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Assessment of the availability of reserves with the expected rising of the wind power in the Danish system

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Abstract

The energy reserves play a key role in the energy systems and because of that its use should be optimized. In a market like Nord Pool which is already optimized, the use of the reserves should be as well. Indeed they are, but when we look towards a horizon of medium to long term, with the expected increase of wind production, the optimization and the influence of the reserves in the system and in the market deserve a new critical examination.

The main goal of this thesis is the study of the operational reserves, the principles and regulations, the market where these reserves are traded and also study the production units associated to reserves and the development of a model containing information regarding the actual use of reserves. This model will be submitted to new scenarios regarding the expected rising of the wind production and will show how this increase of wind power will affect the operational requirements for the reserves.

This work will clarify the explanatory variables included in the model and express a critical analysis of the results obtained.

Resumo

As reservas de energia desempenham um papel fulcral nos sistemas de energia e em consequência disso o seu uso deve ser o mais optimizado possível. Num mercado como o Nord Pool, já por si optimizado, o uso das reserves deve-o ser também. De facto já o são, mas quando se olha para um futuro a médio longo prazo, com o esperado aumento da produção eólica, a optimização e influência das reservas no sistema e no mercado merecem novo olhar crítico.

O principal objectivo desta tese é o estudo das reservas operacionais, os princípios e regulamentos por detrás das mesmas, o mercado onde são negociadas, as centrais produtoras associadas ao controlo das reservas e por fim o desenvolvimento de um modelo que contenha toda a informação relativa ao uso de reservas. Este modelo vai ser submetido a novos cenários que simulam o esperado aumento da produção eólica e vai demonstrar de que forma este aumento vai afectar os requisitos das reservas de energia,

Este trabalho vai clarificar todas as variáveis incluídas no modelo e fazer uma análise crítica dos resultados obtidos.

Acknowledgments

First of all I'm thankful to my mentor Professor Flemming Nissen for all his support, guidance and for his availability to help me during these 5 months.

I must thank my family, in particular my parents and my brother, for all their support and love. Despite the distance I felt them always by my side.

I cannot forget my friends in this journey. The friends I left in Portugal, that are there for me I know, and the ones I make here in Denmark, that I will never forget.

I have to address a special "thank you" to Erik Fieten, his friendship was unique and irreplaceable. I found a true friend here that made me a better person and that also gave me extra motivation to believe in the success of this journey. Gerrit, Pedro, Sofia and Inês thank you for always being around, for your support and companionship. Sofia e Inês your smiles and laughter were source of inspiration as well.

Finally, I am thankful to Southern Denmark University for giving me this life changing experience of writing my thesis abroad.

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List of acronyms

AC	Alternating Current
BRP	Balance Responsible Players
CHP	Combined Heat and Power
DC	Direct Current
ENTSO-E	European Network of Transmission System Operators for Electricity
NOIS	*Nordic* Operational Information System
TSO	Transmission System Operator
UCTE	Union for the Co-ordination of Transmission of Electricity
UDP	Unexpected Deficit of Power
UMM	Urgent Market Message

Chapter 1

Introduction

In this Chapter the problem will be explained as well as its context and the ideas that will be defended.

Initially a general overview about the importance of operational reserves will be presented. Then the reasons and motivation for the work developed will be justified.

Finally the structure of this thesis will be explained.

1.1 - The importance of Energy Reserves.

During the last decades the Danish electrical system has developed very fast and Denmark is now an abounding, well-run and self sufficient system due to the propagation of distributed energy resources (mainly wind turbines and local combined heat and power plants).

Electricity reaches the consumers through a very optimize system and market, open to every player (producer or consumer), in a liberalized and fair way.

The first priority of an electrical system, and the market were its inserted, is to ensure that all the consumers are supplied when it's supposed. It is role of the TSOs (Transmission System Operators), working together, to guarantee the stability and well function of the system, by supervising the system and the market. Energinet.dk, as transmission system operator in Denmark, is responsible for ensuring the stable secure operation of the electricity system in Denmark as well as the international interconnections.

The TSO ensures this through the purchase of a number of regulating reserves and ancillary services.

When an imbalance occurs, for whatever reason, the TSO must respond in a way that the system is not affected severely by it. This is achieved by using operational reserves. Primary, Secondary and Tertiary Control are part of the system as mechanism in case of imbalances in the system. In case of a contingency they are guarantee that the consumption will not be affected by failures in power plants, interconnections or other contingencies.

The requirements for these reserves are planned by ENTSO-E, an organization that gathers all European TSOs, and are defined taking into account measurements, experience and theoretical considerations.

1.2 - The purpose of this thesis

In accordance with its title, this thesis pretends to study, reflect and give new conclusions on how the requirements for reserves should be updated to respond to a future scenario with more representative wind power in the system.

The technical requirements for reserves are decided between all the European TSOs on ENTSO-E platform. These requirements are sustained by years of experience and theoretical considerations. And it's fair to say that the European power system, with these levels of requirements, has been responding well to the imbalances, between supply and demand, when they occur. But this fact doesn't justified that new studies can be made and put these requirements on test by making new assumptions and predicting new scenarios. The technical definition of reserves requirements has not been changed since 1985, so this study it's actual and pertinent and might raise some new questions regarding these requirements.

On the other hand, it's granted that Denmark will raise its levels of wind power in the system. Nowadays, wind power provides 20% of Danish electricity consumption, but the goal is set: 50% by the year 2025. Taking this in consideration, few researches were made to study the impact of this rising in the system, in particular in the requirements for energy reserves.

At the same time, this thesis and the model developed pretends to give an idea of how independent is Denmark when regulating market concerns.

This thesis will present a model that will calculate the amount of reserves necessary to respond to an imbalance in the system and from there realize the number of hours that Denmark was not self-sufficient and had to import reserves through the regulating market.

The model developed was inspired by a concept present in this paper "Probabilistic Evaluation of reserve requirements of generating systems with renewable power sources: the Portuguese and Spanish cases" [1] (see Appendix 2).

This paper presents "an application of probabilistic methodologies to evaluate the reserve requirements of generating systems with large amount of renewable energy sources". The idea in this paper was to study the reliability indices of operational reserves when a large amount of renewable sources is integrated in the system, using deterministic and probabilistic approaches to evaluate the risk associated with specific future configurations of the generating system.

The difference of the model presented in this thesis for the one presented in this paper [1], is that, instead of making probabilistic approaches to set values for the variables, the model in this thesis will make use of real data and withdraw conclusions from there. Besides the model presented in [1] takes in consideration all forms of renewable energy and this thesis will only include wind power which is the major portion of renewable sources in Denmark.

The model built will then be submitted to new scenarios, simulating the increasing of wind production in the system.

For all the arguments here presented it's challenging and rational to do studies in the field of energy reserves.

1.3 - Organisation of this thesis

This thesis is structured in the following manner. In Chapter 2, an overview of the Danish power system. How it is structured, entities involved an historical background and the description of the operational reserves and how they are operated. Then the energy market will be explained, the players, the time schedules and the role of operational reserves in a market perspective. Finally, in this chapter a brief description of the power plants present in the system and an overview on the wind power background in Denmark.

In Chapter 3 the model developed for this thesis is explained. The purpose, goals, variables involved and the assumptions made will be carefully detailed. The first set of results will be presented in this chapter

In Chapter 4 new scenarios will be implemented in the model. Two scenarios involving new assumptions for wind power and generation will be performed. New results will be obtained that will be compared to the results obtained in Chapter 3. In the end a new value for the operational reserve is proposed as well as several conclusions regarding this results and the model itself.

Finally, in Chapter 5, the main conclusions of this work will be summarized and some suggestions or guidelines for future work will be offered.

Chapter 2

State of art

In this chapter a brief review of the state of the art of the Danish power systems and market will be made.

The entire Danish power system and the market where it is included are very complex and optimized. Rules and regulations have been developed through the years in order to improve the efficiency of the system and the accuracy of the market.

The model to be developed in this thesis and the results to be presented will focus on the new paradigms for the requirements of the energy reserves with the expected rising of the wind power in Denmark. With this perspective in this chapter a description of the Danish power system, the energy market and the power plants will be made always regarding the main focus of this report: energy reserves.

Firstly an overview of the Danish power system, it's structure, how it operates and then a close look on how the reserves are planned and put into operation if necessary.

Then the energy market will be explained, the players, the time schedules, regulations and then the most relevant for this report: the regulating market and how the market responds to the imbalances of power.

Finally, a description of the power plants relevant for the regulating market and the operational reserves will be made.

With this chapter it's expected for the reader to get a useful background trough all the Danish Energy system with a strong focus on the reserves, the standard requirements and how they are trade in the regulating market.

2.1 - Danish Power System

Denmark is a Scandinavian country in Northern Europe, southwest of Sweden, south of Norway and bordered to the south by Germany. The country has a total area of 43.098 km2, of about 5.5 million people and consists of a large peninsula Jutland and many islands (Zealand, Funen, Vendsyssel-Thy, Lolland, Falster, Bornholm and a large number of minor islands).

Denmark has been a member of the European Union since 1973, although it has not joined the Eurozone, and it's also a founding member of NATO and the OECD.

From an electrical point of view, the energy system in Denmark is divided in two different areas – DK-West and DK-East.

