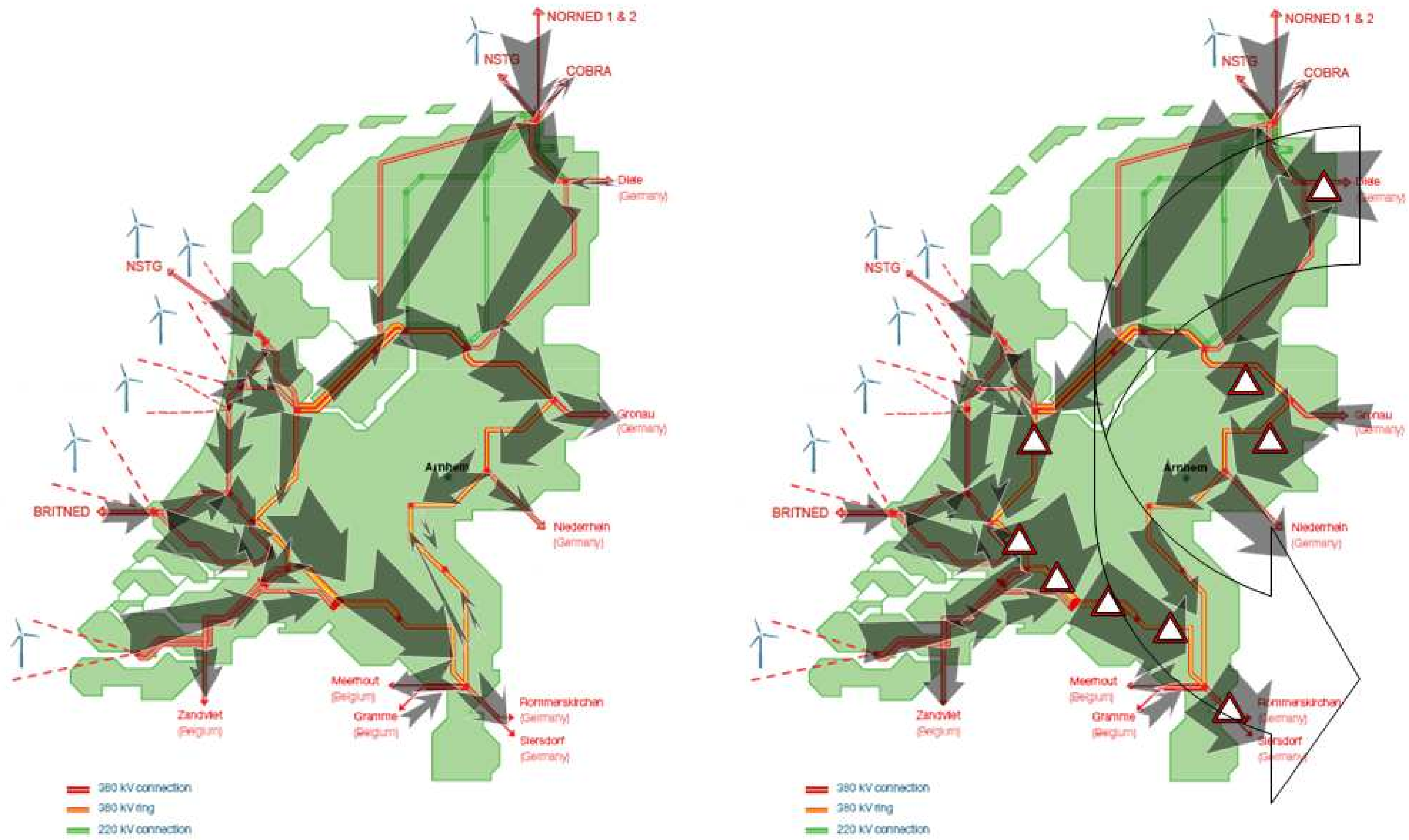


(b) Border branches

Figure 5.11: Comparison of main bottlenecks severity indices for sensitivity to HVDC corridors in Germany.

them in long-term grid studies and a more adequate model for them would be useful by increasing the accuracy of the calculations.

Another brief investigation is performed in order to see how sensitive the results are to changes in the neighbouring grids. To that purpose two scenarios are investigated: one with



(a) Reference Scenario (HVDC corridors in DE)

(b) No HVDC corridors in DE

Figure 5.12: Comparison: power flows in the 380 kV Dutch grid for hour 8080, N situation.

an extra circuit added to the Diele-Gronau line (in Germany close to the Dutch grid), and one with an extra circuit to the Berlin-Wurgau line (far from the Dutch grid). The variations in the risks of overload with respect to the *Reference Scenario* are shown in Table F.2 from Appendix F. It can be noticed that the sensitivity to the neighbouring grid model decreases with distance, but still exists even for the Berlin-Wurgau reinforcement variant. Hence it is important to model accurately the closer parts of the neighbouring grids.

5.4.4 Sensitivity analysis to the offshore grid structure

Another sensitivity analysis is performed with respect to the presence/structure of the offshore grid. Two sensitivity scenarios are investigated and compared with the Reference Scenario:

- **No offshore grid.** This is the Base Scenario presented in the beginning of the current chapter, where all wind is connected radially to shore without the presence of an extra offshore grid. It should be reminded that the Base Scenario already consists of offshore links between countries in the North Sea (Table 5.4).

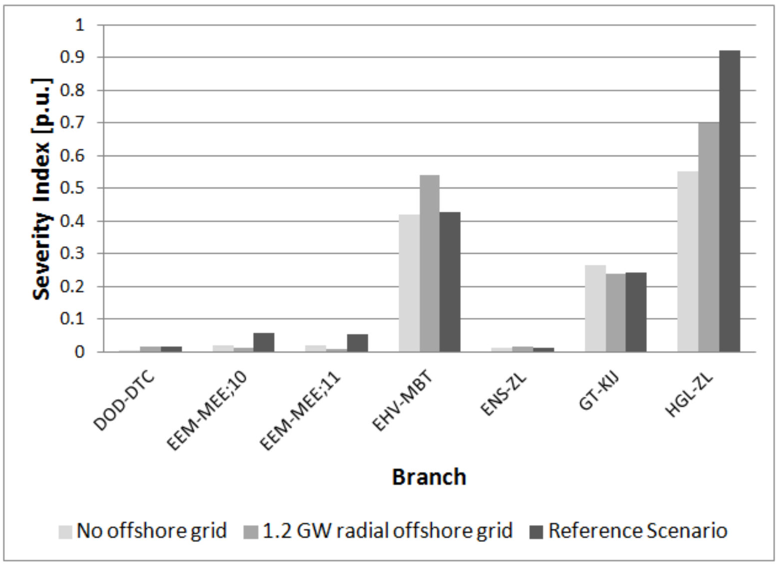
- **1.2 GW radial offshore grid** (see Figure 5.3(a)). This offshore grid case was investigated in Section 5.3.3.

Again the round-the-year security analysis is performed, and the bottleneck ranking is done for the Reference Scenario and the two sensitivity scenarios. Figures 5.13(a) and 5.13(b) illustrate the comparison of the severity indices for the three scenarios. In addition in Table F.5 of Appendix F all the risks of overload can be found; the normalization was performed with respect to the values in italics.

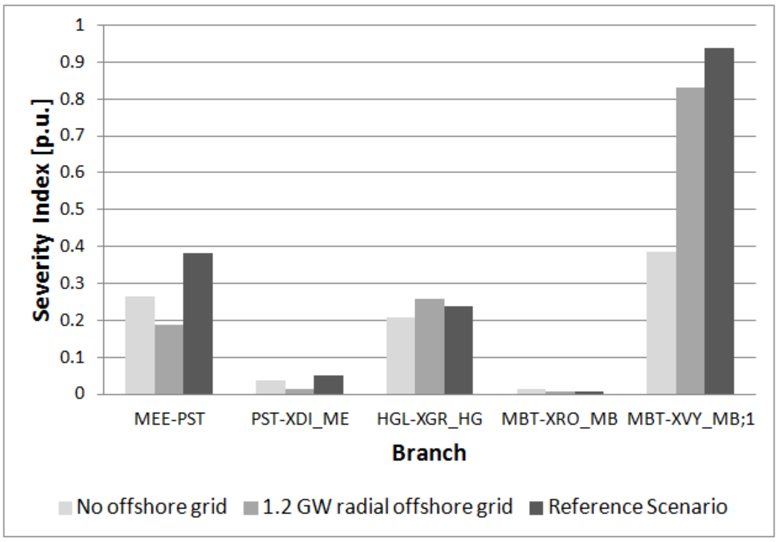
It can be noticed that the presence and structure of the offshore grid definitely have an impact on the power flows in the onshore grid. This is mainly because of an increase in interchange capacity with the neighbouring North Sea systems. If more energy can be exchanged, this obviously has an effect on the flows in the onshore system. For example, due to the offshore grid connection between Netherlands (node 5) and Great Britain (node 1) (see Figure 5.6), in the Reference Scenario, the HGL-ZL, MEE-PST, PST-XDI_ME and MBT-XVY_MB;1 branches are more overloaded than in the other two scenarios.

In this chapter, more interchange capacity in the North Sea area is created by means of an offshore grid. Alternatively, more interchange capacity can be created by new point-to-point HVDC connections between the North Sea countries. In both cases there would be an effect on the onshore grid due to increased power trade.

The results of this section reinforce the idea that it is important to plan together the onshore and the offshore grids. The structure of the offshore grid has also an impact on the onshore grid, and this aspect should not be disregarded when making decisions regarding transmission expansion in the North Sea area.



(a) Interior branches



(b) Border branches

Figure 5.13: Comparison of main bottlenecks severity indices for different offshore grid structures.

5.5 Summary

In this chapter the consequences of the potential development of a transnational offshore grid in the North Sea are investigated with the help of market simulations and load flow calculations. As a starting point, a Base Scenario for North-Western Europe in the year 2030 is developed where a high penetration of renewable energy sources is considered and no transnational offshore grid is modelled, although some offshore links between countries in the North Sea already exist and were taken into account. In addition, interconnection capacities were kept at the 2020 values. Detailed chronological and correlated wind power and solar power time series were developed. The market simulation (unit commitment and economic dispatch) is run for the Base Scenario which shows that a high percentage of the wind energy can be integrated, but considerable amounts of wind energy have to be curtailed.

This chapter further validates the method introduced in Chapter 3 by analysing the security of a mixed offshore-onshore grid with a large penetration of wind energy. The analysis is divided in two parts: one focusing on the offshore grid and one focusing on the offshore grid's impacts on the onshore grid.

In the offshore grid analysis, both market and grid issues are considered for analysing different offshore grid topologies. With the help of zonal market simulations the market benefits of having an offshore grid are assessed. With the help of round-the-year load flow calculations the security of the grid for various combinations of load and generation coming from the market simulation is assessed. In this thesis only security during N situation was tested. It is still a question whether an offshore grid should be N-1 secure in itself. A good approach would be to adjust onshore system reserves to loss of individual offshore grid circuits, and at the same time to use reasonable circuit capacities. The round-the-year security analysis is used for estimating how much offshore grid capacity can be given to the market safely. Three different offshore grid topologies were studied: radial, looped and meshed topologies. The results of the market simulations indicate the benefits (less operating costs, less CO_2 emissions, less curtailed wind) of increased interconnection capacity in the North Sea. Moreover, the results show that the usage of links between hubs belonging to the same country is rather low, as the hubs are connected to the same country market area. The round-the-year security analysis reveals that with the increase of loops in the offshore grid, less of the grid capacity can be given “safely” (i.e. without resulting in overloads during operation with all elements in operation) to the market. Offshore transmission capacity can be better utilized in radial (not looped) grid structures. As the three investigated grid structures are far from optimal, a more suitable offshore grid structure is designed, which is secure and has good utilization factors. In the analysis performed in this work grid security, grid utilization factors, operating cost and wind curtailment were considered separately. A dedicated flow-based grid optimisation model would be useful for a more accurate assessment of grid topologies.

Furthermore, the onshore grid analysis investigates the effects of the designed offshore grid on the EHV onshore grid of the Netherlands. To this purpose a detailed 2020 grid model of the Dutch EHV system and simplified models of the Belgian and German EHV systems are used. The planned North-South HVDC corridors in Germany for the year 2032 are modelled with nodal injection/withdrawal of power. All these constitute the Reference Scenario. The round-the-year security analysis is performed for N and N-1 situations. The occurring bottlenecks in both interior and border lines of the Dutch grid are emphasized and their risks of overload are calculated. Three main bottleneck areas can be observed, all related to strong power flows on the North East-South East and Central West-South East axes of the Dutch grid. More precisely there is a trend of high power flows from the Northern and Western wind and interconnection areas, to the load situated more to the South in the German grid. It is also shown that by adding further reinforcements in the Dutch grid, the internal bottlenecks can be considerably reduced.

Two sensitivity analyses are further performed with the help of the round-the-year security analysis which gives overall results but also pinpoints critical snapshots for more detailed investigation. The sensitivity analysis to the North-South HVDC corridors in Germany shows that the presence of these corridors is essential for wind integration and reduces the high loop flows through the Dutch grid, and the related overloads. These corridors are very important for integrating the North Sea offshore wind in the European grid. Consequently, future studies should model these corridors and more accurate models of their operation are needed. It is noticed that it is very important to model accurately the neighbouring systems, and especially the closer parts of these systems have an effect on the results.

In the second sensitivity analysis the effects of having a different offshore grid structure or even of not having an offshore grid at all, are investigated. The analysis illustrates that the structure and presence of the offshore grid have a significant influence on the power flows in the onshore grid. The changes in generation dispatch and energy exchanges that come with each sensitivity scenario affect the power flows in the Dutch grid and consequently the bottlenecks and their severity.

From this chapter it can be concluded that for a robust planning, onshore grids and offshore grids should be planned together and with consideration of market, operational (how would such an offshore grid be operated and controlled in the interconnected European power system) and grid modelling aspects. To this purpose adequate, more detailed models are needed. Assessing the security of a grid has to be done considering many combinations of load and generation. The round-the-year security analysis introduced in this thesis proved to be very adequate for this, giving a good overall picture of the overloads in the grid.

Chapter 6

Approval procedures and fostering acceptance of transmission lines

This chapter proposes a new approach for speeding up approval procedures for building transmission infrastructure, by improving procedures and better involving the publics in the planning process. First the experiences of Transmission System Operators from some European countries are studied in order to generalize and pinpoint the main weaknesses and strengths of current approval procedures. Recommendations concerning how to reduce the time needed for approval procedures are made. The problem of societal acceptance of transmission lines is analyzed further. Suggestions for better structuring of the decision process in transmission planning, with high involvement of stakeholders, are made. Participatory processes should embrace not only an instrumental rationale, but also normative and substantive rationales. Actions should be taken on two fronts: fostering societal acceptance by enabling appropriate participatory processes, and designing approval procedures by developing clear and harmonised regulations. This chapter is based on the work done within the REALISEGRID research project described in [79, 102, 103] and a continuation of this work in [104].

6.1 Introduction

Planning procedures of new transmission lines generally take a long time. One of the most important tasks of transmission system operators (TSOs) is the planning and development of grid infrastructures. This is especially urgent since Europe needs to expand its extra high voltage electricity grid for ensuring a secure, competitive and sustainable power system [7]. In most European countries the transmission grid expansion planning process has several stages [100]. First the TSO performs studies and decides what grid expansions are needed, after which it presents its planned projects to the external decision makers for approval. Next, the TSO applies for authorization and realization of the project. This process takes on average 5-10 years, going up to 20 years in extreme situations. For projects that involve transmission lines crossing multiple regions or countries, it is important to decide on physical interconnection points at the borders before starting the rest of the procedures. If the authorization process is longer for one of the involved countries, the whole project will be delayed.

Reducing the time needed for infrastructure realization is an objective clearly stated by the European Commission (EC) [15]. It is worth noting that the EC envisages that planning and approval procedures for projects of European interest should be completed in a maximum time span of five years. Improving decision-making processes for new European infrastructure projects is highly important for achieving the EU 2020 targets [16].

The achievement of societal acceptance for the new infrastructure development is one of the key factors that could help speeding up the approval process. However, improving this aspect is a complex process that requires simultaneous action on several fronts (e.g. political, cultural, regulatory, informative). In [16] the main difficulties with authorization procedures are investigated and grouped as: complicated and un-harmonised legal framework for the permitting procedures, lack of political involvement and accountability on these issues, lack of reasonable time limits for authorization procedures, reduced social acceptance of projects, lack of balance between the environmental impact analysis and the necessity of the project.

In order to speed up approval procedures for building new transmission infrastructure it is important to analyse real case studies for recognizing what are the flaws in procedures and what methods can be used for overcoming obstacles in transmission expansion planning. The experience of TSOs from Netherlands, Italy, France, Austria is studied and recommendations concerning how to reduce the time needed for approval procedures are made based on the findings. This research was done within the REALISEGRID (http://realisegrid.rse-web.it) project as described in [79, 102, 103] and illustrates the TSO perspective on approval procedures. Societal acceptance of new electrical infrastructures is the main issue causing long delays in transmission line siting. Hence, it is important to analyze also the perspective of societal acceptance in order to find ways of fostering societal acceptance that can be applied during the planning process. In this chapter the importance of organising an appropriate stakeholder engagement process, based on dialogue and shared solutions, for the specific transmission expansion problem is highlighted. Consequently, societal acceptance of projects can be fostered. This is not an easy task and in order to learn more about how societal dynamics affects societal acceptance of transmission lines, the research is taken one step further in [104] where the case of a France-Spain interconnection, investigated briefly also in the REALISEGRID project, is studied in detail (the case description can be found in Appendix G). After performing an in depth analysis, important conditions for fostering acceptance are found.

