Transmission Planning Under Uncertainty
by Nikolaos Mavroeidis

In partial fulfillment of the requirements
for the degree of Master of Science in
Engineering Policy Analysis at
Delft University of Technology

Transmission Expansion Planning Under Uncertainty

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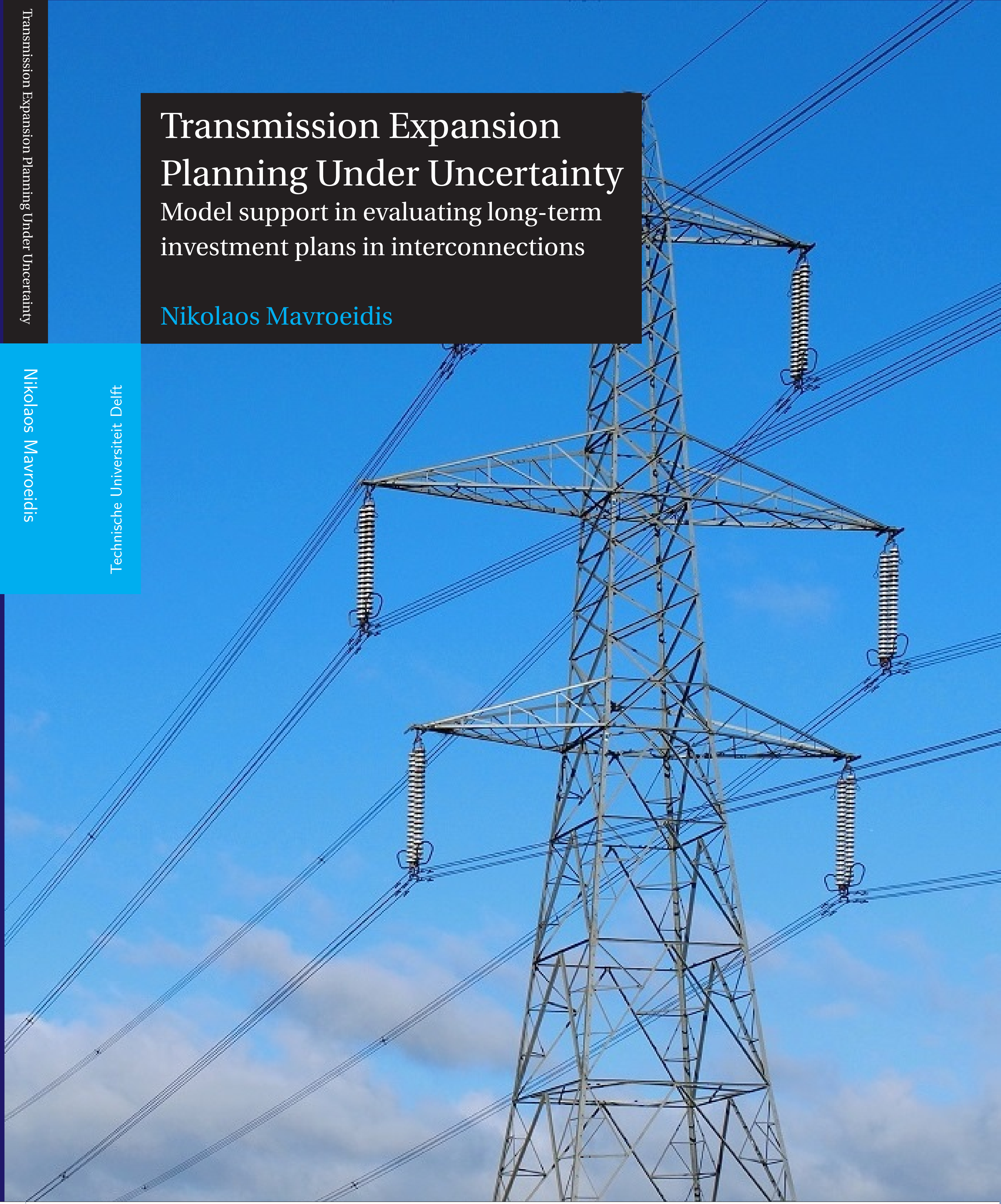
Technische Universiteit Delft



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Model support in evaluating long-term investment plans in interconnections

Nikolaos Mavroeidis

TU Delft Delft University of Technology

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TRANSMISSION EXPANSION PLANNING UNDER UNCERTAINTY

MODEL SUPPORT IN EVALUATING LONG-TERM INVESTMENT PLANS IN INTERCONNECTIONS

By

Nikolaos Mavroeidis

in partial fulfillment of the requirements for the degree of

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Preface

The present thesis signals the successful completion of the two-year Master programme in Engineering and Policy Analysis at the faculty of Technology, Policy & Management (TPM) at Delft University of Technology. The research was conducted in the Energy & Industry section of TPM in close collaboration with the Corporate Asset Owner Department of the Dutch Transmission System Operator (TSO), TenneT TSO B.V.

The goal of this research is to identify how long-term cross-border transmission planning in Europe can be improved in order to deal with the increasing uncertainties in the field. Although the focus is on modeling approaches that can be employed in transmission planning, this thesis also deals with related philosophical issues, such as how to plan for the unknown and how to deal with uncertainty in the long-run. To that end, this thesis provides an evaluation framework for assessing the different modeling types and it reaches analytically to suggestions for the addressing uncertainty in transmission planning.

This report is intended for anyone interested in power systems planning or power systems in general. It can be used by transmission planners for assessing and identifying possible improvements in their planning approaches. Moreover, anyone who is seeking for an alternative methodology rather than the Ten-Year Network Development Plan (TYNDP) of the European Network of TSOs (ENTSO-E) might find the case study explored in this thesis interesting.

Due to the complexity of the problem and the many aspects explored, maintaining this thesis concise and sufficiently elaborative was a great challenge. That is why the reader may observe a plurality of figures used when browsing through the thesis. To that end, the mathematical formulas and descriptions of the models used are kept to a minimum scale.

The core of this thesis' analysis and its academic contribution lie in Chapters 3, 4 and 5. These chapters set the fundamentals for the analyses in the rest of the chapters. For those who are additionally interested in the current practices of transmission planning and their evaluation Chapter 6 is of important value. The same holds for the "modeling enthusiasts" and Chapters 7 & 8, which contain the quantitative analysis of this thesis.

Mavroeidis Nikolaos
Delft, 2015

Acknowledgements

The past seven months were for me an intellectually lonely journey. It was a period of intense individual work and thinking. During this journey, there were moments where I found myself to have stuck on one topic and not progressing enough. It was like I was on a boat in the middle of an ocean and there was no wind or paddles to move. Sometimes I could not find the right balance between time constraints, complexity of the problem and my desire to tackle as many aspects of the problem as I could. Fortunately, during these frustrating moments there were several people who helped me to sail towards the right direction. Without these people this thesis would not have had this form now. Therefore, I seize the opportunity to thank these people for their help and support.

First of all, I would like to thank everyone at TenneT for supporting my work by providing a challenging graduation project, a pleasant working environment and an income. More specifically, I would like to thank my supervisor at TenneT, Gert van der Lee, whose curiosity and desire to explore new concepts and practices, created this project and introduced me to the fascinating world of transmission planning. To be honest, in the beginning of this assignment, I did not expect that I would have such a high degree of freedom to explore and develop new concepts and ideas.

Secondly, I would like to specially thank each of the members of my TU Delft graduation committee separately, whose feedback was more than valuable in completing this thesis. My first supervisor, Laurens de Vries, helped me to clarify the special challenges of my research ("the fundamental methodological problem") and was continuously reminding it to me throughout the project. He was the person that helped me to assure the academic quality and the successful completion of my research. The feedback I received from Aad Correlje, my second supervisor, was proven very important in deriving my conclusions. His characteristic notes "so what?" helped me to look beyond the modeling part and reflect on the results, rather than just observing them. Finally, I would like to thank Prof. Margot Weijnen for devoting so much time to my project. She was always pushing me for more and I thank her for that. Personally, I do not know any other case where the chair of the committee proposed more meetings than the officially three for a master thesis. I thank all four committee members for their time and flexibility as these meetings were proven significant turning points in the whole process.

I will also thank EnergyExemplar for providing me with the academic license of PLEXOS and their continuous help and guidance. It would not be possible to perform these modeling exercises without PLEXOS and certainly it would not be possible to learn such a sophisticated software tool in only a few months.

Moreover, special thanks to my colleagues in TenneT, Rutgert van Houtert, Inge Janssen-Visschers,and Berno Veldkamp for providing me with the necessary data and for being always available to answer my questions. Special thanks to Martti van Blijswijk who introduced me to TenneT, shared his findings and data with me and was always available for (more than one) "anti-stress" meetings.

At this point I would like to thank both the "Lilian Voudouri" foundation in Greece and the TPM faculty of TU Delft for assisting me financially throughout my studies at TU Delft. Without these scholarships, I would not have the opportunity to experience the student life in the Netherlands.

Finally, I would like to thank all my friends who mentally supported me during this project as well as my family who do not complain for my rare trips to Greece.

Mavroeidis Nikolaos
Delft, 2015

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Abbreviations

ACER	*Agency for the Cooperation of Energy Regulators*
ACM	*Authority for Consumers and Markets*
CBA	*Cost-Benefit Analysis*
CEM	*Capacity Expansion Model*
CCS	*Carbon Capture & Storage*
DR	*Demand Response*
DSM	*Demand Side Management*
DSO	*Distribution System Operator*
ED	*Economic Dispatch*
EHV	*Extra High Voltage*
ENTSO-E	*European Network for Transmission System Operators for Electricity*
ENTSO-G	*European Network for Transmission System Operators for Gas*
EV	*Electrical Vehicles*
FACTs	*Flexible Alternating Current Transmission Systems*
GCEM	*Generation Capacity Expansion Model*
IEA	*International Energy Agency*
ISO	*Independent System Operator*
LCOE	*Levelized Cost of Electricity*
MINLP	*Mixed Integer Non-Linear Programming*
NREAP	*National Renewable Energy Action Plan*
NXT	*Network Expansion Tool*
OPF	*Optimal Power Flow*
PCI	*Project of Common Interest*
PCM	*Production Cost Model*
PINT	*Put IN one at a Time*
PSTs	*Phase Shifting Transformers*
RES	*Renewable Energy Resources*
SCDT	*Study Case Development Tool*
SO&AF	*Scenario Outlook & Adequacy Forecast*
TCEM	*Transmission Capacity Expansion Model*
TEP	*Transmission Expansion Planning*
TOOT	*Take Out One at a Time*
TSO	*Transmission System Operator*
TYNDP	*Ten-Year Network Development Plan*
UC	*Unit Commitment*

Executive summary

PROBLEM DEFINITION AND RESEARCH QUESTION

The development of the electric power system has direct economic, societal and environmental consequences in today's society. The last years it has been going through an ongoing restructuring to assure that it fulfills its societal targets: availability, affordability, and acceptability. Deregulation, vertical disintegration of generation, transmission and distribution, spot & forward markets are only some of the measures that have taken place. In parallel, policy objectives on significant RES integration and technological developments in the field of electrical vehicles, demand side response and energy efficiency is going to significant affect the way the system is developed and managed.

The electric transmission system is the lynchpin of the power system chain. From a technical perspective, the electricity transmission system has the prominent role of connecting the generation with the distribution system (and some large consumers). Given the fact that large scale electricity storage is not yet economically feasible, the design and configuration of transmission network should assure that electricity demand and supply are balanced in real time. From a societal perspective, this balancing should be done without disruptions and by utilizing the available generators at minimum cost.

In the European context, European Commission's ambitious policy targets regarding RES integration and reduction of CO_2 emissions are the main drivers for interregional investments in the transmission system. Interconnections between countries are considered to be the TSO's best alternatives to lead electricity prices to lower levels and enhance security of supply and collaboration between transmission system operators (TSOs) is becoming an even prevalent notion. To that end the establishment of the European Network of Transmission System Operators (ENTSO-E) and a respective regulatory authority (Agency for the Cooperation of Energy Regulators-ACER) have established.

All the above mentioned changes set new challenges to the long-term planning of the transmission system. Increased levels of uncertainties due to RES integration, variable load profiles and regulatory changes are added to the development of a co-ordinated planning process. The latest Ten-Year Network Development Plan of ENTSO-E revealed an underinvestment in cross-border capacity and identified that interconnection capacity must double by 2030. It is clear that wrong investment decisions may hamper economic growth, policy goals or any other future developments. Therefore, it is imperative for the transmission planner to re-examine the adequacy of his/her planning process and the tools used in the evaluation process. This thesis will address this issue by answering the question of: *Which modeling approach is the most appropriate for planning cross-border investments at a pan-European level by taking into account the large uncertainties inherent to transmission planning*?

Two core aspects needed to be unraveled and clarified in order to answer the above question: (1) an evaluation of available types of models for transmission planning (2) the identification of major uncertainties and the way to be addressed.

EVALUATION FRAMEWORK & ASSESSMENT OF MODELING TYPES

The starting point of this analysis was the realization that planning models cannot be evaluated and validated properly ex ante. Even ex-post evaluation may be considered an invalid option as also in this case, the model output is assessed against one realization of the future. In essence, one should seek different ways to evaluate planning models. The literature review revealed a lack of a concrete evaluation framework for assessing models for transmission planning. Thus, an evaluation framework was developed classifying 15 criteria in 4 main categories: economic, technical, institutional and social.

The framework was based on notion of fit-of-purpose. It was examined how an ideal modeling approach should be, based on the desires of stakeholders involved in transmission planning. The objectives of three clusters of stakeholders were explored: policy makers, regulator and planner. In combination with the main modeling limitations and constraints, these objectives allowed to identify several evaluation criteria for assessing modeling approaches in transmission planning processes.

The framework was used to evaluate the different modeling approaches. Through the literature review, two main types of models for economic assessment of transmission plans were identified: Production Cost Models (PCM) and Capacity Expansion Models (CEM).

The evaluation demonstrated clearly that CEMs serve better the stakeholders' objectives regarding policy driven and top-down co-ordinated planning approach. This type of model offers a more dynamic way of performing long-term planning, as it simulates several years compared to PCMs which are evaluative in nature and perform short-term operations only. The capability of CEMs to conduct co-optimization studies can be used to explore both possible responses from the generation side and the gas transmission system. Moreover, since they can model the physical transmission system, they can be used to fulfill both technical and economic criteria. A pan-European planning process should be based on an analytical and systematic approach and not on heuristics, as it is currently done.

The main arguments against CEMs are the data requirements and the simplifications that need to be considered in order to make the problem feasible for real-world systems. Data requirements constitute an issue for PCMs as well and can be addressed by maintaining better databases and increasing transparency and data exchanges between involved parties. However, technological developments can be expected in the field with the advent of more powerful solvers and the use of cloud or high-performance computing.

MANAGING UNCERTAINTY IN TRANSMISSION PLANNING

One of the main criteria in the evaluation framework was that the models should be able to adequately capture the uncertainty involved. The starting point of this analysis was the identification and classification of the uncertainties present in transmission expansion planning. A thorough literature review was conducted to identify the uncertainties, which were categorized based on their causes. Market, nature related, demand, individual asset, regulatory, economic, modeling and other uncertainties comprised the main categories. These uncertainties were classified further by using a stylized version of Walker's uncertainty matrix which focused on the level and nature of uncertainty. In parallel, a literature review was performed to identify the most significant uncertainties in terms of their impact on model outputs. These were related to: fuel prices, CO_2 prices, Regulatory uncertainty, Environmental policies, Weather related resources, Load and EVs.

Then, the several methods for managing uncertainty in transmission expansion planning were described and their pros and cons were listed. This enabled us to explore the most appropriate method to address significant uncertainties in the planning process. The whole analysis revealed that variability is the main characteristic of the uncertainties in transmission planning. These variables influence the economic assessment of the projects significantly and thus, they should be handled with methods that are able to capture their dynamics. Stochastic processes, econometric time-series methods and Monte Carlo simulations have been widely used in literature to capture these uncertainties. The inadequacy of deterministic methods in future planning was revealed through a systematic analysis of the main causes and characteristics of uncertainties. In cases where statistical and stochastic models are not feasible (e.g. lack of data), scenario making is still applicable. Variables with high levels of uncertainty should be addressed through scenario analysis, where a wide spectrum of possible future realizations should be considered.

These findings were confirmed by the results of the quantitative analysis. Parameters such as CO_2 prices (to a greater extent) and fuel prices (to a smaller extent) were found to have a considerable impact on the model results (e.g. generation costs). Accounting for only two possible values over 4 scenarios, like ENTSO-E does, does not take into account the interrelations between these parameters and their effect on the outputs. The additional insights that probabilistic or stochastic processes can bring to the planner were demonstrated quantitatively and concerned: 1) identification of the most influencing uncertain variables, 2) indication of ranges of possible values rather than single points, 3) exploration of possible dynamics and correlations between system variables. Since currently decisions on future investments are taken by using these model outputs as criteria (a whole CBA methodology has been designed for this), it is imperative to account for these future dynamics. Finally the inadequacy of the heuristics approaches that ENTSO-E uses for deriving and assessing pan-European transmission planning studies (TOOT and PINT approach).

IMPLICATIONS FOR ACTORS IN TRANSMISSION PLANNING

The main research question revolved around the pan-European transmission planning process and its ability to cope with upcoming challenges in the future energy systems. Our analysis showed that the current modeling approach in transmission planning at a pan-European level lacks a systematic approach that could identify analytically and assess properly possible transmission investments. In addition, there is still room for improvement in the uncertainty analysis, which currently ignores the variable character and the complex dynamics of many of the uncertainties. To align with EU's objectives, transmission planning at a pan-European level should be explorative in nature and develop proactive transmission plans to cope with uncertainty. Such a long-term planning approach would provide more insight to the decision-makers than just evaluative models under poorly developed deterministic scenarios.

Therefore, by taking into account the main findings of this research and the above discussed points, the following recommendations are proposed:

For the policy makers:

- Uncertainty is inherent to transmission planning and cannot be avoided. Long-term transmission planning models should not focus only on obtaining accurate results but also on future exploration. The exact numerical results should not be used blindly.
- Policy driven, top-down planning is feasible but requires significant resources and investments, co-ordination between TSOs and alignment of national regulations. This could be achieved by providing more power and jurisdiction to EU agencies like ENTSO-e, ENTSO-G and ACER.
- A transparent assessment framework that takes into account all benefits and costs of transmission projects should be developed. The assessment should take into consideration the risk and the uncertainty related to the project.

For the transmission planners (TSOs and ENTSO-E):

- Capacity Expansion Models should be set as a basis for long-term transmission planning and be used for exploratory rather than evaluative studies.
- Uncertainty analysis should be improved in two aspects:
    - Scenario analysis should be based on fundamental uncertainties and not driven by stakeholder desires (e.g. market integration).
    - The variability and the complex dynamics between uncertainties should be explored through stochastic processes and Monte Carlo simulations rather than scenario analysis and sensitivity analysis.
- ENTSO-E and TSOs should collaborate closer through information and knowledge exchanges and co-ordinate their national plans.
- ENTSO-E and TSOs should develop and maintain on-line databases with common structure. These databases should include detailed data of the transmission grid and historical data of load, fuel prices, outage rates, power exchanges, weather data and hydrological conditions.
- The transparency of TYNDP study cycle should be enhanced. The assumptions on the scenario analysis and the whole range of data used should be made publicly available. In case of confidentiality constraints regarding data, they could be provided in an aggregate level.
- TSOs and ENTSO-E should extend the collaboration with the research society. Increased transparency could help researchers to conduct analyses and test their models against real-world data. This could offer ENTSO-E significant advantages in planning process (example of WECC).
- Transmission Planners should utilize the recent advancements in cloud computing and high-performance computing in order to reduce the simulation time. This will allow stochastic analyses in their studies.

PART I

Introduction & Thesis Delineation

1

Transmission Planning and Its Challenges

1.1 THE SOCIETAL ROLE OF THE ELECTRIC POWER SYSTEM

It was in the 19th century during the 2nd industrial revolution when electricity was first commercially deployed in Europe. Since then the electric power system has been developed significantly to serve customers in the residential, commercial and industrial sectors. Two centuries later, electricity is present in every aspect of our daily routine from smartphones and laptops to house appliances and railways. In Europe, the total length of the electric power system (transmission and distribution) accounts for 10.3 million km (ENTSO-E, 2014c; Eurelectric, 2013), more than 130 times the perimeter of Europe, and serves approximately 260 million customers (Eurelectric, 2013).

The economic implications of the electric power system are quite straightforward. In 2011, more than 56 thousands enterprises were involved in the electricity sector alone (production, transmission, generation, distribution, trading) which accounts for 85% of the total enterprises in the power sector (EuropeanCommission, 2014). In addition, 53% of total employees and 50% of the total turnover in the power sector belong to the electricity sector (EuropeanCommission, 2014).The economic impact of the electric power system is also reflected in the fact that electricity accounts for almost 22% of the total energy consumption as an end-user product in the EU-28 (EuropeanCommission, 2014). Looking at it from another point of view, one can measure the effect of electricity in its absence. The short-term power shortages, such as those in California in 2000 and in Europe in 2006 and 2003, (study field for many academics ever since) or the chronic shortages in developing countries may reveal these economic and societal consequences.

The importance of the electric power system for society called for regulation and governance structures at an early stage that would assure that electricity would continue to boost economic growth. The regulatory layer in which the electric power systems operate is continuously changing. Major changes in European power systems started in the 1990s when they were influenced by liberalization of electricity markets in the USA and Chile, and when the UK moved to similar regulations (MIT, 2011). Two decades later and after directives from EU Commission, the EU member states need to proceed to unbundling of generation, transmission and distribution systems. Therefore, not only at the physical and operational levels, but also at regulatory level, the electric power system is disaggregated into four different parts which interact with each other: generation, transmission, distribution and consumption (Figure 1.1).

The roles of actors in each of these parts are also distinctive. Power producing companies, consumers and local initiatives can participate in the generation part, which is totally liberalized. On the other hand, the transmission system (>110 kV) is the responsibility of the Transmission System Operators (TSOs), which are few in number (e.g. only one in the

Netherlands, TenneT) due to the natural monopoly nature of the electricity infrastructure. In the distribution system (usually <110 kV), an active role is attached to the Distribution System Operators, (DSOs) which are more numerous than the TSOs (e.g. 4 in the Netherlands).

The electric transmission system is the lynchpin of the power system chain. From a technical perspective, the electricity transmission system has the prominent role of connecting the generation with the distribution system (and some large consumers). Given the fact that large scale electricity storage is not yet economically feasible, the design and configuration of transmission network should assure that electricity demand and supply are balanced in real time. From a societal perspective, this balancing should be done without disruptions and by utilizing the available generators at minimum cost. Any possible imbalances can cause significant volatility in electricity prices and considerable challenges to the TSOs both in the short-term (system operations such as balancing supply/demand) and mid-term (asset management e.g. maintenance) operations and its long-term grid planning.

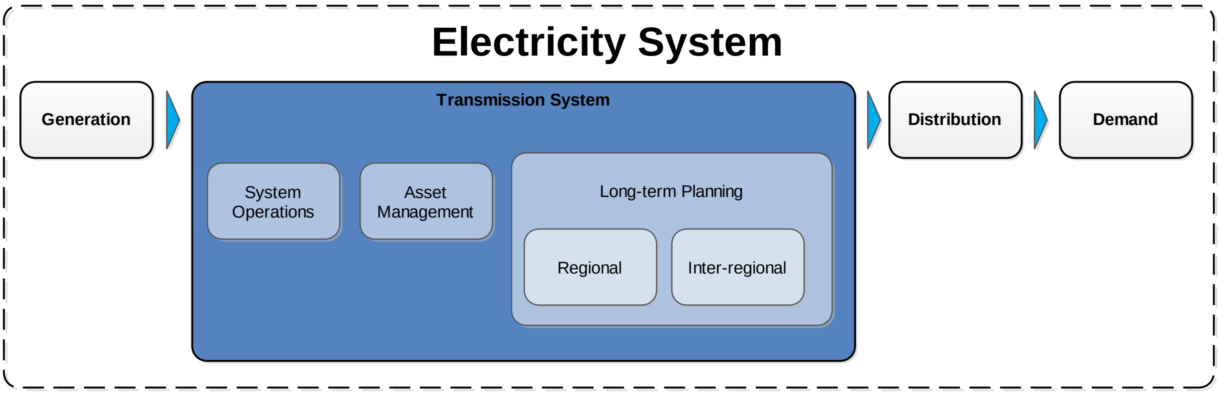

Figure 1.1 - The role of transmission in the electric power system

1.2 CHANGING WORLD, NEW NEEDS

Regulation on electric power systems is designed to assure that the basic societal targets of the power industry are met. These are: availability, affordability, and acceptability (Pfenninger et al., 2014). In the previous paragraph we already discussed the major role of the transmission system in the first two targets: the TSO is responsible for balancing supply and demand without disruptions at minimum cost. The third target concerns the minimization of the environmental impact of the power industry. The transmission system plays a significant role in this as well and not only in terms of landscape changes (e.g. from overhead lines).

1.2.1 RES, EVs and the challenges for transmission system

After the Kyoto protocol, the EU Commission directives forced the EU member states to set plans to reduce their CO_2 emissions and to significantly integrate renewable energy sources (RES) in their generation mix. However, electricity production from RES is not economically feasible everywhere. It depends on the level and location of the natural resources like wind and radiation. Until now, the integration of RES (except hydro) is not happening on large scale. Traditionally, in order to reduce transmission costs and losses, the transmission system was designed to be close to regions with central thermal power plants. These locations were easily identified by taking into account several factors (proximity to natural resources, transportation, availability of cooling etc)(Fleeman, 2009). Since the location characteristics are changing, significant investments in the transmission system are needed to accommodate the forthcoming development of large scale RES units. A recent example is the DC interconnection cable in Germany that will connect the load centers in the South with the large scale offshore wind farms in the North. However, the new investments in the transmission system are not the only challenge of the TSOs.

The most significant impact of a large-scale RES integration will be the impact on the “availability” goal. Taken into account the intermittent character of RES and their forthcoming increased installed capacity (driven by directives), an important challenge for TSO concerns the reliability and the security of the grid. Balancing demand and supply will be an even tougher task and TSOs have to account for these developments in their system planning.

Technological developments in the field of electrical vehicles (EVs), demand side management (DSM), energy efficiency or heat pumps are going to affect the demand side of the system as well. The TSOs will not only have to cope with intermittent generation levels but with extremely variable load profiles as well. Until now the load profiles and levels could be forecasted with a high degree of confidence, at least for the residential and commercial consumers. Demand response (DR) and EVs charging will make these profiles less predictable and will add an extra uncertainty in the supply-demand balancing task of TSOs.

1.2.2 Interconnections and the role of Pan-European Transmission planning

In the European context, the idea that the RES targets (set by EU Commission for 2050) can be only achieved through a close collaboration between the EU member states is becoming more and more prevalent. So far several steps have been realized to facilitate such a development. The most known ones are the establishment of a European Network of Transmission System Operators for electricity (ENTSO-E), a respective regulatory authority (Agency for the Cooperation of Energy Regulators – ACER) and the Energy Union (ENTSO-E, 2015). Although the roles and the responsibilities of these bodies are different, one could identify the ultimate goal that they have in common: the integration and the collaboration of the electricity markets across Europe in order to assure the fulfillment of the “availability, affordability, acceptability” targets (see Regulations 713/2009/EC , 714/2009/EC, 715/2009/EC and Common Rules 2009/72/EC and 2009/73/EC in (EuropeanCommission, 2015a). The integration of the different markets can reduce electricity prices, increase the social welfare, assure system adequacy (even under extreme conditions through imports/exports) and finally it can accelerate the RES integration (renewables can be planned where they can be economically efficient).

The role of the transmission system in these targets is of great importance. Investments on interconnections between countries are necessary for market integration, while internal investments might be beneficial for a greater perimeter of countries. However, in order to achieve this, a coordinated pan-European transmission planning process should be in place. Although there have been some initial steps in this direction (ENTSO-E’s 10-years Network Development Plans, known as TYNDP), planning is still performed in a bottom-up approach based on national goals and interests.

1.3 OVERVIEW OF TRANSMISSION PLANNING

Figure 1.2 shows an overview of the general planning process in transmission systems, without going into modeling or other details. It identifies three phases: (1) the investment signals which trigger the (2) planning process, which in turn will lead to the (3) investment decision.

The stimuli for the evaluation of a proposed plan/project may vary. Inadequacies of the existing transmission grid, investments in the generation side, emergence of new load centers, changes in regulations and technical standards or new environmental policies are reasons that may signal investments either at a regional or interregional level. Moreover, investment signals can arise by developments in gas networks or neighboring power systems and regulations, by changes in the market conditions (e.g. commodity prices), new technological breakthroughs (e.g. EHV XLPE underground cable systems) or by catastrophic events. Due to the long lead time of transmission projects, investment signals are not only based on existing but on expected conditions as well.

This leads to the actual planning process which at a highly aggregate level contains three major parts. The first is the decision making process which concerns questions such as: *who is going to decide on the project?* (e.g. one or more TSOs, the regulator etc) and *How is the decision going to be made?* (e.g. Cost-Benefit Analysis or technical criteria). The second concerns the uncertainty analysis which tries to answer questions like “what are the probable futures?” or “how to deal with uncertainty”. The third part refers to the modeling support tool used for the deriving or evaluating the projects. All the above are decisions that the planner has to take based on his constraints and the available options. The present thesis will focus on the last two parts: the role of modeling types and the uncertainty analysis in the planning process. The distinction is not so clear-cut as one may set restrictions or opportunities on the other. In the rest of the thesis, this will be referred to as the “modeling approach”. The selection of the focusing area will be motivated in Chapter 2, and will be further described in Part II of the thesis.

The whole transmission planning process leads to the proposed investments on the transmission grid. These may concern individual projects (e.g. one interconnections or line) or may be part of a more general investment plan (e.g. the upgrade of the whole national transmission system).

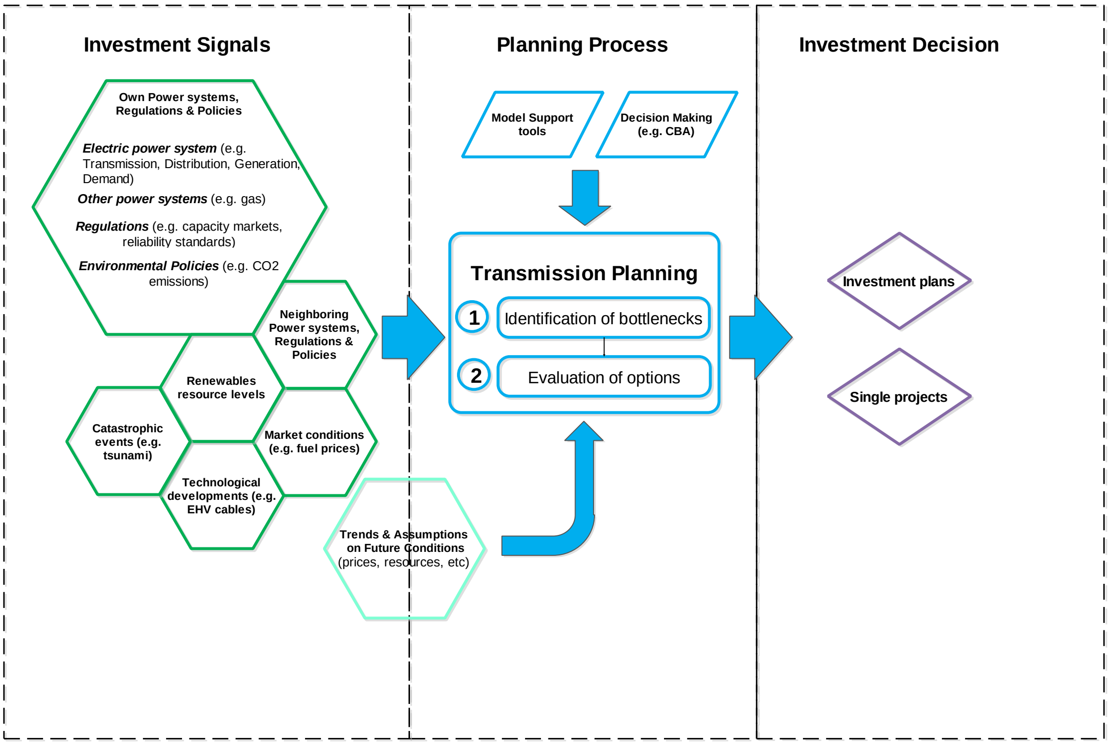

Figure 1.2 - Overview of the general transmission planning process

1.4 THESIS OUTLINE

The structure and the contents of this thesis follow a sandglass-like format (Figure 1.3). The sand-glass starts with the introductory Part I, in which the broad research area of this thesis is introduced Chapter 1 and the research approach is analyzed and motivated (Chapter 2). This gradually brings us to the two main analysis parts of the thesis, whose scope is narrow enough to analyze the research problem: Part II contains the qualitative part and Part III the quantitative one. More on these parts are discussed in Chapter 2. In Part IV the results of the analysis are positioned again in the broader research area of transmission planning, and conclusions and recommendations are derived. Criticism on the research process and choices made in this thesis are also discussed in this part (Chapter 10).

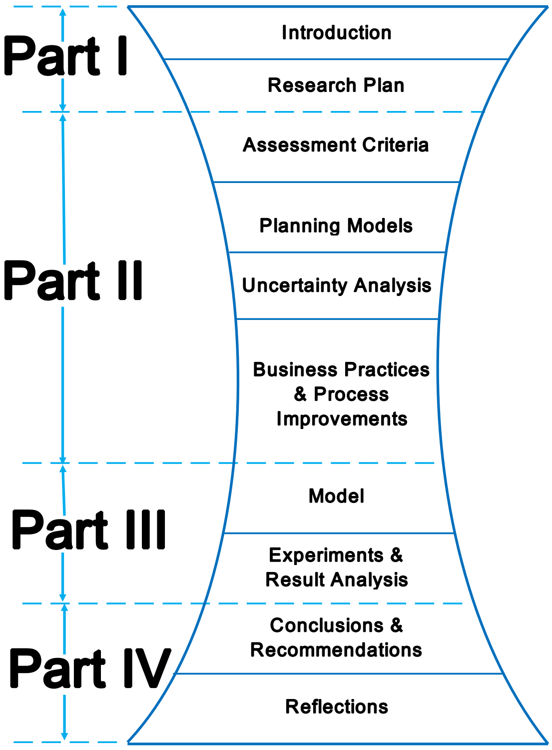

Figure 1.3 - Thesis Outline

2

Research Problem & Design

2.1 TRANSMISSION PLANNING: MULTI-FACETED, BROADLY EXAMINED

In the previous chapter (Chapter 1) the aspects involved in the transmission planning process were briefly discussed. Many of these aspects have attracted the interest of the scientific and business community and constitute main fields of research by themselves. For example the political and economic aspect of transmission investments is discussed in (Puka & Szulecki, 2014), the effect of macro-economic parameters on transmission planning in (Sohtaoglu, 2000), whereas a regulatory assessment transmission investments in (Meeus et al., 2006; Poudineh & Jamasb, 2014; Rubino & Cuomo, 2015).

Figure 1.2 showed investment decisions are usually evaluated based on certain criteria. For example, ENTSO-E in its CBA methodology evaluates transmission projects based on values like improved security of supply, social and economic welfare, RES integration, variation in CO_2 emissions and losses, technical resilience and flexibility(ENTSO-E, 2014e). Similar criteria are used by other entities (CAISO, 2004) as well as regulatory authorities (NMa, 2004). Most of these criteria are quantifiable and their metrics can be obtained by complex and rather sophisticated models (ENTSO-E, 2014e). Thus, it is safe to say that modeling tools do have a critical role in the transmission planning process.

Existing research recognizes this critical role and has focused on developing models that can cope with the increasing uncertainty in the transmission planning process. These models differ in the solution method, treatment of the planning horizon (static or dynamic), consideration of the regulatory regime (regulated and deregulated transmission systems), the treatment of uncertainty and more (R. Hemmati et al., 2013; Latorre et al., 2003). In the literature, transmission planning models can make use of mix-integer optimization algorithms (J. Lin, 2009; Osório et al., 2015; Ruiz & Conejo, 2015; Yang & McCalley, 2011), dynamic programming (Rouhani et al., 2014) or heuristic methods such as genetic algorithms (Arabali et al., 2014), tabu search (Chatthaworn & Chaitusaney, 2014), fuzzy set theory (Maghouli et al., 2011) and colony optimization (Rathore & Roy, 2013). Many of these models are still at a research level and not widely used in practice. Explaining these and evaluating these techniques in detail is outside the scope of this research. However, an overview of these methods can found in (R. Hemmati et al., 2013) and a brief introduction to the mathematics behind them in (Sahinidis, 2004). There have been several commercially available tools that utilize the above algorithms. Overviews on the commercially available models can be found in (Connolly et al., 2010; Foley et al., 2010; Liu et al., 2013).

Uncertainty analysis is highly intertwined with the model used and the way decision making is conducted (Weber, 2004). (R. Hemmati et al., 2013) provides an overview of the major uncertainties in transmission expansion planning (TEP) and the main methods of addressing them, such as Monte Carlo (Yang & McCalley, 2010) or scenario analysis (Buygi et al., 2006). Moreover, there are model algorithms that deal formally with uncertainty, such as stochastic optimization (Cedeño & Arora, 2011), dynamic programming (Xiao, 2013) and robust optimization (Escobar et al., 2014).

2.2 RESEARCH OBJECTIVE

The previous paragraph provided a brief overview of the research in the transmission planning field. So far many models have been developed and many ways to deal with uncertainty have been explored. One question arises naturally: *How may the planner determine which type of modeling approach to use for the transmission planning process?.* Although in literature the modeling options of the planner have been reviewed and it has been discussed how the new challenges can influence the transmission planning process, a framework of analysis of the several options has not been presented yet (R. Hemmati et al., 2013; Latorre et al., 2003). Several studies (from academia and industry) have attempted to evaluate transmission planning methodologies and provide suggestions to improve them in a more systematic way. However, these studies focus mainly on processes of one organization without touching the issue of modeling choices (CAISO, 2004) or without providing a concrete framework of evaluation (Brattle, 2013b).