These two areas are not interconnected. DK-West is synchronous with Continental Europe (former UCTE – Union for the Co-ordination of Transmission of Electricity) while DK-East is synchronous with Sweden, Norway and Finland making it part of the Nordic Electricity System (former NORDEL)

This separation means that the two areas are managed differently in a number of ways. For instance, there may be differences in type of technology, system or structure. This means that some regulations are not identical in Eastern and Western Denmark.

DK-West has a significantly larger local production than DK-East and it's going to be the main focus of this report.

The total installed capacity in Denmark is 13153 MW, divided by these two areas: DK-West and DK-East.

2.1.1. DK-West

DK-West includes Jutland Peninsula and the Funen Island (Figure 2.1).

Figure 2.1 – DK-West transmission system. <u>Source</u>: *"Wind Energy – The case of Denmark" (adapted)*

DK-West is connected to Germany by synchronous Alternate Current (AC) cables, 950MW capacity to import and 1500MW capacity to export. Phase shifting transformers are planned to be installed by 2012 on the two 220kV lines Jutland-Germany meaning that the market capacity will increase from 950/1500MW to approximately 1500/2000MW (import/export). DK-West is also connected to Norway, 1500 MW capacity both ways – the interconnection is called Skagerrak – and connected to Sweden, 740MW to export and 680MW to import – Kontiskan – both interconnections by DC cables.

Cobra-TenneT (TSO in the Netherlands) and Energinet.dk (TSO in Denmark) are performing a Business Case regarding a 600MW HVDC link between the Netherlands and southwest Jutland.

DK-West has different voltage levels from DK-East. They are: 400kV, 220kV, 150kV, 60kV, 20kV, 15kV, 10kV and 0,4kV. The value system chain for the Western Danish energy system can be seen in Figure 2.2.

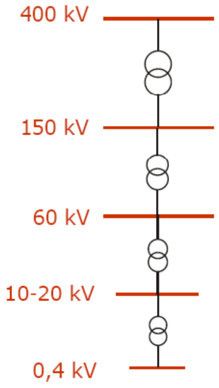


Figure 2.2 - Voltage levels for Western Denmark. <u>*Source*</u>*: "Summer School Power 2009", Flemming Nissen.*

The maximum load in DK-West is about 3.7 GW and the total installed capacity is 8793 MW.

2.1.1.1. UCTE vs Continental Europe

DK-West it's part of ENTSO-E (European Network of Transmission System Operators for Electricity) in the subgroup Continental Europe, former UCTE.

The Union for the Co-ordination of Transmission of Electricity (UCTE) coordinated the operation and development of the electricity transmission grid for the Continental European synchronously operated transmission grid, thus providing a reliable platform to all participants of the Internal Electricity Market and beyond.

In 1999, UCTE re-defined itself as an association of TSOs in the context of the Internal Energy Market. UCTE turned to make its technical standards more binding through the Operation Handbook and the Multi-Lateral Agreement between its members. These standards became indispensable for the reliable international operation of the high voltage grids which are all working at one "heart beat": the 50 Hz UCTE frequency related to the nominal balance between generation and the electricity demand of some 500 million people in one of the biggest electrical synchronous interconnections worldwide.

In its final year of existence, UCTE represented 29 transmission system operators of 24 countries in continental Europe.

On July 1st 2009 UCTE, like all the others 6 existing TSO associations in Europe was wound and ENTSO-E took over all operational tasks. Since that moment UCTE was replaced by a Regional Group called Continental Europe inside ENTSO-E organization.

2.1.2. DK-East

The DK-East area contains many islands including Lolland and Zeoland.

DK-East has different voltage levels from DK-West. They are: 400kV, 132kV, 50kV, 30kV, 10kV and 0,4kV (Figure 2.3.).

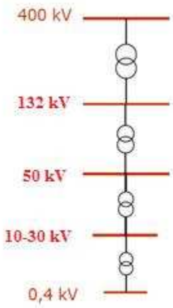


Figure 2.3 - Voltage levels for Eastern Denmark. <u>Source</u>: *"Summer School Power 2009", Flemming Nissen (adapted).*

The transmission grid in Eastern Denmark encompasses cables at the two highest voltage levels, i.e. 132 kV and 400 kV, and the interconnections with South Sweden and Germany.

DK-East is connected to Germany, 550MW both ways by 400kV DC cables – Kontek – and has a AC connection to Sweden, 1700MW (export) and 1300MW (import) – Oresund. The link with Sweden also serves as an interconnection with the Nordic grid.

The maximum load in DK-East is about 2870 MW and the total installed capacity is 4360 MW. DK-East transmission system is shown in figure 2.4.

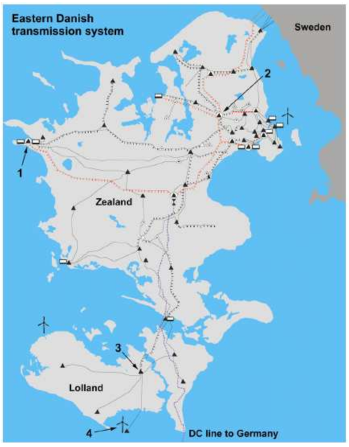


Figure 1. **Eastern Danish transmission system**
Red lines are 400 kV
Black lines are 132 kV
1. PMU at Asnæsværket, 400 kV
2. Two PMU's in Hovegård, 132 kV and 400 kV
3. PMU in Radsted, 132 kV
4. Nysted 150 MW offshore windfarm

Figure 2.4 – DK-East transmission system. <u>Source</u>: *"Phasor measurement of wind power plant operation in Eastern Denmark", Joana Rasmussenl & Arne Hejde Nielsen*

2.1.2.1. Nordel vs Nordic

As stated in the introduction DK-West and DK-East are separate systems. DK East is also part of the ENTSO-E but in a different subgroup, Nordic, former Nordel.

Nordel was founded in 1963 and was a body for co-operation between the electricity leading companies in Denmark, Finland, Iceland, Norway and Sweden, whose objective was to create preconditions for a further development of an effective and harmonized Nordic electricity market.

Among other responsibilities Nordel's objective was to ensure the operational security of the power system, maintain the instantaneous balance between supply and demand and to improve the efficient functioning of the electricity market.

The purpose of Nordel was to issue advice and recommendations promoting an efficient electric power system in the Nordic region, taking into account the conditions prevailing in each country.

As the energy market develops, cooperation between the TSOs has to develop as well. In 2009 Nordel toke the decision to join the new European TSO organization, European Network of Transmission System Operators for Electricity (ENTSO-E). From now on Nordel it's replaced by a Regional Group called Nordic inside ENTSO-E organization.

2.1.3. ENTSO-E

ENTSO-E (the European Network of Transmission System Operators for Electricity) was established on 19th December 2008. The organization has 42 members (TSOs) and will replace regional TSO organizations such as Nordel, UCTE, ETSO, UKTSOA, ATSOI or BALTSO. Those regional activities are transferred to ENTSO-E where the work will continue.

The fact that ENTSO-E is now the only TSO organization in Europe means that this new organization has to be an efficient organization that promote a strong cooperation between all members but has also to be the organization where regional development can continue.

ENTSO-E's vision is to become and remain the focal point for all European, technical, market and policy issues related to TSOs, interfacing with the power system users, EU institutions, regulators and national governments.

Due to this new association, where 42 members agree to cooperate between themselves, ENTSO-E has a big responsibility or the definition of the requirements that sustain the huge interconnected European electrical system, including an important role in defining requirements for the reserves

2.1.4. TSO – Energinet.dk

Energinet.dk is the TSO (Transmission System Operator) in Denmark and it's responsible for the operation of the main electricity and gas transmission systems and for ensuring sufficient supply of electricity and gas to cover consumer demand.

Energinet.dk was formed in August 2005 with retrospective effect as from January 1, 2005. It's an independent public enterprise owned by the Danish state under the Ministry of Transport and Energy.

Energinet.dk is responsible for the regulations of the use of the main electricity supply grid after consultation with grid companies and transmission companies. Energinet.dk is also in charge of managing the security of operation of its own networks in a subsidiary way.

Energinet.dk is only responsible for the operation of its own network. But it is required to inform relevant neighbors in case it assumes some risks to come from outside or to come from inside to be propagated abroad.