The chapter is structured as follows. Section 6.2 focuses on the approval procedures for building new transmission lines. The main findings of analyzing the procedures in some European countries are summarized in two categories, namely obstacles for building new transmission lines, and recommendations on how to overcome them. Section 6.3 focuses on stakeholder participation in the transmission expansion planning process and analyzes the problem of societal acceptance with respect to transmission lines. The role of dialogue in fostering acceptance of transmission infrastructure is emphasized with the help of an in depth analysis of a France-Spain interconnection project. Conditions for fostering societal acceptance are sketched. Furthermore, Section 6.4 gathers all the previous findings in a proposal of a combined approach for speeding-up approval procedures of transmission lines. The findings of the chapter are aggregated in the Summary section.

6.2 Approval procedures from the TSO perspective: obstacles and recommendations

Figure 6.1 illustrates the stages and average durations of the transmission expansion planning process in Europe [100].

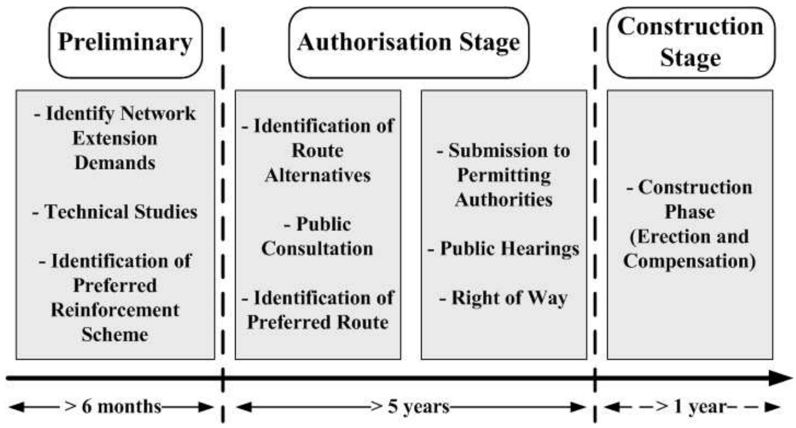


Figure 6.1: Stages and average durations of the transmission expansion planning process [100].

Generally speaking, approval procedures for building new transmission lines cover the following stages [102, 105]: the TSO is the initiator of the project and conducts first a feasibility study. The purpose of this study is to express the need and urgency for network expansion and to plan several route options for building a new transmission line. These options should be feasible from all aspects, namely technical, technical-economical, administrative, social and environmental. The planning authorities are involved in this process formally or informally with regard to spatial planning, environmental aspects etc. This study phase is concluded by requesting the respective authority to permit construction of the transmission infrastructure along one of the proposed routes that proves to be optimal. At the centre of this application is the environmental impact assessment (EIA), which has to be performed according to EU and national laws in all member states. In some countries a strategic environmental assessment (SEA) is also performed beforehand at national level for potential new infrastructures, but its results are not used in the EIA [1]. With respect to national environmental legislation, local authorities will be involved. In addition, a public debate or a formal dialogue is compulsory and each stakeholder has a right to express his/her own opinion. Finally, all other national legal requirements (concerning land

[1]EIA and SEA are both systematic approaches for gathering and assessing environmental issues related to different development alternatives a priori the decision-making process. The difference between the two is that EIA targets physical developments (i.e. transmission lines) while SEA targets higher level development proposals related to policies, laws, strategic plans etc. [106]

and water rights, protection of the right of property building law, environmental protection, conservation of protected species etc.) will have to be met. Only afterwards, will the approval be given by the authority in charge. For building a new line, licenses also have to be obtained, and this process is done after or simultaneously with the authorization procedures. The expropriation phase is effected in the end via either amicable agreements or legal easements. When all approvals and licenses are granted, the construction process can begin.

In the context presented in Section 6.1, the EU research project REALISEGRID was set up to develop new methods, tools and knowledge for helping TSOs in assessing an optimal development of the transmission grid, including the aspects of approval procedures. Consequently, existing approval procedures in a number of European countries were reviewed with the purpose of identifying different ways that are adopted to overcome the barriers to transmission system development. Hence, real case studies, based on the experience of TSOs from Austria, France, Italy, and the Netherlands, were analyzed in order to generalise and pinpoint the main strengths and weaknesses and to select the best practices from the current approaches. The country survey and subsequent TSO consultation process were materialised in a set of obstacles to approval procedures and recommendations on how to overcome the obstacles which are presented further in this section. Also different measures and approaches that can be used for minimising the impact of a new transmission line are detailed. Engaging effectively with stakeholders is not easy, using a facilitator for supervising this process is important. It is important to mention that as it is based on a TSO survey, this section presents the TSO perspective on approval procedures of new transmission lines.

6.2.1 Obstacles

There are mainly two types of obstacles in the path of building a new transmission line [16, 102]: related to authorization procedures and related to societal acceptance of transmission projects.

6.2.1.1 The authorization procedures related obstacles

The authorization procedures related obstacles are firstly due to flaws in the regulatory aspects defining the authorization process. The approval procedures are lengthy due to their inefficient structure. In Austria, Italy and France, stakeholders can object at any time, bringing complaints that need to be investigated and thus cause delay. In the first two countries the authorization process does not follow the schedule set by law, while in France such a schedule does not exist. Not all the countries have clearly defined time steps for the authorization procedures. All surveyed TSOs recognize a failure to meet the schedule for the approval procedures. Moreover, delays can be encountered also because of interdependencies between the licensing process and the EIA in Italy and respectively the National Fitting-In Plan [2] in the Netherlands.

In addition, approval procedures have a high planning and permit risk due to legal and bureaucratic issues. The EIA often is too detailed and costly (in Austria this takes up to 4% of the total project cost), and some of the TSOs (in the Netherlands and Italy) complain of extra delays caused by too many detailed studies that have to be done during the environmental research. More, during the approval process there is no appropriate trade-off made

[2] Rijksinpassingplan

between environmental issues and the public interest for security and efficiency of supply, the latter often being forgotten after the beginning of the process.

The lack of sufficient qualified manpower can also cause delays (authorities are not suitably prepared for a project involving many parties). It often happens that the manpower is insufficient and the personnel have to work simultaneously on more than one EIA. There is also concern that manpower within authorities is insufficiently trained for tackling increasingly complex and tangled permitting procedures.

Furthermore, the differences in regulations and approval procedures between regions and countries constitute a problem when dealing with international projects. Overshooting of European legislation by the national laws, or of national laws by regional laws can create difficult conditions for the approval procedures by setting unreasonably high constraints and by giving space and reasons for the population to complain about or appeal authorizations.

6.2.1.2 Societal acceptance related obstacles

The second type of obstacles refer to (lack of) societal acceptance as a key factor that can cause delays in planning procedures. One of the most striking examples is the Matera-Santa Sofia transmission line in the South of Italy which took almost 20 years to complete due to strong local opposition against a small 7 km line portion [107].

Delays due to public opposition may refer to the failure of the authorities and the TSOs to effectively engage the public within the planning process. Transmission projects usually have national interest and may not be recognized by the local authorities and the population as essential. Often the public does not see any (local) benefits coming from the liberalized electricity market and it increasingly refuses the “traditional” energy supply model (Netherlands, France). Instead, people show a preference for distributed generation and local renewables integration, which allegedly should obviate the need for “large” transmission lines. This is complemented by a growing fear for public health because of electromagnetic fields (EMF) and other environmental concerns. As there are no standardised EMF limits at European level, the subject of EMF effect on human and animal health is a cause of concern for the population.

On the socio-political level [108], there is insufficient support from politicians for transmission line projects (in line also with [16]). In addition, political changes and instability can cause extra delays in the authorization process. On the community acceptance level [108], it is difficult to build lines in both protected natural areas and populated areas. In populated areas the NIMBY (Not In My Back Yard) effect is very high, as people oppose to having lines passing through or close by their properties. On the other hand, it is also extremely difficult to build new lines in natural protected areas. In countries like France where the Natura2000 protected areas are many in number and large in surface this is indeed an issue. There are lengthy discussions on the use of other transmission technologies such as underground cables in order to avoid overhead lines (OHLs) passing through populated and natural areas.

6.2.2 Main recommendations on approval procedures

Considering the problems identified in the reviewing process, the following recommendations for possible solutions have been elaborated together with the TSOs.

All the steps of the approval procedures including the necessary documents, roles and responsibilities should be clearly defined. There should be only one moment in time when parties can object; the Dutch experience proves this is a good solution. Legal consequences should be defined in case of deliberately obstructing the schedule of the approval procedures. A simplification of the authorization procedures for projects of high national or international interest should be considered. In such cases the number of authorities in charge of the authorization procedures should be reduced, preferably to the national level. The Dutch and Italian examples prove that such an approach can speed up the approval process. The process of obtaining licenses should be done after the route for the new line has been approved by the responsible legal instance. In this way, delays caused by repeatedly modifying reports and obtaining new licenses can be avoided.

EU and national legislation should be harmonised and overshooting through national laws should be eliminated. This is a difficult task however, as many countries with their different regulations, views and priorities are involved. Moreover, European-wide standards on EMF to define exposure limits should be developed.

Support and integration are needed. Support from national and local political bodies for projects of national and European importance should be mandatory and defined by law. Politicians should assume their responsibilities and the sensitivity to political instability/changes should be reduced as far as possible. This could be attained by having appropriate (long-term) institutional arrangements [109, 110]. The priority projects of the European Union should be integrated with the TSOs' strategic projects and vice-versa.

The manpower in charge of infrastructure projects at the authorities' level should be sufficient and knowledgeable. People working in parallel on different projects should be avoided in order to speed up the approval procedures.

A legal basis should be created for allowing construction of new transmission lines in natural protected areas, provided that the environmental effects can be reduced and good compensation measures are taken. The possibility of reserving "infrastructure corridors" for important projects should be created. Infrastructure planning should be coordinated. Innovating technologies should be taken into account, and the existing grid should be optimised by extending the lifetime of assets and by using the existing grid to its full potential.

Communication with politicians and the local population should be intensified. To that purpose working groups with local politicians should be organised. These improvements have been recently adopted by all studied countries and they prove to be successful in reducing the public opposition. In addition to all the environmental concerns addressed by the EIA, the costs and benefits of transmission projects should be made clear to all stakeholders. Shared solutions should be promoted through dialogue with regional and local stakeholder organizations and under the supervision of a named neutral party acting as a facilitator. In France, Italy and Netherlands this has been introduced.

Good integration and compensation schemes should be defined in order to envisage: a) the improvement of the integration into the landscape of the new line (this is currently adopted in all the four studied countries); b) the improvement of the integration into the social environment of the new line by compensating the local population for inconveniences and accompanying local economic development proportionate to the actual caused damage (in France and Italy such an approach is already used); and c) the compensation for visual and audio pollution and any other important inconvenience caused during the construction work of a new line. This would increase public acceptance and reduce the opposition to other new projects in the long term.

The SEA can be seen as an opportunity and a tool for preventive discussion with stakeholders for locating new transmission infrastructure. However, only some countries perform such an assessment. In Italy it is done explicitly, while in the Netherlands the SEA is included in the National Zoning Plan for Electricity Supply [3]. Where both a SEA and an EIA are performed it would be important to incorporate the results of the SEA into the EIA for increasing efficiency and clarity.

6.2.2.1 On environmental measures, integration and compensation

There are various electrical measures that can be defined from preliminary phases of projects to reduce the impact on the environment and they can refer to: rationalization (dismantling of part of line, reducing right of way); using technology more environmentally friendly (special pylon); optimization of the route of the new and existing line; adoption of techniques for reducing electromagnetic field (EMF) (e.g. optimization phases, raising pylon, etc.); using cable (at lower voltages and in urban areas); and other.

It is important to keep the impact of new overhead lines to a minimum, by systematically looking to group together infrastructures, either with other installations, or in existing line corridors. More generally, integrating an overhead line means identifying the best possible route, taking into account factors such as geography, residential areas, the natural environment, zones of economic activity (agriculture, existing infrastructures), landscapes and sites. In France, RTE (the national TSO) draws on all its expertise to successfully integrate its installations into the surrounding landscape, whilst taking account of all these factors [102].

During the stakeholder participatory process, 3-D simulation techniques can be used at the various meetings to identify the “route of least impact” for installations at the design stage [102]. This enables each party involved in the consultation to visualise the different possibilities for camouflaging towers offered by the surrounding terrain, and thereby to choose the most suitable location, as far as possible from residential zones. The digital simulation provides a precise depiction of the local geography and terrain, so that each party is able to gauge the actual impact of the line on its environment, accurately and in complete transparency. Current technology is now able to digitise the topography of potential line sites with a very high degree of accuracy. A digital model of the terrain is created based on aerial shots. It takes account of every feature of the existing terrain: roads, bridges, water courses, and so on. The model can then be used to simulate various installations, which are subsequently compared to determine which of them is most appropriate for the local landscape. Technicians can alter the type, height or layout of towers in the scenarios, to display the set-up that best suits the terrain. The model is dynamic, allowing a true and accurate depiction. It is intended to help with discussions and decisions during the meetings with the stakeholders. As a result, every party to the consultation plays a part in deciding where and how the towers are going to be positioned, and can therefore gain an accurate idea of what impact the line is likely to have on its immediate environment. Natural environments should also be taken into account when looking for a route, and when selecting tower types and installing special systems to protect bird life.

[3] Structuurschema Elektriciteitsvoorziening

It is important to support network development projects by taking into account what the inhabitants really expect in terms of territorial planning, economic development and environmental protection, Shared solutions should be built with regional and local actors, and a regulating tool which upholds high environmental, social and economic requirements, in an adequate economic framework should be created.

Compensations are all the measures/actions to reduce the impact of new infrastructures that may be linked to a specific development project of the transmission grid. These measures can be defined at community level or at individual level (compensation of property value or for other caused inconveniences). Also compensation for the inconveniences related to the works at the new infrastructure can be defined at both levels. As shown by the Italian experience in [102], compensatory measures may include the following types of local development support, provided as compensation for the impacts of the new infrastructures: environmental development support, urban development support requalification, and EMF Monitoring Systems. These measures have to be defined together with the local communities during the stakeholder participatory process. When an electrical infrastructure causes unintentional effects on the assets of other parties, the TSO usually has to offer compensation for the caused inconveniences. Attention should be given to compensating both directly and indirectly affected parties. Party *A* is directly affected when the transmission line passes through its property and its property value suffers. If party *B* is the neighbour of party *A*, party *B* can be also be burdened by the new line. Hence, the decrease in property value of party *B* should be also compensated. In some situations, the TSO has to buy a certain part of the property of a party. In such cases, amongst various economical issues, market value has to consider also the possible special value the property may have for its owner. Compensation to individual parties can also be defined for other types of caused inconvenience by the new infrastructure which is not related to land usage and property value deterioration. This has to be agreed with the affected stakeholders.

6.2.2.2 Facilitation of stakeholder engagement process

Good facilitation is essential for the success of a stakeholder engagement process. Hence skilled facilitators that are supervising and guiding the dialogue have to be engaged in the process. They should be in charge of scanning the existent stakeholder groups and helping the stakeholders choosing the right participants for the various meetings that are needed; editing and distributing relevant and sufficient background information needed for a better understanding of the issues under discussion, guiding others in producing documents that can help clarify disagreements or produce new agreement.

The facilitators should be neutral or independent bodies that have no stake in the decision. The other key features of a facilitator are process-management skills and solid background knowledge of the problems under discussion. In addition, at international level, the facilitator should also have the tact and intelligence of handling cultural differences and principles. The successful EC coordinator approach has proved to work at transnational level on strategic projects, but the EC is not actually completely impartial. The Agency for the Cooperation of Energy Regulators (ACER) would be another possibility, but their impartiality should be investigated. ENTSO-E also is not impartial so has to be disregarded. Another solution would be to create a new, independent European body to act as a mediator for interconnection infrastructure projects. Similarly the creation of such a body at national level is recommended (a good example is the National Public Debate Committee in France).

6.3 Societal acceptance of transmission lines: dialogue and participation

From the two types of obstacles distinguished in Section 6.2 the societal acceptance related ones (problems in reaching agreement which result in opposition that may come in different forms) is the most important delay source in building new transmission lines. While the approval procedures related obstacles are due to faulty regulations and procedures, societal acceptance related obstacles have to do with people and the interaction with and between them. And this aspect is very complex and depends on many other factors that can vary from case to case. While the previous section illustrated the TSO perspective, this section will look in detail at the societal acceptance perspective that is the societal view on building new transmission lines and the roles and procedures associated to it.