The research objective of this thesis is to improve the existing transmission planning process by conducting an assessment of the different modeling options available to the planners. However, such an assessment is not straightforward. The next paragraph (Section 2.3) will introduce a fundamental methodological problem in evaluating forward-looking models, like those used in planning, and will argue why the model assessment requires a specific research framework. The structure of this framework will be introduced in (Section 2.6) and it will be the one used in this thesis.

2.3 DECISION SUPPORT MODELS IN PLANNING: MAKING CHOICES IN THE DARK

A planning problem is a wicked problem (Rittel & Webber, 1973) and planners choose to handle it with extensive use of models. The contribution of models to the planning process is critical, even though they represent only a fraction of reality. However, there are two major questions that the planner has to consider before trusting blindly a specific modeling approach. These have to do with the validity of the model algorithm, the assumptions and model results and the suitability of the model for the planning purpose.

The first question can be formulated as "How do I know that the model works as it should work?". This is the common problem of model validation. There has been an extended amount of literature on approaches for model validation. These involve structural tests, extreme value tests, expert elicitation and other (Refsgaard et al., 2006). These techniques test whether the model behavior agrees with the theoretical or expected one. Such tests can be performed for the models used in planning in terms of algorithms and model specifications and they constitute the simple part of validation. The complex part comes with the second question.

The second question that the planner has to consider is: "How do I know that the assumptions in the modeling process will lead to proper results?". This question differs from the previous one, because now the assumptions, which are taken in the first place to develop the model, are questioned rather than the algorithm of the model. For example, if the model does not incorporate strategic behavior of the generation side of the system, how do I know that my plan will be optimal? This can be extended to other modeling options such as whether uncertainty should be incorporated and how (e.g. deterministically or stochastically). For planning models, which are used to derive investment plans for 15-20 years from now, this is a major concern simply because the **future is unknown.** The model results cannot be evaluated by comparing them with real values and there is no way to determine if one modeling approach is better or worse than another. One could argue that the above discussed validation techniques can be also used here to evaluate the results derived under specific assumptions. For example, by performing an ex-post evaluation of an already project or plan, the modeling approach can be validated. By performing the same study with different modeling approaches and comparing the results with the "perfect information" of the past investment, the "winning" modeling approach could be determined. However, even this approach is methodologically flawed as even this examined "future" is only one realization of what could happen. In contrast to models that can be physically verified (e.g. by mathematic equations consistent with physical laws), planning models cannot be validated in a proper way (Pfenninger et al., 2014). Planning models are used for planning network developments without knowing what instance of the future may occur. Therefore, the modeling assumptions cannot really be tested (Prasad et al., 2014).

One approach that has been used to evaluate the robustness of forward-looking models is to measure how the results rank over a wide range of future conditions. These future conditions can be created by using Monte Carlo simulation or other sampling techniques. This approach is widely used in many fields (Wainwright et al., 2015) and can offer useful results regarding the performance of deterministic models if the scenario development is sufficiently conducted. However, when the results of a model that uses a deterministic approach are compared with the ones of a model with a stochastic approach, this method falls to a fallacy. Since the stochastic approach uses probability derived values of parameters to capture the future uncertainty, its results are going to be by default better than the deterministic ones, as they are tested under the same stochastic conditions. This vicious circle in the methodology sets it inappropriate for comparing these two methods.

Last but not least the question that every planner should try to answer has to do with the suitability of the model according to the planning purpose: "Is this the most suitable model to use for my objectives in transmission planning?". The answer is quite subjective and it depends on the objectives of the planner, his criteria, the regulatory framework and the structure of the power system concerned (Strachan, 2011). Thus, the different modeling approaches could be compared directly (by performing simulations) in aspects like familiarity or experience with the method, necessary expertise, financial and temporal constraints. On the other hand, comparing different planning approaches based on the validity and robustness of their results is not straightforward, even if it is an ex ante assessment.

2.4 SCOPE

The above paragraphs explained step by step the problem in transmission planning: How one can determine which type of modeling approach to use without knowing the future conditions and needs. This is of course a rather wide research area and broad question to be answered in a master thesis. Having already reduced the research problem from the general aspects of transmission planning to the modeling approaches, we will need to narrow down the scope of this research further in order to obtain a more in-depth analysis.

Long-term transmission planning involves two kinds of processes: regional and interregional planning. The regional planning involves projects and plans within a country (or state in the US). The main drivers of these projects are technical standards (e.g. reliability), technical upgrade developments (EHV XLPE underground cables) or social reasons (e.g. acceptability of overhead lines). On the other hand, interregional projects or plans involve interconnections between two or more countries. The significance of the interregional projects for coping with the emerging challenges in the energy system (market integration and RES targets of the European Union) has already been discussed in Section 1.2.2. The research framework for the TYNDP study cycle of ENTSO-E (responsible for the non-binding 10-years network development plan for Europe) has continuously been changing since it was first implemented (ENTSO-E, 2014e). Due to the early stages of development of the TYNDP study cycles and due to its significance and implications for the future energy systems in Europe, this thesis will focus on studying the model support tools of a pan-European planning process rather than a national one.

Although the interconnection projects are evaluated with both economic and technical criteria, more weight is given to their economic justification and especially the socio-economic welfare (de Nooij, 2011). The Cost-Benefit Analysis performed by ENTSO-E (ENTSO-E, 2014e), based on an EU regulation EC 347/2013, evaluates the investment projects according to the criteria of Table 2.1. The criteria that are used by other organizations to measure economic assessments of investment plans are similar to those of ENTSO-E. An overview of the economic assessment is provided in (Hesamzadeh et al., 2008) and (Hirst, 2004). As it will be also discussed in Chapter 4, the technical models (reliability & power flow studies) used in either regional or interregional plans are quite established (Quintero et al., 2014) and their validation can be determined by power systems theory. On the other hand, there is no consensus in the academic community for the ideal "economic" models for transmission planning. Thus, the scope of this thesis will be further limited to the examination of the model support tools which deal with the economic evaluation of the projects.

Table 2.1 - Cost and Benefit Categories of ENTSO-E's CBA methodology (adapted from (ENTSO-E, 2014e))

Category	Criterion	Model
Benefit	Improved security of supply	Market & Network
Benefit	Socio-economic welfare	Market
Benefit	RES integration	Market & Network
Benefit	Variation in losses	Network
Benefit	Variation in CO_2 emissions	Market
Benefit	Technical resilience/system safety	Network
Benefit	Flexibility	Network
Cost	Total project expenditures	-
Cost	Environmental impact	-
Cost	Social impact	-

To sum up, this thesis will focus on the following research area: The **model support tools** which are used for the **economic** evaluation of plans and projects in the **pan-European and interregional** transmission planning process.

2.5 RESEARCH QUESTIONS

Based on the above problem definition and scope, the main research question that this thesis is going to tackle can be formulated as follows:

Which modeling approach is the most appropriate for planning cross-border investments at a pan-European level by taking into account the large uncertainties inherent to transmission planning?

This research question contains two core aspects of modeling approaches: (1) the available types of models in terms of algorithms and (2) the way uncertainty is represented in the models. To answer the central research question, these two core concepts have to be unraveled and clarified. The following sub-questions serve this purpose:

1. With what criteria can the modeling types in transmission planning process be evaluated?
2. What are the available modeling types for long-term transmission planning of interconnection investments and how are these evaluated?
3. What are the main uncertainties in long-term transmission expansion planning that should be addressed by the modeling approach and how?
4. What is ENTSO-E's current modeling approach on pan-European transmission planning and how is it assessed?

It is easily observed that different types of sub-questions are formulated above. There are descriptive questions regarding the available modeling types and uncertainty analysis techniques, analytic questions regarding current planning approaches and evaluation criteria, prescriptive questions regarding the possible changes in the current approaches as well as exploratory questions regarding the influence of these changes. This diversity calls for a mixed research methodology that will be described in the next section (Section 2.6).

2.6 RESEARCH FRAMEWORK

The fundamental methodological issue in the validation of forward-looking models does not allow us to investigate which modeling approach is better or worst based on "hard" data of model results. Instead, it is possible to identify limitations of a methodology based on the objectives of the project and the deliverables that the planner desires. This can be achieved with the research framework displayed in Figure 2.1. First, a qualitative analysis that assesses the different options available to the planner according to his criteria is conducted. This assessment can be based on empirical or theoretical data and information. After evaluating the different options, ways for improving the current methodology of the pan-European and interregional planning will be explored and recommendations will be drawn. The non-binding TYNDP of ENTSO-E will be the case study for this thesis. These recommendations will also take into account the constraints of the planner. Finally, to triangulate the research, a model will be built to demonstrate the changes between the current and the proposed methodology. Simulations will be performed based on the recommendations of the thesis and the results will be analyzed. The analysis will reflect on whether the model outputs differ significantly or not and not on a true-false base. In case of minimal differences it is possible, through a feedback loop in the process, to review the proposed changes in the process.

Table 2.2 provides an overview of the research methods that will be used to answer the sub-questions presented in Section 2.5. These methods as well as the question of how the sub-questions will lead to the main one will be briefly motivated in the following paragraphs per analysis block.

Table 2.2 - Research Methods per sub-question

Sub-question	Research Method	Description and Topics addressed
1	Literature Review	• Theory on objectives, benefits, limitations of TEP • Policy documents (assessment of projects) and Planning reports (ENTSO-E, WECC, MISO, CAISO) • Theory on decision making under uncertainty • Theory on transmission investments and regulatory framework
	Unstructured Interviews	• Experts involved in TYNDP study cycle
	First Hand process observation	• Participated in the public consultation workshop and webinar of on-going cycle of TYNDP2016
2	Literature Review and Content Analysis	• Modeling Types in TEP • Based on high-level criteria (sub-question 1)
3	Literature Review and Content Analysis	• Uncertainties in TEP • Based on high-level criteria (sub-question 1)
4	Literature Review and Content Analysis	• As in sub-question 1 for ENTSO-E only • Analysis based on findings of sub-questions 1,2,3
5	Simulations on Optimization Model, Data Analysis	• Simulations are developed to examine the impact of changes in the modeling approach • PLEXOS simulation software is used • Statistical analysis in SPSS and VBA excel

2.6.1 Preliminary Analysis: The criteria I

As already mentioned, this thesis is conducted in close cooperation with TenneT TSO B.V. (hereafter TenneT). Since TenneT is a member TSO of ENTSO-E, many of its experts were/are involved in the study cycles of the TYNDP. The first analysis block involved unstructured interviews with these experts in order to fine tune the theoretical insights found in literature regarding planner's objectives and challenges (Verschuren & Doorewaard, 2010). These interviews are not reported in this thesis as they were conducted in an unstructured and informal way. Moreover, the sample of the interviewees was not high enough to draw general conclusions. The interviews were nonetheless meaningful to this thesis in providing a deeper understanding of the literature.

In addition to this, observations regarding the planning process of ENTSO-E could be drawn with the participation in two public workshops[1] (one in a form of webinar) regarding the TYNDP 2016 study cycle. The observations focused on the transparency of the process, the changes in the methodology and the assumptions of the previous study cycle, scenario analysis and future changes. In parallel, several questions were addressed to the presenters regarding the model results and their validity.

Both processes helped as an initial step to identify some first indications of what a planner (and other stakeholders) expects from the planning process and the criticism to the process. Moreover, they supplemented the results of the second analysis block.

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[1] The TYNDP 2016 public workshops were held on 11/03/15 (in Brussels) and 10/06/15 (webinar)

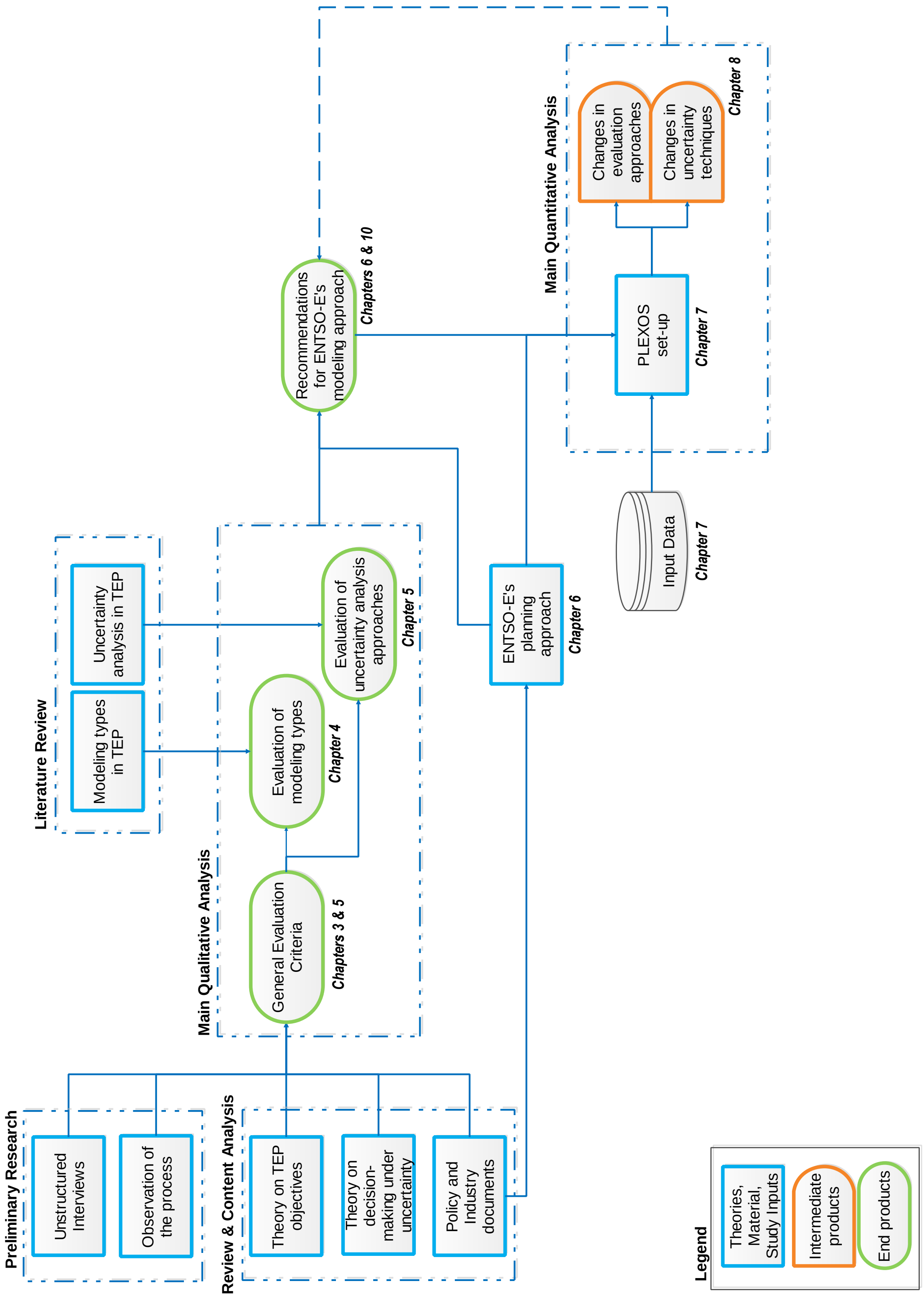

Figure 2.1 - Research Framework and Process

2.6.2 Review and Content Analysis: The criteria II

The main research method that is used to identify the criteria with which the modeling approaches will be evaluated, is a thorough literature review and analysis. The review will be directed towards four main areas: (1) theory on investments in transmission system, (2) theory on the regulatory framework of transmission planning, (3) theory on transmission planning process and (4) public policy documents and official transmission plans from several organizations.

The first three directions are analyzed in order to determine the characteristics of an "ideal" planning approach. More insight will be gained in the following issues: how investments should be identified and evaluated, how their benefits should be allocated, the risk level that the planner is allowed to take in the process and the desired level of detail in the model results. These questions will help to develop high-level criteria which will be then operationalized in order to evaluate the available modeling types.

The fourth direction is examined in order to shift the analysis from theory to industry practices (from an ideal to a more realistic planning approach) and detect realistic criteria for transmission planning projects. Here the planning processes of ENTSO-E and other organizations similar to ENTSO-E (in terms of interregional planning entities) will be explored regarding the objectives of the plans and the evaluation criteria of the project.

2.6.3 Literature Review: The options

Having defined the criteria of an "ideal" planning approach, the available options of the planner have to be evaluated based on these criteria. As the Figure 1.2 demonstrates, the main modeling decisions in the planning process are two: (1) what type of modeling type will be used and (2) how is the planner going to deal with uncertainties. These are the two directions on which the literature review will focus, despite the fact that they are not completely separate one from each other. There are several formal modeling approaches designed to treat uncertainty (like robust optimization techniques) and they will be discussed in Appendix A. In (1) the general modeling approaches and the available optimization algorithms will be presented. In (2) a classification of the uncertainties in TEP will be provided, the most important ones will be elaborated, their possibility to be addressed in TEP will be examined and how they can be addressed will be explored.

A literature review seems the most appropriate research approach to explore the planner's options. A thorough literature review can pinpoint highly promising trends, practices and choices of the planner in the planning process. If this was done on a case-study base, the examined options would be limited and it would be difficult to draw substantive recommendations.

2.6.4 Main Qualitative Analysis: The evaluation

Even though ENTSO-E's TYNDP is a non-binding plan, it has a significant role in determining the Projects of Common Interest (PCIs) (EuropeanCommission, 2015b) . The TYNDP planning approach will be the case study of this thesis and recommendations for its improvement will be provided. The significance of a robust pan-European transmission plan has been already discussed in Section 1.2.2. The recommendations (Chapter 6) will be drawn by taking into consideration the evaluation criteria (Chapter 3), the available options (Chapters 4 and 5) and the current situation in TYNDP and ENTSO-E's constraints (Chapter 6).

The aim of these proposals is to contribute to an effective and efficient pan-European planning process by meeting the objectives of ENTSO-E and thus progressing towards the fulfillment of the EU energy targets.

2.6.5 Main Quantitative Analysis: Testing the recommendations

The previous analysis described how recommendations are derived through a qualitative analysis. To triangulate the results, a quantitative model will be designed. This model will be used to reflect the differences between the current modeling approach of ENTSO-E and the one described in the recommendations part. The recommendations that will be examined quantitatively are adapted based on data availability and time constraints in the context of the Master Thesis. The whole methodological approach of the quantitative analysis (data, system under study, simulations to be performed) is described in Chapter 7 of the thesis. As mentioned before, the comparison between the two approaches cannot be realized in terms of which methodology is better (the new vs. the old one) as there is no reliable validation. Instead, the methodologies will be compared by observing if the results, obtained by these two methods, diverge significantly or not. In both cases the recommendations will be re-examined and adapted accordingly.

The input data for the model are provided by TenneT, whereas the obtained results will be analyzed by using statistical and visual analytics methods. In the thesis, an academic version of a commercially available software package, PLEXOS, will be used for the simulations. PLEXOS from (EnergyExemplar, 2015) is a widely used object-oriented software package for unit commitment and economic dispatch problems (UC-ED), market simulations and long term TEP. It has the feature of performing optimal power flow (OPF) studies either under AC or DC conditions. Moreover, it has embedded some state-of-the-art algorithms related to resource and capacity planning such as co-optimization and stochastic programming. The studies of (Deane et al., 2012; Drayton et al., 2004; Foley et al., 2010; Nweke et al., 2012) show that PLEXOS incorporates many of the algorithms discussed in academia and it offers great degree of freedom for different studies in the energy section.

As already mentioned, the scope of the study is to provide an analysis of how the modeling approach in TEP can be further improved by evaluating the available options of the planner. Thus, building a model from scratch to investigate the effect of the changes in the process would be neither efficient nor effective as a Master thesis project. On the contrary, using a software package which is used by both academia and industry is rather beneficial for the objectives of this thesis. Finally, given the resource constraints, PLEXOS is the only one among TEP software packages that includes state-of-the-art algorithms and provides free academic license.

2.7 RESEARCH RELEVANCE

The thesis is expected to have both societal and scientific relevance. From a theoretical point of view, this research develops a set of criteria for evaluating the different approaches in transmission expansion planning and evaluates the existing modeling types and uncertainty analysis techniques from both academia and industry. From a societal point of view, this thesis provides recommendations/guidelines for designing a planning approach at a pan-European level, which focuses on meeting EU's energy and social targets. Moreover, it enhances the extensive understanding of the planners' options by providing a systematic review and analysis of the available approaches in TEP.

PART II

Qualitative Analysis

3

Modeling approaches in TEP: Evaluation Criteria

3.1 INTRODUCTION

"All models are wrong; some are useful" (Box, 1987). Models are only a representation of reality. Modelers have to make trade-offs between representing the system as accurate as possible and meeting resource and technical constraints. In order to identify the criteria that a model for transmission planning should fulfill, it is imperative to examine the purpose for which that model has been developed. However, as all planning problems, transmission expansion planning is a "wicked problem" (Rittel & Webber, 1973). As such, their solutions cannot be of a "true-or-false" style but are closer to "good-or-bad" (Rittel & Webber, 1973). This is a central notion of this thesis: no matter which model or which uncertainty analysis technique will be used, the final obtained plan will be sub-optimal in reality. However, it is still possible to identify what "good" planning for transmission network means. This information will be used to derive the functional specifications of the modeling support tool in transmission planning.

The chapter begins by identifying what the main objectives of transmission expansion planning from the stakeholders' perspective. Then, it continues by pointing out the limitations of the forward looking models. The evaluation framework and criteria are constructed by taking into account these two analyses.

3.2 WHAT DOES "GOOD PLANNING" MEAN?

The answer is "we do not know". One way to approximate it is by seeking to identify the objectives of transmission planning. The introductory chapter discussed the "availability, affordability, acceptability" targets of the transmission system. The planning process should be able to meet these objectives or provide answers for them. The scheme in Figure 3.1 examines these three targets in more detail. More specifically, this scheme utilizes the fact that the ones that are involved (directly or indirectly) with transmission planning are those who set its characteristics. These are the TSOs, governmental and regulatory bodies as well as the system in which transmission system operates. Investigating the deliverables of the planning process by all these actors will help understand which design options the modeler should address.

More specifically, policy-makers, regulators and planners have certain expectations from transmission planning. Since policy makers and regulators are not directly involved in the planning process, their objectives have to be satisfied by planner's analysis. Ideally, the model should be able to answer stakeholders' questions. This is "what the model should deliver" and defines a clear-cut purpose of the model. However, modeling constraints and other exogenous limitations (uncertainty) do not allow the modeler to develop this "ideal" model. The simplifications and trade-offs the modeler has to take may cause the obtained model to diverge from the "ideal" one (see in Figure 3.1 the softer corners compared to vertical angles). The feedback loop indicates that sometimes the information flow can be reverse. It is possible that stakeholders seek to find answers to their models by using the existing ones. Therefore, the question now shifts from "I have these questions, how should I develop a model?" to "I have these models, how can I use them to answer my questions?". In this thesis, the first question is going to be explored in order to identify the evaluation criteria. This will also help to identify possible research gaps in the modeling part.

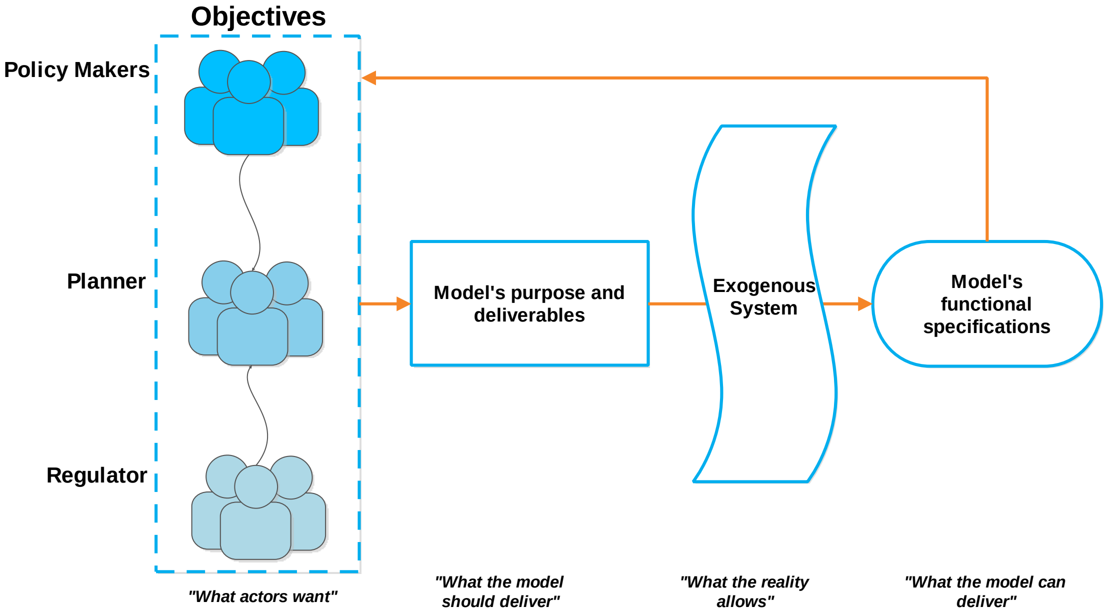

Figure 3.1 - Process for defining model specifications

3.2.1 Policy Makers

For policy makers transmission planning is only a means to an end. Their concern is more of how the development of the transmission infrastructure will help them meet their policies than the infrastructure itself. In this thesis as policy makers we consider the governmental bodies and in case of Europe, the European Union as well (in the USA there can be different policy objectives between the states and the federal government too). The distinction between the objectives of policy makers and (infrastructure) planners becomes clear in the transmission plan's objectives. For example, WECC long-term plan mentions that "*The objective of the Plan is to provide information to stakeholders to support their decision-making processes. It is these decisions [..] that ensure the Western Interconnection is reliable, low-cost, efficient, and environmentally responsible, while appropriately balancing risks and opportunities.*" (WECC, 2013). The same holds for ENTSO-E's TYNDP which "*point(s) to significant investments in the European power grid in order to help achieve the European energy policy goals*" (ENTSO-E, 2014e) or CAISO's study plan which mentions that "*the objectives of the unified planning assumptions and study plan are to clearly articulate the goals and assumptions for the various public policy and technical studies*" (CAISO, 2004).

Policy maker' objectives concern environmental and social policies (like reduction of CO_2 emissions and lower electricity prices respectively). More specifically, European Union has set ambitious targets on emission reductions overall, whereas the member countries have published their National Renewable Energy Action Plans (NREAPs) (ECN, 2011). Policy makers regard investments on interconnection capacities as investments that will help to meet their climate change targets. "Energy Union", regards interconnections as the means for the creation of an internal energy market which subsequently will result in lower electricity prices and economic growth. Finally, recent events with the Ukraine-Russia crisis have increased the importance of energy security in the European system. In a highly interconnected European electricity system, the diversity of the plant mixes between the connected countries will improve the system's resilience to such events and increase countries' energy security (Puka & Szulecki, 2014).

Furthermore, it has been recognized from both industry and academia that considering interconnection projects on a case-by-case basis will lead to sub-optimal plans (MIT, 2011). A top-down planning approach, a planning process that is based on co-ordination between the transmission planning processes of the member TSOs is necessary to achieve the desirable results (MIT, 2011) and the establishment of ENTSO-E and ACER was aiming towards this target (Rubino & Cuomo, 2015). The TYNDP 2014 study cycle already involved a top-down planning approach towards this end through scenario analysis (ENTSO-E, 2014e).

Taking all the above into account, a good model for transmission planning addresses the following issues of policy makers:

- Identifies investments on interconnections that help meeting CO_2 emission and RES integration targets, lower electricity cost and increase energy security targets
- Can be used for a top-down transmission planning process

3.2.2 Regulator

One of the main tasks of the regulatory authorities (either in a national or European level) is to assess transmission investments in terms of costs and benefits and efficiency (ACER, 2015; ACM, 2015) The main objective is to identify projects by TSOs that increase the social welfare and competition in the markets (Puka & Szulecki, 2014). To this end, they require a transparent process (ACER, 2012) in which the allocation of costs and benefits is explicit (ACER, 2013) and the risk is taken into account (ACER, 2014). Moreover, the projects proposed by TSOs should not promote market power as this would result in increasing prices to the consumers (externalities) (ACER, 2013; Buygi, Shahidehpour, et al., 2004; Yang & McCalley, 2011).

The assessment of interconnection projects is a highly complex issue in terms of their benefits. Although their costs can be easily determined, estimation of their benefits is not a particularly straightforward process (Brattle, 2013a). In the TYNDP 2014 study cycle, ENTSO-E created a framework for CBA under the Regulation (EU) No. 347/201311 (ENTSO-E, 2014e) in order to assess the transmission projects and Projects of Common Interest specifically (PCIs). The difficulty in monetizing many of the benefits (such as security of supply) led ENTSO-E to a framework closer to a hybrid of multi-criteria and cost-benefit analysis (ENTSO-E, 2014e). Another challenging task is the assessment of the allocation of project's benefits (CAISO, 2004; MIT, 2011; NMa, 2004). Assessing projects from the national regulator's perspective may lead to the rejection of projects that are beneficial in a wider area (e.g. European level). The need for a framework for cost-benefit allocation in interregional projects has been recognized and the transmission planning process should account for it as well (Lu et al., 2005).

Regulators (like ACM in the Netherlands or ACER in EU level) are also responsible for the gas transmission system (ACER, 2015). Coordination between the two systems, electricity and gas transmission, is expected to lead to beneficial synergies and cost-effective plans (Qiu et al., 2014). This coordination can be both in terms of regulations and plans. EU Commission has called coordination and information exchange between the ENTSO-E and ENTSO-G in drawing their TYNDPs.

Therefore from a regulator's perspective a good modeling approach in transmission planning should have the following characteristics:

- It is transparent in terms of assumptions made, data used and process followed
- It facilitates involvement of concerned third parties
- It takes into account all transmission costs and benefits
- It allocates efficiently the assumed costs and benefits
- It accounts for risk and uncertainty in the project assessment
- It identifies investments that result in increased social welfare and competition (reduced market power)
- It takes into account other systems, such as gas transmission, in its planning.

3.2.3 Planner's objectives

Figure 1.1 provided a high-level overview of the transmission planning process: how the signals for investment trigger the planning process which, through several input blocks, leads to the final decision. The planner's objectives are only implicitly shown. To distinguish from regulators and policy makers, (infrastructure) planners are the actors directly involved with the operation and planning of the transmission networks. These are the TSOs (or ISOs in the USA) for regional planning or networks of TSOs and ISOs for interregional planning (like ENTSO-E and WECC). In the analysis below, shareholders' interests (return on investment(TenneT, 2013)) are not taken into account.

Although the planners align their interests to the ones of policy makers and regulators (Figure 3.1), they have additional objectives regarding transmission planning, mainly of technical nature. Planning for additional interconnector capacity in the long-term is a way to ease their future daily operations in balancing demand and supply and alleviating congestion (Hesamzadeh et al., 2008; Meeus et al., 2006). Ensuring security of supply, maintaining high reliability standards and increasing operation flexibility are some of their main concerns (Buygi, Balzer, et al., 2004b). Another issue is to avoid public opposition in the development of their plans (e.g. overhead lines)(Buijs et al., 2011). Interconnections can have significant impact on the internal power flows and the system has to be tested under extreme conditions of supply and demand in all connected countries (ENTSO-E, 2014e; Escobar et al., 2014; Turvey, 2006). Thus, power flow analyses have to be performed in detailed representations of the connected power systems (CAISO, 2014).

Planners are those that propose the projects to regulators and policy makers. They have to submit concrete plans justified in both economic and technical criteria. A concrete investment plan should define the capacity, location, timing and type (merchant/regulated) of the interconnection, project costs and estimated benefits and its effects on the system (Baringa, 2013). Drawing robust investment plans is rather challenging due to the increased levels of uncertainty inherent to planning (they will be discussed further in Chapter 5).

Although the technical studies are well established and are driven by natural laws, the economic assessment of projects has put many challenges for the planners due to its “social-science” nature. Ideally a model for assessing market-related benefits should include specific assumptions on the behavior of the market participants. Ideally, these assumptions should reflect reality and be as transparent as possible (Neuhoff et al., 2005).

In the European context of collaboration between the TSOs, the planning process has become more demanding in terms of data requirements. The establishment of ENTSO-E aims to the gradual alignment of the planning processes of the member TSOs. Already TSOs are obliged to perform studies with at least two of the four TYNDP scenarios (ENTSO-E, 2014e). This requires data exchange between planners but also models which can process such amount of data without increasing complexity disproportionally.

Considering all the above, a good modeling approach for the planner (Buygi et al., 2006):

- Should provide information on the capacity, location and timing of the interconnection
- Should access the project with both technical and economic criteria
- Should allow for technical studies (reliability & power flow analysis)
- Should represent the physical network of transmission (buses, lines, FACTS, etc)(Lu et al., 2006)
- Should be able to efficiently utilize data structures
- Should take into account uncertainty and produce robust plans
- Should be able to test the system under several generation and demand scenarios
- Should facilitate the collaboration between planners
- Should be easily extendable
- Should realistically model market participants’ behavior

3.3 THE IMPONDERABLE FACTORS IN MODEL DESIGN

The reviews of (Foley et al., 2010; R. Hemmati et al., 2013; Latorre et al., 2003) on models used in energy power systems have clearly demonstrated that until now there has not been a model that can satisfy the desires of all stakeholders mentioned above. As Figure 3.1 shows, there are many limitations that lead modelers to a “softer” design of models, so that it can answer some of stakeholder’s questions. These limitations originate from technical and resource constraints, lack of information or knowledge for the system and finally, uncertainty. Thus, modelers continuously make trade-offs in their assumptions and modeling approaches so as to answer the given questions as sufficiently as possible (given the constraints) and fit their models for their purpose (Pfenninger et al., 2014; Strachan, 2011). These simplifications can both either distort the obtained results (NREL, 2014) or not affect them to a great extent (Francisco D. Munoz et al., 2013). In the end, the model has to be validated for its purpose.

(Pfenninger et al., 2014) identify fives challenges when modeling energy systems in general. The first challenge concerns modeler’s choices on temporal and spatial resolution of the model. Ideally the modeler would like to have a model that provides outputs of high detail in time and space. For example, generator dispatch levels provided every 30-minutes instead of every 2 hours or RES generation in 2kmx2km geographic blocks instead of a whole country. There are two limitations that explain why this cannot be achieved in all models: 1) high granularity in model outputs increases disproportionally the computation time (e.g. in case of dispatch algorithms) and 2) there are no data of such resolution available to be set as inputs (e.g. there are no available capacity factors for RES at 2kmx2km resolution). Although it can be argued that not all models require a high level of detail, in complex problems such as transmission planning, low resolution levels may distort the obtained results or may not yield the expected insights for the decision maker (e.g. where new generation can be located) (Brancucci Martínez-Anido et al., 2013; Geertman & Stillwell, 2009). To solve the problem of temporal and spatial resolution of models, modelers often use models with different purposes to answer their questions or choose to develop an integrated and simplified model.

This leads to the second challenge: how to utilize models from different scales. According to (Pfenninger et al., 2014) scale "*means the relative size of the boundary of an analyzed or modeled system*". This is relevant to the transmission planning process as well. As it will be shown in Chapter 6 ENTSO-E and MISO use a modeling approach that combines a detailed network model and a more aggregate operations model. On the other hand, WECC in this 20-year-ahead plan has developed a planning model which performs operational functions in a simplified way (dispatch and not commitment of the units) and in lower resolution. The choices that the modelers have to make can influence to a great degree the functional specifications of a model and the answers it can provide.

A third challenge is how to address uncertainty in the model. As it will be shown in Chapter 5 there are many ways to model uncertainty: from a fully deterministic model to a model that can perform numerous stochastic analyses. How the modeler will decide to deal with uncertainty has a great impact on the model's specifications in terms of input data, simplifications and computation time. Moreover, research has focused on more formal ways to handle uncertainty, such as stochastic optimization, robust optimization and dynamic programming models (Appendix A). More discussion on the types of uncertainty in transmission planning will be provided in Chapter 5.

The fourth challenge is how to incorporate the human factor in the modeling approaches. Human choices are sources of uncertainty which either at the behavioral or social level can have significant impact on the transmission planning process. Modeling strategic behavior on the electricity market, investment plans on new generation plants is not entirely straightforward (David & Fushuan, 2001; Motamedi et al., 2008; Neuhoff et al., 2005). With the deregulation of power systems, transmission planning depends more on the market-side of the power system and subsequently on the social dimension of economics. Although the profit-maximizing agent of neoclassical theory is used, it may not sufficiently capture human nature in the electricity markets (Pfenninger et al., 2014).

Finally, the fifth challenge concerns how the modeling approach is communicated to the public. Transparency has been identified as one of the stakeholder's desires for the modeling process. Transparency is needed in both modeling structure and assumptions as well as the data structures used. All these should be accessible to any concerned party for review and reproducibility purposes. Transmission planning is a process which apart from complex models, the decision making process stems from interactions with stakeholders and the public. In such a complex problem, the process is as important as the analytical models themselves (De Bruijn & Heuvelhof, 2008; Simon, 1965) and it should be given attention.

3.4 EVALUATION FRAMEWORK FOR MODELING APPROACHES

Taking into account both stakeholders' desires and the modeling challenges, the criteria for evaluating modeling approaches on transmission planning can be clustered into four main categories: economic, technical, social and institutional criteria.

- **Economic criteria:** They refer mainly to the way the economic assessment of the transmission projects is conducted.
- **Technical criteria:** They concern the structure, the assumptions and the technical outputs of the model.
- **Social criteria:** They concern the ability of the modeling approach to capture the social aspect of planning.

- **Institutional criteria:** They refer to the extent the modeling approach can facilitate collaboration between the several institutions involved in transmission planning (TSOs, EU agencies, governments).

The criteria are shown and explained in the following Table 3.1. It should be kept in mind that these criteria are not designed in terms of detailed model specificities but according to what should be answered with these models. In Chapter 4 the models will be judged on whether they are fit for purpose or not. As the scheme in Figure 3.1 shows, due to constraints and limitations on a modeling level or other (data requirements), it is not only an issue of "I want answers to these questions, what model should I use?" but also of "I have these models, what questions can I answer?".