2.1.5. Evolution of Danish infrastructure

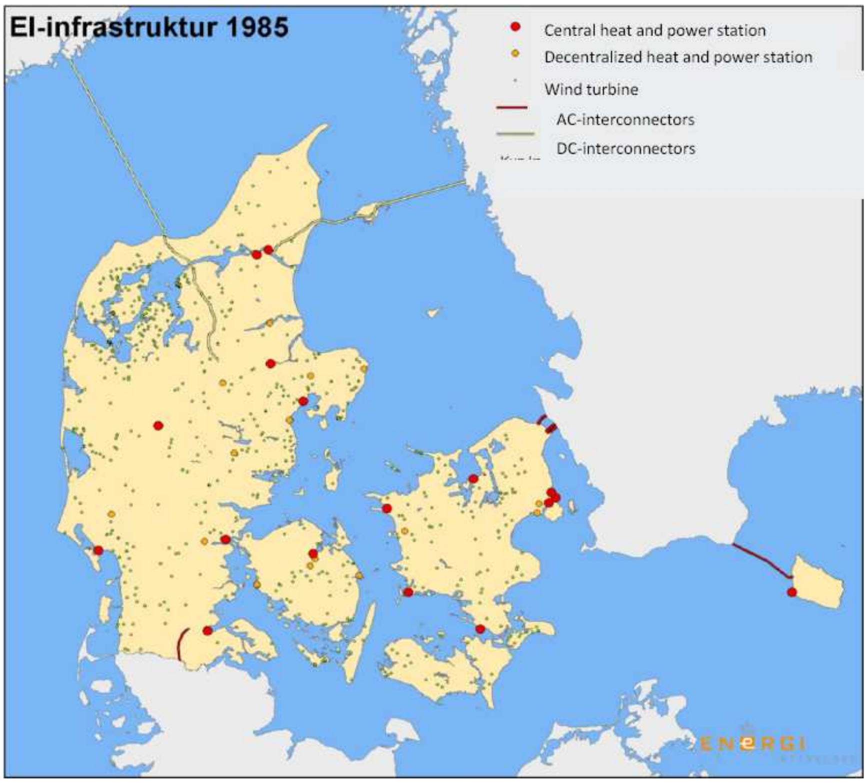


Figure 2.5 – Danish power plants display in 1985. Source: *"Wind Energy – The case of Denmark"*.

Until today, the eastern and western parts of Denmark are not inter-connected, but it's planned a 500 MW DC inter-connection to be co completed during 2010.

Figures 2.5 and 2.6 refer to the increasing deployment of new production units. These two maps illustrate how radically the electricity system has evolved during the last twenty-four years and why Denmark has effectively become the World's leader of distributed power.

The red dots show the location of its sixteen central combined heat and power stations, most of which have been re-powered and up-graded since 1980. Fifteen of these are still there and among these are the World's most thermodynamically efficient, steam turbine power stations. These use up to and over 90% of the fuel (mostly coal) that they consume during the winter period as they generate electricity and distribute heat into the local district heating networks.

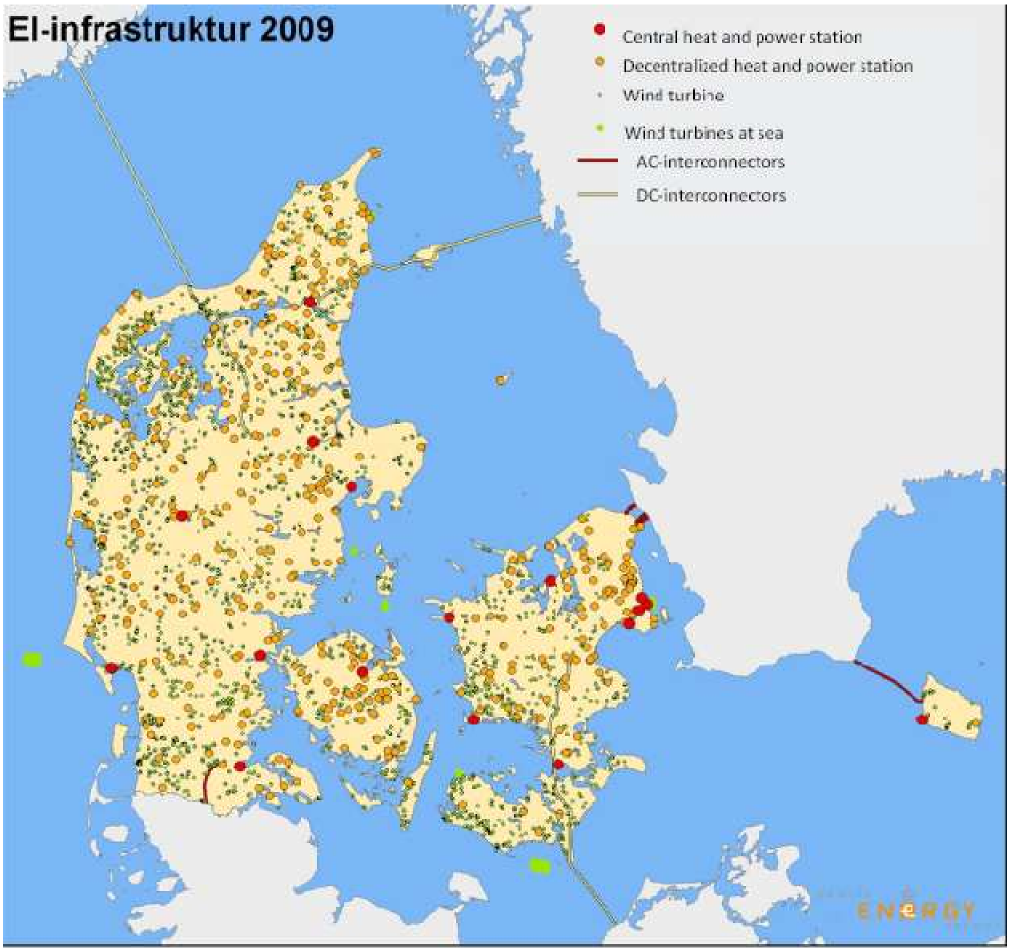


Figure 2.6 – Danish power plants display in 2009. Source: *"Wind Energy – The case of Denmark".*

The brown dots are roughly 600, village-scale, heating-only or small combined heat and power plants having an aggregate power capacity of roughly 1,600 MW, all built during the last fifteen years. These have widened the access of district heat to even quite small villages, saving heating oil, while delivering electricity into the grid, mostly from gas engines.

The green dots represent the location of the 5,500 wind turbines with a total capacity of 3,160 MW of wind turbines (end 2008). Of these, roughly 2,400 MW of wind capacity are in western Denmark and 760 MW are in eastern Denmark.

Both the wind power and decentralized power stations depend for their existence on continuing production, on subsidies.

2.1.6. Energy in Denmark – Background

Denmark is an abounding, well-run and prosperous country and is self sufficient for all its energy requirements. Its oil and gas production from the North Sea will continue to exceed demand until 2018, after which, unless it reduces demand or find another fuel sources, it will become a net hydrocarbon importer. Figure 2.7 shows the location of the oil and gas fields as well as the pipelines connections to the country.

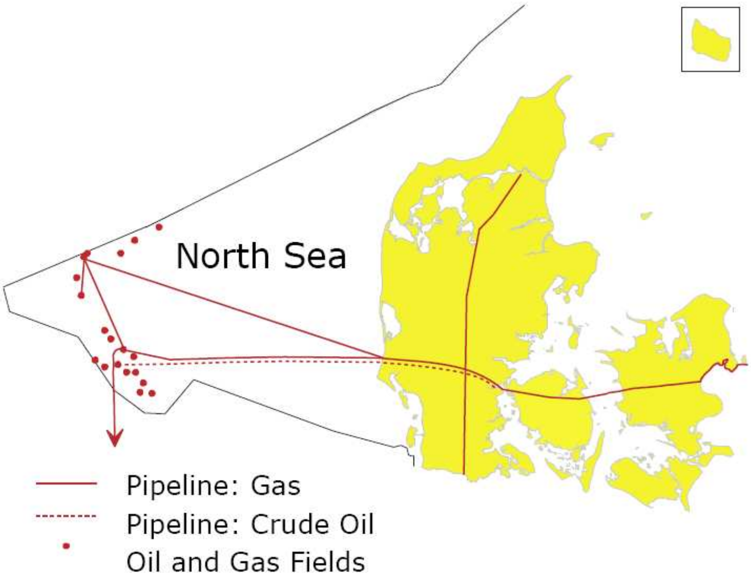


Figure 2.7 – Danish Oil, Gas Fields and Pipelines. Source: “Energy in Denmark 2008”, Danish Energy Agency.

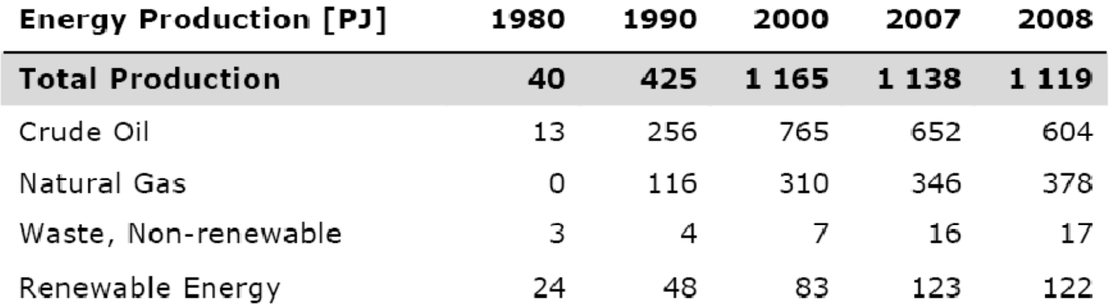
In 2008, Danish oil and gas production came from nineteen fields (sixteen oil and three gas fields). Seven fields are located in the northern part of the Central Graben, while all the other fields are situated in the southern region of the Central Graben. Denmark is the third largest oil producer in Western Europe only behind UK and Norway.

In addition to its hydrocarbon reserves, Denmark is among the leaders in energy savings and renewable energy. It has a well-developed electricity industry that continues the radical transformation which started with the shock of the first oil and second crises at the beginning and end of the 1970s, when most electricity generation was based on oil.