The way people perceive a new transmission line project has direct impact on the societal acceptance of the project. The scientific literature (see for example [111]) has investigated the different issues, also called determining elements, which directly or indirectly influence the public perception and attitude towards new transmission infrastructure. These elements influence societal dynamics, determining eventually the resulting behaviour (acceptance or opposition to the new asset). The factors are: a) impact on property value; b) visual impact of transmission lines; c) impact on human health (due to EMF) and audible noise (due to the line's corona effect); d) impact of lines on the environment (plants and animals like birds and diary cows); e) impact on the economic system; f) impact on the community burdened by a new line as compared with the benefits of neighbouring communities not directly addressed; g) poor or wrong information of public with respect to the new infrastructure to be built and to power system issues in general; h) bad design of the planning process (lack of or reduced public participation in the planning process); i) interpretation of a new line in the neighbourhood as a "home invasion".

It is therefore important to address the above listed issues within the planning process and more specifically during the stakeholder interaction/engagement participatory process, in order to remove any potential obstacle to transmission network expansion. The visual, acoustic and EMF impact can be opportunely minimised by using different measures, including new advanced, yet costly, technologies and components. According to [111] all elements are directly affecting the public perception towards a new transmission line. In addition, elements listed as f)-i), referring to management-related issues of the planning process, have also an indirect effect by influencing the perception of the planning process. The combination of these elements defines the public attitude. Regarding information and attitudes, it should be underlined that the knowledge that people have about a certain issue might influence directly their attitudes towards that issue [112]. Hence, as recommended in Section 6.2 before starting with any stakeholder engagement process, it is essential that all participants have a common understanding of what the problem at hand is and also about how they can participate in solving this problem.

In order to understand societal dynamics and how societal acceptance can be fostered, the success or failure in engaging with stakeholders need to be investigated in detail. There is not much literature available on the topic of societal acceptance of transmission line projects. There are numerous publications on societal acceptance, for example in the fields of renewable energy technologies [108, 113–116], carbon capture storage [117, 118], or siting of waste facilities [119–122]. These topics have in common that the projects have a local character, and that they usually create costs for the local communities, whereas the benefits are generally on the collective level. This is similar to transmission lines, but transmission line siting is an even more complex problem due to the large geographical span of a line, creating many interdependencies between different locations. Furthermore, in Europe there are plans for lines connecting multiple countries, adding a new international challenge to planners.

[123] conducted a study on public beliefs about electricity supply networks in the UK. They state that public opposition to transmission infrastructure projects is provoked by relative invisibility of network organizations and low expectations of participatory involvement. The stakeholder involvement with transmission lines seems to fail to include citizen's perspectives and preferences in the decision making process [123, 124]. Similarly, opposing stakeholders in Norway feel that there is no real possibility for them to influence the project during the participatory phase [125]. Moreover, failing in providing sufficient background knowledge for the participatory process through the media has a negative effect on stakeholder involvement [125].

As a continuation of the work in the REALISEGRID project, [104] aimed to contribute to the understanding of the timely, yet underexposed issue of participation and societal acceptance of transmission line projects. To this purpose a more in depth analysis on one of the REALISEGRID cases investigated in [102], the France-Spain interconnection project (Baixas-Santa Llogaia), was performed, and is presented in the following. The case description can be found in Appendix G.

The usual approval procedures in France are as follows. Normally, after the technical-economical justification of the proposed project, the next step is the concertation and public debate. The term concertation refers to a form of dialogue and co-decision, cooperation among various (opposing) parties that has the purpose of producing a unified proposal or concerted action. Concertation differs from consultation in the sense that it is not a request for advice. It actually implies the mutual exchange of information, open discussion and confrontation between the parties, knowledge sharing and explanation of each other's views, i.e a dialogue. The concertation is geared at finding a route of least impact. After that, there is a public debate where everyone can voice their opinions on the proposed project. Then the project developer decides whether the project will be continued (with or without changes) or not. If it is decided that the project will be continued, a declaration of public interest is made. After this, the details of the project can be worked out.

The proposed interconnection line between France and Spain has a long history. First proposed in the 1980s, in 1984, when Spain began taking steps to join the European Union, an agreement was signed between France and Spain for the sale of electricity to Spain by France. Many studies followed after this agreement, but all the considered plans were abandoned due to various reasons such as public opposition (the crossed regions did not accept the project, or opposition to interference with touristic areas and nature reserves). As in 2003 the project was brought in procedure it met again strong opposition, and at the request of the French and Spanish governments, the European Commission was asked in 2006 to appoint a coordinator. The series of meetings he had with representative groups of stakeholders were succesfully concluded in an intergovernmental agreement that is ratified by

France and Spain in Zaragoza on June 27 2008. The new interconnection line would be a completely underground solution using VSC-HVDC technology (new technology), spanning from substation Baixas (France) to substation Santa Llogaia (Spain). The Zaragoza agreement opened the dialogue with the local communities and resulted in an effective and intense participatory process (called "concertation") where stakeholders decided together step by step the details of the project. After many years it now seems that a solution has been found and the project between Baixas and Santa Llogaia should be functional in 2014.

6.3.1 Acceptance and participation

Societal acceptance has more dimensions[4] [108] out of which the most interesting for the case of transmission lines is community acceptance as it causes most delays [102]. Community acceptance refers to acceptance of projects at local level, and which addresses local stakeholders (affected population, key stakeholders and local authorities). At this level, the interaction between the project developer and the stakeholders plays an essential role and the level of acceptance is mainly influenced by issues such as trust in project developer, and perceived procedural justice (fairness of decision making process) and distributional justice (fairness of distribution costs and benefits).

The society's responses to new technologies and projects are largely determined by the process through which publics are informed and engaged with [126, 127]. That means that not only the characteristics of the technology or project are important, such as the perceived costs and benefits, but also characteristics of the process, such as procedural justice [108]. This suggests the importance of a participatory approach towards decision-making on science and technology, a notion which has been taken up widely [128, 129].

Participation can have different aims [130] and three main rationales can be distinguished: the instrumental, substantive and normative or democratic rationale [131]. The instrumental rationale refers to participation as a means towards a particular end, e.g. to get a specific policy plan or project accepted [132, 133]. The substantive and the normative rationale refer to participation as a goal in itself: participation is a process in which new knowledge and insights can be produced (substantive) [134, 135] or a political right for citizens and a prerequisite for democracy (normative) [136, 137].

The contemporary approach to societal acceptance puts much focus on instrumental goals [126]. However, efforts to get a plan or project accepted may actually prove to be counterproductive as such a rationale seems to resonate a top-down planning approach. It has been shown in the literature that expectations about the public shape the way organizations deal with local publics [126], and having wrong expectations about the public as lacking knowledge and expertise [138] and being defensive, only concerned with their own short-term interest [139, 140], can frustrate the process and even lead eventually to the paradox that efforts to "prevent" public opposition to project plans may actually organize public opposition. Moreover, the instrumental rationale tends to emphasize outcome rather than process. Public responses are produced in an interaction process between actors with different backgrounds, interests, expectations and attitudes towards the technology and the project [113], and this process needs to be taken into account in order to understand how a certain state (e.g. acceptance or resistance) comes about and can change.

[4] socio-political, community and market acceptance

Consequently, this thesis puts forward a broader conceptualization of "societal acceptance" having less emphasis on instrumental and more on substantive and normative goals of participation. This allows for a dialogue between project developers and/or policy makers and stakeholders (publics). The substantive element of dialogue is in its potential contribution to problem structuring [141], i.e. the articulation and evaluation of divergent views and knowledge claims. People must be able to listen to one another and to communicate their viewpoints (competence) and they must have the opportunity to speak out on issues relevant for them (fairness) [142]. This refers to normative elements of dialogue. Other normative elements of dialogue pertain to issues such as fairness of process and outcomes, transparency and representation (who is participating?).

The aim should not be to create acceptance of a given project, but to engage in a dialogue about the project, its conditions and design, in such a way that a robust outcome can be found that is supported by all stakeholders. Finding such a "robust outcome" has been referred to as searching for "congruency of meaning" [143]. Congruency means that a plan can be envisaged that incorporates different viewpoints. It means that stakeholders with different perspectives may not agree on the underlying motives (e.g. values, worldview) for a specific plan, yet they can converge on the level of strategies and solutions. Searching congruency of meaning means that stakeholders are allowed to disagree and not forced or stimulated to reach consensus [144, 145], this being a first step to create the open attitude necessary in dialogue, and paving the way for a problem structuring process [141] that may generate alternative options.

6.3.2 Analysis of participation in the France-Spain interconnection case

In the early years, from the moment the project was announced until 2008, there was quite some public opposition to the proposed interconnection line. People distrusted the TSO and the state bodies, considered them as not being transparent, and felt that their concerns were not taken seriously and their suggestions and ideas not listened to. The tipping point in this process was the moment that a coordinator was appointed by the European Commission. This intervention resulted in the "Zaragoza decision": the decision to build the line completely underground and follow existing infrastructure as much as possible. This decision considered the requests of the local community that were discarded in the early years. Consequently, it re-opened the possibilities of engaging in a dialogue. It suggested to the local community that from this moment onwards their concerns were taken seriously.

From the start onwards, participation was guided strongly by instrumental motives: the goal was to get this interconnection line built. Yet where in the early years public responses were seen as "annoying delayers of a technically and economically good plan", in this second phase they were seen as part and parcel to finding a feasible design of the interconnection line. Normative and substantive elements of participation were added to the instrumental vocabulary in the concertation process. In this section the concertation process that followed after the Zaragoza decision will be analyzed. The substantive and normative elements in this process will be identified and discussed, emphasizing how these have contributed to the constructive process that the concertation process turned out to be. Furthermore it will be discussed how these elements relate to the "congruency of meaning" that was the outcome of the concertation.

6.3.2.1 Substantive elements in the concertation process

Substantive elements are those that facilitate participation as a process in which new knowledge and insights can be produced [134]. The substantive nature of the concertation process resides in its nature as a *dialogue*. Dialogue involves a high degree of participation [130]. In this case, the concertation involved a partnership between stakeholders with initially conflicting viewpoints and interests, who jointly shape the design of the project. The first, and crucial, element in this regard was the fact that the project was open in terms of its specific design. Issues such as routing and infrastructure support, technical characteristics of the equipments etc. were jointly investigated and decided upon. Alternatives could be suggested and were investigated. When participants decided that more detailed investigations on a number of these issues were to be performed, a second phase of concertation was set up.

A second and related substantive element was the informational richness of the joint fact-finding in the meetings and geographical workshops. Stakeholders jointly identified the issues that needed to be discussed and investigated in the workshops, and they jointly decided on the experts to invite. Informational richness of this joint-fact finding process was high as the workshops enabled situated learning [146]. Situated learning means that people learn about a specific option within a specific context. It means asking the seemingly trivial question: what is actually happening in the situation in which this option is applied? Situated learning was enabled by the use of a digital tool for virtual sightseeing. This tool made it possible for all stakeholders to “go out and see for themselves” the implications of alternative options. The relevance of (virtual) site-visits for situated learning has been suggested before based on experiences in stakeholder dialogues [147].

6.3.2.2 Normative elements in the concertation process

The normative rationale for participation is based on the notion that participation is a political right for citizens and a prerequisite for democracy [136, 137, 148]. It presumes that “citizens are the best judges of their own interests” [131]. Normative elements are those that enable people to take part meaningfully in decisions that affect them. In that sense, the substantive elements discussed above are also normative elements. The possibility to co-decide and shape the project, as well as the possibilities to gain detailed information provided stakeholders with the necessary means to exercise influence. The virtual sightseeing tool for example was not only appreciated by participants for its performance, but also because the project developer took the effort to make means available for better analysing the project. In addition, three other normative elements can be identified.

Firstly, each of the geographical workshops was chaired by one of the mayors of the concerned municipalities, rather than someone from national government or some independent actor. This decision was made to emphasize the local character of the analysis to be performed, and as such underlined the idea that local community were experts with regard to their own area and local interests.

Secondly, throughout the concertation, much effort was spent on making all information and reports freely and easily available to anyone interested. This contributed to the transparency of the process. Furthermore the concerns expressed by the public were addressed in the concertation meetings.

Thirdly, through a number of decisions it became clear that input of stakeholders and local community was actually used and concerns addressed. Basically, this third element means that the project developer showed in several ways that suggestions and concerns of the local communities were taken seriously. From a normative point of view, people need to be taken seriously in order to participate meaningfully. An example is the decision to consider a tunnel to cross mountain Alberes at the end of the first phase of the concertation. The “meaningful participation” resulted in the second phase of the concertation for addressing new questions and critical viewpoints of the local community with regard to the tunnel. These concerns were seriously addressed. Two more examples are the establishment of the monitoring committee for the realization of the project (denoting seriousness and openness to dialogue), and the project developer committing itself to investigate how a beneficial contribution to the local economy could be achieved.

6.3.2.3 Congruency of meaning

The concertation process acknowledged the divergent points of view amongst stakeholders. It was set up to act upon earlier conflicts, opposition and disagreement, not by avoiding conflict or focusing on premature consensus, but by taking all ideas, concerns and suggestions seriously. Participants were actually allowed to disagree. Some of the substantive and normative elements in the concertation facilitated searching for congruency of meaning. For instance, the fact that the design of the project was open and that alternative options could be suggested and investigated by participants (first substantive element above) made it possible to identify new, robust solutions that could be supported by all. Furthermore, the local character that was assigned to the geographic workshops made it possible to come up with locally specific solutions (first normative element above). So, congruency of meaning means the convergence of stakeholders on the level of specific options rather than on the level of general principles or ideas. In searching for congruency, different options need to be considered and investigated. This requires accessibility of information and joint decisions on who to invite as experts (second normative element above).

6.4 Approach for speeding up approval procedures

In the previous sections two different perspectives on approval procedures for building transmission lines have been presented, more precisely the TSO and the societal perspectives. Both views contain elements from the instrumental, normative and substantive rationales. While the TSOs embrace more an instrumental rationale by looking for means of getting the project accepted (including the increase of societal acceptance), from the societal perspective the normative and substantive rationales are more important, as people want to have a say not only in accepting or rejecting projects but also in defining projects, or even in general energy visions for the future that might have an impact on their lives. The two perspectives can contradict each other with the opposition between the more instrumental versus the more normative views, but they can also be combined and made to work together and not against each other. Consequently, in order to make the planning process of transmission lines more robust and effective, this thesis proposes that actions have to be taken on two fronts, namely societal and regulatory.

On the societal level, a bottom-up approach is needed, that supports an effective decision making process targeting the increase of societal acceptance by enabling appropriate dialogue-based participatory processes. Participatory processes should adopt a holistic approach by embracing instrumental, substantive and normative notions. This base condition found in this thesis for fostering acceptance through participation has to characterize the participatory process in order to obtain robust solutions by facilitating the search for congruency of meaning. A key element in the planning process is a good information flow between all engaged stakeholders. Hence the stakeholders should be given beforehand both general information about how power systems work and what transmission planning involves, and also background information, such as the costs and benefits of the new transmission project (together with the consequences, see chapters 3, 4, and 5 and the cost of inaction), and any other important information on the problem to be solved. The participatory process should be a dialogue. In this process the reinforcement solution generator introduced in Chapter 4 can be used for showing the differences (in terms of number of reinforcements and impact on system security) between different reinforcement solutions. The reinforcement solutions can be obtained by setting various reinforcement constraints (i.e. assuming that a line passing through a certain area cannot be built). The creation of a skilled and impartial body to act as project facilitator is generally recommended. He should be able to engage with all the participants and guide the process towards a supported solution, solving when necessary cases of minority dissent and isolating “continually antagonistic attitudes”. In addition, it is important to have a thorough evaluation of property value, so as to bring about a fair compensation value that can be agreed by all parties. Compensation schemes have to be proportional both to the actual value of the caused damage and to the importance of the project and they should not foster free-riding strategies amongst stakeholders. It would be useful if the TSOs were supported in their attempts of reaching agreement by authorities such as the State, the Regions and Municipalities, users of the grid and other important bodies. For the authorization phase a simple legal framework and acceleration of procedures is the first help needed from the authorities. Moreover, authorities should give public support and assume their responsibilities. The sensitivity to political instability/changes should be reduced if possible (for example by creating appropriate (long-term) institutional arrangements).

On the regulatory front, a clear regulatory (top-down) approach is needed, harmonized as much as possible (considering that it is difficult to abolish some of the regulatory differences due to various strong national interests) especially when interconnections are involved. It is important that the so called streamlining of approval procedures should not undermine the role of (timely) stakeholder participation in the planning process. The basic targets of a clear and harmonized regulatory approach are related to two main aspects. On the one hand, it is important to act on the legal framework: simplify, harmonize, set time limits and rationalize the procedure (number of entities, number of phases etc.). Clear and harmonised authorization procedures are essential to obtain a fast implementation of priority projects. On the other hand, qualified and impartial bodies should be appointed as facilitators for transmission line projects to promote shared solutions and manage the entire procedure in both national and trans-national cases. With respect to priority projects, their urgency should suggest revising Europe-wide the entire approval mechanisms. The purpose of this action is to streamline the authorization process by creating fast (priority) approval pathways at both national and local levels.

6.5 Summary

In this chapter the challenges in the approval process of new transmission lines are investigated. First the TSO perspective on the approval procedures is analyzed. With the help of a survey on the TSOs' practices and approval procedures in a number of European countries, the main obstacles to building new transmission lines are identified and divided in two categories: related to the structure of approval procedures and related to the societal acceptance (reaching agreement) of transmission projects. Using the positive aspects of the TSOs' practices together with the consultation with the TSO representatives in the REALISEGRID project, a set of general recommendations for overcoming these barriers is proposed.