Table 3.1 - Criteria for evaluating modeling approaches transmission planning

Category	Criteria	Explanation
Technical	**Endogenous investments**	Whether investment plans or projects are derived by the model or not
	Technical studies	Whether the model performs reliability or power flow studies
	Physical network	Whether the transmission network is modeled with its technical characteristics (losses, lines, FACTS etc) or not
	Data requirements	How data intensive is the modeling approach
	Computation time/high resolution ratio	The balance between high resolution in model outputs and computational time
	Simplifications/Assumptions	Reflect the extent to which assumptions and simplifications may have considerable impact on results
Economic	**Benefit Cost allocation**	Whether the model provides information on who benefits from a project (either at consumers/producers difference or between regions at interregional projects)
	Benefit & Cost estimation	Whether all the benefits and costs are estimated or monetized. For a list of the benefits and costs (see Appendix B)
	Uncertainty in assessment	Whether uncertainty is taken into account in the final project assessment. Note: Although uncertainty is present in all categories, it is only stated here, the final assessment of a project, to represent the accumulated uncertainty in the whole process. More discussion on uncertainty is in Chapter 5
Social	**Policy targets**	Whether the model helps to identify roadways to meet the policy targets with social character. Policy targets are: CO_2 emissions, RES integration, low electricity prices through market integration and competition, high energy security.
	Strategic behavior	Whether the model captures the human dimension either in the generation-side (producers) or the demand-side (consumers)
	Simplicity & Transparency	The extent to which the modeling approach (methodology, model, data structures used) provides a good understanding of how investments are derived and their effect on the system. Also, reflects the extent the methodology can be easily reproduced and accessed.
Institutional	**Policy driven top-down planning**	To what extent the modeling approach can be used to derive a co-ordinated and top-down planning approach (e.g. EU level) to fulfill policy goals
	Non electricity transmission sectors	Whether or not the modeling approach interacts with other sectors in the energy system apart from transmission system as generation side or gas transmission system
	Regulations	Whether the model can be extended to incorporate regulatory changes (e.g. capacity markets)

Given the above formulation of the criteria, the assessment of the modeling approaches will be qualitative in nature.

3.5 SUMMARY

In this chapter the evaluation criteria for assessing the different modeling approaches were provided. Furthermore, the analytical method for deriving the criteria was described. The method was based on the scheme of Figure 3.1, according to which the modeling exercise is built to meet certain stakeholders' objectives. The extent to which the obtained model can be used to answer stakeholders' questions can be used as an evaluation method. In case of transmission planning, the objectives of three stakeholder categories are examined: Policy makers, Regulators, and Planners. The final obtained modeling approach is derived from both stakeholders' objectives and limitations or resource constraints (uncertainty, modeling human behavior, transparency, trade-offs between simplifications and computation time). Finally, clustered into four main categories (economic, technical, institutional, social), the evaluation criteria were shown and explained in Table 3.1.

In the following Chapter 4, after a short review of the current incumbent modeling approaches for interregional transmission planning, the obtained criteria will be used to pinpoint the differences between them.

4

Long-term Transmission Planning Models

4.1 INTRODUCTION

There are two major types of models used in transmission expansion planning: technical models and economic models (Quintero et al., 2014). Each category addresses different aspects of the transmission system and provides certain inputs to the decision-making process. The first category focuses on the technical side of a transmission system and consists of power flow models and reliability assessment models (Kyeonghee et al., 2011; Jin Lin et al., 2014). The metrics obtained from such studies are used as inputs to economic or benefit analyses of the transmission projects. The second category addresses the economic side of a transmission system and includes production cost models and capacity expansion models (Barbose et al., 2014; Brancucci Martínez-Anido et al., 2013). Both sub-categories serve as a basis for the economic studies of an investment plan.

In contrast to the regional ones (e.g. country level), interregional studies (e.g. on interconnections) require a business-case to exist (Brattle, 2013a). Since two or more TSOs are involved in interregional projects, the existence of a business case would be used to determine the economic benefits of the investment as well as the cost allocation. That is the reason the economic models are widely used in these cases. As the research questions of this thesis focus on interconnection investments and interregional studies, an analysis of the production cost and capacity expansion models will be conducted.

The present chapter will focus on the assessment of the different modeling types for transmission planning. This will be based on the evaluation framework introduced on the Chapter 3. Before this, the different modeling types the two model types (production cost models & capacity expansion models) will be briefly reviewed. This review will not focus so much on the technical details of the models but on the essence of the models: how each model's functional specifications are connected to transmission planning objectives. (Hiremath et al., 2007) reviews energy models based on 9 dimensions: purpose, internal and external assumptions, analytical approach, underlying methodology, mathematical approach, geographical coverage, sectoral coverage, time horizon and data requirements. Our review will aggregate some criteria (e.g. assumptions and analytical approach) and it will examine them based on the following four criteria: 1) Purpose, 2) Analytical and Mathematical Approach, 3)Inputs and Data requirements, 4)Outputs (Figure 4.1).

First, the two modeling types will be reviewed separately and then (Section 4.4) they will be both compared per criterion category.

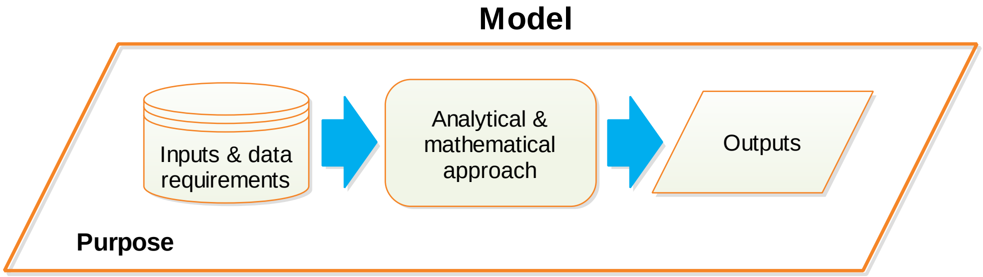

Figure 4.1 - Review criteria of modeling types

4.2 PRODUCTION COST MODELS

4.2.1 Purpose

Production Cost Models (PCMs) constitute the currently most popular modeling tool for assessing the economic benefits of transmission projects (Brancucci Martínez-Anido et al., 2013). PCMs examine economic dispatch or unit commitment (ED-UC) problems and they are mainly used by production companies to determine their operational schedules or assess revenues of their future investments. This leads to an interesting paradox: Although PCMs mainly concern short- and mid-term planning on the generation side of electricity system, they are also used for long-term planning on the transmission side of the electricity system (Francisco D. Munoz et al., 2015).

The reason is that in regulated electricity systems, both transmission and generation planning was performed by one entity, the system operator. Therefore, both generation and transmission planning was performed by the system operator. The assessment of the generation plans was performed using PCMs, and this was the first step of an integrated planning process for the transmission system (Wu et al., 2006). Whether it is the right tool to use for transmission planning in deregulated power systems is examined in Section 4.4.

4.2.2 Methodology and Mathematical approach

PCMs belong to the optimization class of models (Prasad et al., 2014). Originally, PCMs were only able to determine the output levels of generation units (economic dispatch) without deriving commitment schedules. This has been achieved with the advent of computational breakthroughs and evolution of optimization algorithms. Taking into account operational characteristics of generating units (shut-down, start-up constraints etc) they are used for solving unit commitment problems. Of course, the models that perform UC-ED are computationally more demanding than the ones that perform only economic dispatch. The UC-ED problem is a mix-integer problem and a general formulation can be found in (Weber, 2004). Application to large scale problems many times is not feasible or the optimum is not a global, but local[2]. The scientific community has developed several methods and techniques to reduce the simulation time of PCMs. In (R. Hemmati et al., 2013) several solving methods for the above mix-integer problem are described but most of them are still at the research level. In practice, most widely used mathematical methods are the Mixed-Integer Linear Programming (MILP) (Guo et al., 2012; Rouhani et al., 2014; Yang & McCalley, 2011) or Bender's-decomposition method (Heejung & Baldick, 2013; Yang & McCalley, 2010), and heuristics are also used (Murthy et al., 2008; Rezende et al., 2009).

In transmission planning, PCMs are used to evaluate projects on a case-by-case basis. Simulations are performed with and without an investment project in the system (e.g. an interconnection). Metrics with the changes in model outputs are used to evaluate the project under study (see Section 6.2.1 for TOOT and PINT approach of ENTSO-E). This means that investment plans have to be evaluated on a systematic case-by-case basis and for specific years in time and are not the result of an optimization algorithm.

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[2] Meaning that the obtained solution is not overall optimal

4.2.3 Inputs and Data requirements

As Table 4.1 shows, PCMs are information-intensive models. The input data mainly concern the generation and the demand side of the electricity system. In the supply side, information has to be provided per generation plant: number of generating units, installed capacity per unit, fuel type, technical and economic (operational costs) characteristics of the units. Depending on the level of detail in the optimization (e.g. UC-ED or not) the required technical characteristics can be: must-run units, start-up/shut down levels and costs, minimum/maximum up/down time, efficiency rates, planned/unplanned outages, repair time. Solar radiation and wind speed profiles or time-series on capacity factors are required for modeling RES output. The resolution of the data depends on the modeling choices. Depending on the type of the hydro power plant, the required data can vary from production profiles (run-of-river) to more technical characteristics such as reservoir levels and max/min generation capacities (pumped storage or storage) (Brancucci Martínez-Anido et al., 2013). Depending on the modeling detail, information on contracts of generation companies may be required as well.

Apart from the supply side of the system, the load profiles are the only data needed (for a deterministic model) in the demand side. Moreover, data on fuel prices, CO_2 price and reserve margins are also needed for the optimization. PCMs are built as transport models in which the system is represented with nodes (sources and sinks) and connections between them. The main constraints have to do with the equality of incoming and outgoing in every node and the capacity limits of every connection. Therefore there are no significant data requirements regarding the transmission system (Brancucci Martínez-Anido et al., 2013; Jaehnert et al., 2013). In transport models the network is split in several areas of demand and supply (nodes). These areas are connected by transmission corridors, which represent the transmission lines. However, neither the location nor the technical specifications of the line is needed (transformers, line or cable, PSTs). Data input on transmission lines concerns their net transfer capacity and sometimes losses. As it will be described in Chapter 6, PCM in the TYNDP study cycles considers every country as one node and the transmission corridors are the interconnections between the countries. Thus, no internal congestion is examined.

Table 4.1 - Inputs and Outputs of Production Cost Models

Category	Input Data	Outputs
Generation	• Number, type, fuel type and installed capacities of production units • Ramping rates • Start-up costs • Min/max operational levels • Efficiency rates • Planned/Unplanned outages • Must-run units • Time-series for solar radiation and wind speed • Hydrological conditions/flows • Contracts	• Annual plant production and utilization • Hourly production and dispatch • Fuel consumption • RES curtailment needs • Hourly production and dispatch
Demand	• Load profiles • Demand side management	• Unserved load •
Transmission Network	• Transfer capacities of lines	• Cross-border flows
Regulatory input	• Reserve margins • CO_2 price	• CO_2 emissions
Financial inputs	• Fuel prices	• Plant revenues and profits
		• Hourly prices per region/node

Much of this information is not known to the transmission planner. The producer has more information on the technical characteristics and detailed plant costs than the planner. Thus, in the context of transmission planning, these models require significant amount of assumptions and simplification.

4.2.4 Outputs

One of the main reasons on the popularity of PCMs for evaluating transmission projects such as interconnections is that they provide plethora of model outputs, many of which can be used as metrics for assessing the "benefits" of an investment. In general the main model outputs are production levels per unit, production costs (ramping costs and fuel costs), marginal electricity prices, power flows in the transmission corridors, CO_2 emissions, RES curtailment needs and unserved load (Brancucci Martínez-Anido et al., 2013).

4.3 CAPACITY EXPANSION MODELS

4.3.1 Purpose

Unlike PCMs, Capacity Expansion Models for Transmission (TCEMs) are models built exactly for grid planning purposes. By utilizing optimization algorithms they are able to provide investment plans through an analytical process. Although CEMs have been used for long-term resource planning, recently research has also focused on its employment to the transmission system. Therefore, CEMs may address either only the generation or transmission side of the electricity system (GCEM and TCEM respectively) (Cedeño & Arora, 2011; Fan et al., 2010) or a combination of transmission and generation (Liu et al., 2013). For long time, CEMs for transmission (TCEMs) were only developed at research level due to computational constraints. The advent of more efficient solvers and faster processing time has made such problems feasible at large scale as well (Francisco D Munoz et al., 2014).

4.3.2 Methodology and mathematical approach

Mathematically speaking, CEMs are large-scale non-linear mixed-integer programming (MINLP) problems. In (NREL, 2014) a generic formulation that most TCEMs use in academia is formulated. There are several variations of this formulation depending on modeler's objectives or criteria. A comprehensive review can be found in (Liu et al., 2013). The model tries to minimize both transmission investment costs and generation operational costs by deciding which of the candidate transmission lines is going to be built. This optimization is performed for more than one year. Most common constraints concern the nodal balance equations, the flow limits per line, generation constraints and the non-negatively integrality constraints. It should be noted that the transmission network can be modeled realistically based on Kirchoff's laws but increase the computation time (Bahiense et al., 2001; Reza Hemmati et al., 2013).

It can be observed that in order to calculate the generation operational costs, TCEMs contain production cost modeling algorithms as well. However, the implementation of MINLP in large-scale networks requires a significant amount of computation time, which is often infeasible. This is why in real life systems many simplifications are assumed. These may concern the characteristics of the network (e.g. DC instead of AC network topology, reduced number of system nodes, exclusion of phase shift transformers etc.), the algorithm itself (relaxation of the integer constraints) or aggregation of the time horizon. Simplifications can be made on the production cost algorithms as well (NREL, 2014). Since there are already many integer decisions in CEM problems (build/ no-build candidate lines), the algorithm that calculates the production costs is often simplified to perform only economic dispatch rather than unit commitment decisions. (Hobbs & Drayton, 2008; Francisco D. Munoz et al., 2013; NREL, 2014) have explored the impact of such simplifications or approximations to the model results.

4.3.3 Inputs and Data requirements

TCEMs also require a great deal of input data. As production cost modeling is a sub-problem of TCEMs data on the generation side like in PCMs are needed. However, as mentioned before, ramping constraints are excluded in TCEMs for reasons of simplicity. Instead, the location of every generation unit in the grid is needed (in which bus it is). As the optimization may be performed for several years, data on new-built or decommissioned generation capacity are needed to be set as inputs to the models. Therefore, generation forecasts are dynamic and for static as in PCMs in the sense that they change every year. The same holds for the demand data. Load forecasts for the study period need to be set as inputs to the model.

The transmission network can be modeled in great detail and represent the physical transmission network. Networks in CEMs can be represented either as AC or DC networks, allowing for evaluation of reliability and other technical constraints as well (Liu et al., 2013). Decisions already made for the transmission network also need to be set as inputs, and a list of possible candidate lines (decision variables) and their investment costs must be provided. Moreover, information on reliability criteria and availability of financial resources (if budget is set as constraint) are needed. Finally, depending on the TCEM problem formulation, it is possible to need information on geographical and environmental constraints. The latter concerns CO_2 emissions or other regulatory constraints (Francisco D Munoz et al., 2014). The former pinpoints e.g. in which geographic areas lines cannot be built or there is social opposition (WECC, 2013). By adding specific characteristics to network regions, CEMs' algorithms can produce realistic results regarding the geography of the investments or resource plans. For example, if regions within the network are clustered as regions of "lower resource cost locations" (for thermal plants or RES availability) or as regions of "high transmission installation cost" (mountain areas or areas where environmental concern is high), then CEMs can plan for low long-term resource and investment costs (WECC, 2013).

Table 4.2 - Inputs and Outputs of Capacity Expansion Models

Category	Input Data	Outputs
Generation	• Number, type, fuel type and installed capacities of production units (forecasts) • Min/max operational levels • Efficiency rates • Planned/Unplanned outages • Must-run units • Time-series for solar radiation and wind speed • Hydrological conditions/flows • (Investment and O&M costs)	• Annual plant production and utilization • Hourly production and dispatch • Fuel consumption • RES curtailment needs • Hourly production and dispatch • (installed generation capacities)
Demand	• Load profiles forecasts • Demand side management	• Unserved load •
Transmission Network	• Expansion candidates • AC network topology • DC line data • Contingencies • Planned/Unplanned outages • Network losses • Investment and O&M costs	• Investment plan • Power flows • Reliability levels
Regulation related	• Reserve margins • CO_2 price	• CO_2 emissions
Financially related	• Fuel prices • Inflation & discount rates	• Cost of transmission plan • Plant revenues and profits • Hourly prices per region/node

4.3.4 Outputs

The main output of TCEMs is an endogenously derived investment plan through the whole study period. It provides an optimal or near-optimal plan (per scenario) of what and when to build a transmission line. The capacities of the lines are set as input (expansion candidates) and are not determined by the model algorithm. Depending on the granularity of the network under representation, CEMs can be used to identify investments on regional and interregional levels. For example, in case of interconnection investments between two countries, for which there is a detailed representation of their network, TCEMs can identify the location of the interconnection and whether there should be some additional investments within the network of each country. This is highly valuable in cases of top-down expansion plans, such as the studies of ENTSO-E.

Apart from an optimal plan, TCEMs provide information on an operational level: production levels of units, CO_2 emissions, RES integration or curtailment, network flows, information on congestion (depending on network resolution) and reliability metrics. Adding to this, both investment and operational costs and marginal prices are given as outputs (Pina et al., 2013; Yang et al., 2012).

4.3.5 Co-optimization

In transmission-only CEMs, generation resource planning (generation capacity additions and retirements) is set as an input (for several years). Often any interaction with other systems, such as gas transmission networks, is neglected. Recent research has focused on co-optimization algorithms and several models have been developed and used for real world cases. (Liu et al., 2013) provide an extensive overview of the theory and practices behind co-optimization. In case of transmission and generation planning, a co-optimization algorithm optimizes both generation and transmission new-builds and retirement in an incremental way. The same can be applied to an electricity and gas transmission network.

In regulated power systems the benefits of co-optimization are quite straightforward. The lowest-cost solution for both generation and transmission can be found on an integrated model without missing any feedback information that may be lost if the planner had two different models. In deregulated power systems, the added value of co-optimization models is that "co-optimization is a systematic approach to address critical questions in planning"(Liu et al., 2013). Since generation investments are closely connected to transmission investments (and the other way around) an iterative model of building new capacity in both systems can be used to evaluate several "what-if" scenarios. Given the higher lead time of transmission investment compared to the ones of generation, co-optimization can help in enhancing the anticipatory character of planning in transmission. It is possible that a particular transmission investment does not only have an effect on system costs but also on the development of the future system (e.g. regarding the location of installed capacities). In this way, an investment can be assessed with more than simple criteria like system production costs. Such a criterion is the flexibility that a transmission project allows to generators for investing in low-cost regions or in regions with high RES potential, leading ultimately to benefits like meeting RES targets. Section 6.4 will briefly discuss how WECC included and used a co-optimization model to their long-term planning (20-years ahead) in the latest long-term planning study cycle.

4.4 MODEL EVALUATION

In the present section, the different above modeling approaches will be assessed according to the evaluation criteria presented in Chapter 3. The assessment presented is based on the analysis performed on literature, policy documents and company reports on the above described models and their use. The assessment will distinguish between the models presented in Sections 4.3-4.4 only. Models for reliability and power flow studies will not be considered. Moreover, the CEMs that perform co-optimization of generation and transmission system are not considered separately, since they are assumed to be a variation of TCEMs.

The assessment of the models is presented in Table 4.3. The evaluation is qualitative and indicated with the "-","- - ","+" and "++" to indicate the relative differences between the models and the negative/positive evaluation. For example, "-"means that model X does not satisfy this criterion, whereas "- -"means that the model Y also does not satisfy the criterion but to a greater extent than model X. The following sections will provide more detailed comments on the assessment by contrasting the two models in parallel per category of criteria.

Table 4.3 - Evaluation of modeling types for transmission expansion planning

Category	Criteria	Production Cost Models	Capacity Expansion Models
Technical	Endogenous investments	-	++
	Technical studies	-	+
	Physical network	-	++
	Data requirements	-	--
	Computation time/high resolution ratio	-	--
	Simplifications/Assumptions	--	-
Economic	Benefit Cost allocation	--	-
	Benefit & Cost estimation	+	++
	Uncertainty in assessment	+	++
Social	Policy targets	+	++
	Strategic behavior	--	-
	Simplicity & Transparency	-	-
Institutional	Policy driven top-down planning	-	++
	Non electricity transmission sectors	-	++
	Regulations	+	++

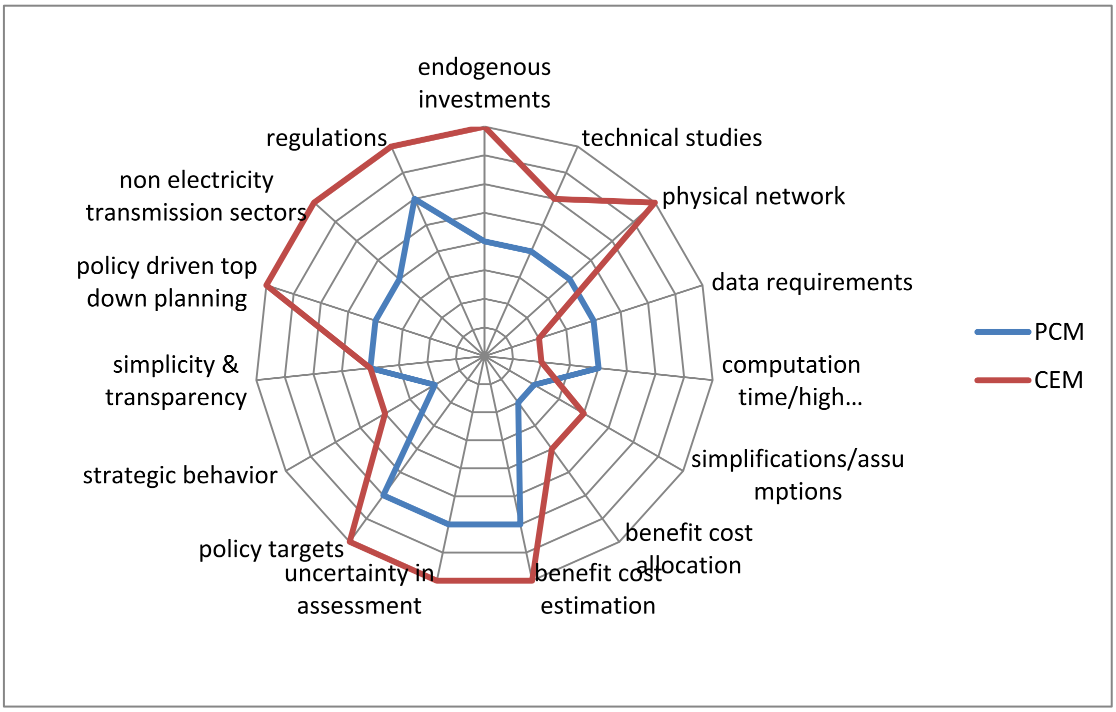

Figure 4.2 - Spider diagram for comparing PCM and CEM in transmission planning

4.4.1 Assessment by the technical criteria

As far as the technical criteria are concerned, CEMs score higher than PCMs as they can model the transmission system to a greater detail, including its physical characteristics (FACTS, PSTs, losses, etc) whereas PCMs are mainly transport models. Although the objective is not to perform detailed reliability and power flow studies but to assess economically the transmission projects, physical laws of the system should not be neglected. The technical system characteristics may influence economic evaluation through feedback loops and physical constraints (Hobbs & Drayton, 2008). In any case, more detailed power flow and reliability studies should be performed for testing contingency situations and other, after a plan has been economically assessed.

Maybe the most important contribution of CEMs is that investments are derived endogenously from the model. Although PCMs consist of optimization algorithms, this optimization is for performing an efficient economic dispatch and not for drawing an expansion plan. Therefore, with CEMs the planner does not need to develop an analytical framework for identifying projects for evaluation (see TOOT and PINT approach in Section 6.2.1). Depending on the network detail, these investments can be at the regional and/or interregional level. The attribute of endogenous plans is not so important in cases where only single projects are examined as in cases on co-ordinated plans. The first is a common process until now in Europe, but there is a gradual shift taking place towards more co-ordinated plans with the establishment of ENTSO-E and Energy Union (ENTSO-E, 2014e; MIT, 2011; Rubino & Cuomo, 2015).

On the other hand, PCMs score better in terms of data requirements, computational requirements and level of detail. The main reason is that input data for PCMs are needed for a single year (the final year) (depending on the analytical framework of the planner maybe more years are also examined), whereas CEMs require projections for several years (10-20 years ahead). Moreover, since CEMs contain production cost calculations in their formulation, their input data in a sense consist of a sub-set of PCMs input data plus a sub-set of investment costs. The exception is when no UC is performed in CEMs (which is the common practice). The high computational time in CEMs is mitigated by the low resolution of model detail in the time step (e.g. per day instead of per hour operations) or by several simplification and assumptions. The simplifications of the two models and the level of detail in their outputs is a topic for discussion.

As it will be shown in Chapter 5, the uncertainty in long-term studies is significant. PCMs seek to evaluate an investment based on detailed information on the generation side of the system, whereas CEMs try to evaluate based on limited or more aggregate information on all sides of the system (detailed in transmission level). In both cases, all these data are just estimations and projections. Since both PCMs and CEMs rely on MINLP techniques it may happened that the obtained solution is a local optimum. This means that with even small changes in the input data, different results can be produced (Lee et al., 2006). The accumulated uncertainty in the input data (technical characteristics of the production units) can be misleading. According to (RAND, 2013) in cases of high uncertainty, maybe studies of an exploratory nature are needed; also ENTSO-E in the TYNDP2014 study cycle recognized the need to shift to a more exploratory study. In that sense, the high aggregation level of CEMs can be more practical and useful for an exploratory analysis.

Although high computational time of MINLP models hampers their extensive use in real-life applications, there have been cases were the benefits of high performance computing or even cloud computing have been used to simulate large scale systems. In (Meyers et al., 2011) is described how PLEXOS and IBM solvers were employed to simulate one of long-term scenarios of California's ISO (CAISO).

In an overall assessment by technical criteria, CEMs seem to be more suitable for long-term studies in transmission planning, with only problem the computation time and data requirements. Assumptions in data will always be a problem and cannot be avoided, whereas developments in processing time and solver will probably set CEM simulations feasible for large systems as well.

4.4.2 Assessment by economic criteria

A recent report from (Brattle, 2015) lists all the benefits that a transmission project may result to (Appendix B). It is clear that a planning methodology based on PCMs over-relies on production cost savings and locational marginal prices and ignores investment and other fixed costs of transmission generation. Figure 4.3 shows that production cost savings are only a fraction of the economic benefits of transmission project.

Benefits can also be long-term capital and operational savings, which can only be estimate with CEMs through an systematic over the years investment plan. Since only a "snap shot" of the system is evaluated in PCMs, the long term impact of a transmission project on the system or market is ignored. Moreover, the methodology based on PCMs assumes that the system retains the same configuration (generation units in specific areas) whether a transmission project has been built or not. This can be flawed in many cases as by definition transmission projects are built to connect load with generation sources. According to Brattle "*paying attention to how benefits and costs accrue over time and across future scenarios will also help planners to* *optimize the timing of transmission investments from a long-term value perspective*" (Brattle, 2015).

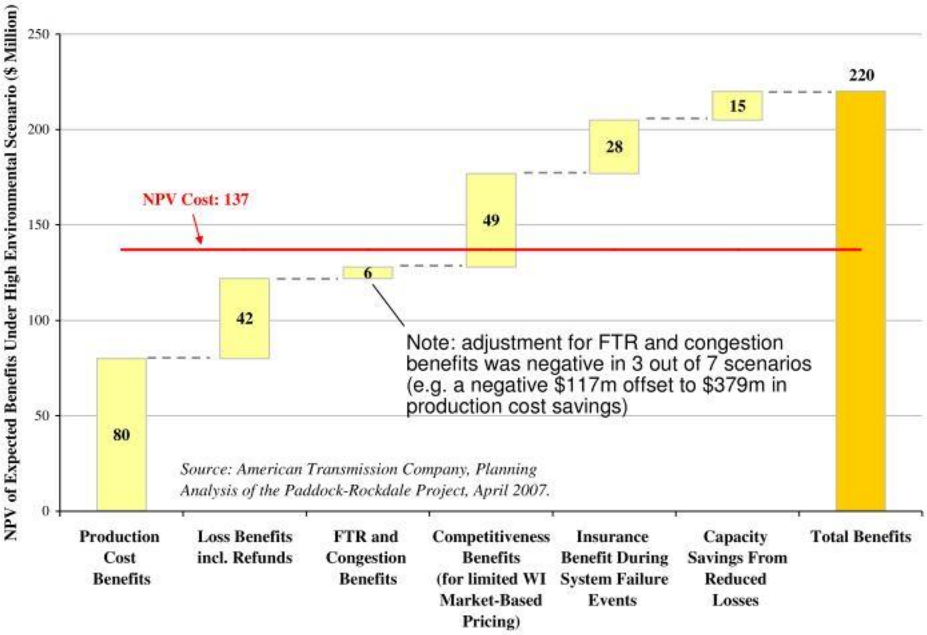

Figure 4.3 - Indicative total quantifiable benefits for a transmission projects (adapted from (Brattle, 2013a))

Cost allocation is a significant issue and an active field of research in transmission planning literature, especially for interregional projects. If cost allocation is not addressed sufficiently, it can be proved a barrier to network expansion (Cameron, 2001; Fulli et al., 2009; MIT, 2011; Saguan & Meeus, 2014). Unfortunately, none of the discussed models can address this issue. However, if the model provides information on who (country/region/consumer/producer) benefits then assigning the costs will be more straightforward. To that end, CEMs may seem more appropriate because: 1) they provide information on a variety of benefit metrics over time and 2) they take into account the physical characteristics of the networks. To illustrate, let us assume an interconnection between country A and country B which has been found profitable in the 1-node-per-country PCM methodology which is currently used. The location of this interconnection in the border of A and B is still unknown and it can have significant impact on the local grids and may prove the project less beneficial. This can be examined by using CEMs of adequate granularity. It can also be achieved by using PCMs in a network in which every country is represented with more than one node. In this way, indication of the internal congestion could be identified, although physical laws of the transmission system are still ignored. Overall, it can be concluded that CEMs score slightly higher than PCMs.

Finally, both models can be used to account for uncertainty. As it will be discussed in the following Chapter, this can be achieved through scenario analysis, Monte Carlo simulations or stochastic analyses. However, formal modeling algorithms to address uncertainties like stochastic optimization, robust optimization or dynamic programming (Sahinidis, 2004) can only be meaningfully utilized in CEMs. These algorithms optimize the objective function under uncertainty (see Appendix A). For CEMs these algorithms will propose plans under uncertainty, whereas for PCMs these algorithms will propose commitment and production schedules under uncertainty. The latter is useful only for short- and mid-term operations and not for long-term planning.

4.4.3 Assessment by social criteria

Regarding the criterion "policy targets" both models are able to provide metrics for most of the policy targets, such as RES integration, socio-economic welfare (in terms of electricity production costs) and CO_2 emissions. However, PCMs as transport models are not able to provide metrics like reliability of the transmission grid or loss of load expectation by itself (ENTSO-E, 2014e). An indication of these indices can be provided by CEMs since the transmission system can be modeled as well.

Both modeling approaches score low in modeling strategic behavior in long-term transmission planning. Although in both models there are formulations that model producers' behavior (Motamedi et al., 2008), these are not widely (if not at all) in practice. Strategic behavior of producers relevant to long-term planning can be identified in both market bidding strategies and their generation expansion plans. Regarding the former, most PCMs and CEMs take the marginal costs as bidding strategy, which ignore strategic behavior and assume perfect competition. Formulations to overcome these problems can be found in (Motamedi et al., 2008; Neuhoff et al., 2005). As far as generation expansion plans are concerned, in both CEMs and PCMs these are set as input data through scenario analysis. Therefore, it is a static analysis. An exemption is CEMs that perform co-optimization of generation and transmission. In that case, generating companies respond to transmission investments and locate their production plants based on several cost indications and the other way around. This approach can be proved rather useful in examining possible behaviors of generating companies (Sauma & Oren, 2006).

Regarding simplicity, none of the two models can be considered simple in terms of modeling methodology. However, PCMs have been widely used over the years and actors in the electricity field are more familiar with their methodology. On the other hand, in terms of transparency, CEMs score higher as their formulation is clear as far as the objectives, constraints and decision variables are concerned. The framework of analysis of PCMs is more complicated as more models are needed for the final assessment. In addition, in the case where whole plans are evaluated the underlying methodology for identifying the transmission expansion candidates still relies on expert knowledge and not on a systematic analysis. As examples from MISO and WECC expansion plans show (see Chapter 6 or (Hirst, 2004; Francisco D. Munoz et al., 2015)), the data structures and assumptions required for such studies can be provided for replication of the analysis. However, most of the CEMs and PCMs are commercial products and their algorithms are not fully accessible to the public.

4.4.4 Assessment by institutional criteria

Regarding institutional criteria the scale leans towards CEMs as they can be used for both top-down and bottom-up planning approaches. In contrast to PCMs, which are evaluative in nature, CEMs have an exploratory and prescriptive character in nature, which allows the planner to use them for defining the road maps to fulfill certain objectives. The optimization algorithm can be formulated in such a way so as to develop strategies that minimize the risk of investments (Chennapragada et al., 2006; Rahmani et al., 2013), accommodate renewables (van der Weijde & Hobbs, 2012) or fulfill CO_2 emissions requirements (Chamorro et al., 2012). The PCM algorithms only focus on commitment and dispatch schedules and cannot provide such plans.

In terms of addressing other sectors in the power system, the option of co-optimization CEMs can be used to examine either the generation side of electricity system (Jae Hyung et al., 2009) or the synergies with the gas transmission system (Qiu et al., 2014). However, significant research still has to be performed in this field.

Finally, as in the case strategic behavior, both models can address changes in the regulation with certain modifications in their methodology or algorithms. For example, (Jae Hyung et al., 2007) developed a model for evaluating transmission investments when a capacity mechanism is in place through a stylized CEM algorithm, whereas (Baringa, 2013) took into account capacity mechanisms in their analysis using PCM simulations.

4.5 SUMMARY

In Chapter 4 the two main modeling clusters were described and evaluated. First, an overview of the technical characteristics of the models was described in terms of model purpose, methodology and mathematical formulation, inputs and data requirements and model outputs. This offered the background for the subsequent evaluation of the models using the aggregate criteria developed in Chapter 3.

The analysis revealed that CEMs are more suitable models for performing transmission planning, although significant technical challenges regarding the computational time have to be overcome. CEMs score on average higher in every main category: technical, economic, social and institutional. The most significant differences are observed in the technical and institutional criteria. CEMs have been designed specifically for long-term transmission planning and their optimization algorithms can be adjusted to different goals and criteria. On the other hand, PCM's purpose was to simulate adequately short- and mid-term operations and assessment and not contacting long-term plans. Therefore, the physical network of transmission system is not taken into account and the algorithms focus on different aspects than deriving an investment plan.

The superiority of CEMs can be explained by the fact that CEM contain production cost algorithms, although less detailed (performs ED and not UC). This raises the issue of accuracy and the effect of simplifications in the model results. It is argued that long-term studies should not be studies that seek accuracy in the results but should focused on exploration of the possible futures. Simpler models often offer more insight to the decision-makers when simplifications make the model outputs more transparent.

5

Dealing with Uncertainties in TEP

5.1 INTRODUCTION

The introductory chapter briefly discussed the new challenges that transmission planners face in their planning process. Most likely, how to address the diffuse uncertainty in the technical, regulatory and economic side of power systems is the main challenge of planners and decision makers. Chapter 4 introduced the types of models used in TEP, discussed their limitations and evaluated them based on the criteria of Chapter 3. The amount of data and assumptions set as inputs to the models were found to be significant limiting factors. An expression regarding modeling processes says “garbage in, garbage out” when referring to the input data. In deregulated power systems within a highly uncertain world (RES variability, economic instability), perfect and complete data is never the case. That is why uncertainty analysis and decision-making under uncertainty have been an active and ever growing field of study for several decades.

This chapter is focusing on these two aspects for the transmission expansion planning problem. First, the uncertainties in TEP problems are classified according to their common characteristics, causes and importance. Then, the techniques for uncertainty management are described and evaluated. Based on the above uncertainty classification and techniques evaluation, Section 5.3.2 analyzes which is the most appropriate uncertainty management technique for each of the discussed uncertainties.

5.2 CLASSIFICATION OF UNCERTAINTIES

In order to answer which uncertainties should be addressed in the transmission planning process and most importantly how a stylized framework by (Walker et al., 2003) for defining and mapping uncertainties will be used. According to (Walker et al., 2003) uncertainties can be clustered based on three dimensions: Location, Level and Nature of uncertainty. Location refers to where the uncertainty is located within the model complex, Level concerns the extent of our ignorance and Nature refers to whether or not the uncertainty is a result of our lack of knowledge or due to the inherent variability of nature.

In our analysis, the Level of uncertainty will not be examined in detail. In the original uncertainty matrix of (Walker et al., 2003), this dimension consisted of five parameters: context, model, inputs, parameters and model outcomes. The models we examined in the previous chapter are optimization models. Apart from strategic behavior (assumptions of how actors react) all the other uncertainties refer to input data. Therefore, it seems more useful to categorize the uncertainties by using a different dimension. This dimension concerns the main category of causes of the uncertainties as given by (Liu et al., 2013).