Denmark's energy policy has set a new course after the oil crises of the 1970s. When oil prices accelerated in 1973 Denmark was one of the OECD countries most dependents on oil in its energy system supply. More than 90% of all energy supply was imported oil. Because of that, the Danish Government at the time launched an active well-define energy policy to ensure the security of supply and enable Denmark to reduce its dependency on imported oil and at the same time invest and develop in renewables technology.

After three decades, Denmark today is among the leaders in energy savings and renewable energy. These fields have been afforded high priority, results have been impressive and there has been a consistently stable economic growth throughout the period.

Figures 2.8, 2.9 and 2.10 show the evolution of the Danish energy system from different perspectives



Energy Production [PJ]	1980	1990	2000	2007	2008
Total Production	**40**	**425**	**1 165**	**1 138**	**1 119**
Crude Oil	13	256	765	652	604
Natural Gas	0	116	310	346	378
Waste, Non-renewable	3	4	7	16	17
Renewable Energy	24	48	83	123	122

Figure 2.8 – Danish Energy Production from the different energy sources. Source: "Energy in Denmark 2008", Danish Energy Agency.

The overall production increased during the 80s and 90s reaching a stable production around 1100PJ during the 00 until today. Oil and natural gas are still the most representative's energy sources (50% oil, 30% Natural Gas) but the Renewable Energy have gained their share of importance in energy production.

Aiming for the goal traced in the 70s Denmark chose a diversified energy supply that concentrate on increased use of renewable energy. Several energy-policy initiatives were launched, including a focus on combined electricity and heat production, municipal heat planning and on establishing a more or less nation-wide natural gas grid. Furthermore, Denmark improved efficiency of the building mass, and launched support for renewable energy, research and development of new environmentally friendly energy technologies as well as ambitious use of green taxes.

In combination with oil and gas production from the North Sea the policy concerned meant that Denmark went from being a huge importer of oil in 1973 to being more than self-sufficient in energy, from 1997. Figure 2.9 illustrate the evolution of energy production and energy production.

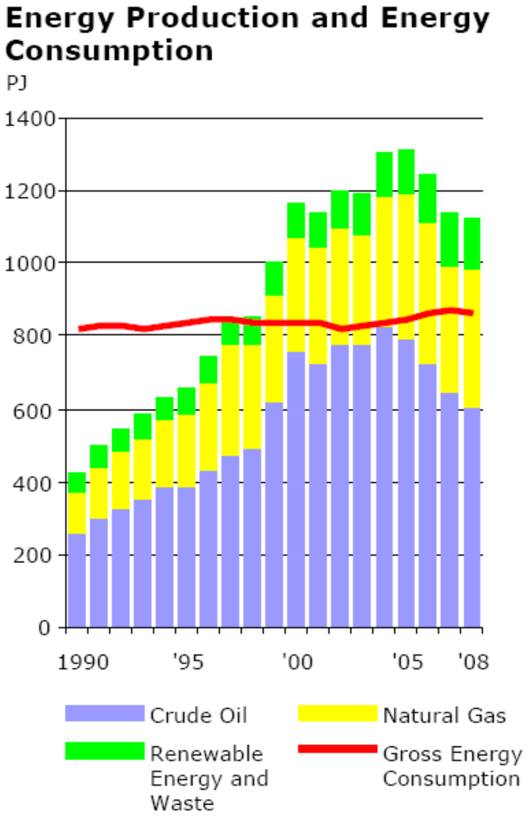


Figure 2.9 – Danish energy production from the different energy sources. Source: “Energy in Denmark 2008”, Danish Energy Agency.

The consistent energy policy traced by the successive governments has made it possible to reduce dependency on fossil fuels and protect the environment while maintaining high economic growth. This active energy policy gathers considerable public backing so there’s a real society concern to save on energy.

Since 1980, the Danish economy has grown by 78%, while energy consumption has remained almost unchanged as we can see in Figure 2.9. In combination with oil and gas production from the North Sea, Denmark went from being a huge importer of oil in 1973 to being more than self-sufficient in energy, from 1997.

Along with a gradual reorganization of the energy supply for increased use of renewable energy, the energy policy has thereby created the foundation for Denmark being able to set ambitious targets for reduction of climate gas emissions.

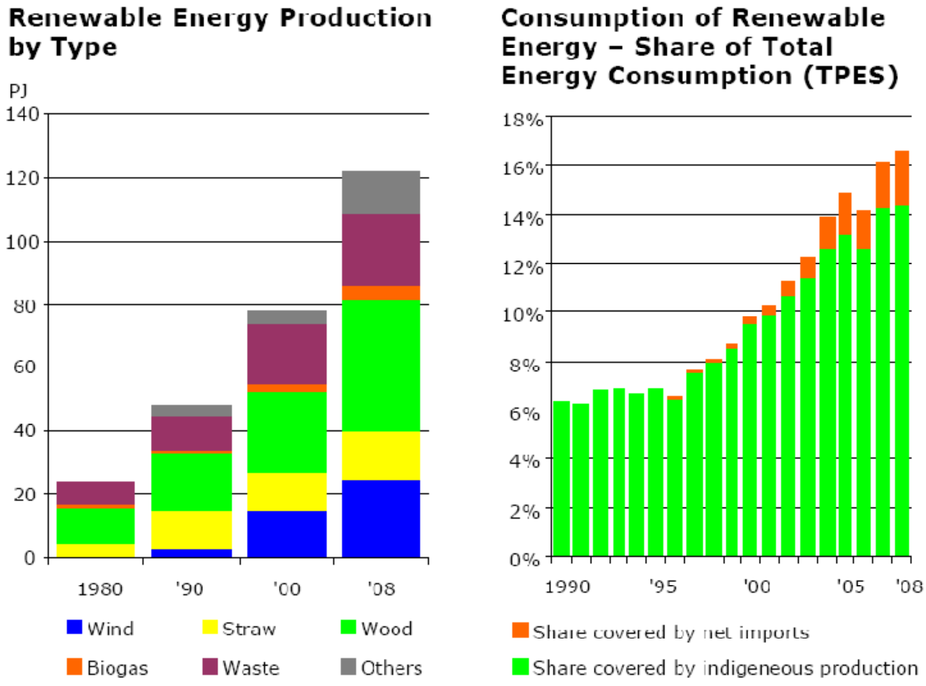


Figure 2.10 – Renewable energy production & Share of total energy consumption. Source: "Energy in Denmark 2008", Danish Energy Agency.

Figure 2.10 shows the strong upward trend in renewable energy production, especially wind and the different types of biomass fuel. Biomass fuel became an important peace in this energy policy because of the development of the combined heat and power production.

Converting different types of biomass fuel (wood, waste, straw) in the combined heat and power production also has great importance to renewable energy production. Straw or wood chips fuel many of the heat only stations.

The share of renewable energy in final energy consumption has increased steadily since 1980 and today's amount it's about 18% as Figure 2.10 also shows.

Doing an overall analysis on this background and keeping into perspective that this energy policy traced by the governments will continue, this report, the model and the conclusions make sense. Today wind power provides 20% of Danish electricity consumption, but the Danish Government recently announced that the goal it's to make it 50% by the year 2025. This expected rising of the wind power may not affect dramatically the Danish system and the market, but when we talk about reserves and their requirements it's valuable and useful to study if this rising should also lead to a new definition of the requirements for the reserves of energy.

2.1.7. Operational Handbook

To make the best possible use of this interconnected system, technical standards, rules and recommendations have been agreed by every member of ENTSO-E in their regional groups.

As it was said before, the Danish System is divided in two sub-systems. DK-West and DK-East are in different regional groups, every one of them with their own Operational Handbook. DK-East, being part of Nordel is subjected to Nordic “System Operation Agreement” and DK-West subjected to “UCTE Operation Handbook”. This last one will be the source of the most important requirements to be known when frequency control and reserves are taking into consideration.

The “UCTE Operation Handbook” is an up-to-date collection of operation principles and rules for the transmission system operators in Continental Europe. The co-operation between every member is required to make the best possible use of benefits offered by interconnected operation. For this reason, the UCTE (and now with ENTSO-E) has developed and organized a number of technical rules and recommendations that constitute a reference for the players of the power system.

This operation Handbook was created in 1950, with several reviews since them and continues to be developed and updated if necessary, reflecting the changes in the technical and political framework. This book shall support consultation and provide assistance to all different parties in issues of system operation, such as Transmission System Operators (TSO’s), generation companies, other associations, trades, customers, politicians, decision makers and others.

The main objective of the “UCTE Operation Handbook” is to set standards in terms of security and reliability, grid operation, control and security. As a collection of all these technical standards and recommendations, this book provides support to the technical operation of the Continental Europe interconnected grid (Synchronous Areas) including operation policies for generation control, performance monitoring and reporting, reserves, security criteria and special operational measures.

The basic subject of the Operation Handbook is to ensure the interoperability and mutual understanding among all TSOs connected to the Synchronous Areas. Standards for the market rules are not within the scope of this Operation Handbook.

2.1.8. Reserves

The electricity is traded in a market environment. Also reserves of energy have their own place in the market (regulating market) but this will be a topic of the next subchapter. The reserves have their own requirements to be fulfilled according to UCTE Operational Handbook. That will be the topic in this subchapter.

To secure and ensure a high quality operation of the synchronous areas, all the generation of power units and consumption of loads connected shall be controlled and supervised. The Load Frequency Control (LFC), the technical reserves and the corresponding control performances are vital to allow TSOs to perform daily operations.