Due to its complexity, extra attention is given in the chapter to the issue of societal acceptance, and the societal perspective on approval procedures for new transmission lines is studied. A French-Spain interconnection project is analyzed as it is a good example of how neglecting the citizen's opinion and guiding participation only according to the instrumental rationale can cause years of delay and how societal acceptance can be fostered by increasing stakeholder participation in the planning process. Fostering acceptance of new transmission lines is not an easy job, yet it is crucial for speeding up the permitting procedures and implementation of projects. This work proposes to guide participatory processes by instrumental, normative and substantive rationales in order to foster acceptance through participation. The combination of the three rationales can lead to reaching congruency of meaning and consequently to a robust project design. What works in what moments in time is furthermore a question that needs more attention as each transmission line project is different. There is no blueprint approach for organizing stakeholder participation in transmission grid planning, yet the France-Spain interconnection project shows that true dialogue can foster societal support.

The two analyzed perspectives can contradict each other with the opposition between the more instrumental TSO view versus the more normative societal view, but they can also be combined and made to work together. Therefore, in order to make transmission line planning more robust and effective, this chapter proposes that actions have to be taken on two fronts, namely societal and regulatory, supporting on the one hand an effective decision making process and on the other hand promoting a clear and harmonized (as much as possible) regulatory approach. The streamlining of approval procedures should not undermine the role of stakeholder participation in the planning process and timely stakeholder participation should be foreseen. The regulations should also foresee the inclusion of a neutral party to monitor the process and to ensure transparency and fairness throughout the process.

Chapter 7

Conclusions and future research

7.1 Conclusions

The liberalization of the electricity sector, the emergence of international electricity markets and increased penetration of renewable energy sources introduce many new challenges to transmission system operators. This is mainly because the number of uncertainties in the power system has very much increased. These uncertainties are related on the one hand to transmission scheduling and operation, and on the other to the future need for transmission capacity. Consequently, more advanced and robust methods for planning the transmission grid are required. In addition, the building of new transmission lines is usually a lengthy process which must be shortened in order to match the fast pace of changes in generation location and capacity, and demands. The main conclusions are presented below, under three categories.

New transmission expansion planning approach This thesis proposed a round-the-year approach for performing security analysis, by combining market simulations with load flow calculations. A statistical assessment of the results by introducing bottleneck criteria, branch risks of overloads and overall branch severity indices, was also developed. It was shown that this new method gives more comprehensive results, by providing a reliable bottleneck ranking based on the risk of overload calculation. In addition, the proposed method can identify bottlenecks that the snapshot method may miss. The round-the-year security analysis pinpoints which physical transmission lines are affected by a given scenario. Furthermore, with the help of the bottleneck ranking criteria the relationships between contingencies and bottlenecks can be emphasized, revealing the most critical sensitivities in the grid. The method also allows comparing different scenarios. It was shown how a comparison between different wind penetration scenarios reveals the relationship between the transmission lines severity indices and the increase in installed wind power. The subsequent changes in the generation mix cause changes in the grid power flows, and therefore in the severity indices of the transmission lines as well. The round-the-year security analysis proved to be computationally feasible for large grids.

The method can also be used at another step in the transmission expansion planning process, namely for testing grid reinforcements in order to get insight into the effect of grid modifications aimed at reducing specific bottlenecks. For a case study of the Dutch transmission grid it was shown how a reinforcement solution (increasing the rated capacity of an overhead line) proposed by the grid planners using the snapshot method, was found to be insufficient when using the round-the-year approach, as the bottleneck was actually not eliminated.

Consequently, a reinforcement solution generator was proposed which makes use of the round-the-year security analysis. To that purpose the concept of grid risk of overload and grid severity index were introduced in order to assess the overall grid congestion level. The reinforcement candidates are formed by doubling of existing circuits and/or by building new lines. For saving computation time, the existing line candidates are limited with the help of the round-the-year security analysis to the most serious bottlenecks and most critical contingencies. The set of possible new lines is served as input to the solution generator. After each step the list of reinforcement candidates is updated. At the end of the process an ordered list of reinforcements is given together with the grid risks of overload and severity index at each reinforcement step.

It was shown that running the solution generator only for a set of critical hours does not represent the whole study year and the big picture is missed. Running the solution generator for all the hours in the year gives robustness to the solution and also good indicators regarding the status of the congestion in the grid at each reinforcement step.

When computing the branch and grid severity indices, weights for the N and N-1 situations (or even N-2) are used. The sensitivity analysis to the choice of weights showed that the solution is stable as both the bottleneck ranking and the list of reinforcements found by the solution generator are generally not affected. The values of the branch and grid severity indices change, but this mostly does not influence the final ranking results and the found list of reinforcements remains unchanged. This proved also that the initial choice of weights is reasonable.

North Sea Transnational Grid case study It was shown that the round-the year security analysis proposed in this thesis can be applied to both onshore and offshore grids (using HVAC or HVDC technology). This was demonstrated a hypothetical scenario of an offshore grid (North Sea Transnational Grid) for the year 2030. Regarding the security of the offshore grid, only the N situation was tested. It is still a question whether an offshore grid should be N-1 secure in itself. The round-the-year security analysis was used for estimating how much offshore grid capacity can be given to the market safely. The results of the market simulations indicate the benefits (in terms of less operating costs, less CO_2 emissions, less curtailed wind) of increased interconnection capacity in the North Sea. Moreover, the results show that the usage of links between hubs belonging to the same country is rather low, as the hubs are connected to the same national market area. The round-the-year security analysis reveals that with the increase of loops in the offshore grid, less grid capacity (relative to the installed capacities) can be used securely (i.e. without resulting in overloads during actual operation). Offshore transmission capacity can be better utilized in radial grid structures.

In addition, the onshore grid analysis investigated the effects of the proposed offshore grid on the EHV onshore grid of the Netherlands (interconnected to simplified Belgian and German grids). Three main bottleneck areas can be observed, all related to strong power flows on the North East-South East and Central West-South East axes of the Dutch grid. More precisely there is a trend of high power flows from the Northern and Western offshore wind and HVDC interconnection areas, going to the load situated in the South of Germany. It is also shown that by adding further reinforcements in the Dutch grid, the internal bottlenecks can be visibly reduced. The presence of the planned North-South HVDC corridors in Germany is essential for wind integration and prevents high loop flows through the Dutch transmission grid, and the related overloads. It was concluded that these corridors are very important for integrating the North Sea offshore wind in the European grid. Consequently, future studies should model these corridors and more accurate models of their operation are needed.

The analysis illustrates that the structure and presence of the offshore grid have a clear influence on the power flows in the onshore grid. The changes in generation dispatch and energy exchanges that come with each adopted scenario affect the power flows in the Dutch grid and consequently the bottlenecks and their severity. An interesting remark is that the same bottleneck areas are identified in the grid analysis of many scenarios. It was concluded in this thesis that for a robust planning, onshore grids and offshore grids should be planned together and with consideration of market, operational, and grid modelling aspects. To this purpose adequate, more detailed models are needed. Assessing the security of a grid has to be done considering many combinations of load and generation. The round-the-year security analysis introduced in this thesis proved to be very adequate for this, as it gives a good overall picture of the congestions in the offshore and onshore grids.

Approach for streamlining approval procedures and fostering societal acceptance of transmission lines In this chapter the challenges in the approval process of new transmission lines were investigated. First the TSO perspective on the approval procedures was analyzed. With the help of a survey of the TSOs' practices and approval procedures in a number of European countries, the main obstacles to building new transmission lines were identified and divided in two categories: related to the structure of approval procedures and related to the societal acceptance (reaching agreement) of transmission projects. Using the positive aspects of the TSOs' practices together with the consultation with the TSO representatives in the REALISEGRID project, a set of general recommendations for overcoming these barriers was proposed.

Due to its complexity, extra attention was given to the issue of societal acceptance, and the societal perspective on approval procedures for new transmission lines was studied. A French-Spain interconnection project was analysed as it is an example of how neglecting the citizen's opinion and guiding participation only according to the instrumental rationale can cause years of delay, and on the other hand how societal acceptance can be fostered by increasing stakeholder participation in the planning process. Fostering acceptance of new transmission lines is not an easy job, yet it is crucial for speeding up the permitting procedures and implementation of projects. This work proposed to guide participatory processes by instrumental, normative and substantive rationales in order to foster acceptance through participation. The combination of the three rationales can lead to reaching congruency of meaning and consequently to a robust project design. What works in what moments in time is furthermore a question that needs more attention as each transmission line project is different.

The two analyzed perspectives can contradict each other with the opposition between the more instrumental TSO view versus the more normative societal view, but they can also be combined and made to work together. Therefore, in order to make the authorization stage of transmission line planning more robust and effective, this thesis concluded that actions have to be taken on two fronts, namely societal and regulatory, by combining approaches supporting on the one hand an effective decision making process and on the other hand promoting a clear and harmonized (as much as possible) regulatory framework. The streamlining of approval procedures should not undermine the role of stakeholder participation in the planning process. The regulations could also foresee the inclusion of a neutral party to monitor the process and to ensure transparency and fairness throughout the process.

7.2 Contributions

The main contributions of this thesis are as follows:

New method and new criteria for assessing the bottlenecks in the grid. As novelty, this thesis proposed to use a round-the-year approach for assessing the security of the transmission grid, that is adequate for (multi-area) power systems with high RES penetration. Market simulations are combined with detailed load flow calculations for getting a complete picture of the congestions in the transmission grid. The consideration of the chronological aspect and the correlation of load and wind speed and solar radiation time series are enabled by the use of the market simulations. In addition, new criteria for prioritizing bottlenecks are developed in this thesis together with a method for ranking them according to a risk-based severity index. The new method allows detailed and insightful results, can be used on a real size grid, and also for analyzing both HVAC and HVDC grids.

Security-based iterative method for proposing network reinforcements. For finding the right (i.e. most effective) grid reinforcements, a round-the-year reinforcement solution generator was developed in this thesis which follows the reduction of grid congestion. As novelty, the solution generator makes use of the proposed round-the-year bottleneck assessment method. This allows a robust evaluation of the overloads in the grid for different reinforcement candidates as all the hours of the year are considered. New criteria for assessing the grid congestion level are defined and used in the assessment of candidates. The decrease of the grid severity index is used to measure the effectiveness of each reinforcement candidate. Consequently, the method gives also a good indication regarding the status of grid congestion at each reinforcement step.

Investigating the potential development of a transnational offshore grid in the North Sea and its effects on the onshore system. This thesis also provided as an additional contribution and as proof of principle an analysis of a combined planning of a possible offshore grid in the North Sea together with the onshore grid, for a high renewables scenario in the year 2030. The round-the-year bottleneck assessment is used in the analysis and detailed time-series for wind and solar generation were developed (considering thousands of locations) and served to the market simulations. As novelty, the relationship between grid design and offshore grid capacity that can be used securely by the market is investigated for different types of grid structures. A set of recommendations for planning of offshore and onshore grids together is made and factors that might help renewable generation integration in the studied scenario are highlighted.

Proposing an approach for streamlining approval procedures of transmission lines and fostering societal acceptance of transmission lines. In order to make the planning process of transmission lines more robust and effective, this thesis argued that actions have to be taken on two fronts, namely societal and regulatory. On the societal level, a bottom-up approach is proposed, that supports an effective decision making process targeting the increase of societal acceptance by a good information flow from and to the stakeholders and affected population. On the regulatory front, a clear regulatory (top-down) framework should be created, harmonized as much as possible especially when interconnections are involved. With respect to societal acceptance, this work highlights the role of dialogue in fostering acceptance of transmission lines with the help of an in-depth case study analysis, and proposes a new holistic approach to stakeholder engagement with transmission lines which embraces instrumental, substantive and normative notions.

7.3 Future research

- For the round-the-year security analysis proposed in this thesis a trade-off between accuracy and computation time was made. Consequently a combined AC-DC calculation approach was used, by performing an AC load flow calculation for the normal operating situations (with all N elements in service) and followed by a DC load flow contingency analysis for the N-1 and N-2 states. Future work should be dedicated to adopting a complete AC contingency analysis which increases accuracy and gives additional insights into voltage security challenges in the grid. Attention should be given to automating the solving of convergence issues, in order to reduce the cases that have to be checked manually. An AC contingency analysis would allow also a round-the-year assessment of the nodal voltages and extra indicators for under and over voltages assessment could be developed. In addition, in the DC load flow model the phase shifting capabilities are not considered. A more accurate modelling of the control capabilities of phase shifters would improve the bottleneck assessment.

- When modelling interconnected power systems more reliable results can be obtained on the one hand by having better grid models of the neighbouring countries, and on the other hand by using Power Transfer Distribution Factors (PTDFs) within the market simulations. A flow-based optimization model would also be useful for achieving a more accurate assessment of grid topologies. In the calculation of branch risks of overload the probability of grid element failure was not considered. It would be interesting to add it to the risk of overload calculations. This combines static and probabilistic planning procedures but requires huge modelling efforts.

- The result of the solution generator is dependent on the initial set of new possible lines that is served as input. It is recommended that a more extensive set is carefully selected. As more candidates means increased computation time, this set can be reduced after the first steps of the solution generator by eliminating the lines that do not improve (much) the congestion in the grid. Also for reducing computation time, early stop conditions can be defined for stopping the solution generator when a certain low and manageable congestion level in the grid is reached. Furthermore, in the presented example only one capacity option for line doubling or for building a new line was considered. It is possible to use more line capacity options as well as upgrading of lines by increasing a capacity of an existing circuit instead of adding an extra circuit to it. As all these increase computation time it is recommended that not too many such options are used. Details of reinforcements can be decided later.

- Regarding approval procedures, it should be examined if more detailed technical information regarding a proposed transmission line project really leads to speeding-up the process. Moreover it should be investigated in practice what information is better to be provided beforehand and what information should be left for later in the process when questions arise. The possibility of using the solution generator in the decision making process could be investigated by creating a series gaming model with the stakeholders. The solution generator can be used to show to the stakeholders the impact of certain decisions on the transmission grid. Last but not least, the information used in this thesis for the stakeholder engagement analysis was obtained a posteriori the authorization process. In order to get more insightful information future research activities should allow realtime gathering of data during the authorization process.

Appendix A

New England test system line parameters

Table A.1: Line parameters for the New England test system

From bus	To bus	No. of circuits	Resistance [p.u.]	Reactance [p.u.]	Charging [p.u.]
1	2	1	0.0035	0.0411	0.6987
1	39	1	0.0010	0.0250	0.7500
2	3	1	0.0013	0.0151	0.2572
2	25	1	0.0070	0.0086	0.1460
3	4	1	0.0013	0.0213	0.2214
3	18	1	0.0011	0.0133	0.2138
4	5	1	0.0008	0.0128	0.1342
4	14	1	0.0008	0.0129	0.1382
5	6	1	0.0002	0.0026	0.0434
5	8	1	0.0008	0.0112	0.1476
6	7	1	0.0006	0.0092	0.1130
6	11	1	0.0007	0.0082	0.1389
7	8	1	0.0004	0.0046	0.0780
8	9	1	0.0023	0.0363	0.3804
9	39	1	0.0010	0.0250	1.2000
10	11	1	0.0004	0.0043	0.0729
10	13	1	0.0004	0.0043	0.0729
13	14	1	0.0009	0.0101	0.1723
14	15	1	0.0018	0.0217	0.3660
15	16	1	0.0009	0.0094	0.1710
16	17	1	0.0007	0.0089	0.1342
16	19	1	0.0016	0.0195	0.3040
16	21	1	0.0008	0.0135	0.2548
16	24	1	0.0003	0.0059	0.0680
17	18	1	0.0007	0.0082	0.1319
17	27	1	0.0013	0.0173	0.3216
21	22	1	0.0008	0.0140	0.2565
22	23	1	0.0006	0.0096	0.1846
23	24	1	0.0022	0.0350	0.3610
25	26	1	0.0032	0.0323	0.5130
26	27	1	0.0014	0.0147	0.2396
26	28	1	0.0043	0.0474	0.7802
26	29	1	0.0057	0.0625	1.0290
28	29	1	0.0014	0.0151	0.2490

Table A.2: NPL parameters for the New England test system

From bus	**To bus**	**Resistance [p.u.]**	**Reactance [p.u.]**	**Charging [p.u.]**
1	5	0.0014	0.0147	0.2396
2	18	0.0013	0.0173	0.3216
5	39	0.0008	0.0128	0.1342
13	19	0.0007	0.0089	0.1342
15	28	0.0009	0.0101	0.1723
16	28	0.0014	0.0147	0.2396
24	29	0.0009	0.0101	0.1723

Appendix B

Solution generator iterations

In Table B.1 all the steps of the round-the-year reinforcement solution generator performed on the New England test system are detailed. In cases with very little overloadings during the N situation with respect to the N-1 situations, the normalised $RO_{grid,N}$ is ignored in the SI_{grid} calculation. This is indicated by putting $RO_{grid,N}$ in between round brackets.

Table B.1: All iterations of the round-the-year reinforcement solution generator.