Table 5.1 - Uncertainty matrix for transmission planning [adapted from (Liu et al.2013) and (Walker et al. 2003)]

Location/Category of uncertainty	Level			Nature	
	Statistical Uncertainty	Scenario Uncertainty	Recognized ignorance	Epistemic Uncertainty	Variability uncertainty
Market uncertainties					
Capital costs (transmission & generation)	✓				✓
Fuel costs (coal, gas, nuclear etc.)		✓			✓
Fuel availability		✓			✓
Emission permit costs		✓			✓
Bids and strategic behavior			✓		✓
Nature related uncertainties					
Water availability	✓				✓
Wind speed (or capacity factors)	✓				✓
Solar irradiation (or capacity factors)	✓				✓
Demand uncertainties					
Load pattern	✓				✓
Load growth	✓				✓
Efficiency growth	✓				✓
Distributed generation and Demand response		✓			✓
EVs growth		✓			✓
EVs charging pattern	✓				✓
Heat pumps	✓	✓			✓
Individual asset uncertainties					
Forced outages (generation units; transmission lines)	✓				✓
Technical characteristics of units	✓			✓	
New built/retirements of units (size, location & timing)			✓	✓	
Regulatory uncertainties					
New reliability standards		✓			✓
Environmental policies		✓			✓
Market rules		✓			✓
Economy and Project uncertainties					
Inflation rates	✓				✓
Construction time	✓			✓	
Other uncertainties					
Technology breakthroughs			✓		✓
New resources			✓		✓
Catastrophic events			✓		✓
Modeling uncertainties					
Solvers (local & global optimum)			✓	✓	

With no doubt all uncertainties displayed in Table 5.1 play a significant role in transmission planning and set limitations to the planner. Market, nature related, demand and regulatory uncertainties have gained the most interest from academia regarding transmission expansion planning and have been examined in several ways. Literature (Chamorro et al., 2012; Fuss et al., 2008; R. Hemmati et al., 2013; Vithayasrichareon et al., 2015) has found the following uncertainties to be the most significant in transmission planning:

- Fuel prices
- CO_2 prices
- Regulatory uncertainty
- Environmental policies
- Generation siting

- Weather related resources
- Load and EVs

These will be discussed in more detail in the following sections.

5.3 UNCERTAINTY MODELING

Table 5.1 demonstrated the level (based on causes), the nature and the significance for each of the uncertainties in transmission planning. As mentioned in Section 3.3, due to resource and technical constraints, the modeler/planner has to decide on which uncertainties he/she has to focus and how these are going to be modeled. The former was addressed in the previous paragraph. This section will discuss how each of the most significant uncertainties should ideally be modeled in the context of transmission planning. First, the most widely used methods to address uncertainty in TEP will be discussed. Then based on the categorization of the several uncertainties based on their characteristics (level and nature) and taking into consideration resource and modeling constraints, the ideal way for representing uncertainty in TEP will be described. Ideally, a fully stochastic model would be desirable, though it is not feasible.

5.3.1 Uncertainty Management methods

In the literature, uncertainty has been addressed in several ways. (Buygi, Balzer, et al., 2004a; Chennapragada et al., 2006; R. Hemmati et al., 2013; Santos & Legey, 2013; Skinner et al., 2013; Uusitalo et al., 2015) have identified several clusters of techniques to deal with uncertainty. In general, uncertainties in TEP can be modeled in the following five ways depending on their level, nature and the available data: *Deterministic equivalent*, *Scenario analysis*, *Monte Carlo simulations*, *stochastic processes* and *mathematical-time series techniques*. Table 5.2 provides an overview of the main pros and cons of each method and Figure 5.1 illustrates visually their differences.

Table 5.2 - Pros and cons of uncertainty management methods

Uncertainty Management Method	Pros	Cons
Deterministic Approach	Fast, simple	Not robust
Sensitivity Analysis	Fast, simple, identify sensitivity of model outputs	May be misleading if used in optimization models (local VS global optima) Does not provide likelihood Ignores possible correlations (univariate analysis)
Scenario Analysis	Simple, Good for non-random uncertainties	Need post-processing for decision-making
Monte Carlo simulations	Solutions more robust, simple	Computational, do not account for non-historical values
Stochastic processes	Solutions more robust, Account for non-observed values	Complex, computationally intensive
Mathematical/time-series techniques	Good for short-term forecasting, identifying correlations	Depends on historical data “future depends on the past” concept

Deterministic equivalent is the simplest approach of all. The modeler recognizes the uncertainty but chooses to ignore it and represent the uncertain parameter or variable with a single value, usually the expected one. This approach can be useful in case where uncertainty does not have a big impact on the results or the dynamics between input and output is straightforward. On the other hand, deterministic models do not account for risk in the assessment and do not provide robust results. This method is not appropriate for variables with a stochastic character and big value range (Santos & Legey, 2013).

To handle uncertainty in deterministic models, sensitivity analysis approaches were developed. The main objective of sensitivity analysis is to examine how model outputs change when input data deviate from the original values. If the model outputs do not change significantly, the results are considered robust with respect to the examined input variables. Sensitivity analysis is widely used due to its simplicity whereas planners are interested to examine to which variables are the model results more sensitive (Tornado Diagrams). Usually sensitivity analysis refers to small changes around the original value. In optimization problems, this may be misleading if the original solution lies in a local instead of global optimum (Uusitalo et al., 2015). Univariate sensitivity analysis does not provide any information on the likelihood of any event and is unrealistic in the sense that it is not expected that only one thing may change. On top of that, univariate sensitivity analysis ignores possible correlation between variations in several parameters, which may over- or understate uncertainty (Refsgaard et al., 2007).

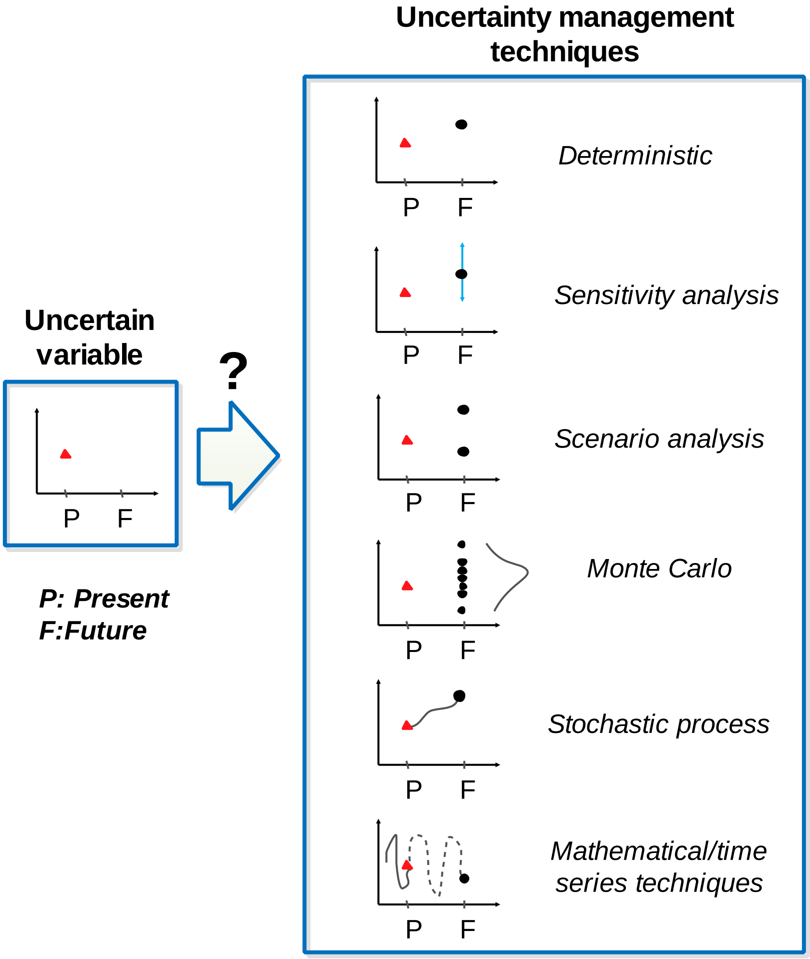

Figure 5.1 - Uncertainty management techniques (visualized)

Scenario analysis can be used when the possible instances of an uncertain variable in the future are known but there is no indication about their probabilities. It can be used to examine the impact of the results in "scenario uncertainty" level or "non-random" uncertainties. Usually, planners examine limited number of scenarios which can consist of several uncertain variables to explore different possible futures. Sometime probabilities can be attached to the scenarios as well. In a sense, scenario analysis can be a wider sensitivity analysis, although their objectives are different. The results obtained by scenario analysis are processed before being presented to decision-makers by using several decision analysis criteria as: minmax regret, expected cost, etc. The latter may lead to sub-optimal plans as well (Buygi et al., 2006).

In Monte Carlo, multiple values of an uncertain input variable are extracted from known probability distributions and then multiple deterministic simulations are performed based on these inputs. The obtained results also follow a probability distribution, which can be used for risk assessment. The main drawback of this method is that it requires a known probability distribution or sufficient historical data in order to approximate it. However, it should be stressed that Monte Carlo cannot be used for forecasting as it only uses past data to derive its values. In that case, extreme events which have not occurred yet (in the examined dataset), may not be captured by the Monte Carlo. Moreover, Monte Carlo simulations ignore possible (temporal) interdependencies that may exist between uncertain variables (e.g. load and temperature). In case a uniform distribution is chosen, Monte Carlo simulation can be used for uncertainty analysis. Uncertainty analysis is a wider sensitivity analysis or a multiple scenario analysis.

To overcome problems with temporal correlations and limited past data, stochastic processes have been developed (Weber, 2004). Stochastic processes differ from probabilistic methods in the sense that they are mathematical models that depict change of a random variable over time. The most common method is the mean-reverting process (Jun Hua et al., 2011; Qiu et al., 2014). Although stochastic processes require high running time, they are recognized as good techniques to capture the randomness of uncertainties with high variability. (Cedeño & Arora, 2011) have shown that transmission plans that considered uncertain conditions performed better than those that considered deterministic conditions.

Finally, econometric methods are used for forecasting reasons and can be either time-series (known as ARIMA) (Bazmi & Zahedi, 2011; Ruiz & Conejo, 2015) or regression models (Chamorro et al., 2012; Guo et al., 2012). Both depend on the existence of historical data. The former forecasts the future based on previous data in which the available time-series are processed (de-seasonalize, trend extrapolation etc.). These types of models are more useful for examining short-term uncertainties and not long-term, as they assume that the "future" will depend on "past" information (Liu et al., 2013; Prasad et al., 2014). Regression models identify correlations between uncertain variables based on historical data and try to examine the development of one based on the development of the rest.

5.3.2 Representing uncertainties in long-term TEP

Section 5.2 answered the question of "Which uncertainties should be addressed in long-term expansion planning?" in terms of significance to the model outputs. This Section (5.3.2) seeks an answer to "how these uncertainties should be addressed and modeled". Three aspects will be taken into account: (1) the classification of uncertainties in terms of level and nature (Table 5.1), (2) the characteristics of the available methods for managing uncertainty (Table 5.2) and (3) the most common practices in academia. A connection between these three aspects has been explored by (Skinner et al., 2013). In their paper they examined the several uncertainty classification methods proposed by academia and analyzed the characteristics of the uncertainties examined in environmental risk assessment. They found that 52% of the studies that examined uncertainty of "variability uncertainty" and that referred to future extrapolation and lied in the input data used Monte-carlo simulations, stochastic processes or sensitivity analysis. Also, 12% of the studies chose the deterministic method to manage uncertainty with the same characteristics. The assessment of uncertainties and the methods to be used in this section will be performed by category of uncertainty as they were provided in Table 5.1.

5.3.2.1 Market uncertainties

Since market uncertainties are driven by market fundamentals, they are of a "variability uncertainty" nature. In most cases historical data can be available and can be used to derive probability distributions of the uncertainties. Therefore, Monte Carlo, stochastic processes and econometric time-series methods may all apply. Capital costs are less variable than fuel costs, CO_2 prices and thus Monte Carlo or even just a simple scenario analysis with or without probabilities attached may be the best approaches (van der Weijde & Hobbs, 2012). However, for the dynamic character of fuel prices and CO_2 prices should be based on stochastic processes (Fuss et al., 2008; Vithayasrichareon et al., 2015; Yang & McCalley, 2010) or regression models (Möst & Keles, 2010). Although Monte Carlo is a simple method and has been used widely (Skinner et al., 2013; Uusitalo et al., 2015), it would not be able to capture values that go beyond historical data.

Strategic behavior and bids in the electricity market can also be modeled by stochastic processes. However, the level of uncertainty is even larger. In case of large-scale TEP models, modeling strategic behavior adequately would be quite difficult and would increase significantly the computation time. On the other hand, the added value of these techniques could be also under scrutiny and the outputs would be characterized by high uncertainty as well. Strategic behavior has been addressed in several TEP models in academia (Motamedi et al., 2008; Neuhoff et al., 2005) but still not commercially available or applicable in real-world systems. Other types of models, such as agent-based modeling (Veit et al., 2009) can be used instead.

5.3.2.2 Nature related uncertainties

For all the nature related uncertainties listed in Table 5.1 rich historical data can be obtained. These can be of high spatial resolution or in an aggregate level. In any case probability distributions can be obtained to simulate the expected patterns. Therefore, Monte Carlo simulation, time-series techniques and weather models can be used (Sansavini et al., 2014; Yang & McCalley, 2010). The latter are rather complex and sophisticated models and they are mainly used for short-term forecasting. Thus, they may not be appropriate enough for long-term models per se. However, since both PCMs and CEMs contain algorithms for short-term operations (ED-UC), they still could be used.

It is important to note that nature related uncertainties play an increasingly larger role in the transmission operations. Due to the EU's ambitious RES integration goals, the future electricity system will involve significant installed capacity of variable RES, which in turn will affect TSOs supply-demand balancing operations and therefore, the planning process. Accuracy in weather forecasts and representation of natural related uncertainty will be important.

5.3.2.3 Demand uncertainties

In the "Demand" category there is a clear distinction between the uncertainties. For the uncertainties placed in statistical level, historical data are available and probability distributions can be derived. For these uncertainties, econometric time series models can be used (Chennapragada et al., 2006; Wang & Hobbs, 2014) since past data can be used to provide information about the future. However, for the uncertainties placed in the scenario level, there is still no data available and little experience. Some of them can be addressed through scenario analysis (EVs growth) while others (EVs charging pattern) can be obtained through simulations and detailed studies (e.g. agent based models) (Liu et al., 2013). In the long-term it is expected that EVs, demand response and distributed generation are going to change significantly the load pattern, adding a variable character to it. Thus, the weekly/daily pattern could be modeled as stochastic processes or ARIMA models (Kiviluoma & Meibom, 2011). The latter models the fact that load is highly correlated with weather data due to renewable energy resources. On the other hand, the yearly load trend is less volatile[3] and can be addressed either through scenario analysis or time-series models.

5.3.2.4 Individual asset uncertainties

The uncertainties related to the production plants and investment plans of the generation companies are mostly of an epistemic nature. Thus, it could be reduced through information exchange between planner and producer. However, due to confidentiality issues, this is not really an option. Instead information can be obtained on the technical characteristics of the units by analyzing similar technologies and production units and reach to a case. The uncertainty associated with the technical characteristics can be approximated sufficiently through studies (public reports etc) and past experience. The forced and planned outages can be obtained through Monte Carlo (Jae Hyung et al., 2009), although the exact distributions are not known for the generation units. In case of real-world systems, approximations in technical characteristics accumulate uncertainty. However, it could be argued that the main purpose of long-term studies should be to explore the dynamics and possible future states than depicting accurately the system (Agusdinata, 2008; Kwakkel & Pruyt, 2013). The latter of course, would be preferable in case of unlimited resources and complete information, which is not realistic.

In case of investment plans, capturing uncertainty is more complicated. Since historical data cannot be used, the development of scenarios could be employed. However, this is not quite as straightforward as the driving forces behind generation investment plans are numerous. This could lead to a not so easily manageable set of scenarios. Since the driving force of generation investments can also be the transmission investments (Liu et al., 2013; Sauma & Oren, 2006), there is a feedback loop which further complicates the scenario-making process. This is the reason co-optimization models have been developed (see Section 4.3.5). These models address this uncertainty through an exploratory and iterative analysis of the dynamics of transmission and generation investments in the long run.

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[3] However, it is still correlated to the weather condition a heating of houses is nature depedent

5.3.2.5 Regulatory and Other uncertainties

The uncertainties in this category are of “variability” nature and “scenario” level. There are not enough historical data to project future conditions or explore correlations with other variables. Possible realizations of these uncertainties can be enumerated, although there is no indication about their probabilities. The most suitable approach is through the development of appropriate scenarios which cover the spectrum of different realizations.

“Other uncertainties” are deeper uncertainties and it is difficult to identify whether they can be reducible or not. In the case of long-term planning processes, these uncertainties could be assessed through a scenario analysis using expert judgment (Skinner et al., 2013; Uusitalo et al., 2015).

5.4 SUMMARY

One of the main criteria in evaluating modeling approaches in TEP of Chapter 3 was that the models should be able to capture uncertainty in decision making. The present chapter focused on this criterion and more specifically it tried to determine which uncertainties should be addressed in long-term transmission planning and how this should be done. The starting point of this analysis was the identification and classification of the uncertainties present in TEP. A thorough literature review was conducted to identify the uncertainties, which were categorized based on their causes. Market, nature related, demand, individual asset, regulatory, economic, modeling and other uncertainties were the main categories. These uncertainties were further classified by using a stylized version of Walker’s uncertainty matrix which focuses on the level and nature of uncertainty. In parallel, a literature review was performed to identify the most significant uncertainties in terms of their impact on model outputs. These were related to: Fuel prices, CO_2 prices, Regulatory uncertainty, Environmental policies, Weather related resources, Load and EVs and generation location. Then, the several methods for managing uncertainty in TEP were described and their pros and cons were listed. This enabled us to explore the most appropriate method for addressing significant uncertainties in the planning process. The whole analysis revealed that variability is the main characteristic of the variables in transmission planning. These variables significantly drive the economic assessment of the projects and thus, they should be addressed with methods that capture their dynamics. Stochastic processes, econometric time-series methods and Monte Carlo simulations have been widely used in literature to capture these uncertainties. The inadequacy of deterministic methods in future planning was revealed through a systematic analysis of the main drivers and characteristics of uncertainties. In cases where statistical and stochastic models are not applicable (e.g. lack of data), scenario making is still applicable. Variables with high level of uncertainty should be addressed through scenario analysis, where a wide spectrum of possible future realizations should be considered.

The next Chapter 6 will provide a brief overview of real-world planning processes. The planning process of ENTSO-E will be assessed by using the analyses of Chapters 3, 4 and 5 in terms of modeling tools and uncertainty analysis. Chapter 6 concludes by providing recommendations for enhancing ENTSO-E’s pan-European planning process.

6

Transmission Planning in Practice

6.1 INTRODUCTION

It is clear from Chapter 4 that a significant number of uncertainties has been addressed by academia in many different ways. Incorporating all these uncertainties to a high degree of detail in one model or one methodological approach is rather challenging or even impractical. Many of the studies were conducted using only parts of the real networks or network in an aggregate form. When it comes to full networks and their detailed long-term planning, the modeling effort and computation time increase exponentially (Liu et al., 2013; Meyers et al., 2011). That is the reason why many optimization algorithms for TEP problems developed by academia are still in research stage. Thus TSOs and other planners decide on their planning methodology based also on a trade-off between the number of uncertainties, the level of modeling and results detail on the one side and the costs and computation and set-up time of the model on the other.

The present section shifts the analysis from the academic field towards the business field. The long-term plans of three organizations will be analyzed: the European Network of Transmission System Operators for Electricity (ENTSO-E, 2014e), the Western Electricity Coordinating Council (WECC, 2013) and the Mid-continent Independent System Operator (MISO) (MISO, 2014) in the USA. All three of these organizations perform long-term and large-scale transmission planning studies. Their methodologies share some common characteristics but what is more important is their differences. The objective of this thesis is to provide recommendations for enhancing a pan-European transmission planning process. Thus, ENTSO-E will be the major point of discussion. State-of-the-art research in academia offered useful information for points of improvement of ENTSO-E's process in Chapters 4 and 5. Reviewing the state-of-the-art practices in industry will help to identify which of these improvements can be applicable to large-scale systems but also to pinpoint in which aspects research should be focused.

Two main aspects will be examined in the planning processes of ENTSO-E, MISO and WECC: 1) the modeling approach and planning methodology used and 2) the uncertainty analysis of every organization. Based on this analysis and the analyses of Chapters 4 and 5, some first recommendations for enhancing ENTSO-E's modeling approach are provided.

6.2 THE NON-BINDING TRANSMISSION PLAN OF ENTSO-E

The main objective of ENTSO-E's TYNDP is to "*ensure transparency regarding the electricity transmission network and to support decision-making processes at the regional and European level*" as it "*point(s) to significant investments in the European power grid in order to help achieve the European energy policy goals*" (ENTSO-E, 2014e). In the next paragraphs, the planning and modeling processes of TYNDP will be discussed, followed by an overview of their uncertainty analysis process.

6.2.1 Planning process and model support

In order to assess investment projects for the TYNDP, ENTSO-E uses a sequential modeling approach which utilizes the aspects of several types of models. According to this approach (Figure 6.2), first an economic assessment of the projects is performed by using a production cost model (PCM) (see Section 4.2) at a pan-European level and more "regional" level. In a Pan-European level all the countries-members of ENTSO-E (the so called perimeter) are included in the study. The results of these studies do not serve as final output of the TYNDP but rather as input for the scenario development phase and data consistency. The scenario development phase (see Section 6.2.2) provides the inputs for the regional market studies, which are those report in the TYNDP report as well. "Regional" refers to the six geographic regions in which ENTSO-E is divided: North Sea, Continental South West, Continental Central & South, Continental South Easy, Continental Central East and Baltic Sea (Figure 6.1). In this way, the problem (in matter of size) becomes easier to solve and can be more easily managed as it facilitates communication between TSO members.

Figure 6.1 - Structure of ENTSO-E regions (retrieved from (ENTSO-E, 2014e))

As Figure 6.2 shows, after projects have been assessed using several CBA indicators, network studies are performed. These are power flow and reliability studies. Again an assessment is performed with CBA indicators of technical nature (Table 2.1). In cases where an investment does not produce technically reliably results, the economic studies are performed again with some changes. The information flow between the economic and the technical studies goes mainly from the first to the second. In case where the examined project leads to technically unfeasible or unreliable results, the necessary changes in the assumptions are made and the economic studies are performed again. In this way, the sequential approach of ENTSO-E incorporates an iterative process.

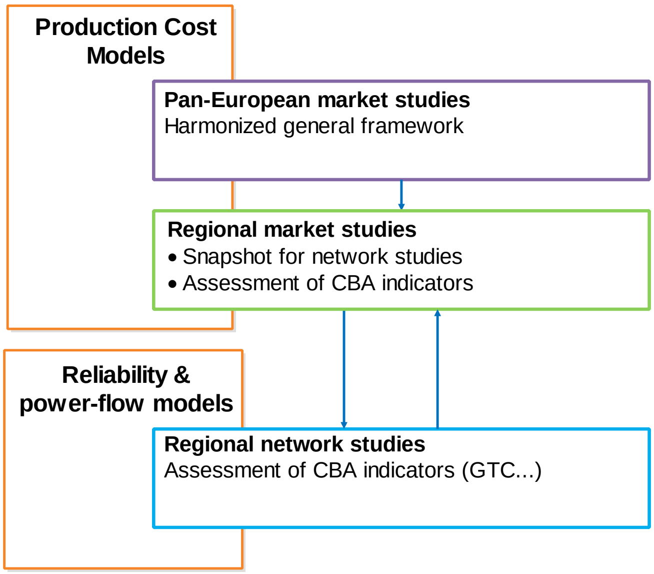

Figure 6.2 – Steps of the modeling process of TYNDP (from (ENTSO-E, 2014e))

As it was discussed in Chapter 4, both technical models and PCMs are evaluative in nature and do not have the capability to produce investment plans endogenously. ENTSO-E examines one future year to examine the investment projects (in this case 2030). In addition to the CBA framework, ENTSO-E has developed two heuristic approaches to identify possible projects. More specifically, ENTSO-E measures the change in CBA indicators when a system change is occurred. There are two approaches for imposing a system change (an investment project) and evaluate it: the Put IN one at the Time (PINT) and the Take Out One at the Time (TOOT) (Figure 6.3). In first case the candidate investment is evaluated by the change it brings to the system when it is added to that (a reference case), whereas in the second when it is taken out (from a reference case which includes many other projects). Currently, ENTSO-E uses the TOOT approach for the assessment of the projects in its plan and proposes PINT to be used for individual projects evaluated e.g. by TSOs (ENTSO-E, 2014e). The TOOT approach is preferred as it evaluates every project without taking into consideration the order to investments. ENTSO-E has developed several rules on this heuristic approach (e.g. regarding competitive projects).

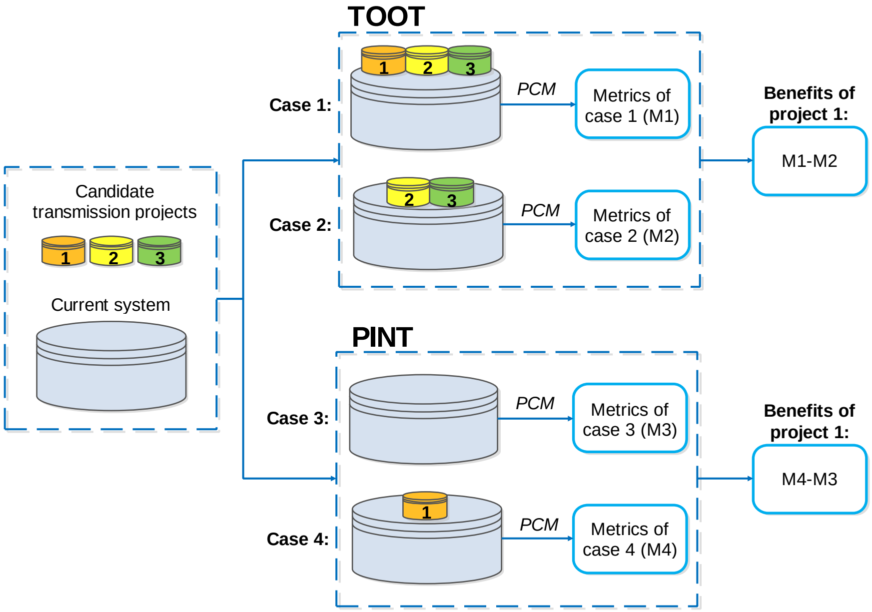

Figure 6.3 - Schematic representation of TOOT and PINT evaluation approaches of ENTSO-E

Two points should be noticed at a modeling level in ENTSO-E planning approach. The first concerns the network representation in each of the studies. In the economic studies with PCMs, the network under study is modeled in a highly aggregated level where every country is represented by one node. These nodes are seen as “copper plates” which means that no internal congestion within the countries is assumed. The nodes are connected between each other through lines that represent the interconnections between countries. The TYNDP-2014 of ENTSO-E included 38 nodes for 34 countries. One node was attached to every country except to Denmark (2 nodes), Luxemburg (3 nodes) and Italy (2 nodes). On the other hand, the power flow model, which is used to identify bottlenecks in the grid, contains a detailed representation of the network topology with all the bus-bars, switches and PSTs (Phase Switch Transformers) either in Direct Current (DC) or in Alternative Current (AC). To illustrate, 6.000 nodes and 10.000 grid elements are included in the Continental Europe model (not including the Baltic and North Sea) (ENTSO-E, 2014e).

The second point for discussion is the information flows when shifting from PCMs to technical models. PCMs provide hourly data for the examined year of power flows between countries and production schedules. In order to serve as input for the network studies, these data have to be disaggregated into the nodes of the detailed system. However, the technical studies do not utilize all 8760 hours of data. Due to computational limits in AC networks, simulations in network studies are performed for specific planning cases. These planning cases (20-30 in number) concern specific moments during the year where the transmission system can be under stress, as in cases of high load periods, low hydrological conditions etc. ENTSO-E uses the approach of planning cases[4] due to the size and complexity of the system under study (trade-off between information accuracy and simulation time).

6.2.2 Uncertainty Analysis and Decision-making Support

The first stage of every TYNDP study cycle is scenario making, the future context that investments will be evaluated at pan-European and regional level. This is the main technique that ENTSO-E uses in decision-making under uncertainty, as almost all fundamental uncertainties are addressed through scenarios. These scenarios are developed for the common Scenario Outlook & Adequacy Forecast (SO&AF) for the ENTSO-E network area, which is complementary to TYNDP and it has been published biannually since 2010 (ENTSO-E, 2014b).

6.2.2.1 Scenario objectives and narratives

Since 2010, the methodology followed in SO&AF is constantly changing in several aspects, such as the number, the purpose and the quantification of the scenarios. The major change in the conceptualization of the scenarios occurred in the 2012 where the purpose of building scenarios[5] turned from being predictive in nature to being more exploratory (ENTSO-E, 2014e). This was motivated by Regulation (EU) 714/2009. This change alone constitutes a significant step of improvement in scenario analysis. Recognizing the difficulty in forecasting in the long-term horizon, ENTSO-E hopes now to “explore all the possible futures” (ENTSO-E, 2014e).

Another aspect that actually shapes the general context of scenario narratives is the distinction of a top-down and a bottom-up approach. This distinction was first conceived in TYNDP2012 and has been implemented since then (TYNDP 2014 and 2016). The distinction becomes clear if we consider the TSOs as the decision-making actors in the bottom layer and ENTSO-E and EU Commission in the top-layer. Currently, the national plans are the ones that shape the future of the grid in Europe and the bottom-up approach is dominant. As mentioned in (Chapters 1 and 3), EU Commission’s objectives on market integration and co-ordination between countries for achieving RES and other targets push towards a top-down approach. That is the reason why ENTSO-E explores it.

The scenario storyline follows a common practice in scenario building where the scenarios are based on a two axes scheme. The axis selection was influenced by the top-down / bottom-up approach as well. In TYNDP 2014 the two axes represent the degree of integration of the European electricity markets (x-axis) and the degree of renewables penetration (y-axis). The four quadrants created form the four scenarios of ENTSO-E. Their narratives had the objective to make the scenarios distinctive in four main categories: Economy and Market, Demand,

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[4] They are mentioned as “Points-in-Time” in TYNDP2014

[5] ENTSO-E often mentions the scenarios as “Visions” to indicate their exploratory nature

Generation, Grid. Based on these narratives and several workshops with internal and external stakeholders, the scenarios were quantified. Table 6.2 provides an overview of which and how uncertainties are incorporated in ENTSO-E scenario analysis as ENTSO-E provides it in TYNDP 2014. It is evident that except demand side response and fuel and emission prices, all the other uncertainties are "inputs" to derive the generation and demand profiles (Figure 6.4). These profiles will be inputs to the PCM in the next study phase.

It should be noted in this point that the current TYNDP 2016 study cycle shifts to several improvements as far as the derivation of the top-down scenarios is concerned. In the last study cycles the allocation of RES units across the ENTSO-E perimeter or the optimization of the production of the thermal units was done based on heuristics rather than an analytic approach. The methodology has now changed and includes optimization algorithms which are based on the costs and resource potential of every region. Although this will not be discussed in detail in this thesis (TYNDP 2016 has not been published yet), it is good to have it in mind as this process resembles the practices of CEMs.

To be able to compare the findings of Chapter 5 with ENTSO-E's approaches regarding uncertainty analysis, the following paragraphs will describe ENTSO-E's practices per uncertainty category.

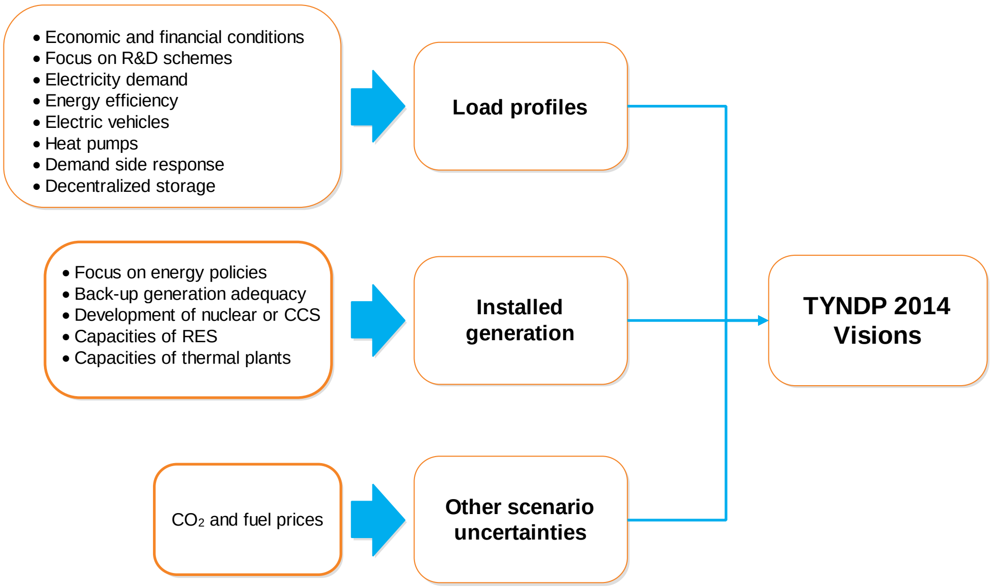

Figure 6.4 - Process of TYNDP 2014 Vision construction

6.2.2.2 Market uncertainties

Capital costs of generation are not taken into account from ENTSO-E as they do not serve as inputs in PCMs but only in CEMs. ENTSO-E examines only the operational and not the investment costs of production. Transmission costs are considered as deterministic values with high degrees of confidence, as they have access to relevant information. Fuel availability and strategic behavior are not modeled in ENTSO-E's planning approach. Fuel and CO_2 prices are addressed by the above mentioned scenarios. More specifically, only two values are considered for CO_2, coal and gas prices in the four scenarios and one for nuclear prices. The combinations of prices are identical for Visions 1 & 2 and for Visions 3 & 4. The assumed values have been derived by the International Energy Agency (IEA) and have been adapted accordingly to assure that there is a shift in the merit order through the scenarios.

Table 6.1- TYNDP 2014 scenarios on fuel and CO_2 prices

Price	Vision 1	Vision 2	Vision 3	Vision 4
CO_2 (€/Kg)	0.031	0.031	0.093	0.093
Hard coal (€/GJ)	3.48	3.48	2.21	2.21
Gas (€/GJ)	10.28	10.28	7.91	7.91

6.2.2.3 Nature-related uncertainties

ENTSO-E models the variability of wind and solar resources by using historical data on capacity factors. These data are of hourly temporal resolution and country-level spatial resolution. Although the data consist of capacity factors per country for the last 12 years, these are not used to derive probability distributions or ranges of uncertainties. Instead, market simulations are performed by using one (usually the most representative) or more years as a reference case.

6.2.2.4 Demand uncertainties

The demand profiles for every scenario are derived by modifying an initial hourly load curve under several assumptions. The hourly load curve is based on historical data. Again, a single load curve is considered the starting point. The modifying assumptions are most commonly reductions or increases in the level of demand or peak consumption formulated as percentages. To illustrate, assumptions on future developments in energy efficiency, peak shaving due to storage, the impact of EVs and heat pumps on the consumption pattern, changes in economic and financial conditions or even the tendency to focus on R&D schemes are used to derive the one and only demand profile that will be used for the simulations. The percentages used differ per scenario and have mostly been derived through workshops with TSO and other experts in order to follow the scenario narratives. The charging profile of EVs is taken as standard through the year.

6.2.2.5 Individual asset uncertainties

The process of deriving the future installed generation capacities is again derived through scenario analysis. There is not a concrete and analytic process in place to derive the generation capacities. For every scenario, guidelines lead the TSO experts to construct the future generation mix, given the current situation. These guidelines are consistent with the scenario narratives. To illustrate, taking into account that in Vision 3's future, the installed RES capacities are higher than in Vision 1, ENTSO-E proposes that there should 100 MW of offshore wind installed in European level in Vision 3 and 80 MW in Vision 1. The same logic is followed with the thermal plants where assumptions concern the type of the fossil plants to be constructed (e.g. gas instead of oil), whether new nuclear power plants are going to be constructed, percentage of increased in installed capacity etc. Thus, ENTSO-E does not account for the timing of the installed capacities until the examined year.

In this point it should be noted that an important step in deriving the installed capacities is the top-down and bottom-up approach. In fact, the overall generation profiles in Vision 1 do not differ significantly with those in Vision 2 and the same hold for Visions 3 and 4 (Figure 6.5). This happens because the installed capacities in the top-down scenarios (Visions 2, 4) are derived from re-allocating resources of Visions 1 and 3 between countries to achieve minimum system production cost and lower reserve levels. The logic behind this approach is consistent with the storyline of Visions 2 and 4 that a pan-European top-down planning and collaboration between countries will allow for lower system costs. The re-allocation methodology was at initial stage when it was first performed for TYNDP 2014. For the forthcoming TYNDP 2016, ENTSO-E shifted towards a more analytical methodology that involves optimization algorithms based on specific production costs.

Regarding the other asset related uncertainties, ENTSO-E clusters the generation units according to their fuel type and age and assumes constant values for the technical and economic characteristics. Forced and planned outages for generation units are modeled through Monte Carlo simulations given a percentage of occurrence. Transmission outages are not modeled as PCM does not represent the physical transmission system.

6.2.2.6 Regulatory and other uncertainties

Changes in the regulations or technological breakthroughs are not directly accounted for in ENTSO-E uncertainty analysis. The distinction between top-down and bottom-up scenarios could be assumed to examine regulatory uncertainty in terms of coordination of the regulations. Regarding interactions with neighboring power systems (not ENTSO-E member countries), ENTSO-E uses fixed values based on historical data on these exchanges or data produced from separate studies of reduced perimeter (this is performed prior to the main analysis).

According to (ENTSO-E, 2014e) next to scenario analysis, a sensitivity analysis could be performed on the demand forecast, the fuel costs and CO_2 price, the discount rate and the commission date of the project.