In the Continental Europe Synchronous Area, the control actions and the reserves are organized in a hierarchical structure with Control Areas, Control Blocks and with two Coordination Centers. This is illustrated in Figure 2.11.

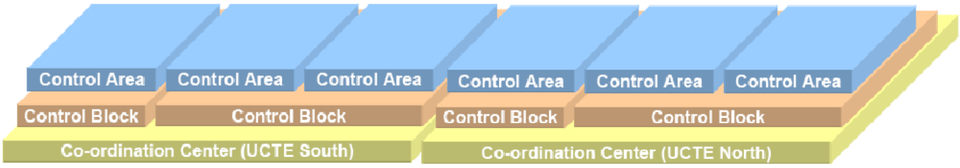


Figure 2.11 – Hierarchical control structure for Continental Europe Synchronous Area. Source: "UCTE Operation Handbook", ENTOSE-E.

Control actions, regarding frequency control, are performed in different successive steps, each one with different characteristics, qualities, timeline and all depending and related with each other. Figure 2.12 explains how these actions are related when there's a deviation in the system frequency.

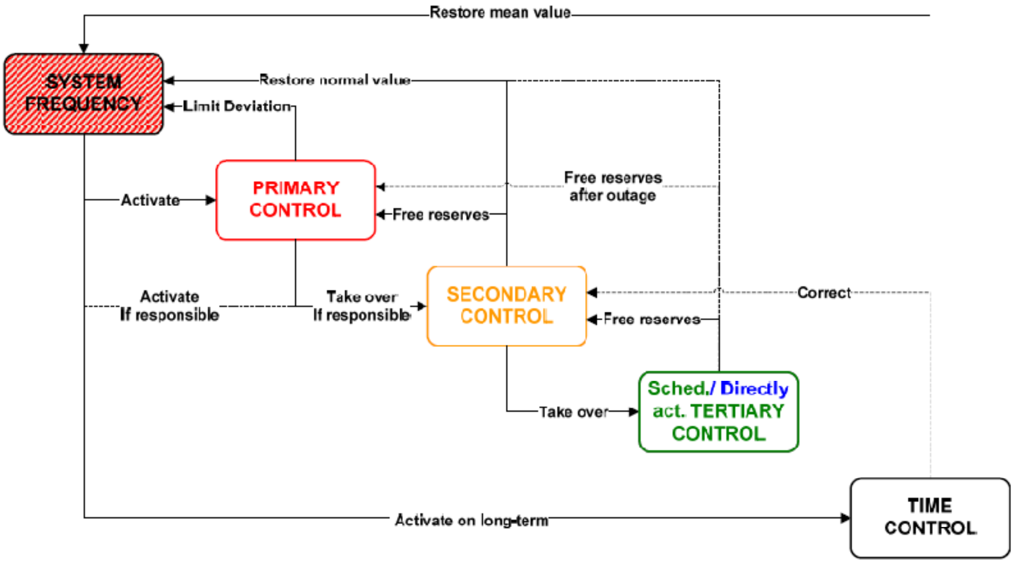


Figure 2.12 – Control scheme put in action when there's a disturbance of the system frequency. Source: "UCTE Operation Handbook", ENTOSE-E.

The Primary Control stars within seconds as a joint action of all parties involved. Then the Secondary Control is put into action by the TSO to replace the primary control. This is made over minutes. Then the Tertiary Control partially complements and finally replaces the secondary control by re-scheduling generation and it's also put into action by the TSO.

Regarding time axis, these distinct control reserves, by obvious reasons, occur in different time frames. Figure 2.13 show how these actions are put in operation in case of an incident.

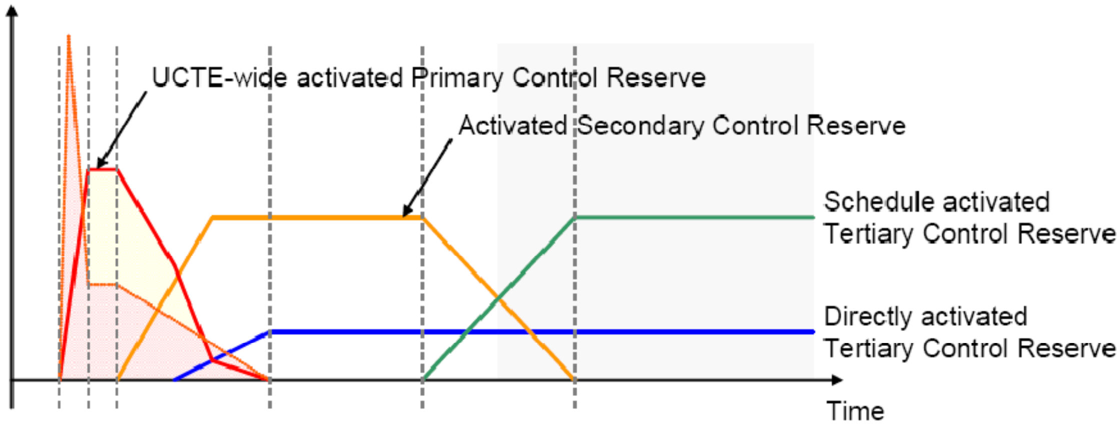


Figure 2.13 – Time line for the activation of reserves in case of frequency deviation. Source: "UCTE Operation Handbook", ENTOSE-E.

When there's a frequency deviation (orange line) the activation of Primary Control Reserve (activated within seconds) is followed up by Secondary Control Reserve (activated within minutes) with this last one being supported and followed up by Tertiary Control Reserve.

After this overall perception of how the reserves are put into action an individual description is made.

2.1.8.1. Primary Control Reserve

In every electrical system, the active power has to be generated at the same time as it is consumed. The power generated must be maintained in constant equilibrium with the power consumed. The consumption must always be supplied. When that doesn't occur there is a power deviation. Disturbances in this balance, causes a deviation of the system frequency.

Disturbances in this balance will be compensated by the kinetic energy of the rotating generating sets and motors connected. In other words, the primary control reserve is put in action.

Store this type of energy is limited, it has to be stored as a reservoir (coal, oil, water) for large power systems, and as chemical energy (batteries) for small systems. It must be available instantly to handle both changes in demand and forced outages in generation, even though this primary reserve is insufficient for controlling the power equilibrium in real-time.

Under every condition, the system frequency must be maintained within strict limits (The setpoint frequency is 50 Hz) so when there's a deviation in the system frequency the regulating units will then perform automatic primary control action in order to re-established this balance.

This deviation in the System Frequency will force the Primary Controllers of all generators subject to activate Primary Control to respond within a few seconds. Until the balance between generated power and consumption is re-established the controllers alter the power delivered by the generators (see Figure 2.14).

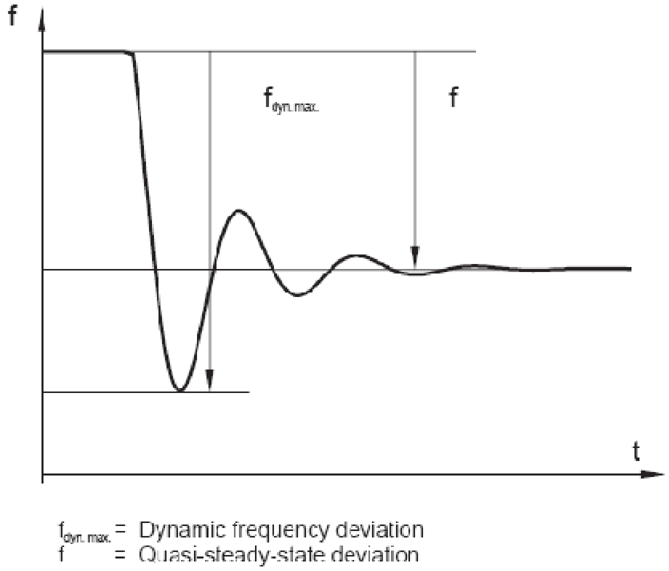


Figure 2.14 – Primary Control re-establishing the system frequency. Source: "UCTE Operation Handbook", ENTOSE-E.

As soon as the balance is re-established, the System frequency stabilizes and remains at a quasi-steady-state value, but still differs from the frequency set-point. Consequently, power cross-border exchanges in the system will differ from values agreed between companies.

Secondary Control will take over the remaining frequency and power deviation after 15 to 30 seconds. The goal of Secondary Control is to restore power cross-border exchanges to their set-point values and restore the System frequency to its set-point value at the same time (a more detailed description will be made ahead in this report).

The variation in the System Frequency is defined as the difference between the rated frequency (fn) and f with the set point value of 50Hz:

$$\Delta \mathrm{f} = f - f_n \tag{2.1}$$

Each TSO must contribute to the correction of a disturbance in accordance with its respective contribution coefficient to Primary Control. These contribution coefficients Ci are calculated on a regular basis for each Control Area or TSO using the equation:

$$C_i = \frac{E_i}{E_u} \tag{2.2}$$

With Ei being the electricity generated in the Control Area and Eu being the total sum of electricity production in all N-Control Areas in the Synchronous Area (in this case Continental Europe)

The contribution coefficients are determined and published annually for each Control Area. The contribution coefficients are binding for the every TSO for one calendar year, so therefore there isn't a fixed value. They are based on the share of the energy generated within one year in proportion to the entire synchronous area. The sum of all contributions coefficients should be equal to 1.