Step k	**Sub step.**	**Grid**	$\mathbf{SI_{grid}}$ **[p.u.]**	$\mathbf{\Delta SI_{grid}}$ **[p.u.]**	$\mathbf{RO_{grid,N}}$ **[%*h]**	$\mathbf{RO_{grid,N-1}}$ **[%*h]**	**TB** for reinf. $\mathbf{r_k}$	**TC** for reinf. $\mathbf{r_k}$
0	n.a.	G_0	1.000E+00	n.a.	3662.7	1553030.9	2 - 3	2 - 25
	1	$G_0 \cup \{2-3\}$	1.035E+00	-3.536E-02	4190.2	1265343.3		
	2	$G_0 \cup \{2-25\}$	6.315E-01	3.685E-01	2601.5	732432.5		
	3	$G_0 \cup \{24-29\}$	1.485E-01	8.515E-01	262.0	473507.8		
	4	$G_0 \cup \{16-28\}$	1.370E-01	8.630E-01	329.6	361193.6		
1	5	$G_0 \cup \{15-28\}$	***1.262E-01***	***8.738E-01***	270.9	360602.0	2 - 3	25 - 26
	6	$G_0 \cup \{1-5\}$	6.509E-01	3.491E-01	1952.6	1382082.1		
	7	$G_0 \cup \{5-39\}$	5.905E-01	4.095E-01	1538.6	1454621.5		
	8	$G_0 \cup \{13-19\}$	9.538E-01	4.616E-02	3444.9	1523288.8		
	9	$G_0 \cup \{2-18\}$	1.369E+00	-3.689E-01	6016.5	1262882.4		
	r_1=15 - 28, $G_1 = G_0 \cup \{15-28\}$, $NPL_1 = NPL_0 \setminus \{15-28\}$							
	1	$G_1 \cup \{2-3\}$	7.011E-02	5.607E-02	0.0	329930.0		
	2	$G_1 \cup \{25-26\}$	***6.204E-02***	***6.416E-02***	(8.0)	291954.9	23 - 34	23 - 24
	3	$G_1 \cup \{24-29\}$	1.129E-01	1.326E-02	184.8	372300.2		
2	4	$G_1 \cup \{16-28\}$	1.207E-01	5.431E-03	252.0	351313.0		
	5	$G_1 \cup \{1-5\}$	7.132E-02	5.486E-02	0.0	335625.1		
	6	$G_1 \cup \{5-39\}$	7.245E-02	5.373E-02	0.0	340964.4		
	7	$G_1 \cup \{13-19\}$	1.263E-01	-1.687E-04	287.1	347449.6		
	8	$G_1 \cup \{2-18\}$	7.006E-02	5.612E-02	0.0	329712.9		
	r_2=25 - 26, $G_2 = G_1 \cup \{25-26\}$, $NPL_2 = NPL_1$							

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Table B.1 – Continued

Step	**Sub step.**	**Grid**	**SI_{grid} [p.u.]**	**ΔSI_{grid} [p.u.]**	**$RO_{grid,N}$ [%*h]**	**$RO_{grid,N-1}$ [%*h]**	**TB for reinf. r_k**	**TC for reinf. r_k**
3	1	$G_2 \cup \{23-24\}$	***1.757E-02***	***4.447E-02***	(8.0)	82698.8	16 - 24	16 - 24
	2	$G_2 \cup \{24-29\}$	6.355E-02	-1.508E-03	0.0	299053.4		
	3	$G_2 \cup \{16-28\}$	5.938E-02	2.654E-03	(0.1)	279463.5		
	4	$G_2 \cup \{1-5\}$	6.161E-02	4.249E-04	0.0	289955.4		
	5	$G_2 \cup \{5-39\}$	6.131E-02	7.232E-04	0.0	288551.2		
	6	$G_2 \cup \{13-19\}$	5.960E-02	2.436E-03	(11.6)	280489.8		
	7	$G_2 \cup \{2-18\}$	6.345E-02	-1.413E-03	0.0	298604.3		
		r_3=23 - 24, $G_3 = G_2 \cup \{23-24\}$, $NPL_3 = NPL_2$						
4	1	$G_3 \cup \{16-24\}$	***3.959E-03***	***1.361E-02***	(8.0)	18633.4	15 - 16	15 - 28
	2	$G_3 \cup \{24-29\}$	1.144E-02	6.133E-03	0.0	53834.2		
	3	$G_3 \cup \{16-28\}$	1.493E-02	2.643E-03	(0.1)	70259.8		
	4	$G_3 \cup \{1-5\}$	1.716E-02	4.175E-04	0.0	80734.2		
	5	$G_3 \cup \{5-39\}$	1.687E-02	7.073E-04	0.0	79370.0		
	6	$G_3 \cup \{13-19\}$	1.513E-02	2.442E-03	(11.6)	71207.9		
	7	$G_3 \cup \{2-18\}$	1.897E-02	-1.400E-03	0.0	89287.3		
		r_4=16 - 24, $G_4 = G_3 \cup \{16-24\}$, $NPL_4 = NPL_3$						
5	1	$G_4 \cup \{15-16\}$	1.808E-03	2.151E-03	(6.9)	8507.3		
	2	$G_4 \cup \{15-28\}$	3.300E-03	6.596E-04	(2.4)	15529.0		
	3	$G_4 \cup \{24-29\}$	1.470E-03	2.489E-03	0.0	6919.3		
	4	$G_4 \cup \{16-28\}$	***1.318E-03***	***2.641E-03***	(0.1)	6204.0	2 - 3	9 - 39
	5	$G_4 \cup \{1-5\}$	3.555E-03	4.048E-04	0.0	16728.4		
	6	$G_4 \cup \{5-39\}$	3.264E-03	6.956E-04	0.0	15360.0		
	7	$G_4 \cup \{13-19\}$	1.520E-03	2.439E-03	(11.6)	7153.1		
	8	$G_4 \cup \{2-18\}$	5.348E-03	-1.389E-03	0.0	25168.5		
		r_5=16 - 28, $G_5 = G_4 \cup \{16-28\}$, $NPL_5 = NPL_4 \setminus \{16-28\}$						
6	1	$G_5 \cup \{2-3\}$	8.899E-04	4.284E-04	0.0	4188.1		
	2	$G_5 \cup \{9-39\}$	1.224E-03	9.403E-05	0.0	5761.5		
	3	$G_5 \cup \{24-29\}$	1.360E-03	-4.124E-05	0.0	6398.1		
	4	$G_5 \cup \{1-5\}$	6.067E-04	7.116E-04	0.0	2855.3		
	5	$G_5 \cup \{5-39\}$	***5.652E-04***	***7.531E-04***	0.0	2659.7	16 - 17	14 - 15
	6	$G_5 \cup \{13-19\}$	8.295E-04	4.258E-04	(2.1)	4200.2		
	7	$G_5 \cup \{2-18\}$	1.253E-03	6.521E-05	0.0	5897.1		
		r_6=5 - 39, $G_6 = G_5 \cup \{5-39\}$, $NPL_6 = NPL_5 \setminus \{5-39\}$						
7	1	$G_6 \cup \{16-17\}$	4.234E-04	1.417E-04	0.0	1992.7		
	2	$G_6 \cup \{14-15\}$	2.614E-04	3.037E-04	0.0	1230.4		
	3	$G_6 \cup \{24-29\}$	7.003E-04	-1.352E-04	0.0	3295.9		
	4	$G_6 \cup \{1-5\}$	4.989E-04	6.625E-05	0.0	2347.9		
	5	$G_6 \cup \{13-19\}$	***2.505E-04***	***3.147E-04***	0.0	1178.8	16 - 21 22 - 23	16 - 21 22 - 23
	6	$G_6 \cup \{2-18\}$	8.800E-04	-3.148E-04	0.0	4141.2		
		r_7=13 - 19, $G_7 = G_6 \cup \{13-19\}$, $NPL_7 = NPL_6 \setminus \{13-19\}$						
8	1	$G_7 \cup \{22-23\}$	***3.332E-05***	***2.172E-04***	0.0	156.8	6 - 11	4 - 14
	2	$G_7 \cup \{16-21\}$	3.481E-05	2.157E-04	0.0	163.8		
	3	$G_7 \cup \{24-29\}$	2.402E-04	1.026E-05	0.0	1130.5		
	4	$G_7 \cup \{1-5\}$	2.467E-04	3.804E-06	0.0	1160.9		
	5	$G_7 \cup \{2-18\}$	4.365E-04	-1.861E-04	0.0	2054.4		
		r_8=22 - 23, $G_8 = G_7 \cup \{22-23\}$, $NPL_8 = NPL_7$						

Continued on Next Page…

Table B.1 – Continued

Step	**Sub step.**	**Grid**	**SI_{grid} [p.u.]**	**ΔSI_{grid} [p.u.]**	**$RO_{grid,N}$ [%*h]**	**$RO_{grid,N-1}$ [%*h]**	**TB** (for reinf. r_k)	**TC** (for reinf. r_k)
9	1	$G_8 \cup \{6-11\}$	1.968E-05	1.364E-05	0.0	92.6		
	2	$G_8 \cup \{4-14\}$	***8.691E-06***	***2.463E-05***	0.0	40.9	2 - 3	26 - 27
	3	$G_8 \cup \{24-29\}$	3.070E-05	2.614E-06	0.0	144.5		
	4	$G_8 \cup \{1-5\}$	2.915E-05	4.165E-06	0.0	137.2		
	5	$G_8 \cup \{2-18\}$	2.191E-04	-1.858E-04	0.0	1031.1		
		r_9=4 - 14, $G_9 = G_8 \cup \{4-14\}$, $NPL_9 = NPL_8$						
10	1	$G_9 \cup \{2-3\}$	1.044E-04	-9.570E-05	0.0	491.3		
	2	$G_9 \cup \{26-27\}$	4.059E-06	4.632E-06	0.0	19.1		
	3	$G_9 \cup \{24-29\}$	***3.272E-06***	***5.418E-06***	0.0	15.4	4 - 5 6 - 11	4 - 5
	4	$G_9 \cup \{1-5\}$	7.501E-06	1.190E-06	0.0	35.3		
	5	$G_9 \cup \{2-18\}$	1.743E-04	-1.657E-04	0.0	820.5		
		r_{10}=24 - 29, $G_{10} = G_9 \cup \{24-29\}$, $NPL_{10} = NPL_9 \setminus \{24-29\}$						
11	1	$G_{10} \cup \{4-15\}$	1.275E-06	1.997E-06	0.0	6.0		
	2	$G_{10} \cup \{6-11\}$	5.950E-07	2.677E-06	0.0	2.8		
	3	$G_{10} \cup \{1-5\}$	***4.675E-07***	***2.805E-06***	0.0	2.2	2 - 3	1 - 2 1 - 39 4 - 5
	4	$G_{10} \cup \{2-18\}$	3.761E-06	-4.887E-07	0.0	17.7		
		r_{11}=1 - 5, $G_{11} = G_{10} \cup \{1-5\}$, $NPL_{11} = NPL_{10} \setminus \{1-5\}$						
12	1	$G_{11} \cup \{2-3\}$	8.075E-07	-3.400E-07	0.0	3.8		
	2	$G_{11} \cup \{1-2\}$	1.700E-07	2.975E-07	0.0	0.8		
	3	$G_{11} \cup \{1-39\}$	4.462E-07	2.125E-08	0.0	2.1		
	4	$G_{11} \cup \{4-5\}$	2.762E-07	1.912E-07	0.0	1.3		
	5	$G_{11} \cup \{2-18\}$	***1.487E-07***	***3.187E-07***	0.0	0.7	6 - 11	4 - 5
		r_{12}=2 - 18, $G_{12} = G_{11} \cup \{2-18\}$, $NPL_{12} = NPL_{11} \setminus \{2-18\} = \emptyset$						
13	1	$G_{12} \cup \{6-11\}$	***0.000E+00***	***1.487E-07***	0.0	0.0		
	2	$G_{12} \cup \{4-5\}$	0.000E+00	1.487E-07	0.0	0.0		
		r_{13}=6 - 11, $G_{13} = G_{12} \cup \{6-11\}$						

Appendix C

Coupling of market simulations and load flow calculations

Each time step of the market simulation results in a dispatch of the generation for each generation type per region and the load for each region. Next to that, resulting exchanges from each region to its interconnected neighbours are calculated in the market simulations. The market simulation results can be linked to the load flow model, and this is further described according to [78].

C.1 Mapping the generation

The results of the market model provide hourly values for the generation split by categories based on fuel type and technology. For each generator unit in the grid model the appropriate category of the market model is selected. For every region the dispatch of the generator units for each generation category is done based on two subsequently applied principles, first by dispatch order (priority) and next by dispatch of individual generator units.

The dispatch group represents a list of generator units that have the same dispatch order within a given generation category. This can be seen as a merit order within the list of all generator units belonging to the same category. This concept is presented in Figure C.1.

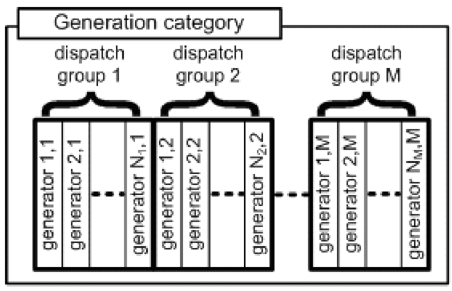

Figure C.1: Generation units of the same category arranged in dispatch groups [78]

The dispatch groups are ordered based on the generator units portfolios chosen for the study. For each dispatch group *m* the total maximum dispatch generation is calculated as the sum of the total maximum capacity of all generators within the group ($P_{cap,group,m}$). The market simulation result is split on the dispatch groups according to the specified order. Starting from the first dispatch group the generators are dispatched to their maximum capacities, until a dispatch group *m* has been reached where the remaining power to dispatch (P_{disp}) is smaller than the total maximum capacity of the generators in that group $P_{cap,group,m}$. In this case not all generators can be dispatched to their maximum capacity and two principles can be used for the dispatch of the individual generators: proportional scaling Eq. C.1 and linear scaling Eq. C.2.

$$P_{disp,gen,i,m} = \frac{P_{cap,gen,i,m}}{P_{cap,group,m}} \cdot P_{disp},\ i = 1..N_m \tag{C.1}$$

$$P_{disp,gen,i,m} = \frac{P_{disp}}{N_m},\ i = 1..N_m \tag{C.2}$$

$P_{cap,gen,i,m}$ is the capacity of the *i*-th generation unit in the *m*-th dispatch group and N_m is the number of generation units in the *m*-th dispatch group.

In general embedded generation units are not explicitly modelled in the grid model, i.e. solar PV and wind turbines connected to the distribution network [1], but they are represented in the market simulations and must thus be taken into account in the load flow model. The total of all the dispatched embedded generation per region is summed ($P_{disp,gen\ embed}$) and later netted with the total load of the region.

C.2 Mapping the load

The market simulation only provides the total load per region for each modelled time-step. In the grid model, this load needs to be divided among all the loads at the individual buses in the modelled region. For each load in the grid model, a part conforming to the system load pattern and a part for which the pattern is fixed, are identified. In these conforming and fixed loads there should be no contribution from embedded generation. Fixed loads can be large industries with a known constant load profile. The total fixed load in a region ($P_{ld\ fixed}$) is obtained by summing up the fixed loads at all buses. Similarly the total conforming peak load ($P_{ld\ conf}$) per region is obtained. The total conforming load that should be dispatched is given in Eq. C.3.

$$P_{disp,ld\ conf} = P_{disp,ld\ total} - P_{ld\ fixed} - P_{disp,gen\ embed} \tag{C.3}$$

Where $P_{disp,ld\ total}$ is the total dispatch of the region's load in the market simulation. Furthermore, for each individual conforming load the dispatch of the time-step is calculated using proportional scaling as in Eq. C.4.

$$P_{disp,ld\ conf,i} = \frac{P_{disp,ld\ conf}}{P_{ld\ conf}} \cdot P_{ld\ conf,i},\ i = 1..N_{ld\ conf} \tag{C.4}$$

[1] Big wind power plants which are connected to the transmission grid are modelled in the grid model.

$N_{ld\ conf}$ is the number of conforming loads in the region and $P_{ld\ conf,i}$ is the active peak power of the *i*-th conforming load in the region. It should be noted that one bus can have multiple loads attached.

C.3 Mapping the exchanges

The market simulations result also in an electricity exchange from each region to its neighbouring region for each simulated hour. The modelled area in the market simulations and the area covered in the grid model do not necessarily coincide. The exchanges between the regions that are included in both models should not be influencing the load flow results as they are recalculated, more accurately, by the load flow. The exchange to the regions outside the area of the grid model should be set explicitly for each time step. Furthermore the market model contains only one connection between each interconnected regions, where there can be multiple tie-lines between regions in the grid model. The presented approach takes into account all these issues in a pragmatic and general way. For each interconnection a set of tie-lines is defined and the dispatch is set proportional to a preset weighting value for each tie-line.

An equivalent load is placed on each of the tie-lines that are associated with the specific border to model the dispatch of the exchange. The direction of the exchange is taken into account by adapting the sign of the magnitude of the equivalent load: Eq. C.5 if the "from-region" is in the grid model, and Eq. C.6 if the "to-region" is in the grid model.

$$P_{disp,exch,i} = w_i \cdot P_{exch},\ i = 1..N_{ties} \tag{C.5}$$

$$P_{disp,exch,i} = -w_i \cdot P_{exch},\ i = 1..N_{ties} \tag{C.6}$$

w_i is the weight of the *i*-th tie-line for the border, P_{exch} is the exchange between the from-region and the to-region and N_{ties} is the number of tie-lines on that border. A border between two regions that are both in the market simulations and the grid model will get assigned two loads with the same magnitude, but with an opposite direction. This leads to a net zero flow. For exchanges where only one of the two regions is represented in the grid model, this will lead to the desired net exchange.