Table 6.2 - Uncertainties in ENTSO-E scenario analysis

Uncertainty	How?
Economic and financial conditions	They are reflected in the growth rate of electricity consumption: higher economic growth→ higher electricity consumption
Focus of energy Policies;	Distinction between top-down (V2, V4) and bottom-up scenarios (V1, V3).[6] This difference was reflected in the generation capacities that are set in each scenario per country
Focus of R&D schemes	Reflected in additional energy efficiency. This results in reduction of demand.
CO_2 and fuel prices	Based on IEA scenarios V1, V2: IEA World Energy Outlook 2011, Current Policies V3, V4: IEA World Energy Outlook 2011, 450 scenario, year (2030, 2035)
Electricity Demand	% change from base case (hourly load curve)
Energy Efficiency	% change from base case (hourly load curve)
Electric vehicles	% of penetration that impacts the hourly load curve given assumptions on projected population, EVs/population and load pattern of EVs
Heat Pumps	Same logic as EVs
Demand Side Response	DSR is modeled as fictitious generation peak units that start when prices rise and before actual peak units in the system start (TYNDP, 2014, p.39)
Back-up generation/adequacy	Assumptions on generation are adapted accordingly so as to achieve low/high levels of back-up capacity
Development of Nuclear or CCS	Based on given direction (e.g. assume that is new facilities are built/not built etc)
Capacities of RES	Relative % increases from current state (onshore wind, ocean, RES Hydro, biomass/pellets/waste Given installed capacities(e.g. 100 MW) for Offshore wind, solar Indication for consistency: NREAP, EU2020
Capacities of thermal plants	Based on given direction (e.g. assume that is new facilities are built/not built; 80% of new fossil plants tend to be gas plants etc)
Decentralized Storage	They are assumed to satisfy a given % on the peak load (4-8%) in V1. Assumed to be installed capacity with duration of one hour. (guidelines V1-3 p.32)
Smart Grid Solutions	This is reflected in the EV penetration, directions for storage and generation capacities; interconnections. No extra modeling effort or assumptions are made

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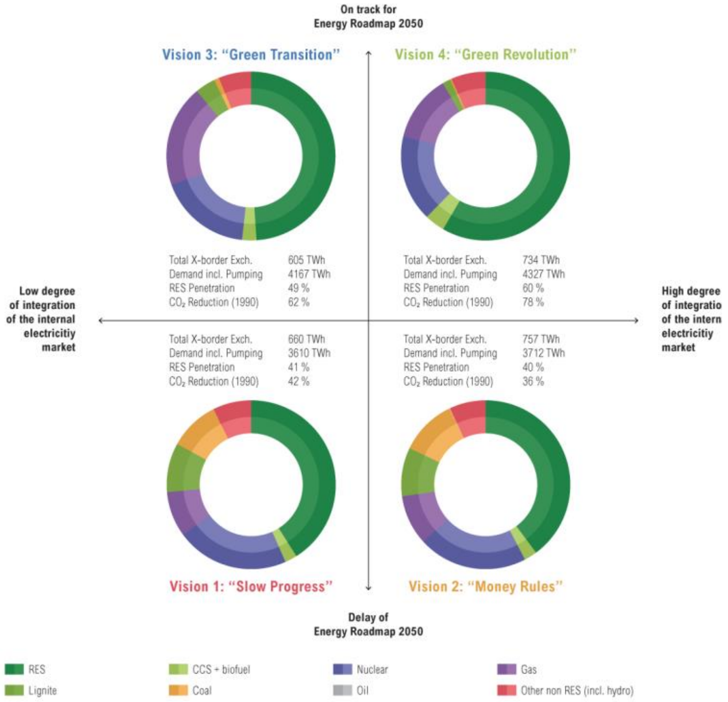
[6] The bottom-up scenarios are nationally constructed, and thus show less European energy policy focus. On the other hand, top-down scenarios set the conditions that would arise if there were strong implementation of EU policies

Figure 6.5 - Generation mixes per scenario of ENTSO-E (retrieved form (ENTSO-E, 2014e))



6.3 COMPARISON WITH MISO'S TRANSMISSION EXPANSION PLAN

The 10-years transmission expansion planning process of MISO resembles to some point that of ENTSO-E (MISO, 2014). Common methodological steps can be found in both uncertainty analysis and model use. Regarding the former, both organizations use scenario analysis for capturing several of the uncertainties and use probabilistic methods only for simulating the outages in the generation capacity (Monte Carlo). The models and the types of studies that MISO uses are the same as ENTSO-E: economic studies using PCM and technical studies for measuring the reliability and the congestion of the grid.

The most striking differences between the two planning process have to do with how each organization draws the future installed generation capacity. In a sense, MISO's approach is more automated than the one followed by ENTSO-E. In contrast to ENTSO-E which derives the installed capacity based on directives and guidelines (with correction of adequacy report), MISO uses a generation expansion planning model (EGEAS). This model is similar type to the capacity expansion model for transmission that it was described in Section 4.3 but for generation. It provides an aggregated, least cost plan on installed generation capacities per year taking into account capital costs, demand, emission costs, retirements, reliability standards and renewable energy targets. Here lies also the difference between scenario analysis of ENTSO-E and MISO, in which the capital costs of generation are included and capture possible developments in the technology or attractiveness of every generator.

The second difference regarding the methodology of determining the installed capacities has to do with the siting of the generation plants. The generation capacity plans of EGEAS are not location specific. MISO has a siting methodology to assign every resource to a specific bus in the system (state and region) by using GIS software and several siting guidelines based on several mandates and permits. Based on these results, MISO expert identify possible transmission candidate investments and evaluate them through different scenarios. The investments that are robust in most of the scenarios are chosen for the final plan.

6.4 COMPARISON WITH WECC'S TRANSMISSION EXPANSION STUDIES

The latest cycle of long-term transmission expansion studies of WECC included significant changes in the methodology and which differs significantly from the ones already described. WECC's methodology is close to both types of models (CEM, PCM) described in Chapter 4 and it is the only one that implements it in such a large scale. More specifically, WECC's long-term studies concern two parts: the 10-years ahead transmission planning and the 20-years ahead. Each of these study horizons uses different models, data and assumptions. Their only connection is the information flow: the result of 10-years ahead serves as a starting point for the 20-years ahead. The main reason for this change in the methodology is that "*WECC recognizes the increased uncertainties in 20-year-ahead horizon*" and adapts accordingly the models and reason they are used (WECC, 2013).

The 10-years ahead studies use a production cost model developed for WECC. It is a common UC-ED like the ones used in ENTSO-E and MISO and its focus is to examine capacity addition on specific projects. The interesting thing is that WECC does not perform dispatch over a range of possible future scenarios but simulates only one scenario. This scenario (called as "Common Case") is the trajectory of the WECC region in the next 10 years and is developed through workshops and stakeholder meetings. The final results were examined for uncertainty through sensitivity analysis on natural gas prices, hydro conditions and load. No other fundamental uncertainties were taken into consideration. These were accounted for the 20-years studies. Based on their results, information can flow back to the 10-years studies and adapt the derived plan.

The CEM of WECC (called as Long-Term Planning Tool-LTPT) has the focus to help decision makers understand "potential energy future and decisions needed to achieve those futures". It consists of two models which are simulated under several scenarios: the Study Case Development Tool (SCDT) and the Network Expansion Tool (NXT). The scenarios are based on several policy, technological and economic developments as well as environmental considerations. They are defined by a scenario matrix set by the axes: Technology Innovation in Electric Supply and Distribution (x-axis) and Economic Growth in WECC region (y-axis). These axes are completely different from the ones in ENTSO-E. Both MISO and WECC pay attention of future technological costs in their scenario analysis.

Based on the scenario narratives and quantification, the SCDT optimizes generation planning by incorporating resources into the system with the result of 10-years study results as a starting case. The resources are incorporated based on several policy and technical constraints (reliability, adequacy etc.). Given that WECC draws an interregional plan for each member state, the policy constraints are satisfied in 4 layers: Local policy goals (RPS targets etc), generic policy goals (no-location specific), system energy goal (resources to meet load demand), system peak demand goal (resources to meet peak demand). After a generation plan has been initiated, NXT performs a transmission system optimization to create a feasible alternative. It makes use of MILP in a simplified (in term of system representation) DC power flow model with Branch and Bound as the solution method. The investment costs on transmission and generation are used for LCOE adjustment in the production units. This is an iterative process which continues until resource and transmission selections are not changing from one iteration to the next. Finally, the obtained system is examined under several system cases regarding load such as heavy summer, winter etc.

Apart from these models, WECC uses several ancillary its studies. Among them models for creating hourly profiles of solar and wind resources, technical models (steady-state and reliability models) and models for determining the behavior of hydro generators.

6.5 DISCUSSION ON ENTSO-E'S PLANNING APPROACH

The analyses in the preceding Chapters regarding modeling types (Chapter 4) and uncertainty analysis (Chapter 5) in combination with the analyses of ENTSO-E's, WECC's and MISO's planning methodologies, reveals that there are still points of improvement in the TYNDP study cycle. This section will discuss which points in ENTSO-E's methodology should be reconsidered and why. More specifically, ENTSO-E's objectives in comparison with its current practices will be examined. This will lead to the recommendations of the next Section 6.6.

6.5.1 Selection of modeling type

Section 4.4 discussed the major benefits of capacity expansion models instead of production cost models for transmission expansion planning. ENTSO-E's objective to examine a top-down policy driven plan does not align with its model selection. The fact that TYNDP is currently a non-binding plan, allows for further exploration and improvement in the process. Its studies should concentrate on answering prescriptive and exploratory questions rather than evaluating future conditions with PCMs. The choice of the latter offers them a rather static solution in which many aspects are derived through scenario analysis. Using CEMs would offer ENTSO-E the ability to examine possible roadways to meet EU targets. Since the analysis focuses on multiple years and not on a single one, flexible plans could be developed and explored. Moreover, using CEMs would offer a systematic selection of projects rather than the TOOT approach which ignores the timing of the investments. The high temporal resolution and the computational time should not be a problem for ENTSO-E as it already moves to such simplifications. TYNDP's network studies perform simulations only a limited number of cases (point-in-time). Moreover, the case of WECC has demonstrated that a real-world application is feasible.

On the other hand, if a transition to a new modeling type is not yet applicable, the current method could be enhanced. Studies on PCMs could be performed for several years to depict the dynamics, whereas the selection of projects under study could be performed automatically (Lumbreras et al., 2014) and not with the TOOT approach. Moreover, the representation of the network in the PCM of ENTSO-E could be more detailed to capture the internal congestion. More nodes per country could be modeled depending on the regions, the network characteristics and the pricing zones (Lise et al., 2008).

6.5.2 Deriving future generation capacities

The second main point for improvement concerns how ENTSO-E derives future generation capacities. Currently ENTSO-E derives these capacities based on national plans and several guidelines depending on each scenario narrative. There is no analytic way of deriving them and the generations investment costs are ignored. As shown both MISO and WECC have such analytical methods to derive future capacities: either generations-only resource planning models or co-optimization models. The first needs also a GIS software for determining the siting of the new generation capacities and it is preferred when a PCM is used (installed capacities are set as input in the model). The latter identifies the location of the generation capacities endogenously and in response to transmission investments.

In the TYNDP 2016 study cycle, ENTSO-E has recognized the need to perform resource planning analytically. It has developed an optimization algorithm to re-allocate the RES generation capacities of bottom-up scenarios based on the costs per country and the RES potential in order to derive the top-down ones. This is an improvement but it only happens at the study year and does not lead to a different scenario in terms of generation. Therefore, at a system level the changes are marginal. The next step for ENTSO-E should be to develop a model to provide it with generation capacities through the years. Recent research on CEMs that support co-optimization between generation and transmission (like WECC's model) has showed the benefits of such models in exploratory studies (Liu et al., 2013). Such a method could be quite insightful when a top-down planning approach is concerned. Compared to the current process, both options require some investment by the side of ENTSO-E and several data structures to set the layers for possible siting of new generation sources. However, a systematic resource planning methodology can facilitate ENTSO-E's top-down approach and its network studies.

6.5.3 Co-optimization of electricity transmission with other systems

Both EU Commission and ENTSO-E have recognized the necessity to move towards an integrated system planning, one that will incorporate many sub-systems in the European power system (ENTSO-E, 2014a). ACER has suggested for alignment and further collaboration of ENTSO-E and ENTSO-G in their TYNDP. The first steps in this collaboration involve information exchange between these two organizations. However, there is still significant room for improvement in designing a research methodology that will combine the two planning processes.

This could be facilitated by CEMs that perform co-optimization of these two networks. Such models take into consideration the synergies that may exist between the gas and electricity transmission networks. This can be more efficient than designing a complex methodology that has as a basis information exchange in several steps of the process but also more effective as feedback information loops are endogenous in the models.

Recent research on CEMs that support co-optimization between generation and transmission (like WECC's model) has showed the benefits of such models in exploratory studies (Liu et al., 2013). Moreover, there are quite insightful when a top-down planning approach is concerned. Currently ENTSO-E draws 4 scenarios, 2 of which are based on bottom-up plans and 2 on top-down. These top-down scenarios are derived by re-allocating the resources of the bottom-up. Therefore, at a system level the changes are marginal. Co-optimization in CEMs performs this endogenously along with transmission investment and seems more appropriate for ENTSO-E's study objectives.

Apart from the benefits of co-optimization models described in Section 4.3.5, there can have an additional advantage that generation resource planning is also endogenous to the model. This is also a significant improvement to ENTSO-E's approach on deriving the future installed capacities and it will be discussed in the next paragraph.

6.5.4 Scenario Analysis

The main technique for uncertainty analysis within ENTSO-E is scenario and sensitivity analysis. This is a common technique in plans of other large scale systems as well, due to its simplicity. With its 4 scenarios ENTSO-E wants to capture and examine a "wide spectrum of future possible conditions" (ENTSO-E, 2014e). However, their analysis (top-down VS bottom-up) does not utilize all 4 scenarios but rather 2 basic scenario and 2 slightly different versions. These limited ranges were the outcome of several workshops with TSO experts and can be explained by the fact that people make future projections based on past data. Especially for random uncertainties, this cannot always be true.

The underutilization of the 4 scenarios can be reduced by detaching scenario making from policy objectives and goals. This will also boost the exploratory and prescriptive nature of the TYNDP study: instead of asking "What will happen if we do this?" the question can be "If these happen, how do we reach our objectives?". Currently, the x-axis in scenario matrix represents the "degree of market integration" and is used to capture the top-down and bottom-up approaches. If instead, this axis was replaced by another major uncertainty such as technological breakthroughs (capital costs for RES or thermal generation), then the possible future conditions could be set wider. The top-down analyses could be performed in addition to these scenarios or could be done endogenously with the use of CEMs, as discussed in previous Section.

6.5.5 Uncertain parameters

As discussed in Chapter 5, not all variables should be examined by scenario analysis. Many of the examined variables in ENTSO-E's modeling approach have or will have a stochastic behavior in the future. These are fuel prices, weather data and load, and will play an important role in future power systems.

Fuel prices are variables that are modeled in a stochastic or probabilistic way in academia or other studies and they constitute a significant factor that determines the merit order to the generation units (Cludius et al., 2014). For long-term studies of a Pan-European level, differences in prices within the examined year are not very important. Therefore stochastic behavior of the fuel prices is not necessary. It is, however, useful to perform a Monte Carlo analysis for a range of fuel price combinations so that their influence to the model results is examined. Since production cost models are the main basis for the economic analysis of candidate projects, fuel prices play an important role in the results and have to be examined with more than a scenario analysis of 2 possible values for the prices.

Weather data or data on capacity factors of RES (solar, wind offshore and onshore) may seem to not have a significant impact on today's studies. However, since in all future power system situations, installed RES will constitute a significant percentage of the total installed capacity (Brouwer et al., 2014), the variability of the weather conditions will significantly influence the model results regarding generation mix and consequently, production costs. Currently ENTSO-E holds historic weather data for last 13 years but performs simulations with only one of them, the year that seems more "representative". Again, it is probably time constraints that underutilize such rich weather data in ENTSO-E's studies. What could be done instead would be to use these data to stochastically derive one study-year that would serve as input to PCMs (van der Weijde & Hobbs, 2011). The data of this year will not be identical with any of the past years but will utilize all their information. There are many complex models that can perform such a task or even simpler ARIMA models. In any case, it would be beneficial to also focus on the analysis of weather profiles along with their long-term studies, in a similar way to that of WECC (in collaboration with NREL).

Finally, the logic in constructing the load profiles should account also for variability (Sansavini et al., 2014). Currently, ENTSO-E derives load profiles by incorporating the effect of energy efficiency, EVs and storage to the current profiles in a static way. In the future, the effect of EVs and decentralized production are expected to change current load patterns to a great extent. Stochastically deriving load profiles within PCMs may be computationally intensive within ENTSO-E's studies. However, these profiles can be derived separately and used only as inputs in PCMs, resulting in the same processing time. No matter how it is going to be done, ENTSO-E should pay more attention to deriving future load profiles, and there are many studies in academia that can show the way.

6.5.6 Data exchange/structures

All the above suggestions require a great collaboration between the TSO members and ENTSO-E. The databases of ENTSO-E are continuously improving so as to assure that data exchange can be performed efficiently and that the process is transparent. Both objectives still have space for improvement, which is understandable due to the relatively recent operation of ENTSO-E. In terms of data exchange, the lack of data of contemporary system conditions of the member countries is striking. Currently only the system conditions in a Vision level are known, even to the member TSOs. In terms of transparency, ENTSO-E provides only the final results and some scenario assumptions, such as prices and total installed capacities. Neither the way the scenario narratives are transformed to hard data nor the generation capacity assumptions are publicly available. Compared to practices in US, where all the assumptions and input data are publicly available for any concerned party, this is a main drawback. Maybe the most significant one is that there is no feedback towards ENTSO-E that could improve their process.

In any case, long-term planning studies are data intensive and both ENTSO-E and TSO members should cooperate to build and maintain such databases. Given the suggestions of the previous paragraphs, the databases of ENTSO-E should include data on the categories given in Table 6.3. Extensive timeseries or information that is not easily available (confidentiality issues) are needed. In general, the following data are needed for a complete transmission planning process.

Table 6.3 - Required data structures for Transmission Expansion Planning (adapted from (Liu et al., 2013))

Categories	Required Data	Comments
Historical conditions	Hourly load & variable generation data Fuel prices Hydro conditions Bilateral transactions Generation (forced & planned) outage rates Transmission maintenance histories Inflation and discount rates Reserves for system adequacy Contingencies Imports and exports	Data for previous N years, load and variable generation data should be correlated with weather conditions or be weather normalized
Existing and planned infrastructure	AC network topology, AC circuit data, DC line data, fossil & renewable generation data, storage and demand response existing long-term bilateral contracts, contingencies (N-1 & N-1-1)	
Resource options	Generation, storage, demand response, and their maturation rate	Investment and operational characteristics of each option, geographical dependence of data
Transmission options	AC line, DC line, transformer, circuit breaker and voltage control equipment	Investment and operational characteristics of each option,

		candidate transmission investments
Future conditions	Forecasted system conditions, bilateral contracts, global scenario descriptions (policy, technology or load related)	Depends on planning horizon (with suitable end effects calculation), employ technique to choose a good set of global uncertainties

6.6 RECOMMENDATIONS FOR ENTSO-E'S PLANNING APPROACH

Chapter 6 discussed the methodology of ENTSO-E in its non-binding transmission expansion plans. The main limitations and advantages of its approach have been discussed throughout this thesis. The present section will briefly address these limitations again and will identify points of improvement. The alternatives to ENTSO-E's approach were discussed in the literature review of this thesis. Chapters 3, 4 and 5 and described the major developments in uncertainty analysis and model support in transmission expansion planning, both from an academic point of view and business practices. These alternatives will be filtered to match ENTSO-E's objectives and resources (costs, etc).

Below are listed the suggestions for further enhancing ENTSO-E's process to meet with the rising uncertainty in the field of transmission planning. These suggestions concern two aspects in ENTSO-E's planning methodology: the modeling approach, uncertainty analysis and the cooperation with member TSOs. These are:

- ENTSO-E should take into consideration recent developments in the long-term planning models and change its study methodology. ENTSO-E's top-down planning process should be performed in an analytical way by using Capacity Expansion Models instead of Production Cost Models and heuristics.
- Future installed generation capacities should be derived through an analytical process and not by using guidelines based on scenario narratives. The scenario parameters could be used as inputs to Capacity expansion models for generators (like MISO) or for generation and transmission co-optimization models (like WECC)
- ENTSO-E's planning should focus on utilizing co-optimization tools either for investigating the dynamics between generation and electricity transmission but also the interdependencies of gas transmission and electricity transmission networks.
- ENTSO-E's scenario analysis approach should be reconsidered. The scenario axes should be unbundled from the policy objectives, which leads to the "top-down"/"bottom-up" approaches. Instead, the scenario axes should represent fundamental uncertainties (such as technology growth).
- ENTSO-E's modeling approach should explicitly take into consideration the stochastic behavior of fuel prices, CO_2 prices, weather data and load and model them accordingly: Monte Carlo, time-series, stochastic processes.
- ENTSO-E should increase transparency in the whole TYNDP study cycle by sharing information and relevant data with the public. In parallel, it should develop and maintain databases with the member TSOs, so as to develop further its planning process.

PART III

Quantitative analysis

7

Model conceptualization

7.1 INTRODUCTION

The analysis in the previous chapter (Chapter 6) revealed that there is still room for improvement in the current transmission planning process on cross-border investments within the Europe. These improvements concern changes in both the modeling type and uncertainty analysis followed. A possible transition will require significant effort and time to be fully completed. A reasonable question is whether ENTSO-E would be willing to devote resources and time in changing the incumbent methodological regime or not and if yes, how is this going to be implemented. The answers to these questions lie in ENTSO-E's practices in TYNDP study cycles. Changes in both modeling types (Section 6.2.1) and uncertainty analysis (Section 6.2.2) in the last TYNDP study cycles, although incremental, reveal the disposition of ENTSO-E for continuous improvement. However, any improvements are likely to happen in stages (per study cycle) rather than in all-in-one step. Given the computational challenges of the CEMs and co-optimization models as well as the lack of previous experience with them (European TSOs rely mainly on PCMs for transmission planning) makes it hard to shift towards CEMs at the current stage. Therefore, changes in the uncertainty analysis methods are more likely to take place first.

The present thesis will attempt to implement some of the suggestions as demonstration cases. The results of these cases will feed back to the recommendations of Chapter 6, this time through quantitative analysis. Given the reasons mentioned in the previous paragraph and due to time and resource constraints, the quantitative analysis will mainly focus on the uncertainty analysis part of the modeling approach. Thus the examination of co-optimization and CEMs is left outside the scope of the quantitative part. The main objective of the simulations will be to illustrate to compare the current approach with an approach in which some of the suggestions are included.

Section 7.2 provides an overview of the simulation methodology followed. More specifically it begins by laying down the parameters that will be examined and why and then it describes how the simulation sets are constructed. Section 7.3 is concerned with the input data and the main assumptions made in the simulations. The chapter ends with Section 7.4 in which several tests are performed to examine the validity of the model. The results are demonstrated and analyzed in Chapter 8.

7.2 SIMULATION METHODOLOGY

7.2.1 Parameters under examination

In Sections 5.3.2 and 6.5.5 it was argued that modeling fuel prices, CO_2 prices, weather data and load profiles deterministically is not adequate. Section 6.2.2.1 discussed how scenario analysis in TYNDP is limited to two main scenarios in case of fuel and CO_2 prices as well as the generation profiles (top-down scenarios similar to bottom-up scenarios). The modeling exercise of this thesis will mainly focus on Monte Carlo analysis of fuel and CO_2 prices, as these affect directly the economic evaluation of the projects through the production cost savings. By performing a Monte Carlo analysis on these uncertainties, an exploratory analysis on the interdependencies between prices and project assessment can be performed. Another reason that this modeling exercise in focusing on fuel and CO_2 is the fact that these are the only major uncertainties that are not incorporated in the load and installed generation profiles. This was discussed in detail in section 6.2.

Although load profiles and installed generation capacities are also important for the assessment of cross-border transmission projects (especially the latter), this thesis will treat these uncertainties the way ENTSO-E does, which is through scenario analysis. The main reason is the lack of transparency in ENTSO-E's approach for deriving the several scenarios for the load and installed generation profiles, which does not provide the current profiles per country (see Figure 6.4 and Section 6.2.2.1). If these were available, Monte Carlo simulations could be performed on the several input assumptions to draw different scenarios (by varying the percentages/assumptions of Table 6.2). TYNDP 2014's studies can be used as a benchmark for the simulations performed in this thesis. That is the reason why TYNDP 2014's data are mainly considered and not from other data sources. Moreover, it makes sense to use these data are the suggestions of the present study focus on ENTSO-E's practices.

Finally, treating stochastically weather data is left outside the scope of this study due to time constraints. Several time-series models for weather data have been used in several other studies (see Section 5.3.2.2) and they are easy to be implemented. It would be interesting to perform such studies in case were extreme scenarios of installed generation capacities were present (by using the method described in the previous paragraph) if it was not for the time constraints.

7.2.2 Simulation Sets

As mentioned, the quantitative part of this thesis will focus on the suggestions regarding the probabilistic inputs in long term studies on transmission planning. The simulations will focus on four main aspects:

- Examination of the sensitivity of model outputs to the input parameters (Tornado diagrams, see section 5.3.1)
- Measurement the error on model outputs compared to error of model inputs (both deterministic and probabilistic).
- Comparison of different scenarios (Visions) under the same probabilistic inputs
- Identification of correlations between inputs and models outputs.

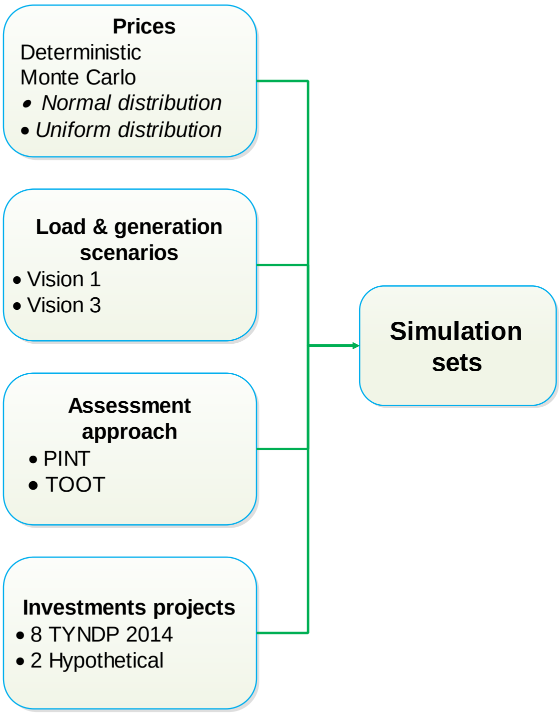
Finally, a fifth aspect will be examined, which is not related to the uncertainty analysis but to the evaluation approaches of projects of ENTSO-E. This is:

- Comparison of the TOOT and PINT approach (see section 6.2.1) used by ENTSO-E in TYNDP and its implications.

In order to examine these five aspects in the planning process, several simulation sets have to be performed. These sets are different for every examined aspect. An overview of the parameters/variables/different options that will differentiate the several simulations sets (referred hereafter as degrees of freedom) is shown in Figure 7.1. A brief introduction of how the simulation sets were constructed for every examined aspect will be provided in Chapter 8.

The first degree of freedom concerns the uncertain parameters and their representation. As mentioned these are CO_2, coal and gas prices. They will be represented either as deterministic values or through Monte Carlo in which they follow normal or uniform distributions. The different distributions represent the perception of the "future". In case of normal distributions, the planner assumes that the future prices will move around an average value and they will slightly deviate. On the other hand, in case of uniform distributions, equal probabilities are assumed for every possible value in the specified range. How these distributions were derived in described in Section 7.3.4. How many variables will be sampled through Monte Carlo depends on the simulation set and the examined aspect.

The second degree of freedom are the installed generation capacities and load profiles as they are reflected in TYNDP2014 scenarios. For some simulations sets only one scenario will be used whereas other will require more scenarios to demonstrate their differences. This study has focused on the two bottom-up scenarios of ENTSO-E, Vision 1 and Vision 3 (Section 7.3.4).



(see Table 7.2)

Figure 7.1 - Degrees of Freedom and Simulation set-up

The third degree of freedom is the assessment approach, TOOT or PINT. Most of the simulations will only use the PINT approach. In this approach a project will be evaluated by examining the system changes when the transmission system consists of no new investment projects and when it includes a new investment project. The TOOT and PINT are the same when only one project is under examination.

Finally, the fourth degree of freedom concerns the decision of how many and which transmission projects will be examined. For the first two examined aspects a hypothetical investment between the Netherlands and Germany will be examined, whereas for the latter an inventory of interconnection projects examined in TYNDP 2014 is used. The latter is used in order to order to be able to directly contrast the obtained results with the TYNDP ones. These projects are described in section 7.3.1.

7.3 BASE DATA AND ASSUMPTIONS

This study is mainly focusing on ENTSO-E's long-term planning approach. Therefore, the data and results from its latest published TYNDP study cycle will be used. Data on TYNDP 2014 were provided by TenneT or were acquired from ENTSO-E's website. The following paragraphs describe the main assumptions made in the quantitative part of this thesis regarding the transmission network, the generation capacities, the demand profiles and the scenario and uncertainty analysis.

7.3.1 Transmission Network

As mentioned in section 6.2.1, ENTSO-E uses a PCM for the economic analysis of its planning studies. As such, the transmission network is underrepresented (see section 4.2). The only required information concerns the countries included, the number of nodes per country and the capacity limits of the interconnections between the nodes. No losses in the transmission system are assumed.

Due to data and time constraints, the examined system will be a reduced network of the one used in TYNDP 2014. Table 7.1 shows the countries that are included in the examined network topology (perimeter) and the number of nodes assumed per country. This perimeter is selected as between these regions the main bottlenecks are identifies by ENTSO (ENTSO-E, 2014e). Countries that do not belong to this perimeter will be treated as exogenous and their respective data will be derived by given timeseries which have been provided by TenneT. It should be noted here that in order to model bi-directional flows between countries in the perimeter and those outside it, several dummy generators and energy purchasers were modeled in the out-of-perimeter nodes. The capacity limits of interconnections between countries are also provided by TenneT as well. These data consist the base case for studies in 2030 where no other investment project is assumed.

Table 7.1 - Perimeter of the networks under study

Countries	Number of nodes per country
Netherlands	1
Germany	1
Austria	1
Belgium	1
France	1
Switzerland	1
Italy	2
UK	1
Norway	1
Denmark	2
Sweden	1
Total	13

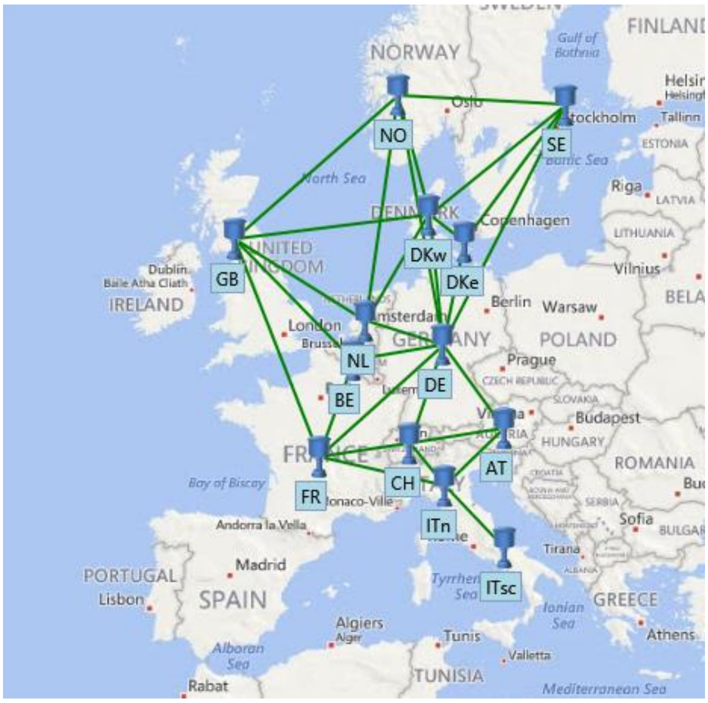


Figure 7.2 - Network under study (PLEXOS output)

Table 7.2 shows the list of candidate interconnection projects that will be examined in the simulations sets. The names of the first eight projects and their costs are derived from TYNDP 2014 (ENTSO-E, 2014e). The last projects concern hypothetical investments between the Netherlands and neighboring countries. The cost of the transmission expansion projects was derived by the TYNDP-2014. For the last two project assumptions the costs were derived based assumptions on the length (km), the capacity (MW) and the type (e.g. HVDC) of the interconnection. The total costs for every project can be seen in

Table 7.2 - Candidate interconnection projects

Project ID (from TYNDP2014)	Project Name	Capacity limits (MW) (for opposite direction)
225	DE-BE New	1000
198	DE-CH New	1400
179	DE-DKe New	600
183	DE-DKw New	500
176	DE-SE New	600
175	DKw-DKe New	600
199	FR-CH New	1000 (1500)
121	GB-BE New	1000
N/A	NL-BE New	1000
N/A	NL-DE New	1000

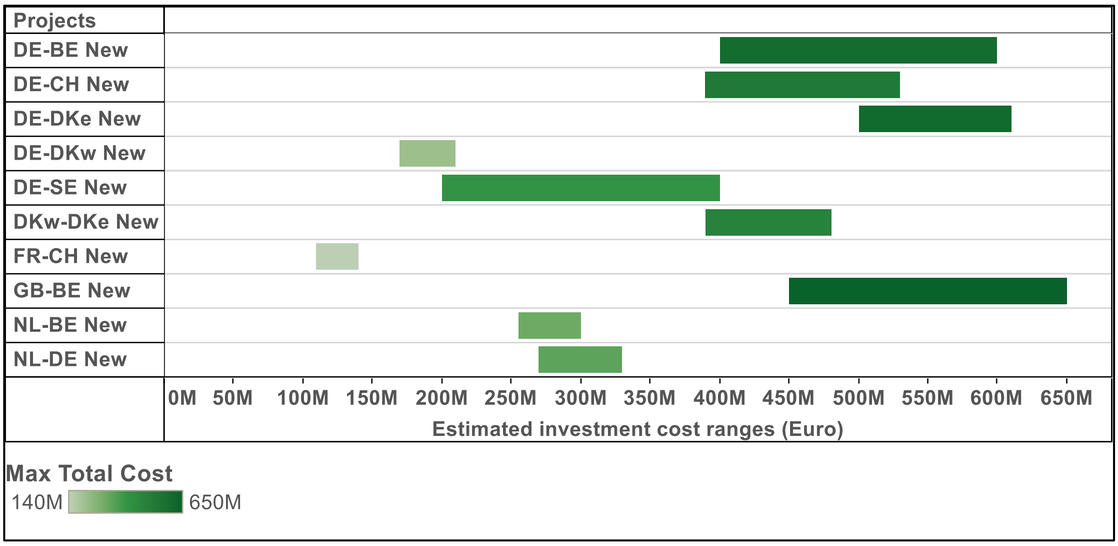


Figure 7.3 - Total investment costs of the examined projects

7.3.2 Installed Generation Capacities

The data on the generation capacity in every node of the one-node-per-country network are taken by TYNDP-2014. Therefore, the production plants are not given by company owner or age or production unit, but they are clustered in fuel categories. In this way there are 7 categories of thermal power plants divided by main fuel, which can be further disaggregated into 24 categories (excluding RES). This study will aggregate the data into 3 categories: ***Coal*** (Hard coal & Lignite), ***Gas***, ***Nuclear***. Data on oil and CCS will be disregarded as they only constitute 1-2% of the total generation capacity in all four scenarios. For every plant category their technical and economic characteristics are given. These are: *efficiency rates, CO_2 emission factor, variable O&M costs, start-up fuel costs, ramping times, probability of outages (planned or unplanned), reserve limits*. The values assumed in this study lie between the ranges used in TYNDP 2014. Although the capacities of specific units within a category are not given, the number of units that belong to each category is known. If there are special conditions or rules on must-run units in each category, the number of must-run units is given. All units that belong to a category are assumed to have equal capacities. Where applicable biofuel units are also included in this study.

Along with the thermal capacities, the dataset contains the installed capacities of ***wind*** and ***solar energy sources*** as well as ***hydro power plants***. For the former the *capacity factors* for wind and solar given as time-series of hourly resolution for the year 2013. This study assumes three types of hydro power plants: ***run-of-river***, ***reservoir hydro plants*** and ***pumped storage***.

For the run-of-river plants their *production levels* are provided as time-series for the whole year in an hourly resolution. For reservoir and pumped storage hydro plants time series on the *reservoir levels* in an hourly resolution is provided. In case of pump storage the *pumping limits* are also modeled.

7.3.3 Demand

Data for the demand in every node in the one-node-per-country network is given in an hourly resolution. These load profiles already incorporate assumptions on future developments such as EVs, heat pumps etc. Therefore, there are different load profiles for different scenarios. The final demand profiles are derived by subtracting from the load profiles the profiles of "generation from other RES" and "generation from other non-RES", which are also provided as time series by ENTSO-E. Figure 7.4 shows an example of the load time series used for simulations in Vision 1. These are hourly profiles of generation by sources that are not captured in the previous generation data.

Finally, the power exchanges with countries that do not belong to the perimeter will be modeled using time-series data as fixed amount around the year.

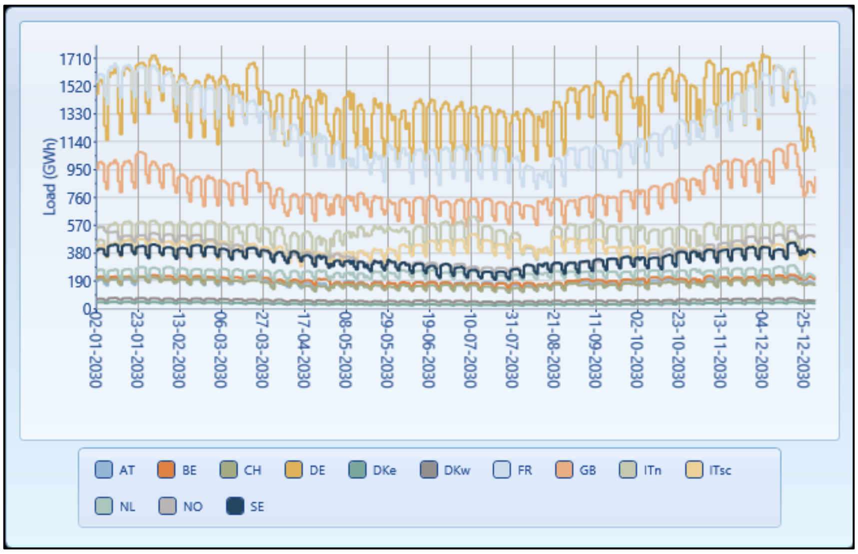


Figure 7.4 - Daily load profiles per country for Vision 1 (PLEXOS Output)

7.3.4 Uncertainty Analysis

In all simulation sets ENTSO-E's scenarios regarding load, generation capacities, timeseries of out-of-the perimeter countries and prices will be used. As described in Section 6.2.2.1 and can be seen in Figure 6.5 and Table 6.1, the top-down scenarios do not differ significantly from the bottom-up ones in terms of prices and total installed generation capacities. Given this fact and due to time constraints only the bottom-up scenarios of TYNDP 2014, Vision 1 (V1) and Vision 3 (V3) will be explored. This is not expected to influence the results of this study.