The total Primary Control Reserve P_{Pu} for the entire Continental Europe Synchronous Area is determined by ENTSO-E taking account of measurements, experience and theoretical considerations. The shares P_{Pi} of the Control Areas are defined by multiplying the calculated reserve for the synchronous area and the contribution coefficients Ci of the various control areas. In form of equation:

$$P_{Pi} = P_{Pu}.C_i \tag{2.3}$$

The overall Primary Control Reserve for the Continental Europe Area is agreed to be 3000 MW. DK-West must supply a total of 32.1MW upward or downward regulation.

Primary Control activation is triggered before the frequency deviation Δf exceeds 20mHZ. The entire Primary Control Reserve is activated in response to a quasi-steady-state frequency deviation of 200mHz or more, meaning that if the frequency deviation Δf exceeds +/- 0,2Hz power generation must be reduced by the value of the entire Primary Control Reserve.

The time table of the primary control reserves should be similar in all control areas in order to minimize the damages. The primary control reserve of each control area (in accordance with the corresponding contribution coefficient Ci) must be full activated within 15 seconds for disturbances of less than 1500 MW and within a linear time limit of 15 to 30 seconds in response to a disturbance of 1500 to 3000 MW. Also Primary Control Power must be delivered until the power deviation is completely offset by the Secondary or Tertiary Control Reserve of the Control Area where the imbalance occurred.

2.1.8.2. Secondary Control Reserve

Primary Control allows a balance to be re-established when the system frequency differs from the set point value (at a quasi-state frequency deviation Δf) due to an imbalance between generation and demand created by a contingency.

When there is a change in the system frequency all control areas contribute to the control process, this imbalance does not only affect the area where the imbalance occurs. In fact an imbalance between generation and consumption in any control area will cause power interchanges between individual control areas to deviate from the agreed values. The function of Secondary Control (also known as load-frequency control or frequency-power-control) is to keep or restore the system frequency to its set point value of 50 Hz and also restore the power interchanges with adjacent control areas to their programmed schedule values. Also, the Secondary Control must ensure that the full reserve of Primary Control power activated will be made available again.

For the Primary Control all the control areas provide mutual support, but in the Secondary Control process only the control area affected its required to undertake Secondary Control action for the correction. Because of this, the parameters for the Secondary Controllers need to be programmed in order to insure that, ideally, only the controller in the affected zone will star the Secondary Control Power.

The demand should always be covered at all times either by electricity produced in the control area or with electricity imports. To maintain this balance, generation capacity for uses as Secondary Control Reserve must be available to cover every contingency, either due to power plant force outages or any other type of disturbance that affect the well-being of the system frequency.

Secondary Control is applied to selected generator sets in the power plants comprising the control loop under the supervision of the TSO and put into operation when the TSO requires.

Looking back again to Figure 2.13, the Secondary Control is timely dissociated from the Primary Control. It starts after the primary control but before the ending of the primary control and operates for periods of several minutes.

Since it is technically impossible to guard against all random variables affecting the electrical system, the volume of reserve capacity will depend upon the level of risk which is assumed acceptable between the parties involved in the supply of the demand. The size of the Secondary Control Reserve should take into account the typical load variations, schedule changes and generating units and it’s done by reference to deterministic or probabilistic approaches. The recommended Secondary Control Reserve is illustrated in figure 2.15.

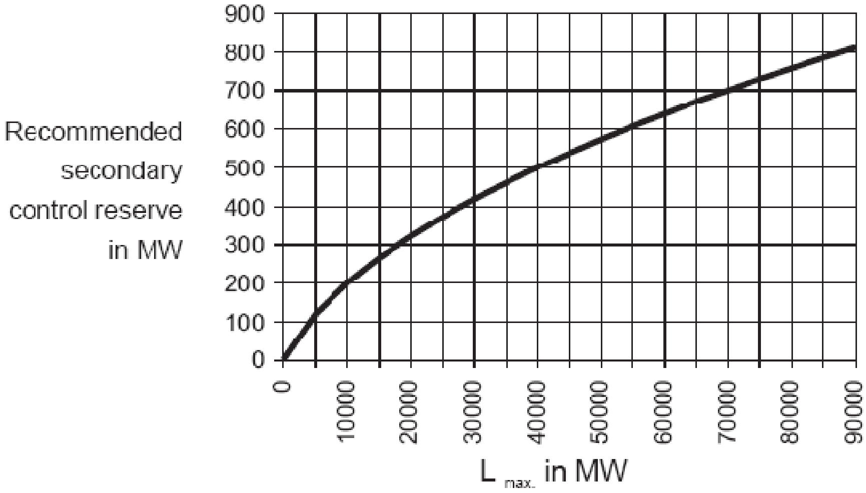


Figure 2.15 – Recommended Secondary Control Reserve in MW related to the maximum load in MW. Source: “UCTE Operation Handbook”, ENTSO-E.

If the surplus of consumption is on a continuous basis, even though the availability of this reserve capacity, immediate action must be taken to restore the balance, for instance by the use of Tertiary Control. It’s imperative that sufficient transmission capacity must be maintained at all times to accommodate reserve control capacity and stand by supplies.

2.1.8.3. Tertiary Control Reserve

The Tertiary Control is a manual change in the working points of generators in order to guarantee the provision of an adequate Secondary Control Reserve at the right time and distribute the Secondary Control Power to the several generators in the best way possible (in terms of economic consideration). The Tertiary Control is activated manually by the TSO and the reserves are therefore called manual regulation reserves.

This manual reserves should restore the Secondary Control Reserve when required like is showed in Figure 2.16

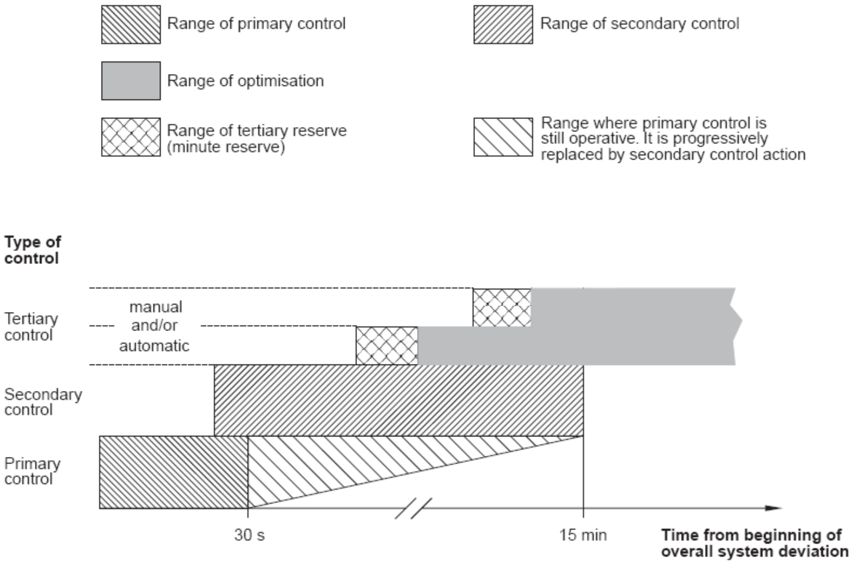


Figure 2.16 – Time schedule for the overall system deviation. Source: "UCTE Operation Handbook", ENTOSE-E.

This reserve is also called 15 minute reserve because there must be a maximum time delay of 15 minutes between the requests from the control centre until the reserve is fully activated.

To calculate the capacity required for Tertiary Control it must be taken into account, for instance, the units shut down for repair or maintenance, limitation on capacity associated with restriction in fuel supplies, environmental restriction, limited capacity of hydroelectric plants. Also take in account the value already established for the primary control and also that these tertiary reserves should cover variations in production and consumption. It's also important to take in account the system conditions, given that network constraints may reduce scope for the transmission of power produced.

Each Control Area has to have access to sufficient Tertiary Control Reserve to follow up Secondary Control after a contingency. The total Tertiary Control Reserve must be available to cover the largest expected loss of power (generation unit) in the Control Area (N-1 criterion). To insure that, reserve contracts between companies and the TSO can be made meaning that a component of the required amount of Tertiary Control Reserve is already fulfilled.

A total of 680 MW is currently reserved for manual regulation in DK-West. This means that the TSO for every hour of operation has this capacity reserved to respond against any kind of disturbance.

After all this procedures, if this amount of reserves are still not enough to guaranteed the re-establishment of the system then the TSO was to make use of the regulating market and import extra reserves. In fact this is a very important topic in this project and will be one of the key variables in the model as it will be explained in the chapters ahead.

2.2 - Energy Market

The Danish Electricity Market is a free market on which all electricity consumers are able to buy electricity from a supplier of their choice. This conception of market was established since 1 January 2003 in order to create a competitive market.

The Danish electricity market is part of the Nordic electricity market – Nord Pool. This Nordic market was the result of both Danish and the other EU authorities that were looking for a liberalization of the electricity market in order to stimulate free competition in electricity production and trade. So, since 1 January 2003, Nord Pool became the wholesale market that facilitates trades between producers and traders.

This liberalization forced the entire Danish electricity sector to reform the rules and prepare new performance requirements of the system in order to manage the mutual relations between electricity traders, grid companies, system operators and all the market players.