Appendix D

Base Scenario additional description for 2030 North-Western Europe

D.1 Modelling of hydro power plants

For the hydro power plants from Norway and Sweden, new weekly hydro long-range schedules were used as shown in Figure D.1 with the purpose of giving more space to wind. The total annual hydro energy is assumed to be 137.4 TWh for Norway and 65.6 TWh for Sweden. The new schedules were obtained considering more aspects than currently is done. In the case of Norway, the schedule was made by considering weekly load demand in Norway, weekly available wind energy in Norway as well as interconnection capacity. For Sweden the schedule was made by considering Swedish weekly load demand, weekly available wind energy and minimum output requirements of the conventional thermal generating units. For both countries it was checked that the reservoir maximum is not exceeded by using weekly hydro inflow and reservoir data from Nord Pool Spot.

The hydro energy levels in France (annual total of 62 TWh) and Germany (annual total of 23.5 TWh) were considered based on 2008 yearly and monthly production data from ENTSO-E [9]. The hydro profiles were developed by considering the monthly hydro production levels and dividing the monthly energy between more weeks (Figure D.2).

For the hydro power plants in the other countries constant available weekly hydro energy levels were assumed (summing up to annual values of 7.8 TWh in Great Britain, 0.4 TWh in Belgium).

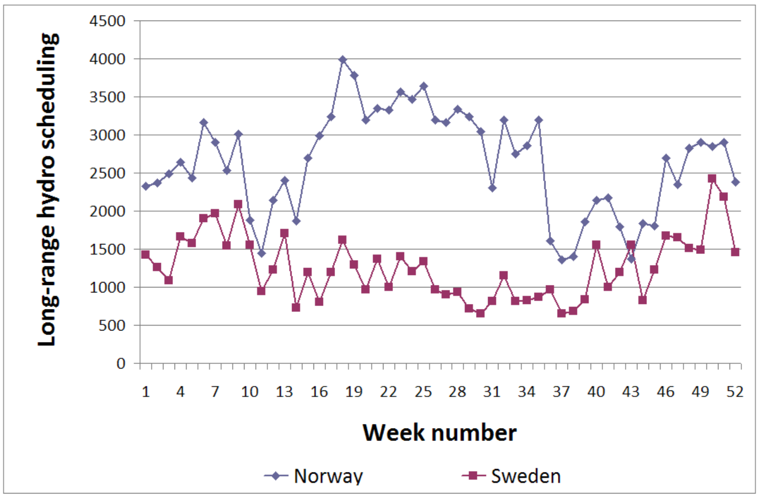

Figure D.1: Weekly long-range hydro scheduling for Norway and Sweden, values given in [GWh].

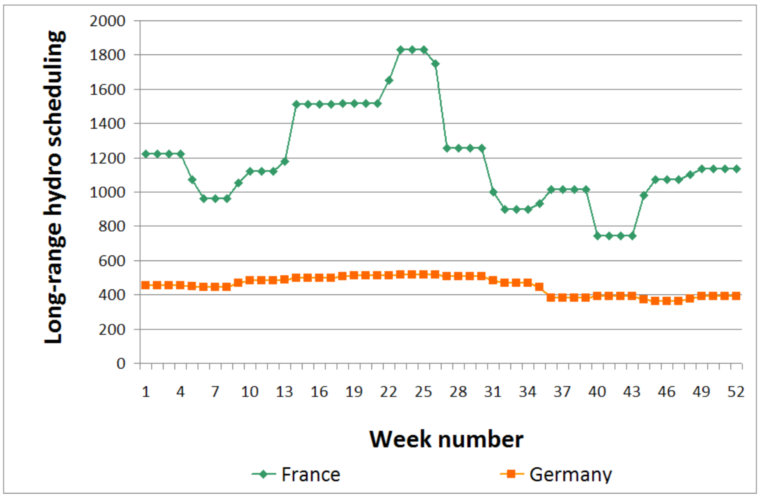

Figure D.2: Weekly long-range hydro scheduling for France and Germany according to 2008 monthly production levels, values given in [GWh].

D.2 Conventional generation installed capacities

Table D.1: Scenario of installed capacities for conventional generation for 2030

Country	Installed capacities in [MW]							
	Gas	**Coal**	**Lignite**	**Oil**	**Mixed fuel**	**Nuclear**	**Hydro**	**Pump storage hydro**
BE	10.14	1.88	0.00	0.00	0.00	2.06	0.12	1.30
DE	29.61	22.62	17.21	1.06	0.00	0.00	3.70	11.00
DK	2.59	1.76	0.00	0.57	1.98	0.00	0.00	0.00
FR	10.00	1.74	0.00	8.78	0.00	67.07	21.50	3.78
GB	33.28	18.63	0.00	0.00	0.00	11.95	1.14	3.00
NL	20.64	9.14	0.00	0.00	0.00	0.48	0.00	0.00
NO	1.23	0.00	0.00	0.00	0.00	0.00	28.57	2.80
SW	1.20	0.22	0.00	2.16	0.00	10.40	16.40	0.00
Totals	108.69	55.99	17.21	12.57	1.98	91.95	71.43	21.88

D.3 Net Transfer Capacities

In Figure D.3, the NTC matrix with the NTC values used in the market simulation for the direct country-to-country market links is presented.

To \ From	BE	DE	DK	FR	GB	NL	NO	SW
BE		1000		3700	1000	1437		
DE	1000		3100	2850		3900	1400	600
DK		3100				700	1600	2020
FR	2068	3200			3000			
GB	1000			3000		1000	1400	
NL	1648	3700	700		1000		1400	
NO		1400	1600		1400	1400		5200
SW		600	2400				5200	

Figure D.3: NTC matrix for the country-to-country market links, values given in [MW].

D.4 Wind power scenario

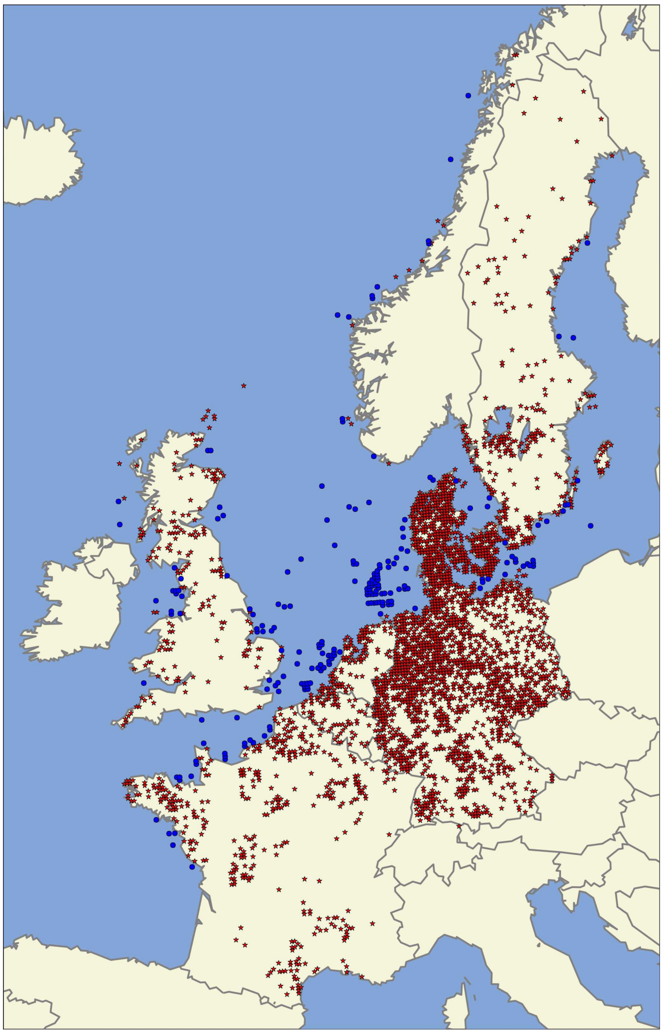

Figure D.4: Wind power time series locations: blue dot - offshore, red star - onshore.

For making the wind power time series some important aspects are considered: hub height, turbine type, decay length, locations and capacities of wind farms and wind speed time series. The hub height is chosen to be 90 m for both onshore and offshore wind farms. The wind speed time series at 90 m height above ground level for the year 2007 (a medium wind year) are based on a meso-scale regional re-analysis model with a grid of 9x9 km[1]. The locations of the onshore wind farms are considered as per 2011 and are taken for Germany from [149] and for the rest of the countries from [150], and the capacities are scaled up. For

[1]Meteorological data have been derived based on a meso-scale regional re-analysis by Sander + Partner, Switzerland.

offshore wind farms, locations and capacities for current and future wind farms available at [91] are used. For each location the closest point in the meso-scale model is taken, and the data is aggregated per found coordinates. The locations used for making the wind power time series are shown in Figure D.4.

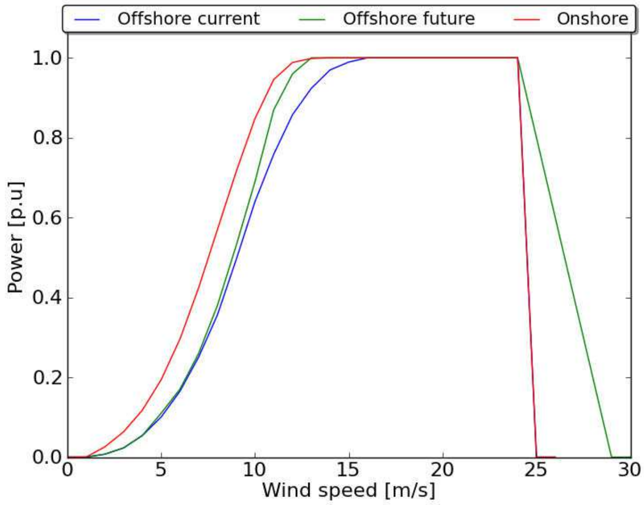

Figure D.5: Normalized power curves for the used wind turbines.

For onshore farms only one type of turbine is used (as only current wind farm locations are considered) and for offshore two types of turbines are used, old and new (because in the scenario distinction can be made between current and future wind farm locations). Availability factors of 0.95 for offshore and 0.98 for onshore wind turbines are considered. The normalized turbine power-curves are illustrated in Figure D.5. A multi-turbine approach [151] is used for each considered location with a wind speed correlation decay length of 723 km for onshore and of 500 km for offshore locations.

D.5 Solar power scenario

For developing the solar power time series less locations for radiation time series are used (Figure D.6) in comparison to the wind speed time series, due to data availability. Solar power time series are developed for Germany and for France. The installed capacities in 2030 per country are 13 GW for France [9] and 66 GW for Germany (German government's targets for 2030). The geographical distribution of the installed capacities is done as it

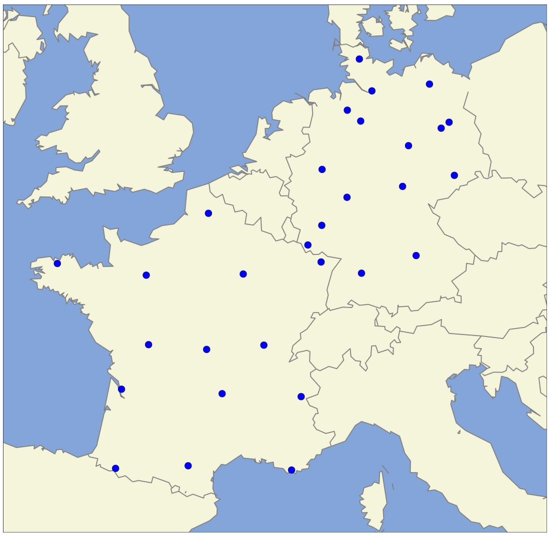

Figure D.6: Locations for developing solar power time series.

follows:

- For Germany: detailed data regarding the current installed capacities per postal code obtained from [149] as per 2011, is aggregated per postal code zone and ultimately per federal state. Then the increase up to 66 GW is done proportional to the product of the normalized surface per federal state and the normalized population density per federal state. Hence, in the states with both high surface and high population density the increase is higher. For each state a location is considered, resulting in a total of 16 locations. Data regarding the federal states geographical information as well as postal codes is obtained from [152].

- For France: a share of 30% of the total capacity in the Northern half of the country and of 70% in the Southern half of the country are assumed. These shares are distributed equally between the considered locations (14 in total).

Global radiation for the year 2005 was obtained from [153] for all the locations. It is assumed that all solar modules are crystalline silicon photovoltaic modules which are inclined at a fixed optimum angle. The optimum angle β is dependent on the latitude of the installation and is calculated as in [154]. For the calculation of the solar power production the method described in [155] is used. The power output was computed taking into account the global inclined radiation, and temperature and radiation-dependent module efficiency.

As a source for the ambient temperature data from a meso-scale regional re-analysis model [2] is used for all the locations. The maximum available power reaches almost 95% of the total installed capacity, which is an overestimation due to input data limitations. After comparing the solar generation profiles in terms of daily/seasonal variability and average energy content with the ones from [156], the quality of the time series appears reasonable (as mentioned before the generated time series have an overestimation in the output relative to the installed capacity). Moreover, the peak overestimation is challenging as more solar generation has to be absorbed by the system. In Figure D.7 the total German solar and wind power time series for a winter week and a summer week are illustrated. The seasonal and random complementarity of solar and wind power availability can be noticed.

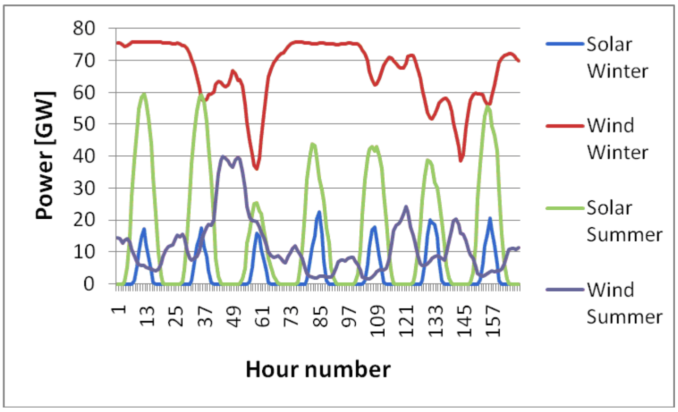

Figure D.7: Solar and wind power time series for Germany: a winter week and a summer week.

[2]Meteorological data have been derived based on a meso-scale regional re-analysis by Sander + Partner, Switzerland.

Appendix E

NSTG onshore grid model data

Table E.1: Main bus names and abbreviations for the Dutch 380 kV system

Interior Bus name	**Abreviation**
Interior buses	
Beverwijk	BVW
Bleiswijk	BWK
Borssele	BSL
Boxmeer	BMR
Breukelen	BKL
Crayestein	CST
Diemen	DIM
Dodewaard	DOD
Doetinchem	DTC
Eemschaven	EEM
Eemschaven Oudeschip	EOS
Eindhoven	EHV
Ens	ENS
Geertruidenberg	GT
Hengelo	HGL
Kreekrak	KRK
Krimpen aan de IJssel	KIJ
Lelystad	LLS
Maasbracht	MBT
Maasvlakte	MVL
Meeden	MEE
Moerdijk	MDK
Oostzaan	OZN
Oterleek	OTR
PST, Meeden	PST
Simonshaven	SMH
Tilburg	TBG
Vijfhuizen	VHZ
Wateringen	WTR
Westerlee	WL
Zwolle	ZL
Border buses	
Diele/Meeden	XDI_ME
Gronau/Hengelo	XGR_HG
Niederhein/Doetinchem	XNR_DT
Rommerschirchen/Maasbracht	XRO_MB
Van Eyk/Maasbracht 1	XVY_MB;1
Van Eyk/Maasbracht 2	XVY_MB;2
Zandvliet/Kreekrak	XZA_KRK

Table E.2: Modelled 380 kV AC branches in the Dutch system

380 kV corridor	**Number of circuits**	**Rated capacity per circuit [MVA]**
	Interior corridors	
BSL-TBG	2	2633
BVW-OZN	2	1645
BVW-VHZ-BWK	2	2910
BWK-KIJ	2	2633
BWK-WTR	2	2910
CST-KIJ	2	2633
DIM-BKL-KIJ	1	1645
DIM-LLS-ENS	2	1974
DIM-OZN	1	1909
DOD-DTC	2	1645
DOD-MBT	1	1645
DOD-BMR-MBT	1	1645
DTC-HGL	2	1645
EOS-EEM	2	2633
EOS-ENS	2	2633
EEM-MEE	2	2633
EHV-MBT	2	1645
ENS-DIM	2	2633
ENS-ZL	2	1645
GT-KIJ	2	1645
GT-MDK	2	2633
GT-MDK-KRK-BSL	2	2764
GT-TBG-EHV	3	1645
HGL-GR	2	1645
HGL-ZL	2	1645
MEE-ZL	2	2633
MVL-SMH-CST	2	2910
MVL-WL	2	2650
OTR-BVW	2	2633
OTR-DIM	2	2633
OZN-DIM-KIJ	1	1645
WTR-WL	2	2633
	Border corridors	
MEE-PST	2	1000
PST-XDI_ME	2	1383
DTC-XDT_NR	2	2633
HGL-XGR_HG	2	1481
KRK-XZA_KR	2	1481
MBT-XVY_MB;1	1	1267
MBT-XVY_MB;2	1	1218
MBT-XRO_MB	2	1645