The probability distributions for the fuel and CO_2 prices are indirectly derived by ENTSO-E's ranges in their Visions. Table 6.1 showed the ranges of values that ENTSO-E uses for the fuel and CO_2 prices. The first cluster of distributions assumes equal probabilities between the possible values and a slightly wider range than ENTSO-E does. Thus, Monte Carlo simulations are performed with variables that follow a uniform distribution (Table 7.3).

The second cluster of distributions represents the possible values that the planner may choose. In this cluster, the values of the stochastic variables follow a normal distribution. The mean of this distribution is equal to the average of the min and max values of ENTSO-E's ranges for V1 and V3. The relative standard deviation is equal to 10-20% of the mean (Table 7.4). This is used to simulate the fact that planners choose not to deviate very much from historical data or assume more probable "futures" than others.

For every stochastic variable, whether it follows a uniform or normal distribution, 100 runs were simulated. The simulations with and without the project were performed with the same seed, so as to be able to compare the production cost savings on the same basis. The histograms of samples for each variable for both assumed distributions are provided in Appendix

C. Figure 7.5 provides an overview of the uncertainty space that each variable covers in case of normal and uniform distribution through a 3D scatter plot.

Table 7.3 - Uniform Distribution: Assumptions

Variable	min	max	mean
CO_2 (€/Kg)	0.02	0.099	0.0595
Hard coal (€/GJ)	2	3.975	2.9875
Gas (€/GJ)	6.6	11.34	8.97

Table 7.4 - Normal Distribution: Assumptions

Variable	Mean	%St.deviation (relative to mean)	St.devation (absolute value)
CO_2 (€/Kg)	0.062	0.2	0.0124
Hard coal (€/GJ)	2.85	0.1	0.2845
Gas (€/GJ)	9.10	0.1	0.91

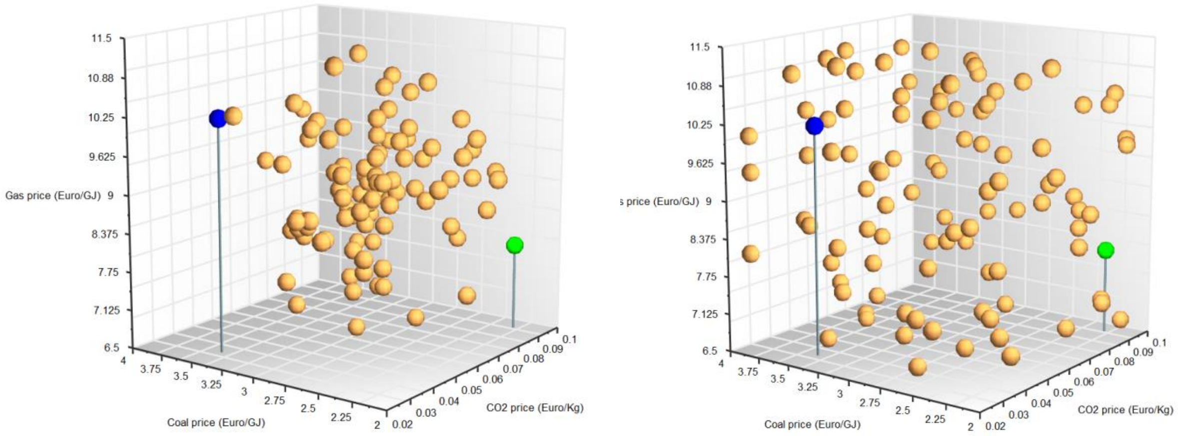


Figure 7.5 - Uncertainty space of fuel and CO2 prices in case of normal (left) and uniform (right) distributions

7.4 VALIDATION ON SYSTEM SET-UP

This thesis utilizes a commercial model, PLEXOS, for performing the several simulation sets. This software package has been already validated in several other cases (CER, 2011). Therefore, there is no need to validate its algorithms or process. However, several validation tests have to be performed to assure that the inputs were properly incorporated, the validity of the assumptions and simplifications made and that the proper model settings were chosen.

There are several formal validation tests described in the literature (Prasad et al., 2014; Refsgaard et al., 2007). In the following sections, extreme case tests and comparison with ENTSO-E's results are showed.

7.4.1 Comparison with ENTSO-E's results

To assure that the data were appropriately entered and the right settings were chosen, the results on generation mix between on ENTSO-E's results on Vision 1 and PLEXOS output will be compared. The results are expected to differ at some point since the two systems differ in size (this thesis explores a reduced version of ENTSO-E's system) and several ENTSO-E's modeling choices are not known. These can be, for example, which year was used for RES capacity factors or which repair time of the generation units was assumed. Moreover, simplifications and assumptions on several parameters may have affected the system behavior. Despite that, it is expected that basic behavior in terms of generation mixes or exchanges between countries will be the same. Indeed, as , Figure 7.7 and Figure 7.7 show, the results between the two studies are very close to each other. Thus the model works as it was expected.

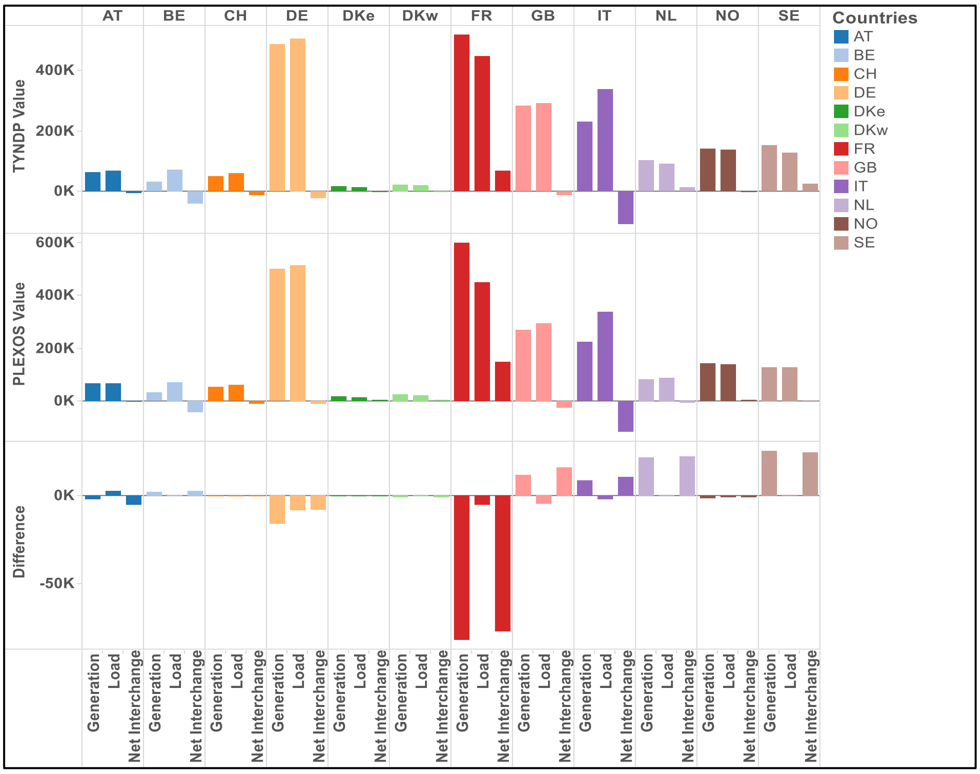


Figure 7.6 - Validation test for Vision 1: Load, Production and Exchanges per country

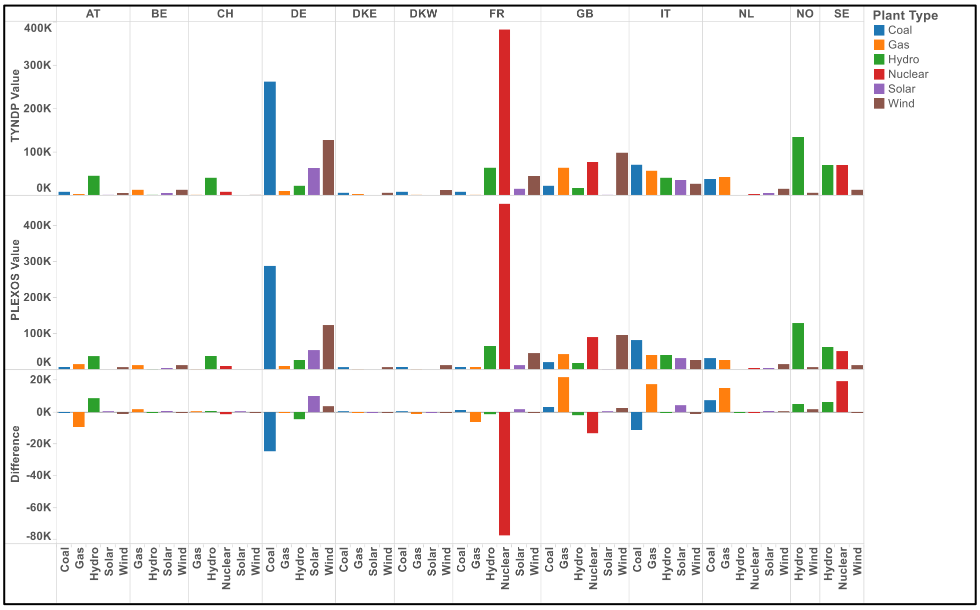


Figure 7.7 – Validation test for Vision 1: Generation mix per country

7.4.2 Extreme case tests

The second cluster of tests concerns the extreme value tests. The extreme values assumed in these tests may concern the fuel and CO_2 prices. Since these variables will be modeled through Monte Carlo it is interesting to examine whether the model responds correctly to their changes. In Figure 7.8 the system changes when the gas price is set equal to zero is examined. It can be seen that in the case of zero gas price the production of the gas units is increased. This was expected in theory. Thus, the model is expected to show the right behavior given the inputs set.

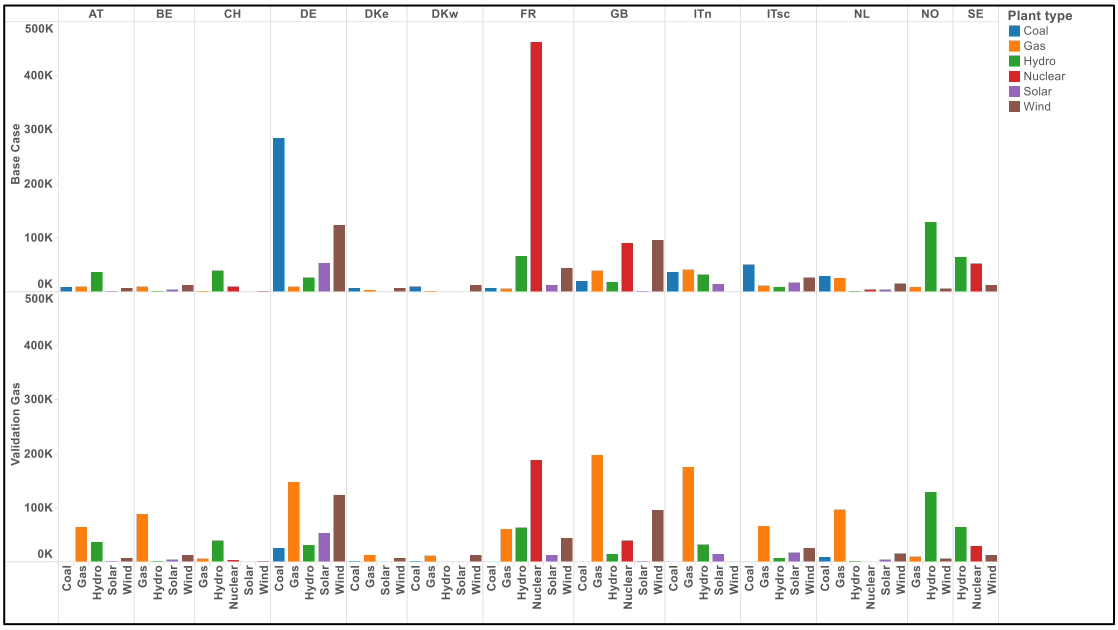


Figure 7.8 - Extreme case validation test: Gas Price equal to 0 Euro/GJ

8

Experiments and analysis of results

8.1 INTRODUCTION

Chapter 8 focuses on presenting the results obtained by a large number of experiments. Analysis of the results and discussion about possible implications will be provided in parallel. The main objective of this modeling exercise is to identify how different are the deterministic and the stochastic approaches and what insights offer the latter ones compared to the former. Thus, although the model provides several pieces of information per country, per time step (hour) and per sample (100 samples per simulation), most of the results that will be presented here will concern the system as a whole. These results could be used to examine many interesting questions regarding impact of cross-border capacities or CO_2 prices on fulfilling RES targets in Europe or per country, but are outside the scope of this study.

Three metrics will be used to represent the system conditions and changes: production cost savings, CO_2 emission reduction and average marginal cost of electricity. The first two metrics consist indicators of ENTSO-E's CBA methodology (see Table 2.1), whereas the last one is used as an indicator for market integration. The results will be presented as per examined aspect as these were described in section 7.2.2.

8.2 COMPARISON OF STOCHASTIC AND DETERMINISTIC CASES

The first simulation sets explored how different is the project assessment when a deterministic and a probabilistic approach is followed for both Vision 1 and Vision 3 using the PINT approach. The changes that the projects of Table 7.2 bring to the system in terms of production costs are given in Figure 8.1 to Figure 8.4. In case of deterministic approach the values of ENTSO-E for fuel and CO_2 prices are taken, whereas in case of probabilistic approach Monte Carlo sampling is performed in all three variables simultaneously. Several observations can be derived by these figures regarding uncertainty analysis and project assessment. These are:

- In most of the cases the deterministic value lies between the total range of the probabilistic approach. In projects like "*DE-DKw new*" seems to be no difference if using either the deterministic or the probabilistic approach. However, in project "*DE-CH new*" if the planner had relied only on the deterministic value of Vision 1, he/she would ignore a significant amount of price combinations which lead to production costs increases rather than reductions.
- For many of the projects the possible ranges regarding the production cost savings is significantly large. This is an indication that sensitivity analysis may not be adequate to examine changes in the results when the deterministic approach is followed.
- Comparing the relative changes in model outputs, it can be seen that the production costs (Figure 8.1- Figure 8.2) are more variable than the CO_2 emissions given the same stochastic inputs (Figure 8.3 - Figure 8.4).
- The benefit metrics however, keep the same trend in both cases (e.g. when a project shows positive production cost savings, it also shows positive emission reductions).

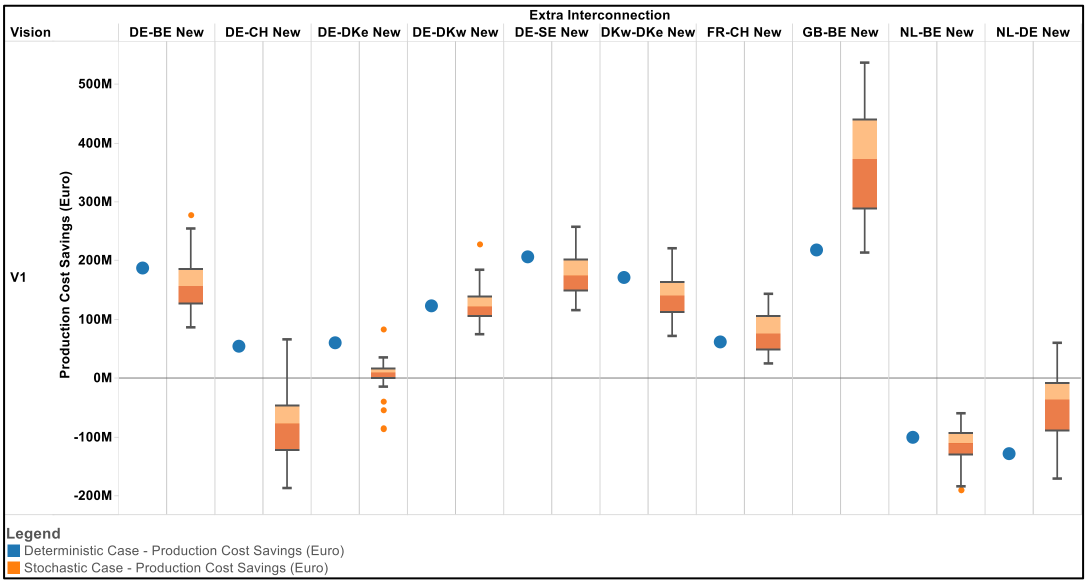


Figure 8.1 - Vision 1: Production Cost Savings per examined project for deterministic and probabilistic inputs

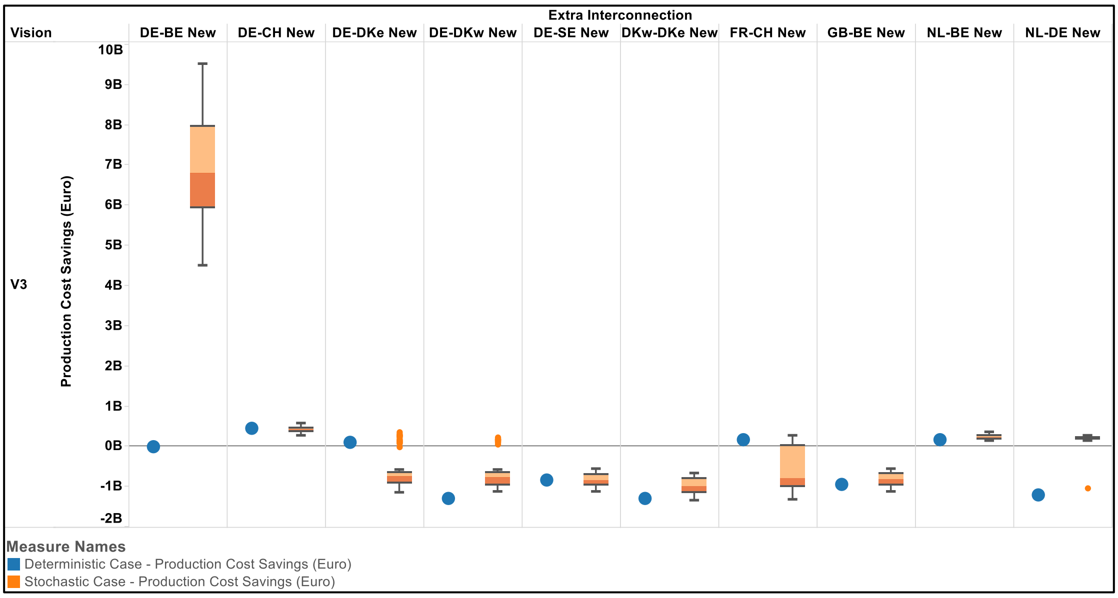


Figure 8.2 - Vision 3: Production Cost Savings per examined project for deterministic and probabilistic inputs

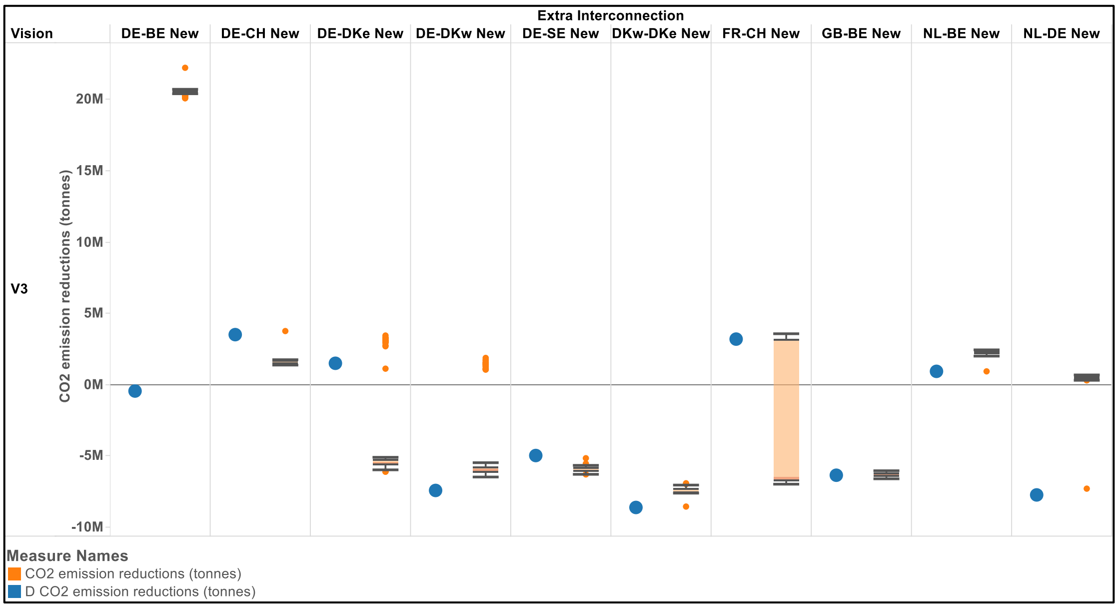


Figure 8.3 - Vision 1: System emission reductions per examined project for deterministic and probabilistic inputs

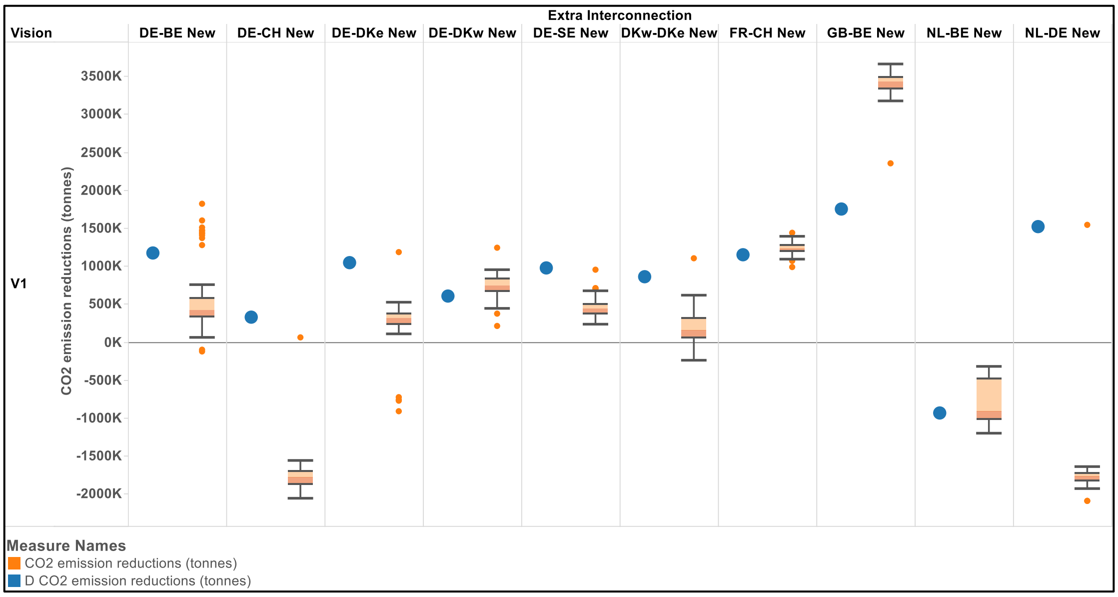


Figure 8.4 - Vision 3: System emission reductions per examined project for deterministic and probabilistic inputs

Figure 8.5 shows in one graph how different are the two Visions of ENTSO-E. It should be kept in mind that the same values for the probabilistic inputs on prices were set in both Visions. The following observations can be made by this figure:

- In most of the cases there are no values that the benefit metrics in the two Visions coincide. In this respect, ENTSO-E’s bottom-up scenarios can be used to explore a wide range of possible futures.
- However, this difference between scenarios strengthens the argument of section 5.3.2 that the most significant uncertainty is the derivation of future installed capacities and their location. The lack of an analytical approach for deriving them in ENTSO-E’s methodology (Section 6.2.2) may significantly distort the results.

- The results shown in Figure 8.5 raise reasonable questions regarding the post-assessment of scenario analysis results. For example, should only projects that have positive metrics in both scenarios be implemented or some "futures" seem more probable than others? Currently, ENTSO-E only provides the assessment of the projects per scenario. The decision of which projects are going to be implemented is left to the decision makers. There are several formal ways for post-assessment of scenario analysis results(e.g. minmax regret) which have been criticized by academia for their usefulness in real life applications (Buygi, Balzer, et al., 2004b). In a sense, scenario analysis may make the decision making process harder or lead to sub-optimal plans (Francisco D Munoz et al., 2014). In Appendix A it is described how stochastic optimization techniques can be used to provide one single solution that is robust under all scenarios. However, PCMs cannot utilize these techniques for transmission planning as their algorithm optimize dispatch schedule and not investment plans (Section 4.2),

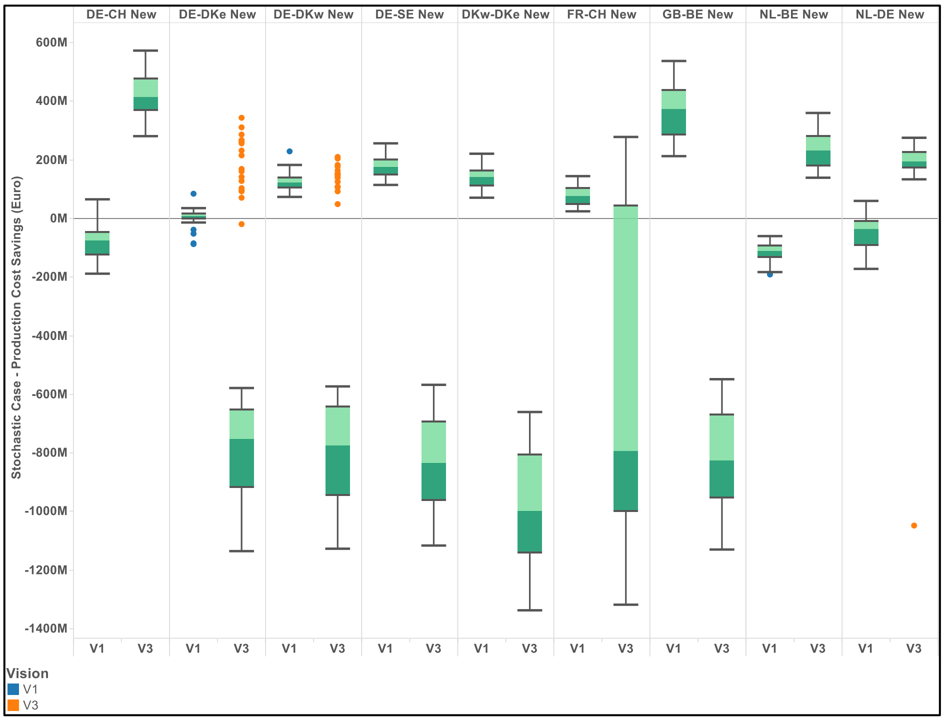


Figure 8.5 - Comparison of probabilistic ranges for production cost savings in Visions 1 and 3

8.3 TOOT VS PINT APPROACH

One may observe that the metrics on production cost savings and emission reductions calculated in this thesis do not completely coincide with ENTSO-E's data. This happens for a variety of reasons. First, the system under examination is different, resulting in different total costs and emissions. Second, different assumptions were made. Third and most important, different approach was followed. In the above project assessment the PINT approach was examine. On the other hand, ENTSO-E assesses the projects in TYNDP using the TOOT approach, including much more projects to be implemented in its base case. The choice of the assessment approach can lead to different results and can be seen in Figure 8.6.

In these simulation sets, deterministic evaluation of the examined projects was performed following both the PINT and the TOOT approach. In case of PINT, only four projects were found beneficial in Vision 3 whereas in case of TOOT, six projects showed positive benefits. Only three of the projects were common in both cases. This comes to strengthen the qualitative analysis in Sections 4.4.1 and 6.5, according to which:

- The use of PCMs and heuristic approaches in deriving transmission plans may not lead to optimal plan. CEMs that endogenously derive transmission plans (location and timing) are more suitable to that end.

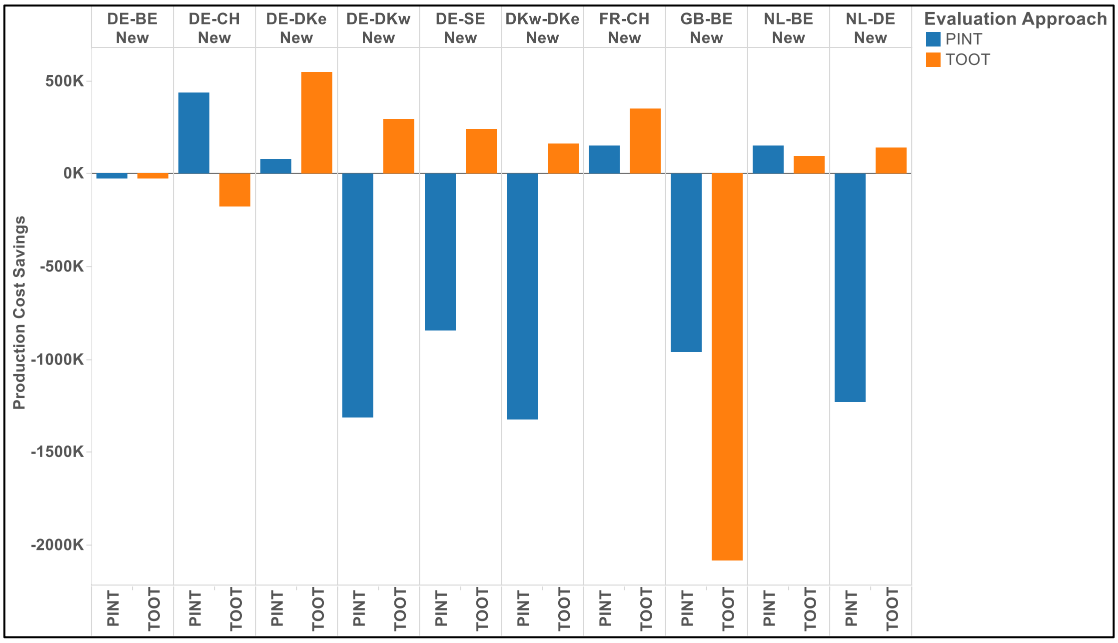


Figure 8.6 - Production cost savings per project using PINT and TOOT approach

8.4 IDENTIFICATION OF CORRELATIONS BETWEEN INPUTS AND OUTPUTS

Apart from the box-plots shown in Figure 8.1- Figure 8.5, Monte Carlo simulations can offer the planner/decision maker useful information for the interdependencies and correlations between variables. Figure 8.7 shows scatterplots between production cost savings in V1 and V3 for each of the examined variable. The panels in the right depict the spread (the difference) between gas and coal prices. This spread shows is used to show which combinations of gas and coal prices occurred in the simulations. In the graphs shown here the all the projects of Table 7.2 have been considered in one simulation case.

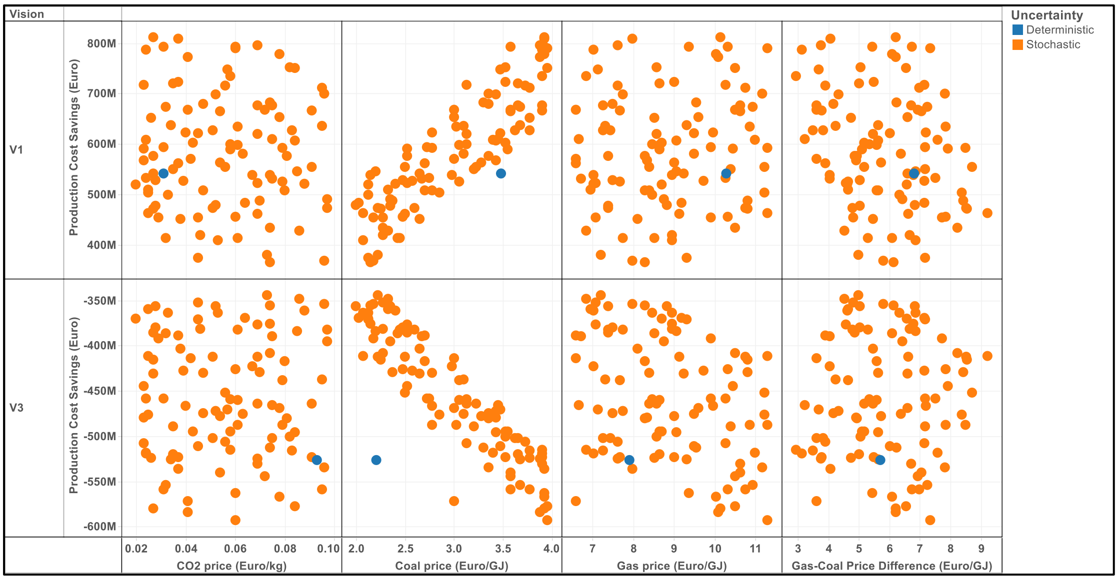


Figure 8.7 - Scatterplots between probabilistic prices and production cost savings for Visions 1 and 3

A reasonable question is then: "So what? What can the decision maker do with this information?". Figure 8.1 showed that different project react in a different way to price changes.

It would be interesting then to examine how and why this happens. This will help the decision maker get a better understanding of the system and its dynamics. The interdependencies in a Europe-wide electricity system are numerous and the effects of small changes can be unknown. Identifying correlations through statistical or other analysis can be used for this purpose. Such graphs can be also used to identify.

The statistical analysis of the results is outside the scope of this study. However, it can be easily observed that several trends occur in case coal prices. Identifying why these trends occur and why they are different per Vision (which is actually per different installed capacities) can offer the planner more insight on the system dynamics. Additionally, it can also be used to properly identify the tipping points which lead to different behavior. For example, in Figure 8.8 most of the points are concentrated in a very limited area. There is only one exception which lead to higher emission reductions in case of Vision 1 and lower in case of Vision 3. This point (CO_2 price=0.041 Euro/kg, Coal price=3 Euro/GJ and Gas price=6.6 Euro/GJ) significantly alters the system behavior and is worthy of examination. Possibly more samples could provide the planner with more tipping points for examination.

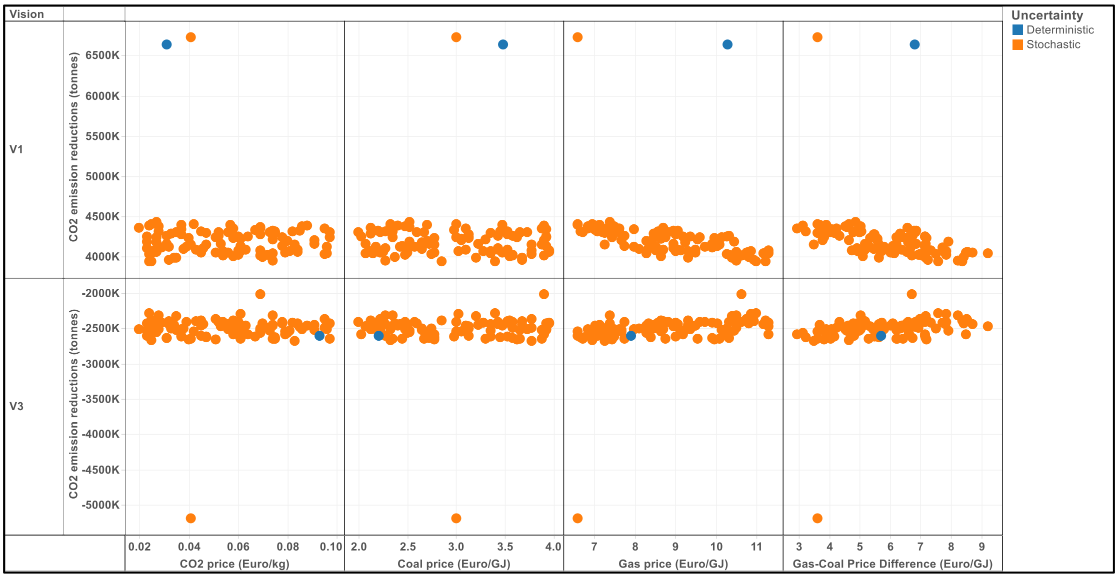


Figure 8.8 - Scatterplots between probabilistic prices and emission reductions for Visions 1 and 3

8.5 SENSITIVITY OF RESULTS TO UNCERTAIN PARAMETERS

For this part of the analysis 5 types of simulations were performed. The first type involved a deterministic model with values for CO_2 and fuel prices equal to the average of the limits of their uniform distributions. The other four simulation sets include Monte Carlo sampling of the examined variables. The non-used variables remain constant and equal to the values used in the deterministic simulation. Thus, keeping everything else same, the impact of each variable to the model results can be examined. For these simulations no additional interconnection project was examined as the main purpose is to examine the deviations in the primary results.

The Appendix contains the histograms that show the model results in each of the 4 Monte Carlo simulations: CO_2 prices, gas prices, coal prices, and gas and coal prices combined. The results on system production costs (in Euro), the CO_2 emissions (in tonnes) and the average system electricity prices (Euro/MWh) are examined.