This “new free” Danish Electricity Market was preceded, back in 1999, by the unbundling of the transmission grid from electricity generation. The grid become independent and all electricity market players have equal opportunity to use it. The liberalization of the electricity market was the consequence of this new reorganization.

In a market perspective there’s still a division in the Danish System. DK-West (also known as DK1) and DK-East (DK2) are still independent but booth included in the Nord Pool Market.

On the electricity market, it is primarily TSO’s (Energinet.dk in Denmark) role to monitor the hourly day-ahead spot market (Nord Pool Spot) and the regulating power markets where producers and consumers submit their bids.

Nord Pool Spot is a power exchange with two market places for electricity trading: Elspot and Elbas. Trade on Elspot is based on the auction principle. Players trade on Elbas to obtain balance when Elspot is closed. Nord Pool also operates an exchange for financial trading/hedging where trading is conducted in the same way as on a traditional stock market, and players can hedge against price fluctuations by trading options.

In order to promote competition in the Danish economy and to prevent a supplier of abusing its dominant position by withholding production to the detriment of consumers The Danish Competition Authority, under the Danish Competition Act, is responsible for supervising the electricity market. The Danish Competition Council it’s the legal tool to decide suspicious behaviors by the players.

Nord Pool runs the largest physical power market in the world, offering both day-ahead and intra-day markets to its participants. 317 companies from 20 countries trade on the exchange market. This market provides a place for producers, energy companies and large consumers to buy or sell physical power guaranteeing settlement for the trade.

All the Balance Responsible Players (BRP) who meet the requirements set by Nord Pool are given access to bid in this market. Trading requires signing a balance agreement with the TSO or an open power delivery agreement with a balance responsible part in the bidding area in question.

Participants from outside the Nordic countries can also trade in this market on the same terms within the exchange area and through individual “capacity-windows” procured either through a capacity auction or long term rights for usage of interconnectors.

2.2.1. The Elspot Market

On Elspot, hourly power contracts are traded daily for delivery in the next day’s 24-hour period. It’s called the “day-a-head” market. It is the first market for dealing energy and it’s open until 12:00 of the day before the day of operation (Day of operation is the day when the energy dealt is delivered).

In order to handle grid congestions the Nordic market is geographically divided into bidding areas, Sweden (SE) and Finland (FI) constitute one bidding area each. Denmark has to bidding areas (DK1 and DK2) and Norway is usually divided into two or three bidding areas (NO1, NO2 etc) according to Norwegian TSO decision. Participants in the market must take into account this division on they bid in the market.

The price is calculated based on the balance between bids and offers from all the market participants. The price is found in the intersection point between the market’s supply curve and the demand curve like it is illustrated in Figure 2.17. This price mechanism adjusts the flow of power across interconnectors to the available trading capacity given by the Nordic TSOs previously.

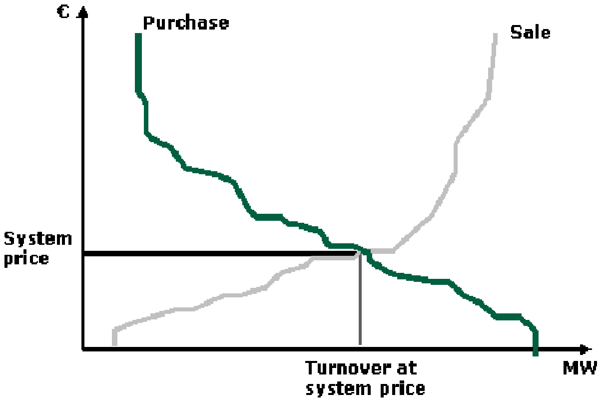


Figure 2.17 – Supply (Sale) and Demand (Purchase) curve meet to achieve the System Price. Source: Nord Pool

The Elspot is a market based on the Symmetric Pool model. When the deadline for submission of bids has passed (12h of the day before the day of operation), bids for demand and offers for supply are aggregated into two curves for each delivery hour. The system price for each hour is determined by the intersection of these two aggregated curves.

These aggregated curves are representing all bids and offers for the entire Nordic region, meaning that the System Price achieved its equal for every region. But, in fact, this will not happen. The system price here calculated does not take into account the trading capacities between the bidding areas. If there's grid congestion in the transmission lines (bottleneck) meaning that the flow of power between bid areas exceeds the capacity allocated for that connection, two or more area prices are created as a price mechanism to relieve this grid congestion.

The TSOs from every area affected can also managed bottlenecks by counter trade.

Counter trade consists in solving the bottlenecks by making a purchase on the one side of a bottleneck and a corresponding sale on the other side. Energinet.dk it's the responsible for this counter trade in Denmark. By using counter trade, Energinet.dk reduces the consequences of bottlenecks for the players, thus creating a stable framework for the electricity market. Energinet.dk uses counter trade in two instances: to ensure the trade capacities that have been announced to Nord Pool Spot and to obtain price equilibrium that would otherwise be impossible.

When making bids in Elspot all volumes are stated in MW per hour. Purchases are designated as positive numbers, sales as negative numbers.

There are 3 types of bids in Elspot, in a supplier perspective: the hourly bid, block bid and flexible hourly bid. The "hourly bid" is the basic type. Each participant selects the range of price steps for the Hourly Bid individually. The "block bid" gives the participant the opportunity to set an "all or nothing" condition for all the hours within the block. The block bid is an aggregated bid for several hours, with a fixed price and volume throughout these hours. The flexible hourly bid is a sale bid for a single hour with a fixed price and volume. This hour is not specified. Instead the bid will be accepted in the hour with the highest price in the calculation

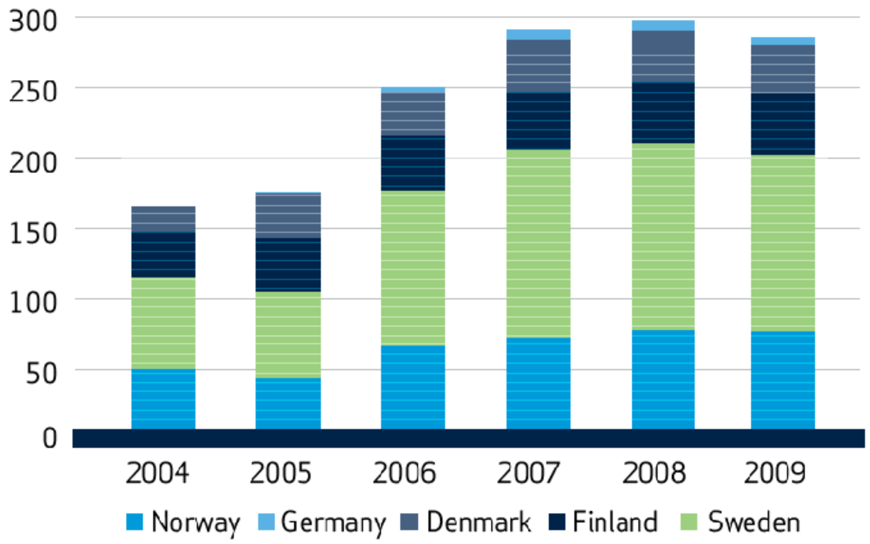


Figure 2.18 – Elspot turnover by country in TWh. Source: “Annual Report 2009” Nord Pool

Elspot market is the main market for electrical energy reaching 288TMh of volume traded per year (Figure 2.18)

2.2.2. The Elbas Market

On Elbas (Nord Pool’s intra-day market), adjustments to trades done in the day-ahead-market (Elspot) are made until one hour before the delivery hour. The Elbas market is open from 17:00 of the day before the day of operation until one hour before the hour of operation.

The purpose of Elbas market is to make it possible for players to buy and sell as required In order to ensure balance right up to the delivery hour in case, for instance, of a forced outage. It can also be used to deal energy that was not accepted at the Elspot market.

In this market, players can make bilateral transactions up to one hour before the delivery hour but these bilateral transactions can only be made within each individual bidding area. If a BRP (Balance Responsible Player) make his bid and some other BRP accepts they only have to communicate this agreement to the TSO of their area. If no bottlenecks are affecting the interconnection this agreement is accepted and the deal is made.

Elbas is an alternative to the balancing market for at least some of the imbalances that companies may have after the day-ahead trades are published. Those imbalances might occur due to a forced outage or a forecasting mistake. Elbas reduces the risk of those companies being in imbalance by offering another chance to bid again in the market. But, because the price is known prior to the hour of delivery and not afterwards, bid in this market might carry a great economical risk, due to the high volatility of the prices.