Table E.3: Modelled 380 kV AC branches in the Belgium and German networks

380 kV corridor	**Number of circuits**	**Rated capacity per circuit [MVA]**
German corridors		
Berlin - Hamburg	2	1645
Berlin - Wahle	5	1645
Berlin - Wurgau	6	1645
Neurott - Wurgau	6	1645
Neurott - Wahle	4	1645
Neurott - Rommerskirchen	8	1645
Niederrhein - Rommerskirchen	8	1645
Gronau - Niederrhein	8	1645
Gronau - Wahle	7	1645
Diele - Gronau	5	1645
Diele - Hamburg	2	1645
Hamburg - Wahle	5	1645
Diele - XDI_ME	2	1645
Gronau - XGR_HG	2	1645
Niederrhein - XDT_NR	2	1645
Rommerskirchen - XRO_MB	2	1645
Belgian corridors		
Lint - Van Eyck 1	1	1645
Van Eyck PST 1 - Van Eyck 1	1	1473
Gramme - Van Eyck 2	1	1645
Van Eyck PST 2 - Van Eyck 2	1	1473
Courcelles - Gramme	2	1645
Courcelles - Lint	2	1645
Avelgem - Eeklo	2	1645
Eeklo - Lint	2	1645
Lint - Zandvliet	2	1645
Zandvliet_PST - Zandvliet	2	1473
Zandvliet PST - XZA_KR	2	1910
Van Eyck PST 1 - XVY_MB;1	1	1563
Van Eyck PST 2 - XVY_MB;2	1	1645

Table E.4: HVDC corridors in Germany

HVDC corridor	**Capacity [MW]**
North-South	
Diele - Rommerskirchen	6000
Diele - Neurott	12000
Hamburg - Neurott	6000
Berlin - Wurgau	2000
Wurgau - Neurott	4000
to Belgium	
Rommerskirchen-Gramme	1000

Modelling of flows on the North-South HVDC corridors in Germany.

```
if P_Diele > 2000 [MW]
  do
     if P_Diele < (2000+18000) [MW]
       do P_go_Neurott = (P_Diele − 2000) ∗ 2/3 [MW]
          P_go_Rommerskirchen = (P_Diele − 2000) ∗ 1/3 [MW]
     else
          do P_go_Neurott = 18000 ∗ 2/3 [MW]
             P_go_Rommerskirchen = 18000 ∗ 1/3 [MW]
             exit fi od od
     P_Neurott = P_Neurott + P_go_Neurott
     P_Rommerskirchen = P_Rommerskirchen + P_go_Rommerskirchen
     P_Diele = P_Diele − P_go_Neurott − P_go_Rommerskirchen
     exit fi od
if P_Hamburg > 2000 [MW]
  do
     if P_Hamburg < (2000+6000) [MW]
       do P_go_Neurott = (P_Diele − 2000) [MW]
     else
          do P_go_Neurott = 6000  [MW]
             exit fi od od
     P_Hamburg = P_Hamburg − P_go_Neurott
     P_Neurott = P_Neurott + P_go_Neurott
     exit fi od
Flag_Berlin_Neurott = False
if P_Berlin > 2000 [MW]
  do if P_Wurgau < −2000 [MW]
       do if P_Berlin < (2000+2000) [MW]
            do P_go_Wurgau = (P_Berlin − 2000) [MW]
          else
               do P_go_Wurgau = 2000 [MW]exit fi od od
          P_Berlin = P_Berlin − P_go_Wurgau
          P_Wurgau = P_Wurgau + P_go_Wurgau
       od
  else if P_Berlin < (2000+2000)  [MW]
         do Flag_Berlin_Neurott = True
            P_go_Neurott = (P_Berlin − 2000) [MW]
       else
            do P_go_Neurott = 2000 [MW]
               exit fi od od
       P_Neurott = P_Neurott + P_go_Neurott
       P_Berlin = P_Berlin − P_go_Neurott
       exit fi od od
```

Modelling of flowson the North-South HVDC corridors in Germany (continuation).

if $\mathsf{P}_{Wurgau} > 2000$ [MW]
do
if $\mathsf{Flag}_{Berlin\_Neurott} = \mathsf{False}$
do $\mathsf{P}_{max} = 4000$ [MW]
else
do $\mathsf{P}_{max} = 2000$ [MW]
exit fi od od
if $\mathsf{P}_{Wurgau} < (2000 + \mathsf{P}_{max})$ [MW]
do $\mathsf{P}_{go\_Neurott} = (\mathsf{P}_{Wurgau} - 2000)$ [MW]
else
do $\mathsf{P}_{go\_Neurott} = \mathsf{P}_{max}$ [MW]
exit fi od od
$\mathsf{P}_{Wurgau} = \mathsf{P}_{Wurgau} - \mathsf{P}_{go\_Neurott}$
$\mathsf{P}_{Neurott} = \mathsf{P}_{Neurott} + \mathsf{P}_{go\_Neurott}$
exit fi od exit

Algorithm E.1: Modelling of flows on the North-South HVDC corridors in Germany

Table E.5: Onshore grid connection points for the NSTG

Country	**Onshore grid node**	**NSTG node**
Belgium	Eeklo	12
Germany	Diele	15
	Hamburg	16
Netherlands	Eemschaven	14
	Oterleek	13

Table E.6: Onshore connection points and installed capacities for the offshore wind not connected to the NSTG

Country	**Onshore node**	**Installed wind [MW]**
Belgium	Avelgem	615.2
	Eeklo	1151
Germany	Berlin	5409
	Diele	4651
	Hamburg	554
Netherlands	Borssele	1328
	Beverwijk (IJmuiden)	228
	Maasvlakte	2094
	Oterleek	1139
	Vijfhuizen	2387
	Wateringen	212

Appendix F

NSTG onshore grid security analysis: additional tables

Table F.1: Risks of overload for the 380 kV NL interior and border branches. Comparison for two reinforcement scenarios.

Branch	Reference Scenario		Reinf_1		Reinf_2	
	RO_N	RO_{N-1}	RO_N	RO_{N-1}	RO_N	RO_{N-1}
	[%*h]					
Interior branches						
DIM-BKL	0	37	0	37.8	0	0.4
DIM-OZN	0	15.6	0	20.4	0	90
DOD-DTC	0	2156.7	0	1757.5	0	34.5
DTC-HGL;1	0	41.4	0	28.7	0	0
DTC-HGL;2	0	22	0	21.7	0	0
EEM-MEE;11	0	7385.4	0	0	0	0
EEM-MEE;12	0	7242.2	0	0	0	0
EHV-MBT	53.3	43070	114	***48330.9***	0	5380.8
ENS-ZL	0	1837.5	0	714	0	33.6
GT-KIJ	4.5	30652.5	0	0	0	0
HGL-ZL	***365.4***	32894.4	0	28	0	0
MVL-SMH	0	2.7	0	2.7	0	0.5
TBG-EHV;1 and 2	0	696.5	0	1281.4	0	0
TBG-EHV;3	0	533	0	1078.3	0	0
TBG-GT	0	2.3	0	13.6	0	0
Border branches						
PST-XDI_ME	13.6	6018	42	7422.6	7.6	3018.6
HGL-XGR_HG	7.5	27553.5	7.2	28520	10.2	29340.5
MBT-XRO_MB	0	730.1	0	881.6	0	938.1
MBT-XVY_MB;1	24867.6	31222.8	24453.6	30857	***28328.3***	34929.9
MEE-PST	1948.1	38506.6	2633.4	***42153.8***	1139.6	33615

Table F.2: Variation of risks of overload with changes in the German grid model.

Branch	**Reference Scenario**		**Extra circuit Berlin-Wurgau**		**Extra circuit Diele-Gronau**	
	$\mathbf{RO_N}$	$\mathbf{RO_{N-1}}$	$\mathbf{\Delta RO_N}$	$\mathbf{\Delta RO_{N-1}}$	$\mathbf{\Delta RO_N}$	$\mathbf{\Delta RO_{N-1}}$
Interior branches						
DIM-BKL	0	37	0	-14.8	0	-13.2
DIM-OZN	0	15.6	0	-4.1	0	-2
DOD-DTC	0	2156.7	0	-229	0	163.3
DTC-HGL;2	0	41.4	0	-15.4	0	5.4
DTC-HGL;1	0	22	0	-5.5	0	1
EEM-MEE;10	0	*7385.4*	0	13.6	0	*664.6*
EEM-MEE;11	0	*7242.2*	0	-15.7	0	*638.2*
EHV-MBT	53.3	*43070*	-23.6	*-1351.4*	-22.7	*-3820.4*
ENS-ZL	0	1837.5	0	49.5	0	-202.3
GT-KIJ	4.5	*30652.5*	8.3	*-585.6*	-3.5	*-1775.1*
HGL-ZL	365.4	*32894.4*	67.7	*-906.7*	-115.8	*-10668*
MVL-SMH	0	2.7	0	-0.9	0	-0.9
TBG-EHV;1 and 2	0	696.5	0	-38.5	0	-158.6
TBG-EHV	0	533	0	4.2	0	-67.7
TBG-GT	0	2.3	0	-2.3	0	-2.3
Border branches						
PST-XDI_ME	13.6	*6018*	-0.1	178.5	21.4	*1426.8*
HGL-XGR_HG	7.5	*27553.5*	-3	*-1120.7*	-2.1	*4525.1*
MEE-PST	*1948.1*	*38506.6*	82.4	25.3	*571.3*	*4750.2*
MBT-XRO_MB	0	730.1	0	-136.1	0	-98.2
MBT-XVY_MB;1	24867.6	31222.8	-129.2	-105.8	-7.6	-250.8

Table F.3: Grid model comparison: risks of overload for the 380 kV NL interior and border branches.

Branch	No HVDC in DE RO_N	No HVDC in DE RO_{N-1}	Reference Scenario RO_N	Reference Scenario RO_{N-1}
	[%*h]			
Interior branches				
DIM-BKL	638	5799.6	0	37
DIM-OZN	0.8	5579.4	0	15.6
DOD-DTC	0	12522.4	0	2156.7
DTC-HGL;1	2603.5	42433.6	0	41.4
DTC-HGL;2	1494.3	38302.2	0	22
EEM-MEE;10	0	5897.6	0	7385.4
EEM-MEE;11	0	5820	0	7242.2
EHV-MBT	5187.5	102660.5	53.3	43070
ENS-LLS	0	325.6	0	0
ENS-ZL	0	934.8	0	1837.5
GT-KIJ	7632.7	***124239.5***	4.5	30652.5
HGL-ZL	***14756***	91598.9	365.4	32894.4
KIJ-BKL	0	52.8	0	0
KIJ-OZN	0	4.5	0	0
MEE-ZL;1	0	133	0	0
MEE-ZL;2	0	131.1	0	0
MVL-SMH	0	3.3	0	2.7
TBG-EHV;1 and 2	13.2	13491.5	0	696.5
TBG-EHV;3	13.3	12574.4	0	533
TBG-GT	13	2567.8	0	2.3
Border branches				
PST-XDI_ME	30588.7	105846.3	13.6	6018
HGL-XGR_HG	866.2	40799.7	7.5	27553.5
MBT-XRO_MB	976.5	20971.4	0	730.1
MBT-XVY_MB;1	17568.9	23036	24867.6	31222.8
MEE-PST	***82645.5***	***196418.4***	1948.1	38506.6

Table F.4: No HVDC corridors in DE: criteria and risks of overload for the 380 kV NL interior and border branches.

Branch	C01 [%]	C02 [h]	C03 [%]	C03 hour	RO_N [% * h]	C11 [%]	C12 [h]	C13 [%]	C13 hour	RO_{N-1} [% * h]
Interior branches										
DIM-BKL	105.8	110	129.1	7899	638	110.8	537	152.7	788	5799.6
DIM-OZN	100.2	4	101.7	2612	0.8	110.2	547	153.8	788	5579.4
DOD-DTC	0	0	0	n.a.	0	108.8	1423	144.5	785	12522.4
DTC-HGL;1	105.1	293	164	8080	2603.5	117.3	2214	231.2	8080	42433.6
DTC-HGL;2	106.35	410	169.8	8080	1494.3	117.6	2411	236.1	8080	38302.2
EEM-MEE;10	0	0	0	n.a.	0	109.7	608	155.6	8353	5897.6
EEM-MEE;11	0	0	0	n.a.	0	109.7	600	155.3	8353	5820
EHV-MBT	108.3	625	163.1	8080	5187.5	139.5	2599	269.6	8080	102660.5
ENS-LLS	0	0	0	n.a.	0	104.4	74	117.4	788	325.6
ENS-ZL	0	0	0	n.a.	0	105.7	164	125.1	1509	934.8
GT-KIJ	112.7	601	195.2	8080	7632.7	138.5	3227	353.7	8080	124239.5
HGL-ZL	115.5	952	163.2	7218	14756	132.05	2858	244.9	7218	91598.9
KIJ-BKL	0	0	0	n.a.	0	103.3	16	116.8	7899	52.8
KIJ-OZN	0	0	0	n.a.	0	104.5	1	104.5	7899	4.5
MEE-ZL;1	0	0	0	n.a.	0	103.45	38	111.5	8080	133
MEE-ZL;2	0	0	0	n.a.	0	103.5	38	111.5	8080	131.1
MVL-SMH	0	0	0	n.a.	0	101.1	3	102.3	8249	3.3
TBG-EHV;1 and 2	101.1	12	124.4	8080	13.2	112.1	1115	175.6	8080	13491.5
TBG-EHV;3	101.9	7	123.4	8080	13.3	111.6	1084	174.2	8080	12574.4
TBG-GT	106.5	2	112.3	8080	13	107.4	347	157.6	8080	2567.8
Border branches										
PST-XDI_ME	130.65	998	226.5	8042	30588.7	147.7	2219	350.7	8042	105846.3
HGL-XGR_HG	112.2	71	149.3	785	866.2	124.3	1679	255.8	785	40799.7
MBT-XRO_MB	106.3	155	179.1	8080	976.5	119.4	1081	254.3	8080	20971.4
MBT-XVY_MB;1	112.15	1446	152	2192	17568.9	113	1772	154.6	2192	23036
MEE-PST	146.3	1785	309.9	8042	82645.5	155.05	3568	481.6	8042	196418.4

Table F.5: Risks of overload for the 380 kV NL interior and border branches. Comparison for various offshore grid configurations.

Branch	**No offshore grid**		**1.2 GW radial offshore grid**		**Reference Scenario**	
	RO_N	**RO_{N-1}**	**RO_N**	**RO_{N-1}**	**RO_N**	**RO_{N-1}**
	[%*h]					
Interior branches						
DIM-BKL	0	143.5	0	176.4	0	37
DIM-OZN	0	75.4	0	262.5	0	15.6
DOD-DTC	0	791	0	1942.5	0	2156.7
DTC-HGL;1	0	31.2	0	46	0	41.4
DTC-HGL;2	0	8.4	0	18.5	0	22
EEM-MEE;10	0	2702.7	0	1435.1	0	7385.4
EEM-MEE;11	0	2644.8	0	1401.2	0	7242.2
EOS-EEM	0	0	0	11.4	0	0
EHV-MBT	62.1	40181	114.8	43035.3	53.3	***43070**
ENS-ZL	0	1612.8	0	2377.2	0	1837.5
GT-KIJ	1.5	34447	7.5	29184.4	4.5	30652.5
HGL-ZL	176	29991.7	263.2	28138.8	***365.4**	32894.4
MVL-SMH	0	2.7	0	7.8	0	2.7
TBG-EHV;1 and 2	0	703	0	888	0	696.5
TBG-EHV;3	0	588.2	0	745.5	0	533
TBG-GT	0	0	0	6.2	0	2.3
Border branches						
PST-XDI_ME	4.2	4219.4	0	1757.7	13.6	6018
HGL-XGR_HG	12.6	24326.4	0	30151.2	7.5	27553.5
MBT-XRO_MB	0	1386	0	837	0	730.1
MBT-XVY_MB;1	9687.6	14688	22021.1	27734.7	***24867.6**	31222.8
MEE-PST	2099.9	24293.5	1008	18779	1948.1	***38506.6**
KRK-XZA_KR	0	2.8	0	2.7	0	0

Appendix G

The France-Spain interconnection project: Baixas-Santa Llogaia

This appendix is based on two main sources: REALISEGRID [102] and the website [157] of the public engagement process of the project on the French side where detailed reports and information are available. The reports that can be found are on the one hand reports and verbatim transcripts for each of the meetings during the public engagement process, as well as final reports of the public engagement process [158, 159]. The other information refers for example to additional clarifying documents (i.e. regarding EMF exposure) provided during the public engagement process. In Spain there was also a public engagement phase, but this will not be discussed in the current work. This interconnection has been examined as an example of an ongoing transmission expansion planning process and the steps of the public engagement process which eventually led to the approval of the route.