Figure 8.9, Figure 8.10 and Figure 8.11 are formulated as Tornado diagrams to show the sensitivity of the model outputs to the several inputs. The range of the several metrics (red and blue bars) is given compared to the base case (the value of the deterministic run is given with grey line). This differs from the graphs provided in the previous sections in the sense that, in this case, only one variable at a time is changing. It is evident that even in an ideal case where only one variable is unknown, the deterministic modeling approach can only capture part of the possible futures and the impact of the input parameters in the model outputs can be considerable. An indicative case in the range of production costs in case of a probabilistic CO_2 price in Figure 8.9. Such a range is considerably large for any future evaluation. Choosing the middle value in a range and deciding upon it may entail a big range of uncertainty space that is still unexplored and it may still happen. It is evident that CO_2 prices is the factor that affects more the results and with considerable deviation from the average. On the other hand CO_2 price seems to affect negligibly the average system prices. The rest show almost the same sensitivity to the results and the same variance. The same seems to hold for the system emissions, which are more affected when a Monte Carlo is performed on both coal and gas prices (probably the spread of gas and coal prices is increasing to larger extend than when one variable was probabilistically sampled). The distributions of every metric per Monte Carlo sampling are provided in Appendix E.

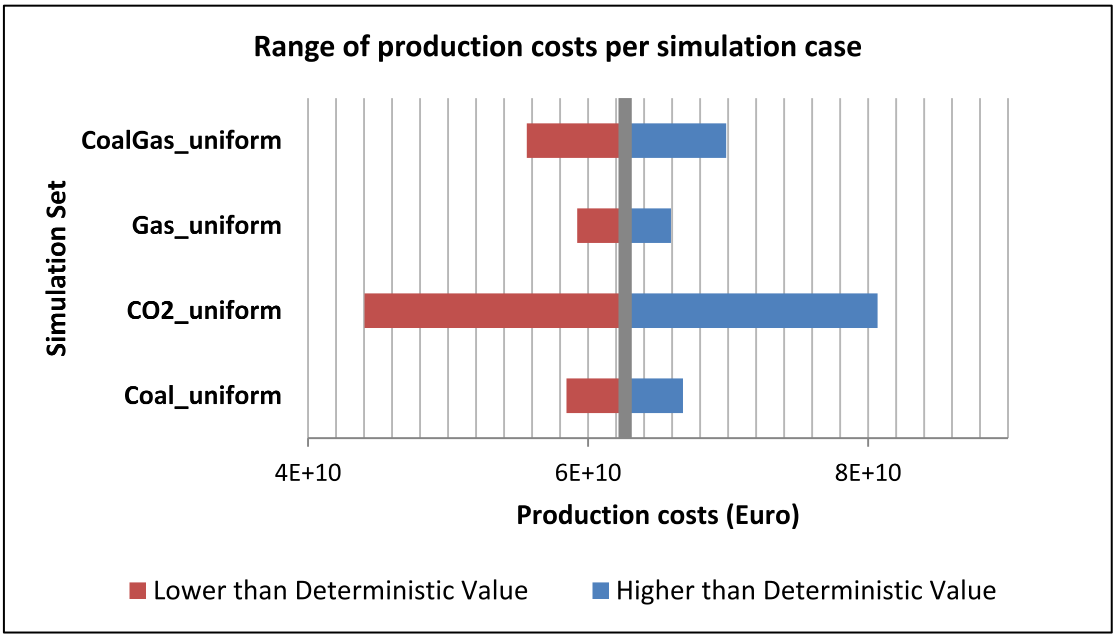


Figure 8.9 - Range of production costs per simulation case

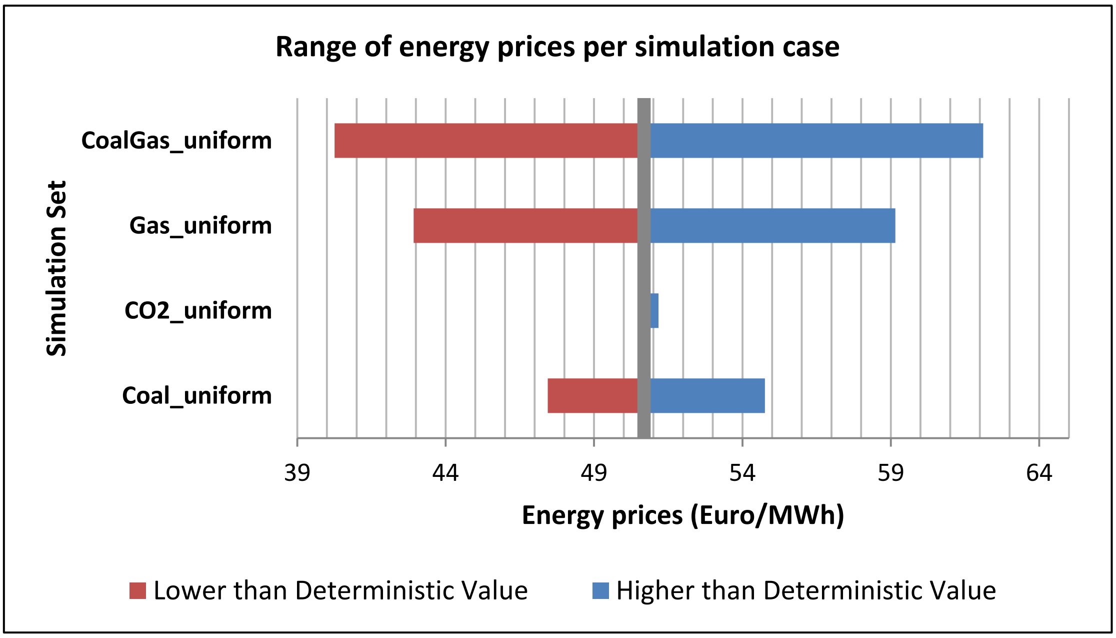


Figure 8.10 - Range of electricity prices per simulation case

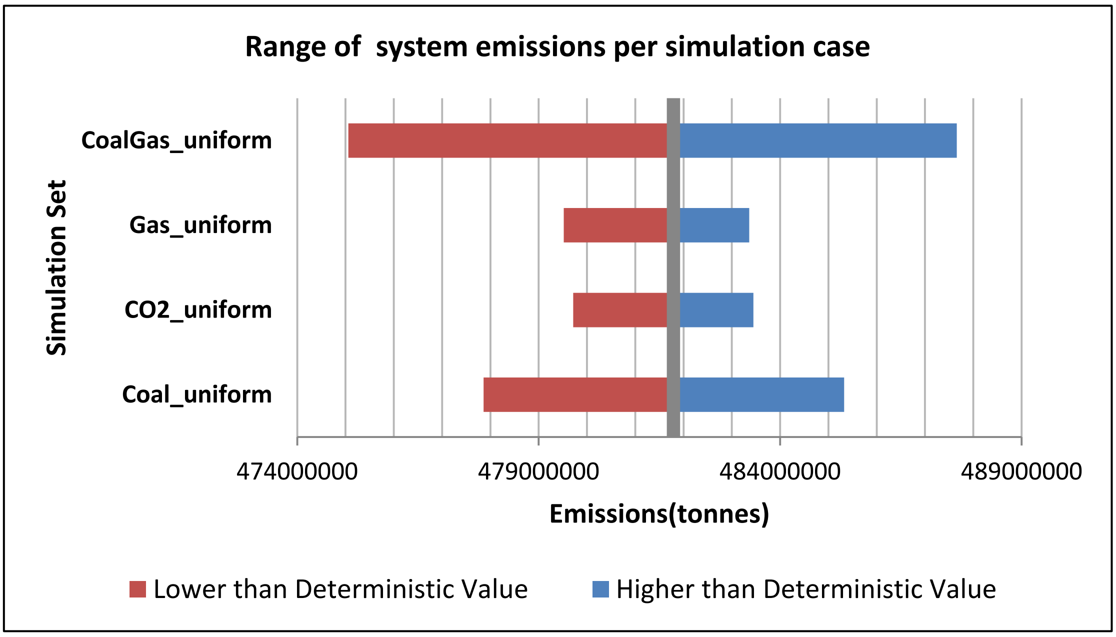


Figure 8.11- Ranges of system CO_2 emissions per simulation case

8.6 PERFORMANCE OF DETERMINISTIC MODELS

Moving away from model sensitivity to the input parameters, the second part of the analysis will focus on measuring how uncertainty may influence the project assessment. Again the main tool for obtaining our results is Monte Carlo analysis. The first cluster of simulation sets performs Monte Carlo (for 100 samples) for each of the uncertainties (CO_2 prices, Gas prices, Coal Prices, Gas & Coal Prices), keeping the rest constant and equal to the values of ENTSO-E's Vision 1. In this cluster the uncertain parameters follow the normal distributions described in Chapter 7 and simulate the possible deterministic cases that the planner could have simulated based on ENTSO-E's data. The second cluster of simulations differs from the first in the fact that the uncertain parameters follow uniform distributions. These are used to simulate the possible futures in this study.

The Monte Carlo simulations are performed twice: one without the project in the system and one with the project (PINT approach). The examined project is an extra interconnection of 1000MW between the Netherlands and Germany (see Table 7.2). Based on these simulations, the production cost savings are calculated for every sample/planning case. In total, 4(simulation sets)*100(runs in every simulations set)*2 (simulations with and without the project)*2(one for the planner cases and one for future cases) = 1600 runs were performed, resulting to 800 calculated production cost savings. These savings were compared on a sample-by-sample case: e.g. Production cost savings of Sample 1 of the Monte Carlo of CO_2 prices with normal distribution (what the planner had calculated) was compared with the Sample 1 of the Monte Carlo of CO_2 prices with uniform distribution (what actually occurred). Figure 8.12 show schematically how much the planner's estimation on CO_2 prices was deviating from the actual values. Similar figures for the fuel prices have been placed in the Appendix F. Taking into consideration that every future outcome is possible (here the possible range was seen almost equal to ENTSO-E''s one), this analysis aims to examine what is the error on project assessment compared to the error on estimating the future.

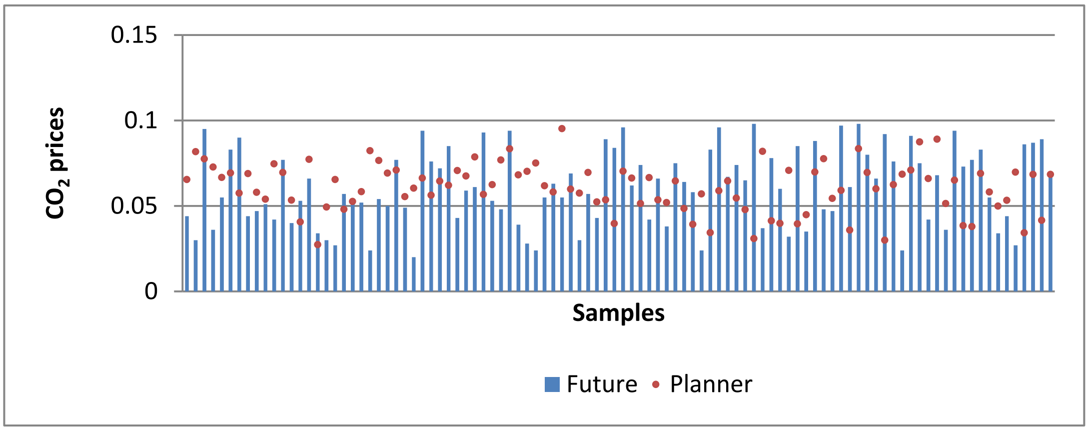


Figure 8.12 - CO_2 prices per sample for the uniform and normal distributions

In Figure 8.13 the mean absolute error (MAE) of the planner's estimates on production costs and prices against the realized ones has been calculated and expressed as a percentage of his average estimations (average of the 100 samples per case). It can be observed that a MAE of 38% on estimating the future CO_2 prices (other keeping constant and same as the future) by the planner's side can result in a MAE of 82% on production costs. Similar observations can be made for the fuel prices. In fact, their impact is larger on the savings estimations.

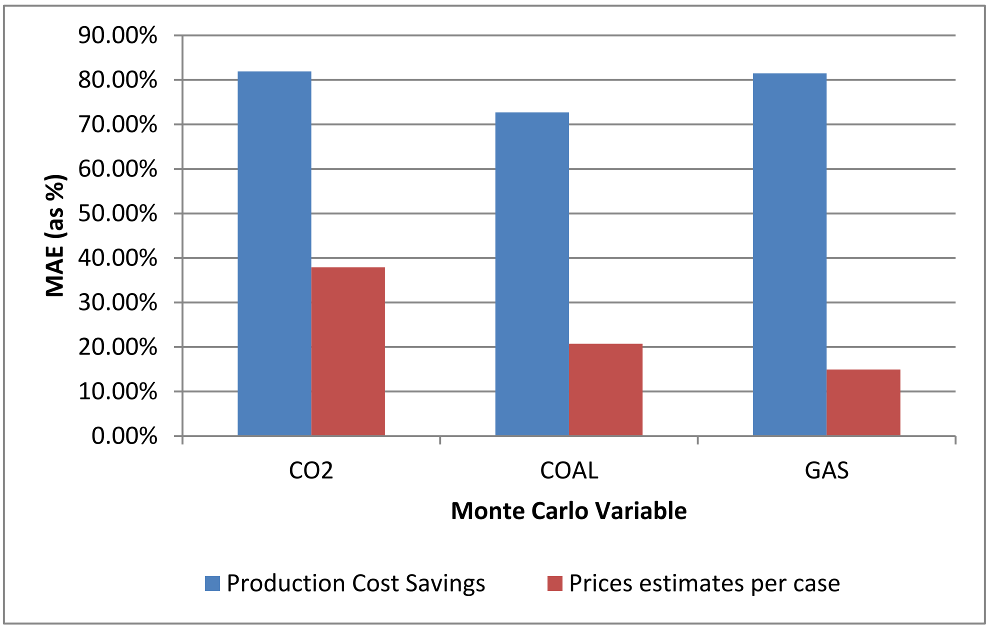


Figure 8.13 – Mean Absolute Error as % of Planner's Average Estimations

The above results were expected as already in Section 2.3 the fundamental methodological problem of deterministic models was described. The added value of this modeling exercise was to show how the forecast errors are translated to estimation errors. This relation is not one-to-one. Although the future cannot be perfectly forecasted or estimated, this modeling exercise reveals that it still makes sense to improve the several forecasting techniques or uncertainty analysis methods. Even though there will always be error in estimates this can be kept to a minimum. The Appendix F the distributions of the errors in estimating the production cost savings in each case.

8.7 SUMMARY

In Chapter 6 we argued for several changes in the modeling approaches of ENTSO-E in drawing the TYNDP. Due to time and resource constraints there was not the possibility to implement all these changes in a modeling exercise and directly compare the results. Instead this Chapter mainly focused on the uncertainty analysis part. Four main aspects were examined. These aspects either served the purpose of demonstrating the inadequacy of the deterministic models for long-term planning (Section 8.6) and comparing them with probabilistic ones (Section 8.2) or analyzing the sensitivity of the model outputs to several model inputs (Section 8.5) and exploring the dynamics between the several model variables (Section 8.4). Finally, the approaches of ENTSO-E for evaluating pan-European projects were examined by analyzing the benefits of several projects under the PINT and TOOT approach (Section 8.3).

The most interesting findings of this chapter can be summarized in the following:

- Probabilistic models may offer the decision maker with more insights than deterministic models especially in cases that turning points (e.g. from positive to negative benefit metrics) can be observed. This is also useful when taking into account the investment costs.
- How sensitive are the model results to probabilistic inputs is project specific. The high interdependencies between systems may cause unexpected behaviors. Therefore, it is better to account for uncertainty for all the cases.
- ENTSO-E's bottom-up scenarios, Visions 1 and 3, are indeed quite distinctive from each other to be used for an exploratory analysis. However, since for both Visions the same combinations of prices were set as inputs, what distinguish them are the generation and load profiles. Given the importance of installed generation capacities in future exploration, ENTSO-E should consider of a more analytical approach to derive them, either by using GCEMs or co-optimization models. Such models could also utilize algorithms specifically developed to deal with uncertainty, such as stochastic optimization.
- The CO_2 prices were found to have the largest impact of the estimation of production costs. Therefore, it is suggested to be modeled in way that captures its variable nature (Monte Carlo or stochastic processes).
- Probabilistic analyses can be used to examine possible interdependencies and correlations between the system variables. In that sense, probabilistic models may offer the decision makers on why the system reacts in a specific way and what he/she expect in the future.
- Modelers should focus on improving the accuracy of their forecasting and forward-looking models. It was shown that even a small error in price estimation may cause significant errors in evaluation of a project.
- Finally, it was shown that ENTSO-E heuristic approaches to evaluate investment projects, TOOT and PINT, have significant limitations. This strengthens this thesis suggestion that deriving investment decisions endogenously should be one of the primary goals in modeling approaches in transmission planning.

PART IV

Conclusions

9

Conclusions & Recommendations

9.1 CONCLUSIONS

The European Commission's ambitious policy targets regarding RES integration and reduction of CO_2 emissions are the main drivers for interregional investments in the transmission system. Moreover, interconnections between countries are considered to be the TSO's best alternatives to lead electricity prices to lower levels and enhance security of supply. The latest TYNDP study cycle states that interconnection capacity in Europe must double by 2030. So far, an underinvestment on interconnection capacity has been observed. This can be attributed to economic conditions, regulatory and other uncertainties or possible risk-averse behavior of investors. Another reason may be the fact that until now the main drivers for transmission expansion were technical and not economic criteria. The multiple benefits of transmission enhancements call for an appropriate economic assessment. Towards that direction, ENTSO-E has recently developed a common CBA framework to evaluate transmission projects. The increasing uncertainties in the planning field and the complex dynamics of the actors involved increase the complexity of transmission planning. It is clear that wrong investment decisions may hamper economic growth, policy goals or any other future developments. However, there is limited experience with economic assessment of projects and with the modeling tools and approaches that could be utilized. Therefore, in this thesis, the following research question is constructed and probed:

Which modeling approach is the most appropriate for planning interconnection investments at a pan-European level by taking into account the large uncertainties inherent to transmission planning?

Our analysis showed that the current modeling approach in transmission planning at a pan-European level lacks a systematic approach that could identify analytically and assess properly possible transmission investments. In addition, there is still room for improvement in the uncertainty analysis, which currently ignores the variable character and the complex dynamics of many of the uncertainties. To align with EU's objectives, transmission planning at a pan-European level should be explorative in nature and develop proactive transmission plans to cope with uncertainty. Such a long-term planning approach would provide more insight to the decision-makers than just evaluative models under poorly developed deterministic scenarios.

The thesis has both societal and scientific relevance. From a theoretical point of view, this research develops an evaluation framework, a set of criteria for evaluating the different approaches in transmission expansion planning and evaluates the existing modeling types and uncertainty analysis techniques from both academia and industry. From a societal point of view, this thesis provides recommendations/guidelines for designing a planning approach at a pan-European level, which focuses on meeting EU's energy and social targets. Moreover, it enhances the extensive understanding of the planners' options by providing a systematic review and analysis of the available approaches in transmission expansion planning.

The sub-questions that needed to be unraveled and clarified in order to reach the above conclusion are described below:

1. **With what criteria can the modeling types in transmission planning process be evaluated?**

The starting point of this analysis was the realization that planning models cannot be evaluated and validated properly ex ante. Even ex-post evaluation may be considered an invalid option as also in this case, the model output is assessed against one realization of the future. In essence, one should seek different ways to evaluate planning models. The literature review revealed a lack of a concrete evaluation framework for assessing models for transmission planning. Thus, an evaluation framework was developed classifying 15 criteria in 4 main categories: economic, technical, institutional and social.

The framework was based on notion of fit-of-purpose. It was examined how an ideal modeling approach should be, based on the desires of stakeholders involved in transmission planning. The objectives of three clusters of stakeholders were explored: policy makers, regulator and planner. In combination with the main modeling limitations and constraints, these objectives allowed to identify several evaluation criteria for assessing modeling approaches in transmission planning processes.

2. **What are the available modeling types for long-term transmission planning of interconnection investments and how are these evaluated?**

These criteria were used to evaluate the different modeling approaches. Through the literature review, we revealed two main types of models for economic assessment of transmission plans and distinguished them based on their purpose and technical characteristics: Production Cost Models (PCM) and Capacity Expansion Models (CEM).

The evaluation demonstrated clearly that CEMs serve better the stakeholders' objectives regarding policy driven and top-down co-ordinated planning approach. This type of model offers a more dynamic way of performing long-term planning, as it simulates several years compared to PCMs which are evaluative in nature and perform short-term operations only. The capability of CEMs to conduct co-optimization studies can be used to explore both possible responses from the generation side and the gas transmission system. Moreover, since they can model the physical transmission system, they can be used to fulfill both technical and economic criteria. A pan-European planning process should be based on an analytical and systematic approach and not on heuristics, as it is currently done.

The main arguments against CEMs are the data requirements and the simplifications that need to be considered in order to make the problem feasible for real-world systems. Data requirements constitute an issue for PCMs as well and can be addressed by maintaining better databases and increasing transparency and data exchanges between involved parties. However, technological developments can be expected in the field with the advent of more powerful solvers and the use of cloud or high-performance computing.

3. **What are the main uncertainties in long-term transmission expansion planning that should be addressed by the modeling approach and how?**

One of the main criteria in the evaluation framework was that the models should be able to adequately capture the uncertainty involved. The starting point of this analysis was the identification and classification of the uncertainties present in TEP. A thorough literature review was conducted to identify the uncertainties, which were categorized based on their causes. Market, nature related, demand, individual asset, regulatory, economic, modeling and other uncertainties comprised the main categories. These uncertainties were classified further by using a stylized version of Walker's uncertainty matrix which focused on the level and nature of uncertainty. In parallel, a literature review was performed to identify the most significant uncertainties in terms of their impact on model outputs. These were related to: fuel prices, CO_2 prices, Regulatory uncertainty, Environmental policies, Weather related resources, Load and EVs.

Then, the several methods for managing uncertainty in TEP were described and their pros and cons were listed. This enabled us to explore the most appropriate method to address significant uncertainties in the planning process. The whole analysis revealed that variability is the main characteristic of the uncertainties in transmission planning. These variables influence the economic assessment of the projects significantly and thus, they should be handled with methods that are able to capture their dynamics. Stochastic processes, econometric time-series methods and Monte Carlo simulations have been widely used in literature to capture these uncertainties. The inadequacy of deterministic methods in future planning was revealed through a systematic analysis of the main causes and characteristics of uncertainties. In cases where statistical and stochastic models are not feasible (e.g. lack of data), scenario making is still applicable. Variables with high levels of uncertainty should be addressed through scenario analysis, where a wide spectrum of possible future realizations should be considered.

4. **What is ENTSO-E's current modeling approach on pan-European transmission planning and how is it assessed?**

The modeling approach of ENTSO-E was thoroughly described and assessed in terms of both modeling types used and uncertainty analysis techniques followed. It was found that:

- ENTSO-E should take into consideration recent developments in the long-term planning models and change its study methodology. ENTSO-E's top-down planning process should be performed in an analytical way by using Capacity Expansion Models instead of Production Cost Models and heuristics. The quantitative analysis in this thesis reveal the inadequacy of the heuristics approaches, TOOT and PINT, in deriving and assessing transmission plans.
- Future installed generation capacities should be derived through an analytical process and not by using guidelines based on scenario narratives. The scenario parameters could be used as inputs to Capacity expansion models for generators (like MISO) or for generation and transmission co-optimization models (like WECC). The importance of generation capacities to the scenario building was also demonstrated in the modeling part of this thesis.
- ENTSO-E's planning should focus on utilizing co-optimization tools either for investigating the dynamics between generation and electricity transmission but also the interdependencies of gas transmission and electricity transmission networks.
- ENTSO-E's scenario analysis approach should be reconsidered. The scenario axes should be unbundled from the policy objectives, which leads to the "top-down"/"bottom-up" approaches. Instead, the scenario axes should represent fundamental uncertainties (such as technology growth).
- ENTSO-E's modeling approach should explicitly take into consideration the stochastic behavior of fuel prices, CO_2 prices, weather data and load and model them accordingly: Monte Carlo, time-series, stochastic processes. The additional insights that probabilistic or stochastic processes can bring to the planner were demonstrated quantitatively and concerned: 1) identification of the most influencing uncertain variables, 2) indication of ranges of possible values rather than single points, 3) exploration of possible dynamics and correlations between system variables.
- ENTSO-E should increase transparency in the whole TYNDP study cycle by sharing information and relevant data with the public. In parallel, it should develop and maintain databases with the member TSOs, so as to develop further its planning process.

9.2 DISCUSSION AND IMPLICATIONS FOR ACTORS IN TRANSMISSION PLANNING

The main research question revolved around the pan-European transmission planning process and its ability to cope with upcoming challenges in the future energy systems. The transmission system can have direct consequences for the economic growth and the environmental impact. The EU Commission has recognized the importance of transmission system in fulfilling their policy and environmental goals as well. However, transmission planning is a complex procedure. The liberalization of the electricity regimes made the operation of transmission system more dependent on market dynamics and developments. As a consequence, the long-term planning of the grid depends substantially on the highly variable market dynamics as well. To this end, a main challenge is how to plan in the long-term by taking into account the short-term horizon.

Adding to that, the misalignment of national regulations and the different interests between the national TSOs make a truly pan-European transmission planning rather complex. The establishment of ENTSO-E and its obligation to develop a bi-annual pan-European plan for transmission was the first step. However, this plan is a non-binding plan and transmission planning in Europe is still driven by national plans and policies. Although this thesis focused on the modeling aspect of transmission planning, it was made clear that technical issues are not the only constraints. Political aspects also play an important role and sometimes hamper the planning process (e.g. information exchange).

Although in this study improvements in the planning process were proposed, they have to be planned carefully. Changing a planning procedure is a deep change within an organization and deep changes are always hard to implement. In case of transmission planning, shifting to CEMs will require significant resources in terms of budget, training of the modelers and maintaining data bases. Maybe the most difficult part is to convince the involved parties and experts that this change has to be made. The fact that Production Cost Models have been used extensively in the electricity sector may cause inertia in a proposed change.

There are three options for implementing the new modeling approach: (1) either start the change at both TSO and ENTSO-E level, (2) start the change at a TSO level first and expect to be adopted by other TSOs and ENTSO-E later or (3) start the change centrally at ENTSO-E level and expect that this will be considered as a paradigm for the national TSOs. The implementation of the first two options may be hindered internally at a TSO level as it will be hard to change practices of so many years. Shifting the planning modeling approach first at ENTSO-E level can be successful for the following reasons.

First, (i) ENTSO-E is the organization responsible for a pan-European planning process. Thus, it is more interested in examining the effects of a policy-driven top-down approach. (ii) ENTSO-E is a recently established organization in which changes can be more easily implemented. This can also be observed by the fact that the methodology followed in each of the first three TYNDP study cycles (two of them official) is different. This is going to happen for the upcoming cycle as well. Although these do not concern fundamental changes, it seems that there is a desire to improve the process and the modeling approach. (iii) The TYNDP is a non-binding and exploratory plan. In this sense, new study methodologies can be tested and implemented because they are not final project assessments and there is no regulatory authority that has to approve the changes. (iv) The TSO experts involved in TYNDP planning will be more willing to explore the new methodologies if these concern their side-tasks in TYNDP and not the national plans for which they are accountable. Being risk-averse in such a complex process and not be willing to be the first mover in changing a methodology can be justified. This is different when ENTSO-E becomes the first mover. The involvement in ENTSO-E's studies could serve as a way to make the transition in the national modeling approaches smoother. (v) ENTSO-E currently maintains databases from all TSO members. Thus, it will be easier to extend these databases and use them for the new modeling approach. If that kind of databases exists, the shifting towards the new modeling approach by TSOs can be also facilitated.

Therefore, by taking into account the main findings of this research and the above discussed points, the following recommendations are proposed:

For the policy makers:

- Uncertainty is inherent to transmission planning and cannot be avoided. Long-term transmission planning models should not focus only on obtaining accurate results but also on future exploration. The exact numerical results should not be used blindly.
- Policy driven, top-down planning is feasible but requires significant resources and investments, co-ordination between TSOs and alignment of national regulations. This could be achieved by providing more power and jurisdiction to EU agencies like ENTSO-e, ENTSO-G and ACER.
- A transparent assessment framework that takes into account all benefits and costs of transmission projects should be developed. The assessment should take into consideration the risk and the uncertainty related to the project.

For the transmission planners (TSOs and ENTSO-E):

- Capacity Expansion Models should be set as a basis for long-term transmission planning and be used for exploratory rather than evaluative studies.
- Uncertainty analysis should be improved in two aspects:
    - Scenario analysis should be based on fundamental uncertainties and not driven by stakeholder desires (e.g. market integration).

  - The variability and the complex dynamics between uncertainties should be explored through stochastic processes and Monte Carlo simulations rather than scenario analysis and sensitivity analysis.
- ENTSO-E and TSOs should collaborate closer through information and knowledge exchanges and co-ordinate their national plans.
- ENTSO-E and TSOs should develop and maintain on-line databases with common structure. These databases should include detailed data of the transmission grid and historical data of load, fuel prices, outage rates, power exchanges, weather data and hydrological conditions.
- The transparency of TYNDP study cycle should be enhanced. The assumptions on the scenario analysis and the whole range of data used should be made publicly available. In case of confidentiality constraints regarding data, they could be provided in an aggregate level.
- TSOs and ENTSO-E should extend the collaboration with the research society. Increased transparency could help researchers to conduct analyses and test their models against real-world data. This could offer ENTSO-E significant advantages in planning process (example of WECC).
- Transmission Planners should utilize the recent advancements in cloud computing and high-performance computing in order to reduce the simulation time. This will allow stochastic analyses in their studies.

9.3 LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

In this thesis we tried from the beginning to limit the scope of the research into the modeling approaches of the planning process and their evaluation. Therefore, the current thesis can be improved and extended in many ways. Some of them are the following:

Regarding the scope

- The thesis focused on the modeling aspect of interregional transmission planning in Europe. However, it would also be interesting to examine how this planning can be improved in terms of process and challenges: collaboration between TSOs, tasks and assignments, the role of ENTSO-E, public involvement. We touched on these issues but not in depth; only up to the extent they affected the modeling approach.
- Another aspect of the planning process that was considered as constant was the metrics for assessing the transmission projects. ENTSO-E's CBA framework was considered as given and it was only discussed up to the point it intersected with the modeling approach. A study focusing on the transmission benefits and costs and how these can be incorporated in the models would be interesting. The distribution of benefits and costs in interregional planning has been found to hinder interregional planning processes. Thus, it can also be an attractive area of research.
- The present thesis did not distinguish between merchant and regulated interconnection projects. The choice of the type of interconnection and how this affects the assessment framework could be studied. This would also add a fourth member to the group of stakeholders that we examined to construct the evaluation framework.
- Additionally, the decision making process of transmission planning could be examined. Should the tool to assess projects be a CBA framework or should the obtained model data be further processed (e.g. min max regret criterion)?

Regarding the methodology and the modeling approach

- The thesis developed an evaluation framework for assessing modeling approaches in transmission planning. This framework was created through an extended literature review on the objectives of the actors involved in the planning process. It would be interesting to validate or even extend this framework through a series of workshops or structured interviews with various experts from the field.
- The quantitative part of the analysis could be explored further. The present thesis focused mainly on demonstrating the inadequacy of deterministic scenarios in capturing

the variability of certain parameters. This analysis could be extended so that it examines other variables (like weather data) as well.

- Apart from the uncertainty analysis, the development of a capacity expansion model could be realized and compared against production cost models under the same conditions.
- In case a capacity expansion model is developed, sophisticated algorithms to deal with uncertainty, such as stochastic optimization can be performed. Such studies have been performed for the WECC region and the UK in Europe, but it would be interesting to see what costs savings it would bring at an EU-level.

10

Reflection

10.1 INTRODUCTION

It was about middle of November when the first discussions for conducting my master thesis project in TenneT had started. My first goal was already accomplished and was taken out of my bucket list: "*Choose a complex topic for your thesis that has also a practical value*". The project fitted perfectly to both my electrical engineering background and my current studies in engineering and policy analysis. Words like "planning", "uncertainty" and "scenarios" were part of the daily conversations with my fellows in the master. I was full of energy and confident that I would be able to find the best planning process and use a fully stochastic model that could be used everywhere. Naïve, but it was necessary to start working on such a highly complex problem with enthusiasm. As a consequence, the scope was narrowed down, the methodology was formulated based not only on the study objectives but also on time and other constraints, and simplifications in the modeling approaches had to be made. A reflection on how these aspects and the general process may have influenced the results or what could be done differently will be provided in the next sections.

10.2 REFLECTION ON THE SCOPE

This project started with one very practical question: "*Are stochastic models better than deterministic ones?*". Unfortunately, an answer to this question cannot be really provided in the case of planning. The fundamental methodological problem of validating forward-looking models, which was described in Section 2.3, constituted the major reason why the research question had to change. This brought us to a more general question: "*Which models are good for transmission planning*?". This question could be answered but it should become more specific for a master thesis: "*Which models are good for transmission planning at interregional and pan-European level?".* This change did not affect the research result. On the contrary, it helped to focus on the importance of economic criteria for transmission planning, and not on reliability criteria. Furthermore, it helped to identify the inadequacy of the currently used production cost models. If the scope had been limited to the evaluation of single interconnection investments, the need for endogenously derived projects and an analytical process of identifying projects would not have been taken into consideration. In contrast to PCMs, CEMs can perform such analyses. Since CEMs were found to be more suitable for the development of a single and unified European network, the same can hold for the national networks. Therefore, CEMs can be used for the internal development of the network as well.

From the beginning, it was outside the scope to develop a model for transmission planning. Such models, in order to be valuable for large-scale application, require great technical expertise and a lot of time. Instead, an evaluation of the currently available models was performed and points for improvement were identified. One could argue that given the criteria developed in this thesis for an "ideal" modeling approach in transmission planning, the next step would be to develop such a model. Would I be able to build such a model? Probably not. The literature review showed that so far no model has been able to capture all the points that the stakeholders (who are involved in the planning process) would like to address.

This brings us to another aspect: *Why not to examine how strategic behavior influences the transmission planning in more detail?* An answer to that question would be interesting and highly valuable for transmission planners. However, such an answer cannot be given adequately in a master thesis context. The literature has addressed this issue and there is no applicable model capable of addressing this in the long-term planning context. However, our analysis for the option of co-optimization between generation and transmission planning demonstrated that it can be used for this purpose. Not strategic behavior in terms of market bidding but in terms of investment plans.

Questions which could be answered in a master thesis could be "*Why didn't you examine the effect of using a sophisticated stochastic process in transmission planning models?*" or "*Why didn't you study the decision making process?*". The first is more related to technical and not TBM, studies. The latter is of TBM caliber but completely different from the original question. Could we add this question to our initial one? Maybe, but then the scope would be too broad for a master thesis.

This thesis tried to find an answer to a practical problem with considerable societal and environmental impact. Although long-term planning models should offer insight into future developments and assessment, most of the time they are treated as the holy grail of decision-making. Policy makers and planners often pay too much attention to the model outputs and ignore the inherent uncertainty. Since models are the backbone in the decision-making process in transmission planning, this thesis tried to address this issue: What modeling approaches should be used and how? Although with a different scope, this has been the issue in other researches as well, either in academia or in the consulting industry (Brattle, 2013b; CAISO, 2004; Drayton et al., 2004; Hirst & Kirby, 2002; Liu et al., 2013; Francisco D. Munoz et al., 2015; Quintero et al., 2014). The main conclusion of all these studies is that significant changes have to be made in the transmission planning process either in the uncertainty analysis, the economic evaluation of the projects, the models used or the process itself. In essence, the present thesis examined whether there is a need for such methodological changes in the European context and more specifically, regarding the uncertainty analysis and the models of ENTSO-E.

10.3 REFLECTION ON THE METHODOLOGY AND MODELING APPROACH

As mentioned earlier, there was a fundamental problem in assessing modeling approaches: which model or which uncertainty analysis technique is better? This thesis would be able to answer this question if the research on time travel had been already successfully completed. We could simply make a plan and travel through the time space to evaluate the results. Unfortunately, this is not a realistic option. On the other hand, the lack of time travel journeys provided me with the intellectual exercise of the last months.

This led to the research framework of Figure 1.3 and the framework for defining evaluation criteria of modeling types of Figure 3.1. There is a common denominator in these figures: literature review and analysis. An extensive literature review was performed in two parts. The first part involved research on developments in academia regarding transmission planning models, decision making under uncertainty, evaluation of transmission projects, criticism on planning models in general, uncertainty analysis in transmission planning and beyond. It focused on identifying all the state-of-the-art theories and practices in academia, in order to know the available options of the planner. The second part focused on current industry practices in transmission planning, stakeholders' objectives, public policy documents, regulations and review of commercially available models. In this way, the main objectives of transmission planning and possible constraints were identified. The developed evaluation framework was based on the idea that we can characterize a model as useful for our planning process or not when we examine if it answers our questions and satisfies our planning desires. Although the methodology of identifying evaluation or performance criteria through literature review on the objectives of the object under study has been widely used (e.g. (De Vries, 2007) for evaluating capacity mechanisms, (Hakvoort et al., 2009; Neuhoff et al., 2011) for assessing congestion management methods), there are some points in which this evaluation framework could be better designed.

First, the framework could contain some quantifiable criteria. This would enable us to validate and enrich the results of assessing the different modeling approaches. This was not applicable because we chose to focus on highly aggregated criteria and not on detailed technical criteria. Moreover, the quantification of the criteria would require developing and performing simulations on both models (PCMs and CEMs), which, as it will be discussed later, was not feasible in the given timeline. This was mitigated by performing some illustrative and exploratory simulations regarding uncertainty analysis in PCMs in the quantitative part of this thesis.

Second and most important, the evaluation framework was not reviewed by experts involved in the field. Two things can be said in this respect. (1) The whole analysis of identifying evaluation criteria could be developed through structured interviews, workshops, Delphi method or online questionnaires to experts. This would have the following advantages: (i) it would save time from reviewing all these documents, (ii) provide more insight into the stakeholders' objectives and goals. The latter could be used in order to categorize further the criteria obtained based on their importance. For example, criteria could be clustered and rank as of essential, major or minor importance. However, it would require careful planning in identifying and organizing workshops or interviews and assuring the diversity of field experts (regulators, planners, modelers, policy makers). In the end, though, it might save me time from studying the literature, I would likely spend the same amount of time on organizing and evaluating these meetings. Another aspect, as mentioned earlier, is that people do not like changes in something they have already been doing for years. Probably, the assessment of the models or the uncertainty management techniques would be biased towards existing practices either due to cognitive dissonance of the experts or due to lack of knowledge (e.g. for CEMs). In this sense, the interviews can have a subjective character and this might lead to misleading results. In order to compensate the lack of interviews' input in our study, the literature review focused also on identifying analyses that contained stakeholders' interviews. For example, the questionnaire and responses in Neuhoff's et al. analysis on models of strategic behavior, provided us with significant insight into the opinions of field experts (Neuhoff et al., 2005).

(2) If not designed from the beginning by stakeholders' consultation, it could be validated by them once created, e.g. through e.g. Q-methodology. The time constraints and the accessibility to the stakeholders were the main reasons for not doing this. Luckily, since this thesis is performed in collaboration with TenneT, informal discussions regarding the usefulness of the models and their limitations and challenges took place. However, since in essence these are one-sided opinions (planner), they were not part of the major methodology.

Finally, there is no doubt that the modeling part could be designed in order to include comparison of the modeling types apart from uncertainty analysis techniques. This was not done due to time and data constraints. Regarding data constraints, there was the following problem. In order to compare and evaluate how different the obtained results are when using a PCM and a CEM, the data structures should be the same. Thus, replicating ENTSO-E's study of TYNDP 2014 by using a CEM could do the job. Unfortunately, the TYNDP 2014 data were available only for the year 2030. This was problematic as CEMs reach gradually to 2030 by analyzing every year. Without having 2015 as a starting point, the results of this model exercise and TYNDP exercise would not be directly comparable. Another way would be to replicate TYNDP's study by using PCMs under certain conditions and assume the same conditions by using CEMs. Unfortunately, this would require double time in order to be thoroughly performed and to reflect on the differences. Given time constraints, it was chosen not to include it in this thesis.

10.4 REFLECTION ON THE PROCESS AND STUDY RESULTS

Although this study had a different scope, starting point and methodology, some of the conclusions of this research come to confirm other similar studies, especially in terms of modeling uncertainty (Brattle, 2013b; CAISO, 2004; WECC, 2013), using a more detailed network representation(CAISO, 2004), top-down planning (MIT, 2011; WECC, 2013), model characteristics (Hirst & Kirby, 2002) , co-ordination of gas and electricity transmission (WECC, 2013) and transparency and data exchange between TSOs (WECC, 2013).

The most satisfying moment during this thesis was when I discovered the paper from (Francisco D. Munoz et al., 2015) in the first week of July 2015. This paper, written by top lead experts in the field of transmission planning, was published in June 2015 and while I was reading it, its structure seemed familiar: 1) Introduction, 2) Currently available modeling types for transmission planning (PCMs and CEMs), 3) Current practices in transmission planning (the plans of CAISO, MISO and WECC were reviewed), 4) Optimal transmission planning which focused on co-optimization, long-run uncertainty, time granularity and option value, 5) use of computing tools in the planning process. Those who have read this thesis so far will also spot the resemblances with the above paper. It seems that I did not spend the last months doing something academically insignificant.

Apart from my initial objective of "*finding the best planning process and using a fully stochastic model*", all the other objectives regarding my thesis were satisfied. I was able to work on a research topic that I find interesting, fits my background and also has a practical and scientific value. I was lucky enough to work in TenneT and have easy access to data and discussions with experts in the field. From my colleagues and previous experience I know how hard is to find the right data. Moreover, I satisfied my need to learn something new every day. Before starting this thesis, I had an idea of uncertainty, scenario analysis and modeling. However, for the field of transmission planning I had to start from scratch. That's why my EndNote library is full of 853 papers, policy documents, presentations and industry reports. The complexity of the problem often frustrated me and made me change the structure of my thesis at least 4 times. While working independently throughout the thesis, I found the meetings with my supervisors and the graduation committee very enlightening: their remarks and concepts helped me to deliver this end product.

During the whole process, I did not only learn new theories and concepts, but I also developed new skills. I learned how to use the software of PLEXOS at sufficient level in one month, I learned to use data visualization software (Tableau) and I started "playing" with the statistical tools R and SPSS; at the same time, the Macro Commands in Excel became my right hand in sorting out the data before simulations.

I would change four things if the time travel machine had been discovered: (1) I would perform structured interviews to validate the evaluation framework, (2) I would read less literature, (3) I would spend more time on the modeling part and (4) I would arrange more meetings with my supervisors.

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Appendix A

Addressing uncertainties through optimization techniques

In transmission expansion planning (TEP), there are currently four large clusters of methods to deal with uncertainty of the solution in the optimization problems problems: scenario analysis, stochastic programming, robust optimization and dynamic programming. This section is going to describe these methods by providing indicative state-of-the-art studies.

SCENARIO ANALYSIS

Scenario analysis is the mostly used method in practice, as can be easily comprehended and implemented, even with deterministic models (Henry et al., 2004). Every scenario consists of different values for a set of uncertain variables. Most of the time, these values have been generated by using Monte Carlo simulation or researcher's judgment (usually based on workshops). Therefore, every scenario is different and gives a different picture of the examined future situation. Then, the model is solved deterministically multiple times and these results are examined by the researcher and the decision maker. Critics of scenario analysis argue that such an approach in dealing with uncertainty does not provide useful recommendations to decision makers (Buygi, Balzer, et al., 2004b). Giving the broad range of uncertainties that the scenarios cover, the solutions are many times contradictory making it difficult for the decision makers to choose the optimal plan. Decision makers usually choose a plan that performs well in most of the cases (in average) whereas in fact it is not optimal at all. Proponents of scenario analysis, on the other hand, raise the point of whether one should seek for optimality or for robustness given the uncertainties of the future (Rahmani et al., 2013). Robust solutions however, often result to costly investment plans. Finally, as mentioned in previous section, scenario analysis is a technique especially useful for simulating non-random uncertainties.

STOCHASTIC PROGRAMMING

A more complex technique, which, however, provides better results than scenario analysis is stochastic programming (Cedeño & Arora, 2011). The main difference between these two approaches is that the latter ensures that the solution is optimal under all scenarios, providing, thus, decision makers with one set of actions. This is achieved by splitting the model decisions in two parts (2-stages stochastic programming): in the first stage a decision is taken without taking into consideration the uncertainty, which appears in the second stage (Desta Zahlay et al., 2013). Therefore, all solutions are feasible because of the first stage. Multi-stage models are also under research (Qiu et al., 2014). However, for large power systems, the results obtained by such models do not differ than two-stage ones.

The models based on stochastic programming are computationally intensive and research focuses on scenario reduction methods (Jae Hyung et al., 2009), decomposition approaches and stochastic sampling (Jun Hua et al., 2011) in order to improve it. Moreover, in order to maintain the feasibility of the solutions under every scenario, the solutions often lead to costly investment plans. As a result, research on stochastic programming is also focusing on the proper determination of probabilities or relaxation of the constraints (Donohoo et al., 2013). Finally, since stochastic programming optimizes the expected value of the objective function under all scenarios (e.g. average values), it does not provide clear solutions as does not account for risk-attitude of the decision maker (Torbaghan et al., 2014). This problem is solved with robust optimization technique (Ruiz & Conejo, 2015).

ROBUST OPTIMIZATION

Robust optimization technique tries to find the optimum of an objective function consisting of multiple criteria. In every criterion a weight is attached (Bokan et al., 2014; Rahmani et al., 2013). This method takes into account that there will be cases where uncertain parameters take values that have low probability but high impact, and adjusts the value of the objective function accordingly. Therefore, ensures feasibility under all scenarios (Escobar et al., 2014). The results obtained appear to be more robust when the examined period unravels than the other two discussed methods (Ruiz & Conejo, 2015).

However, the choice of the weights is often critical to the problem solution and there is high computational burden in simulating large systems. For this reason, many times, scenarios based on extreme cases are modeled for each variable, instead of deriving them stochastically. Again, the “optimality under all scenarios” attribute comes with the price of a costly and highly redundant power system (Ruiz & Conejo, 2015).

DYNAMIC PROGRAMMING

Dynamic programming is the last cluster of methods that are used to deal with uncertainty. It is a sequential technique and solves the problem in stages, starting from the end towards the start of the period. Optimality is ensured in the whole time period. The uncertainties can be represented as variables of particular distribution that move the state of the system from the one stage to the other (Dusonchet & El-Abiad, 1973). However, the number of uncertainties increases exponentially the computational time needed, making dynamic programming is not yet applicable for large scale expansion problems (Zheng et al., 2014). Research on approximation methods on dynamic programming (ADP) have made it feasible, even in the detail of the solution and the system representation are still on an aggregate level (Xiao, 2013).

DISCUSSION ON METHODS

Transmission expansion planning relied for many years on optimization techniques using deterministic scenarios. Stakeholders still use such models for their TEP even in deregulated power systems. They seek for optimality into the uncertain future, while the question should be mainly how to cope with uncertainty and provide robust decisions. The four clusters of methods to deal with uncertainty were described in the previous paragraphs. As discussed, dynamic programming and robust optimization are still far from being applicable to real-world electricity networks. Most of the TSOs use commercially available tools and models to design their planning strategies. These tools were mainly designed for executing deterministic analysis and have not been fully adapted to the new developments in academia. Some tools incorporate several stochastic aspects (Monte Carlo simulation), whereas others try to implement stochastic programming techniques in their algorithm. The latter are mainly products of university research and need high computational time to be applied in large systems. The papers of Connolly et al. (2010) and Foley et al. (2010) provide a useful overview of the models used in transmission expansion planning.

The inadequacy of available tools to handle uncertainty has led the TSOs to use scenario or sensitivity analysis in their TEP. Scenario analysis can be proven quite insightful if the question is not optimality but robust decision making. In order to achieve this many different scenarios have to be simulated. However, in practice, TSOs tend to use only a few scenarios (usually four) in their analysis. Initially, scenario analysis had a predictive character and was mainly performed as an effort to forecast the future (ENTSO-E, 2014d). Since forecasting in the long-term is a difficult task, this was done in limited scale (usually three forecasts: worst, best and base case). Recently, driven by the realization that future cannot be easily predicted, research shifted from predictive to explorative scenario analysis: define and use scenarios that cover most of the probable futures, not forecasted ones. However, influenced by the previous analysis, these scenarios are still limited in number. An example is the ten-year network development plan of the European network of TSOs (ENTSO-E, 2014d) which attempts to perform such an explorative scenario analysis by using four scenarios. The main question then is whether a limited number of scenarios is adequate for transmission planning and how these scenarios are developed. An answer could be to apply concepts introduced by RAND corporation on exploratory modeling analysis (Bankes, 1993) and computer assisted scenario development (Parker et al., 2015). This has not been used in practice for TEP problems, but it seems that it would add robustness in the results to the current process.

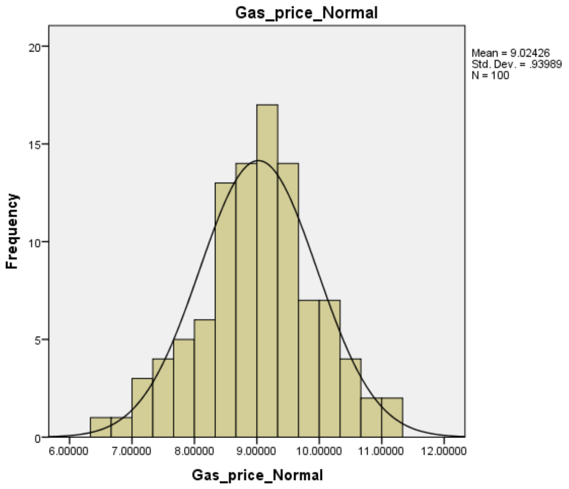
Appendix B

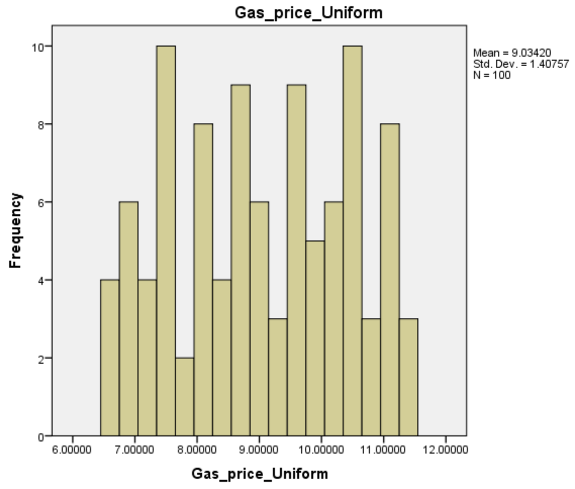
Potential Benefits of transmission projects (adapted from (Brattle, 2013a))

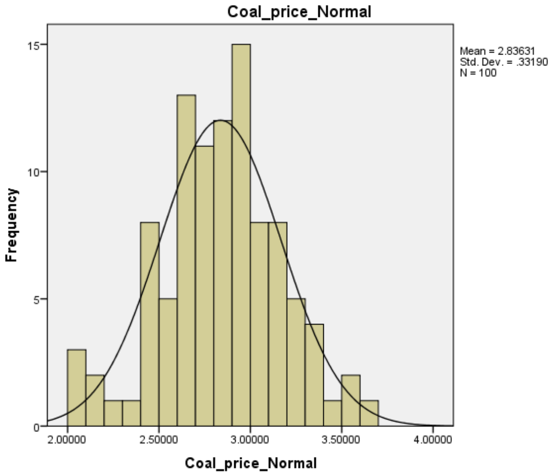
Benefit Category	Transmission Benefit
1. Traditional Production Cost Savings	Production cost savings as traditionally estimated
1a-1i. Additional Production Cost Savings	a. Reduced transmission energy losses b. Reduced congestion due to transmission outages c. Mitigation of extreme events and system contingencies d. Mitigation of weather and load uncertainty e. Reduced cost due to imperfect foresight of real-time system conditions f. Reduced cost of cycling power plants g. Reduced amounts and costs of operating reserves and other ancillary services h. Mitigation of reliability-must-run (RMR) conditions i. More realistic representation of system utilization in "Day-1" markets
2. Reliability and Resource Adequacy Benefits	a. Avoided/deferred reliability projects b. Reduced loss of load probability or c. Reduced planning reserve margin
3. Generation Capacity Cost Savings	a. Capacity cost benefits from reduced peak energy losses b. Deferred generation capacity investments c. Access to lower-cost generation resources
4. Market Benefits	a. Increased competition b. Increased market liquidity
5. Environmental Benefits	a. Reduced emissions of air pollutants b. Improved utilization of transmission corridors
6. Public Policy Benefits	Reduced cost of meeting public policy goals
7. Employment and Economic Development Benefits	Increased employment and economic activity; Increased tax revenues
8. Other Project-Specific Benefits	Examples: storm hardening, increased load serving capability, synergies with future transmission projects, increased fuel diversity and resource planning flexibility, increased wheeling revenues, increased transmission rights and customer congestion-hedging value, and HVDC operational benefits

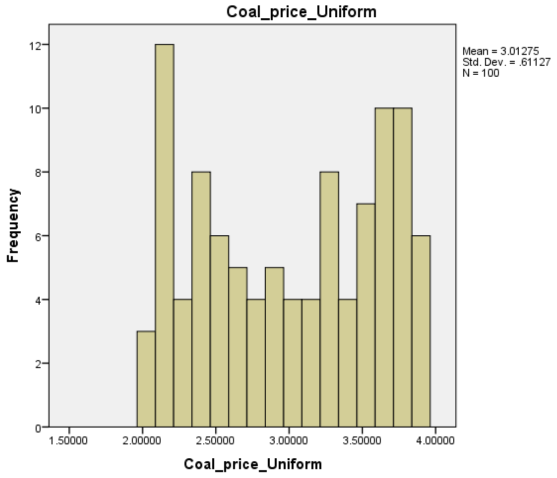
Appendix C

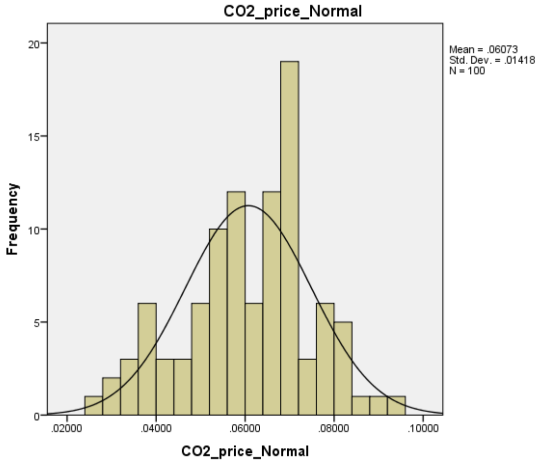
Distributions of uncertaintain parameters

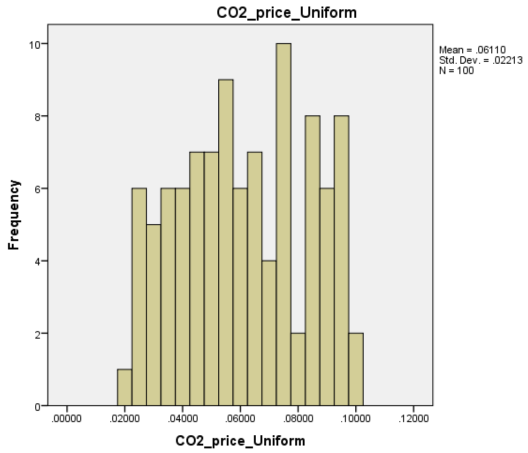

Gas_price_Normal


Gas_price_Uniform


Coal_price_Normal

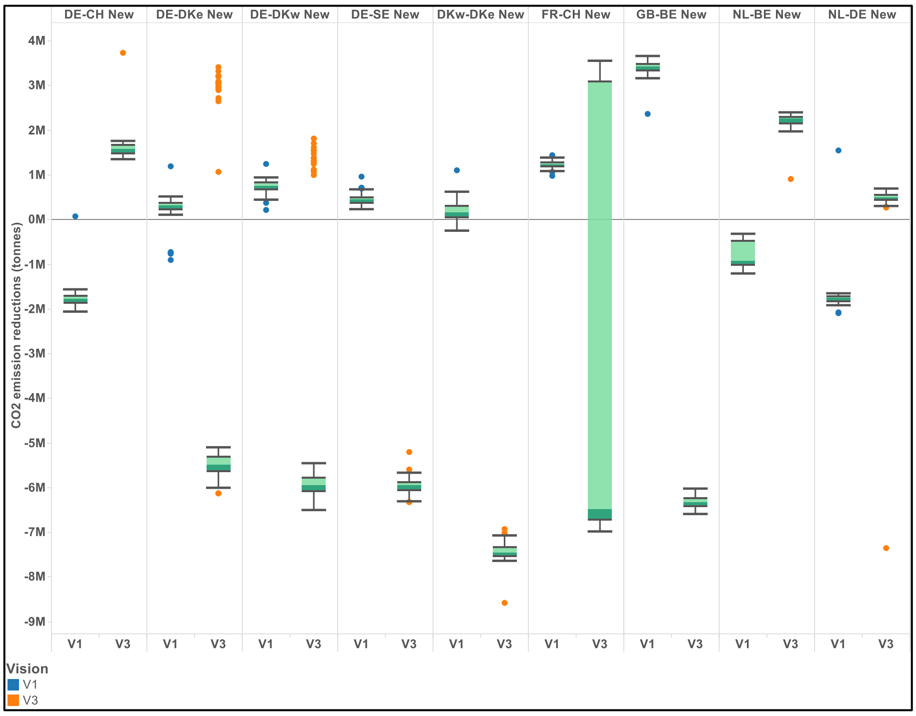

Coal_price_Uniform


CO2_price_Normal

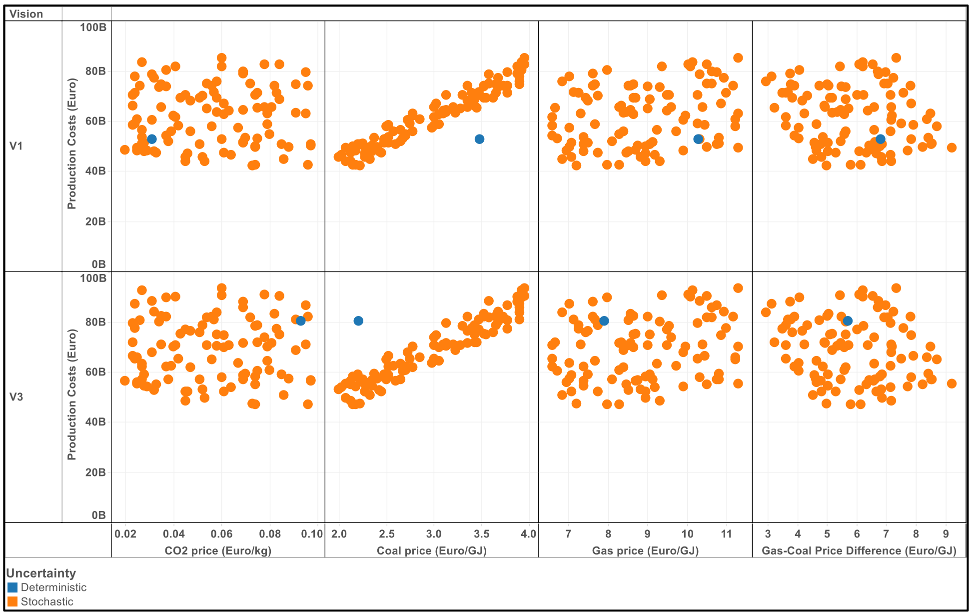

CO2_price_Uniform

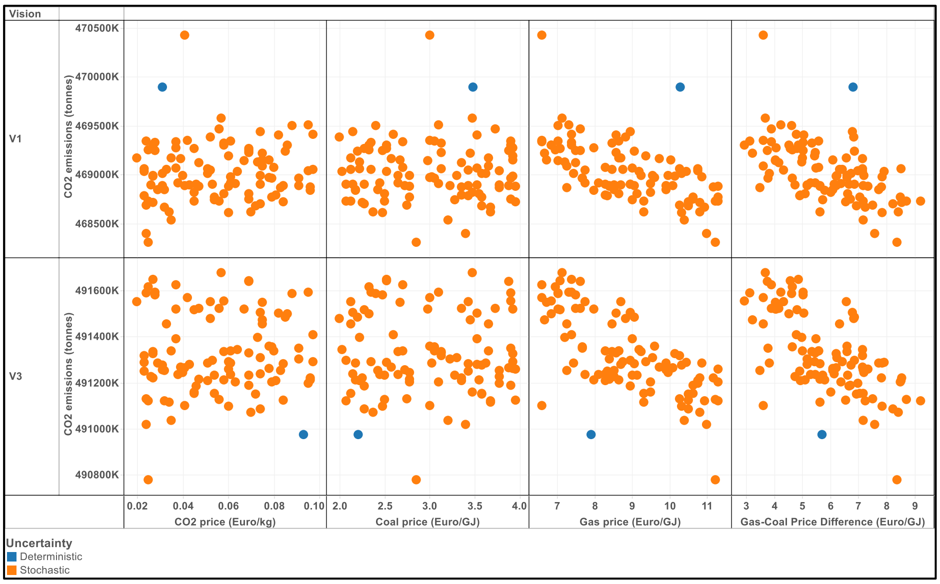
Appendix D

Comparisons of Visions and scatterplots between variables



No Projects

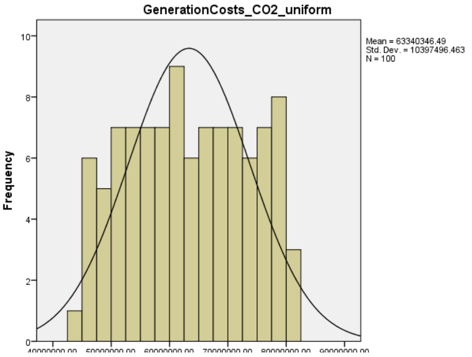


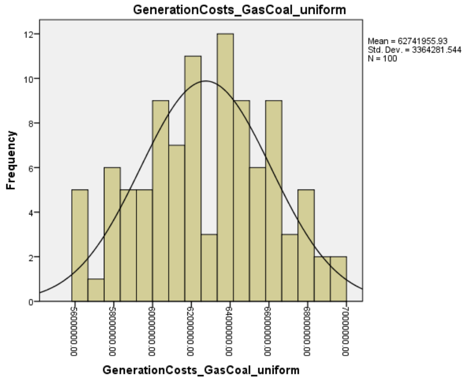

Vision
V1
V3
CO2 emissions (tonnes)
470500K
470000K
469500K
469000K
468500K
491600K
491400K
491200K
491000K
490800K
0.02
0.04
0.06
0.08
0.10
CO2 price (Euro/kg)
2.0
2.5
3.0
3.5
4.0
Coal price (Euro/GJ)
7
8
9
10
11
Gas price (Euro/GJ)
3
4
5
6
7
8
9
Gas-Coal Price Difference (Euro/GJ)
Uncertainty
Deterministic
Stochastic

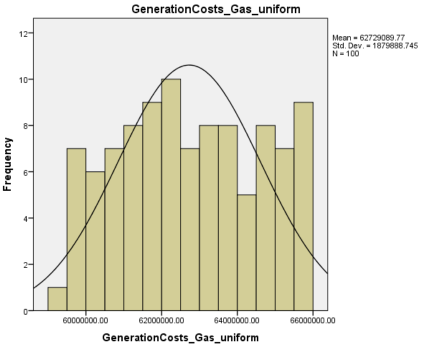
Appendix E

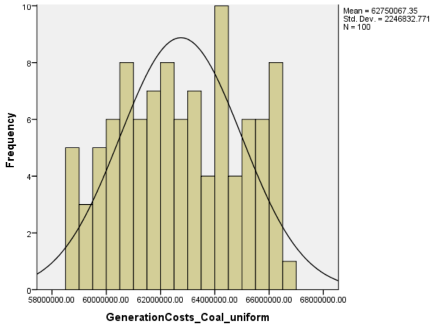
Metric’s Distributions per Monte Carlo simulation

System Production Costs per Monte Carlo Simulation

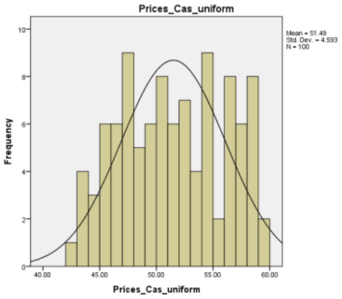


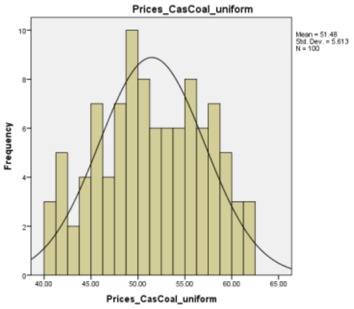


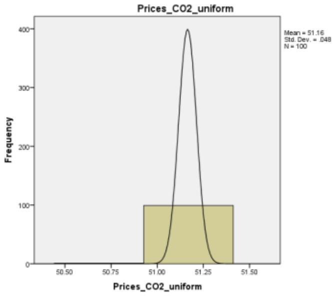


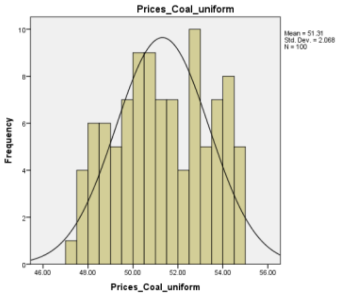


System Average Electricity Prices per Monte Carlo Simulation

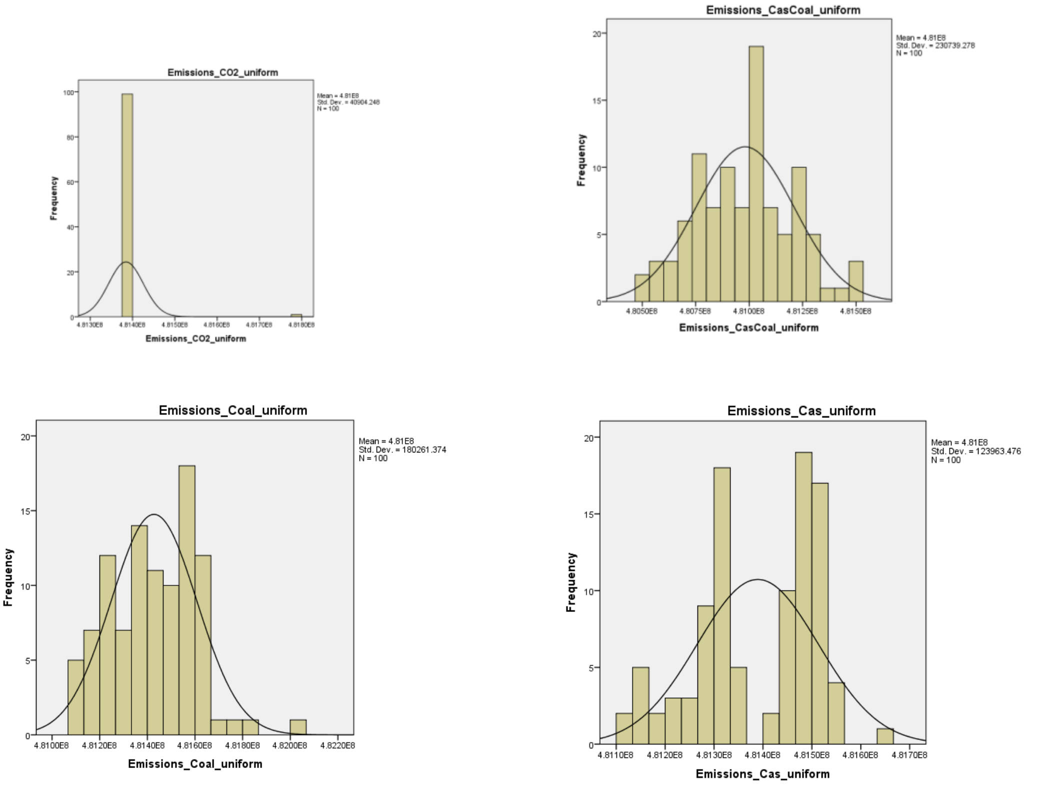






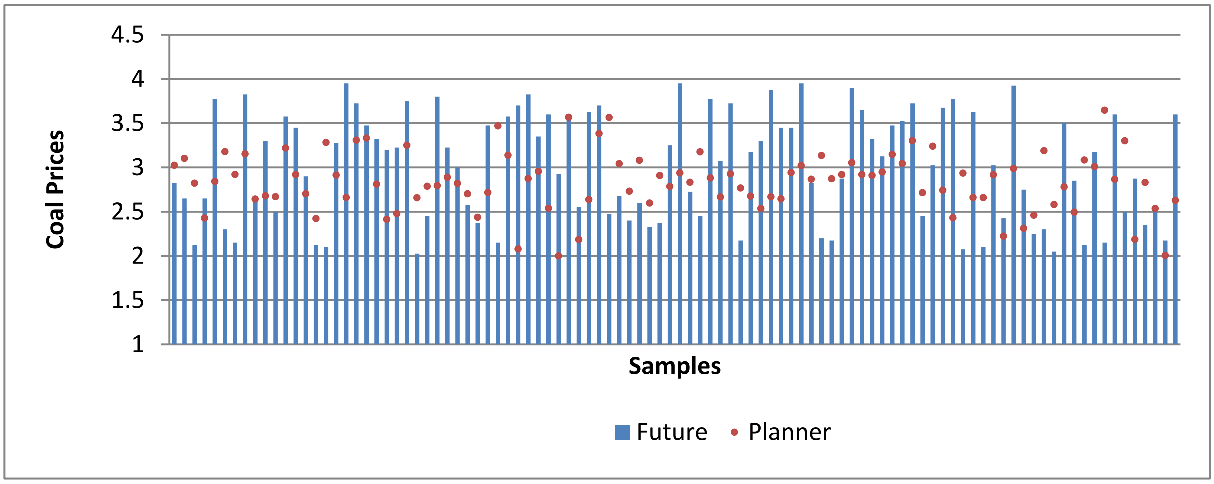


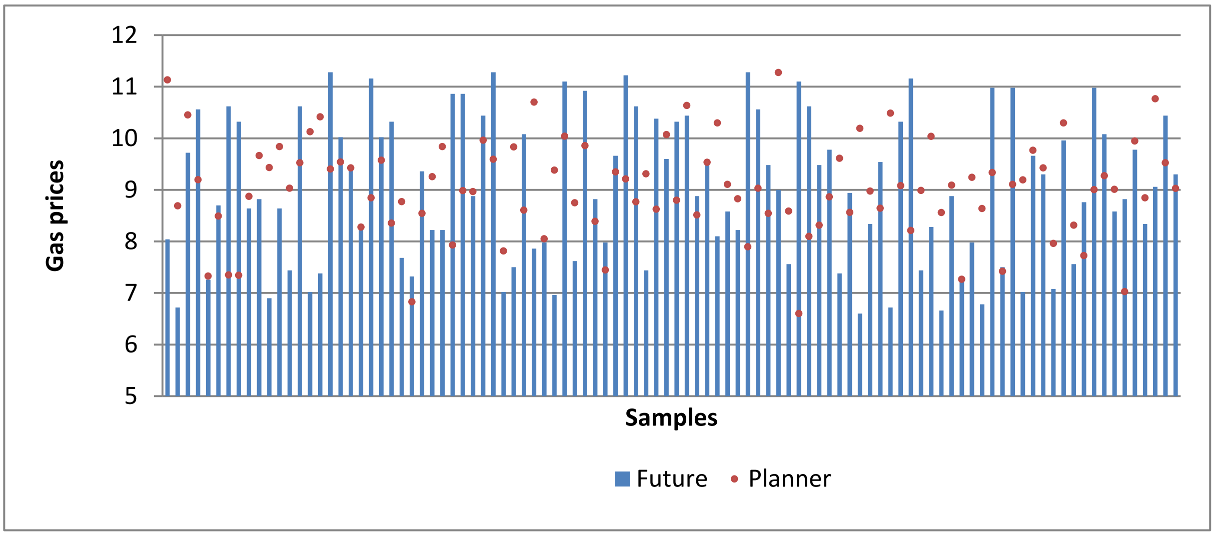
System CO_2 emissions per Monte Carlo Simulation

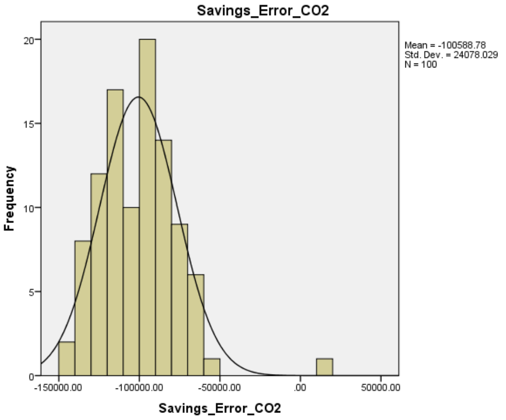


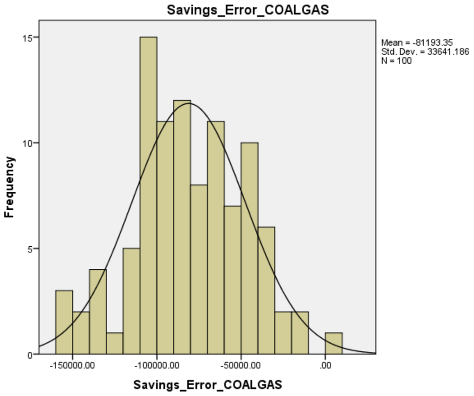
Appendix F

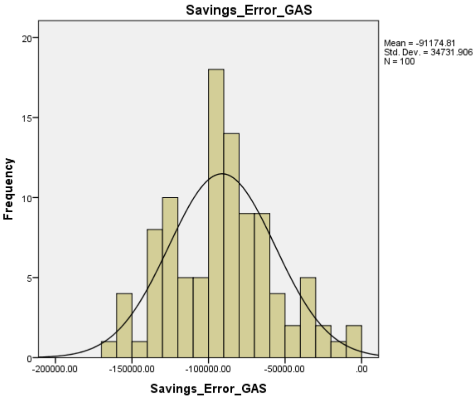
Planner Vs Future and Estimation Errors

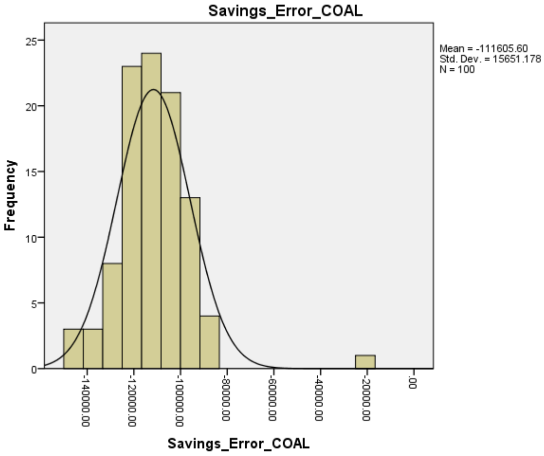





Savings_Error_CO2
Mean = -100588.78
Std. Dev. = 24078.029
N = 100
Frequency
0
5
10
15
20
-150000.00
-100000.00
-50000.00
.00
50000.00
Savings_Error_CO2


Savings_Error_COALGAS
Mean = -81193.35
Std. Dev. = 33641.186
N = 100
Frequency
0
5
10
15
-150000.00
-100000.00
-50000.00
.00
Savings_Error_COALGAS


Savings_Error_GAS
Mean = -91174.81
Std. Dev. = 34731.906
N = 100
Frequency
0
5
10
15
20
-200000.00
-150000.00
-100000.00
-50000.00
.00
Savings_Error_GAS


Savings_Error_COAL
Mean = -111605.60
Std. Dev. = 15651.178
N = 100
Frequency
0
5
10
15
20
25
-140000.00
-120000.00
-100000.00
-80000.00
-60000.00
-40000.00
-20000.00
.00
Savings_Error_COAL