The proposed interconnection between France and Spain has a long history. First proposed in the 1980s, this project aims to install a double circuit extra-high voltage line (400kV) in the Pyrenees-Orientales region, traversing to Spain. In 1984, when Spain began taking steps to join the European Union, an agreement was signed between France and Spain for the sale of electricity to Spain by France. Many studies followed after this agreement, but all the considered projects were abandoned due to various reasons such as public opposition (the crossed regions did not accept the project, or opposition to interference with touristic areas and nature reserves). Finding an interconnection route was a difficult task. After many years it now seems that a solution has been found and the line between Baixas and Santa Llogaia should be functional in 2014. In the next sections we shall focus on the period from 2003 onwards, as in 2003 a new project proposal for the France-Spain interconnection is made, covering the same geographical area as the final project that is currently under construction. In [160] the technical details of the project can be found. Table G.1 illustrates the story timeline which focuses on the French part of the interconnection.

The usual approval procedure steps in France are as follows. Normally, after the technico-economic justification of the proposed project, the next step is the concertation and public debate. The term concertation refers to a form of dialogue and co-decision, cooperation among various (opposing) parties that has the purpose of producing a unified proposal or concerted action. Concertation differs from consultation in the sense that it is not a request

Table G.1: Story timeline

Moment	Description
2003	New plan for an overhead line interconnection between France and Spain is proposed and meets strong opposition during the public debate
November 2006	France and Spain decide to ask for a European coordinator for facilitating the project implementation
September 2007	Mr. Mario Monti is appointed as coordinator by the European Commission
27 June 2008	France and Spain ratify in Zaragoza an intergovernmental agreement specifying the general characteristics and implementation modalities of the interconnection line
October 2008	The French TSO RTE contacts the French National Public Debate Commission (CNPD) which decides that a specific concertation is necessary, respecting the principles of public debate
December 2008	Mr. Mercadal is appointed as a guarantor by the CNDP
19 January 2009 - 20 April 2009	The first phase of the concertation process
24 November 2009 - 22 March 2010	The second phase of the concertation process
May 2010	Application for public utility declaration

for advice. It actually implies the mutual exchange of information, open discussion and confrontation between the parties, knowledge sharing and explanation of each other's views, i.e a dialogue. The concertation is geared at finding a route of least impact. After that, there is a public debate where everyone can voice their opinions on the proposed project. Then the project developer decides whether the project will be continued (with or without changes) or not. If it is decided that the project will be continued, a declaration of public interest is made. After this, the details of the project can be worked out.

G.1 The 2003 project proposal and the community's response

In 2003 a new plan of an overhead line with two 400 kV circuits between Baixas and Bescano crossing the plain of Roussillon (see Figure G.1) is proposed in France as part of the France-Spain interconnection project. The concertation, and afterwards the public debate are organised in that year. The local communities form the NGO "Non a la THT" which means "No to the extra high voltage". This NGO provides a forum for debate and reflection on the problems of extra high voltage lines and of consideration of other energy alternatives. Moreover, the affected local governments form a defense union (Sydeco THT 66) for the Pyrenees-Orientales communities between extra high voltage lines. Faced with determination by the RTE (the French Transmission System Operator) to continue with the proposal for a double-circuit 400 kV line between Baixas and Bescano, the local communities decide that action should immediately be taken. Demonstrations are organised in the region, supported by thousands. The NGO makes use of the services of independent experts for fighting against the line project. A press communicate written by one of those independent experts after the 2003 public debate [161], points out how the situation is perceived by the public. The trust in the state bodies is very low as they are thought to be subjective and "cleverly infiltrated by agents of lobbying power". The state bodies together with the TSO seem to have failed to show transparency with respect to the real need of the project: they are accused to cover trade concerns. The strong association between RTE and EDF (the national French generating company) favoured also distrust in RTE's honesty (in the past, RTE and EDF used to be one company). Moreover, the response of RTE is found to be a "more than light" document that discarded the public requests of an underground line and maintained the original - overhead line - layout of the project. The local and regional representatives consider it feasible to construct the line underground, following the rail infrastructure of the future high speed train TGV between Perpignan and Barcelona. Due to the public opposition, the Minister of Industry asks RTE to explore other alternatives. The RTE failure to engage with the citizens and to consider their opinion and requests in the definition of the project made citizens feel ignored, determining the local representatives to refuse further cooperation. This points to a lack of perceived procedural justice.

Figure G.1: Geographic span of the proposed line.

G.2 Intervention of the European Commission: the Zaragoza decision

Faced with difficulties in identifying a solution that would satisfy both countries and that would be accepted locally, France and Spain decide in November 2006 to ask for a European coordinator to facilitate the implementation of the project. In September 2007, Mr. Mario Monti is appointed as a coordinator by the EC. Mr. Monti starts his mission by opening a dialogue-based consultation. He meets with a group of stakeholders: representatives of the two governments, TSOs and local actors (local governments and NGOs). These series of meetings end in June 2008. Based on its findings and expert reports, France and Spain ratify in Zaragoza, June 27 2008, an intergovernmental agreement that specifies the characteristics and modalities of implementation of the new interconnection transmission line, which should be a completely underground solution using VSC-HVDC technology. The connection would span from substation Baixas (in France) to substation Santa Llogaia (in Spain), and with a route relying as much as possible on existing infrastructure (highways, roads). It is decided to create a French-Spanish mixed-capital corporation called INELFE to continue this project. This corporation is comprised equally by the two TSOs (RTE in France and RED in Spain). Finally, the public's voice seemed to be heard as the project proposal which was agreed upon in Zaragoza considered the citizens requests from 2003. This decision was the one that would bring back together RTE, the authorities and the citizen representatives and would open a door for further dialogue/concertation. The fact that the EC intervened may have also played a part in acknowledging the importance of the project.

G.3 Beginning of the concertation

RTE, the project developer on the French side, contacts the French National Public Debate Commission (CNDP) again, after 5 years, in October 2008. Because the meetings of Mr. Monti with the stakeholders were a follow-up of the public debate that took place in 2003, and because the decision of an underground line is in line with the older suggestions of the regional and local governments, CNDP decides that a new public debate is not appropriate. Instead, a specific concertation is deemed necessary. A guarantor is appointed by CNDP (in the person of Mr. George Mercadal who was also the president of the 2003 public debate committee) in December 2008.

The stakeholders involved in the new concertation are the members of the NGO “Non a la THT”, representatives of the local governments (the Sydeco THT 66 union), representatives of the French government (senators and deputies of the concerned sector), and members of the NGO “Defensa de la Terra”. They form the advisory committee of the concertation together with the president of the regional mayors’ union, the president of the general council and representatives of the project developer (RTE), as requested by the CNDP regulations. The stakeholders prefer a new public debate rather than a concertation process and not all of them acknowledge the project justification. Despite that, they agree to go over this disagreement to participate in the concertation for exercising vigilance regarding the implementation of the new plan. By participating they could discuss the characteristics of the project, its route, the various building options, with the main purpose of guaranteeing a minimal impact on the population and the environment.

Until this point, the decision to have a concertation is the result of the Zaragoza decision and the project is only broadly defined. In the concertation the project details are further defined, based on discussions and studies commissioned during the concertation. Hence, aspects such as routing and infrastructure support, provisions of obstacle clearance, technical characteristics of the cable and converter stations are decided upon during the concertation.

G.4 The first phase of the new concertation process (19 January - 20 April 2009)

A great part of the first concertation phase, supervised by CNDP, is focused on the concerns of the stakeholders. CNDP organises two committees for answering the first expressed concerns, each chaired by an external member representing the “CNDP guarantor”: one on “Direct current and health” and one on “Underground and environment”. In the first committee the TSO informs and discusses with the stakeholders the issue of electromagnetic fields, for both direct and alternating current technologies. During the meetings of the second committee, a number of issues are discussed: the environmental characteristics of the affected zone, the various techniques of installing the underground line depending on the terrain type and the associated general potential impacts, the possibility of merging the line trace with the various other types of existing infrastructure, the heating characteristics of the cables and the heat dissipation. An important role plays the usage of a modern digital tool for visualizing the terrain that is used in the concertation process and also in public meetings. This tool allows virtual site visits, is very detailed and has a high resolution. It can be used real-time during the meetings, allows easy moving, 3-dimensional visualization, distance measurement, and offers the possibility of visualizing the route options. The participants particularly appreciated the tool for its performance and the fact that the project developer spends the effort of making means available for better analyzing the project.

The first phase of the concertation process results in: identification of possible line routes, comparison of the identified routes, proposal for the route of least impact, and choosing a tunnel as the solution for crossing the mountain area. The choice of a tunnel crossing the mountain is highly appreciated. Moreover, the participants decide that more detailed investigations have to be performed, and consequently a second phase of the concertation process follows.

G.5 The second phase of the new concertation process (24 November 2009 - 22 March 2010)

During this phase a more detailed route research is performed, supervised by CNDP. The concertation in the second phase is organized into four geographical workshops. Each workshop is asked to develop a detailed route for its part of the region covered by the project. The workshops' participants are representatives of the local governments (members of Sydeco THT 66) and NGOs ("Non a la THT" and "Defensa de la Terra"). The control of each geographical workshop is given to one of the mayors of the concerned municipalities in order to emphasize the local roots of the analysis to be performed. The route resulting from these workshops is proposed in the application for public utility declaration.

Each workshop takes into account the following issues and studies: topographic studies, flora, fauna, Natura 2000 area, geological and hydro geological studies, crossing issues (e.g. crossing railroads, roads, and rivers), location of cables and impact on the magnetic field. Each workshop meeting is transcribed verbatim and a report is published on the website of the concertation. The guarantor puts INELFE in charge of gathering input from experts nominated by the NGOs participating in the concertation.

The most sensitive issues relate to the part of the trajectory that crosses mountain Alberes, area where the technical difficulties are numerous and environmental awareness high. The idea of RTE to cross this area underground by means of a tunnel was welcomed initially by most stakeholders. However, in the second phase it meets three main difficulties connected to the recent experience of the local population with two much larger high-speed train tunnels that were dug through mountain Alberes.

Firstly, part of the population of the Perthus village refuses to have a new tunnel passing under a part of the village. The population was exposed to noise and vibrations during the digging of the train tunnels and they expect more nuisance caused from the rolling noise of trains driving through the tunnels. Hence they refuse an extra nuisance caused by digging the new electricity line tunnel. According to RTE there is an accumulation of infrastructures in this area which may lead to a saturation of the population and consequently causes refusal. A solution is found after a geological study is carried out for examining ways of avoiding a passage under the village Perthus, while ensuring the realization of the tunnel under good technical feasibility conditions.

The second concern is about the consequences of the new line tunnel on mountain Alberes' water resources. Some people attribute the drying up of some sources and the loss of other water resources of the massif to the two railway tunnels. This represents an important concern as the water supply of the villages is provided almost exclusively by the water resources of the massif, and also because of the proximity to the Boulou hot springs, which are an important economic and touristic factor. Hence a hydrological study of mountain Alberes is performed for avoiding such unwanted effects. This study results in the selection of provisions for the excavation process, which are incorporated in RTE's commitments.

Thirdly, questions are raised about the processing and storage of waste resulting from digging the tunnel. The previous experience with high-speed railway tunnels counts here again. To deal with these concerns, contacts are made with the local governments to jointly review possible waste storage areas, promoting the integration into the landscape of the created volume.

G.6 End of the concertation

The concertation is closed in a meeting on 22 March 2010. The corresponding communication is distributed to the public in the beginning of June 2010. The new line segment has about 65 km, out of which 35 km is in France in the Pyrenees-Orientales. Moreover, the project preserves the landscape and passes through the massive Alberes via a dedicated 8 km tunnel. At the end of the concertation, all stakeholders unanimously agree that the organization of a concertation under the authority of the guarantor instead of a new public debate was actually a good choice. Although there was disagreement amongst the politicians, NGOs and the project developer, all participants testify that during the process there was a constructive spirit, a desire for transparency, a sense of understanding and respect, managed and supervised by the CNDP. In total 13 external persons and experts participated throughout the process. This allowed to improve the completeness of the process and to make the debates more informed and neutral. The external persons and experts contributed during the meetings and presented their views on RTEs presentations or proposed studies, on electromagnetic fields, environmental studies, hydrologic studies, and tunnel studies.

A monitoring committee is established to allow the stakeholders to make sure that the project developer complies with the commitments made during the concertation, this committee continuing listening to the stakeholders, and trying to meet as much as possible their demands.

The project developer agrees to make sure that this project contributes to the local companies, workforce and economy. INELFE installs a local representative and with the help of manufacturers and businesses, intends to perform a detailed analysis in this direction for facilitating the usage of local workforce during the project's construction phase.

G.7 Access to information

Throughout the whole concertation process the public was constantly informed through various means. Information resources were available on the website of the concertation: [157], allowing them to learn about the concertation and to ask questions. Information letters were made available in the town halls and also sent by post at the beginning of both new concertation phases and also at the end of the concertation. Entry forms for asking questions were attached. Moreover, information panels were made available in the town halls and additional prints of the concertation letters and the question entry forms were available to the public in the town halls and in the newspapers (l'Independent and Midi Libre). Press conferences were organised by the CNDP representatives at the important moments of the concertation process, in which RTE constantly participated. Public meetings were organised on special topics at the initiative of some of the mayors. RTE participated in three of these meetings. The concerns of the public were presented and discussed in the concertation meetings (committees and geographical workshops) in order to make sure their concerns were addressed.

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Glossary

List of symbols and notations

Below follows a list of the most frequently used symbols and notations in this thesis.

N situation	Operation with all N grid elements in service
$N-1$ situation	Operation with N-1 grid elements in service
$N-2$ situation	Operation with N-2 grid elements in service
C01	Branch loading median for the overloaded hours during N situation
C02	Branch total number of overloaded hours during N situation
C03	Maximum loading of overloaded branch during N situation
C11	Branch loading median for the overloaded hours during N-1 situation
C12	Branch total number of overloaded hours during N-1 situation
C13	Maximum loading of overloaded branch during N-1 situation
C14	Total number of branches that can be congested due to a given branch being taken out (N-1 situation)
C15	The total number of branches that if taken out cause the congestion of a given branch (N-1 situation)
C21	Branch loading median for the overloaded hours during N-2 situation
C22	Branch total number of overloaded hours during N-2 situation
C23	Maximum loading of overloaded branch during N-2 situation
RO	Risk of overload
$\overline{RO}$	Normalized risk of overload
RO_N, RO_{N-1}, RO_{N-2}	Risks of overload for the N, N-1, and N-2 situations for a branch
$\overline{RO}_N$, $\overline{RO}_{N-1}$, $\overline{RO}_{N-2}$	Normalized risks of overload for the N, N-1, and N-2 situations for a branch
SI	Severity Index for a branch
w_N, w_{N-1}, w_{N-2}	Weighting factors for the N, N-1, and N-2 situations
$RO_{N,i}$, $RO_{N-1,i}$, $RO_{N-2,i}$	Risks of overload for the N, N-1, and N-2 situations for branch i
$\overline{RO}_{N,i}$, $\overline{RO}_{N-1,i}$, $\overline{RO}_{N-2,i}$	Normalized risks of overload for the N, N-1, and N-2 situations for branch i
SI_i	Severity Index for branch i
$RO_{grid,N}$, $RO_{grid,N}$	Grid risks of overload during the N and N-1 situations
SI_{grid}	Grid severity index
$[RO_{grid,N}]_{str}$,$[RO_{grid,N-1}]_{str}$	Grid risks of overload during the N and N-1 situations for grid structure str
$[SI_{grid}]_{str}$	Grid severity index for grid structure str

List of abbreviations

The following abbreviations are used in this thesis:

AC	Alternating current
CSC	Current Source Converter
DC load flow	Linearised load flow
DC	Direct current
DSO	Distribution System Operator
EC	European Commission
EHV	Extra High Voltage
EIA	Environmental Impact Assessment
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ISO	Independent System Operator
NSTG	North Sea Transnational Grid
OPF	Optimal Power Flow
PST	Phase shifting transformer
PTDF	Power Transfer Distribution Factor
RES	Renewable Energy Sources
SEA	Strategic Environmental Assessment
TEP	Transmission Expansion Planning
TSO	Transmission System Operator
UC-ED	Unit Commitment - Economic Dispatch
VSC	Voltage Source Converter

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Ana Roxana Ciupuliga,
Arnhem, September 2013.

List of publications

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Curriculum vitae

Ana Roxana Ciupuliga was born on October 4, 1984 in Bucharest, Romania. She attended secondary school at the Tudor Vianu National Computers College in Bucharest where she graduated in 2003 (mathematics-computers). Between 2003 and 2008 she studied Electrical Power Systems at the Power Systems Faculty of University Politehnica of Bucharest. In the last months of her studies (March 2008 - June 2008) she was a guest student at Politecnico di Milano, where she worked on her Diploma project ”Supplying systems for electrical high speed transportation”. She graduated in September 2008 and was ranked the second in her year. From October 2008 until January 2013 she was with the Electrical Power Systems group of Delft University of Technology, where she worked as a PhD researcher. The topic of her research focused mainly on transmission expansion planning under increased uncertainties, with integration of renewable energy sources. During her PhD she was involved in the REALISEGRID EU FP7 project and in the Dutch funded North Sea Transnational Grid study. In February 2013 she joined TenneT TSO B.V. as a long term grid planner (netstrateeg), within the Grid Strategy group of the Asset Management Department.

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