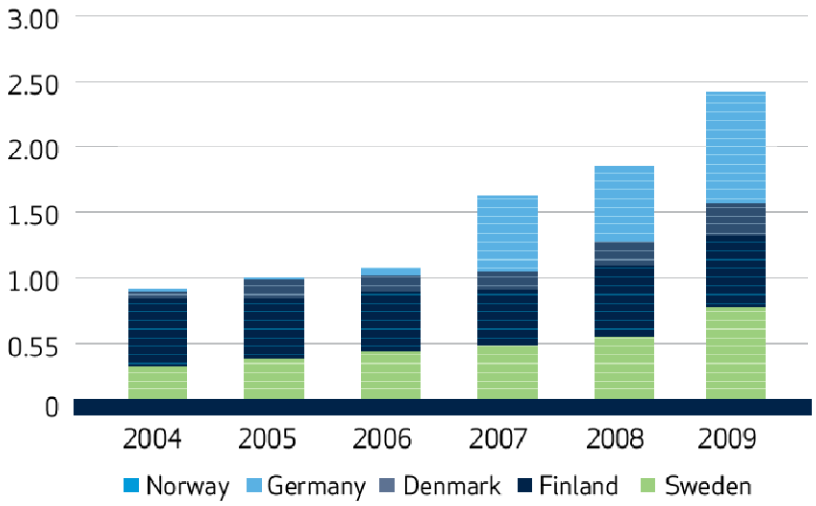


Figure 2.19 – Elbas turnover by country in TWh. Source: "Annual Report 2009" Nord Pool

Elbas is still a small market, only about 2.5 TWh are traded in this market, but the results through the years show a promising increase and, in fact, it's expected that this intra-day market gains more relevance in the Nord Pool market

2.2.3. The Regulating market

The regulating market is a tool for the TSO to keep balance between total generation and consumption of power in real time. It's a market to guarantee the system's stability.

After the Elspot market is concluded, the BRPs have sent their plans to the TSO so the power system is in principle planned to balance for the next 24 hours. However, deviations between the contracted and the actual supply might occur due to forced outages, interruptions in the grid or even changes in weather.

With this market the BRP can adjust their balances until the hour of operation, either by changing existing agreements or by settling new ones on the intra-day market. The power traded here is called balancing power.

Also the TSO have the responsibility to maintain the overall balance and security of the power system, so if physical adjustments have to be made to generation or consumption, to cover the net imbalances of the players, the TSO must buy "regulating power". This regulation is conducted using different kinds of operational resources or reserves.

For the TSO, this commitment of maintaining the balance in the delivery hour is achieved by buying upward or downward regulation reserves on the regulating power market.

The TSO receives from the players bids for upward regulation or downward regulation. The bids are submitted until 45 minutes before the hour of operation. A bid for upward regulation indicates how much the player asks to be paid to sell a certain volume of regulating power corresponding to reduced consumption or increased production. A bid for downward regulation indicates how much the players is willing to pay to buy a certain volume of regulating power corresponding to increased consumption or reduced production.

These bids submit are sorted in a common Nordic regulation list according to rising or falling prices like it's shown in Figure 2.18.

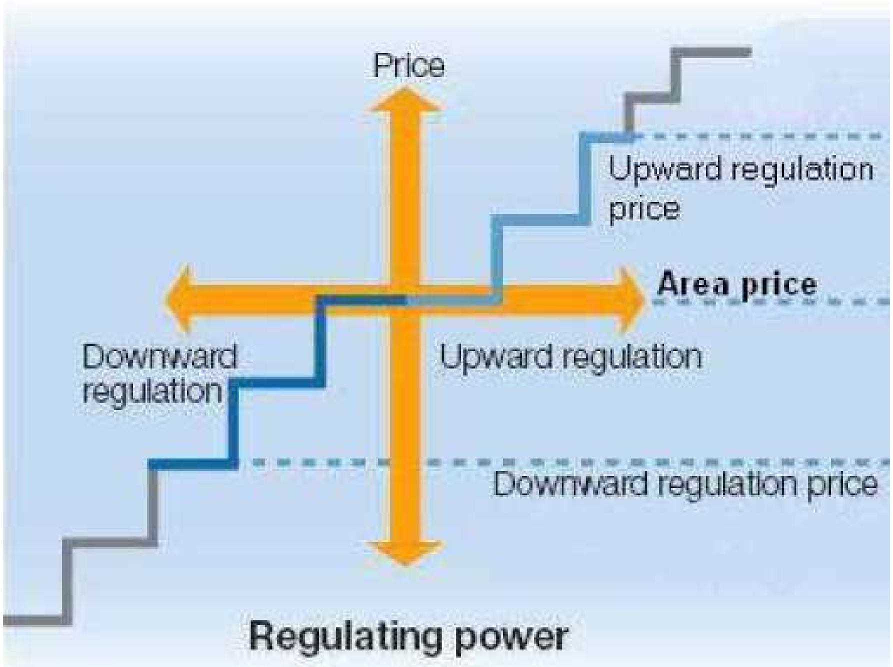


Figure 2.20 – Up and Down Regulation curves at the NOIS List. Source: ENTSO-E

This list is available to all Nordic TSOs in a common information system called NOIS list (Nordic Operational Information System).

Looking at Figure 2.20, if upward or downward regulation is needed during the hour operation, these bids are used in price sequence. If there's a deficit of power meaning that the demand is higher than the supply, the TSO of the area selects the cheapest bid to compensate this imbalance, which can be by down regulating the consumption, reducing the demand, or by up regulating the production, increasing the supply.

The players whose bids have been selected to regulate are paid the equivalent of the highest price for upward regulation or the lowest price for downward regulation. This means that the player is paid by an equal or better price than their bid price. This is done to stimulate bids.

Has been said before, a total of 680 MW must be always reserved for manual regulation (requirement established in UCTE Operation Notebook). In order to ensure that commitment Energinet.dk therefore concludes reserve capacity agreements, according to which Energinet.dk pays BRP a fixed payment to those players to have capacity available for upward or downward regulation. In fact there is a period of time (until 9:30 the day before the day of operation) where power plants can bid for availability of capacity for the reserves used in the regulating market (secondary and tertiary reserves) where they get paid, if accepted, for not bidding some capacity in the spot market and putting it available at the regulating market.

This way, for every hour the TSO guarantees that there will always be 680MW of capacity for reserves. So, in case of a disturbance that affects the balance between the generation and consumption the TSO activates these manual reserves within 15 min. If this capacity (680MW), that was already accorded among the TSO and the BRPs involved, is not enough to respond the imbalance then the TSO makes use of the NOIS list and import the remaining power needed to restore the balance.

This all process of regulating power is very important in this project. Especially in the way the model is going to be built. One of the main goals of this study is to evaluate how many hours the TSO had to make use of this NOIS list and import reserves from the neighboring systems.

2.2.4. Bilateral Contracts

There's a way for the BRP avoid the risk of bidding in the market. Due to constrain in the grid area, prices differs from the system price so there's always a risk in bidding in this type of market.

A way of hedging that risk is by making use of Bilateral Contracts. These contracts were introduced to provide the possibility of players purchase or sell energy in an agreement that will not be affected even when the markets are split into one or more price areas.

A producer and a consumer can reach to an agreement for selling/buying power, communicate this agreement to the TSO of their areas and if there's no bottlenecks affecting the area the contract is accepted.

Bilateral contracts can be done until the end of the Elbas market and can be done in a short-term basis or in a long-term basis.

2.2.5. Timeline

The time line for the Nord Pool Electricity Market is illustrated in Figure 2.21 and more detailed in Figure 2.22.

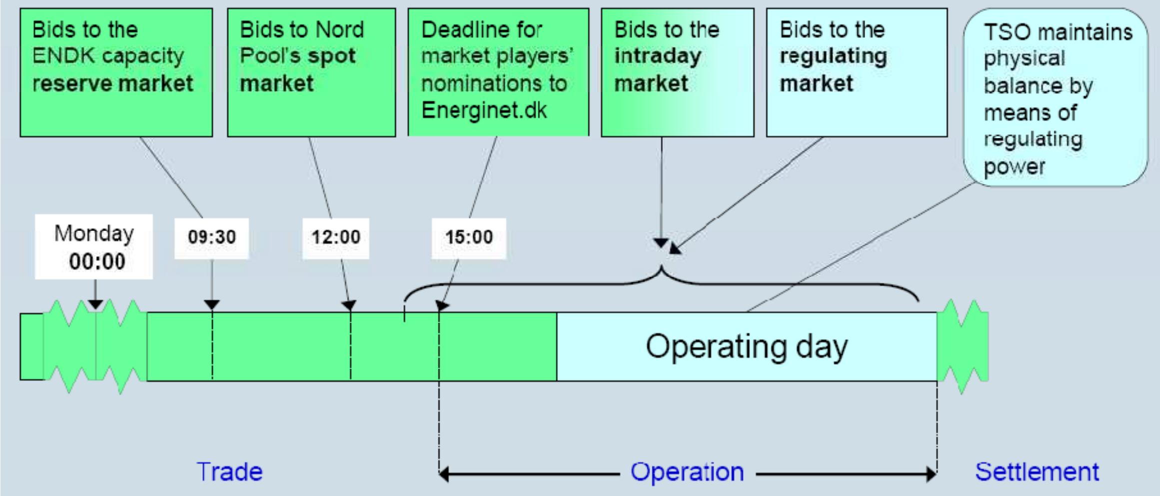


Figure 2.21 – The phases of the power market. Source: “The Power Market in Denmark”, Energinet.dk

Every day until 9:30 players can bid for the reserve market and get agreements with the TSO for reserve capacity.

Every day by 10:00, the Nordic transmission system operators make guaranteed transfer capacity between the bidding areas available to Elspot for the following day of operation.

12:00 it’s the deadline for bidding for trade in electricity for the following day of operation (buying and selling bids). Subsequently, Nord Pool calculates the price and at 14:00 announces the traded volumes and prices.

At the same hour (12:00) the Nordic TSOs release the exchange capacity to Elbas Market and this market stars until one hour before the delivery hour.

The regulating market takes place also at 14:00 until 45 minutes before the delivery hour.

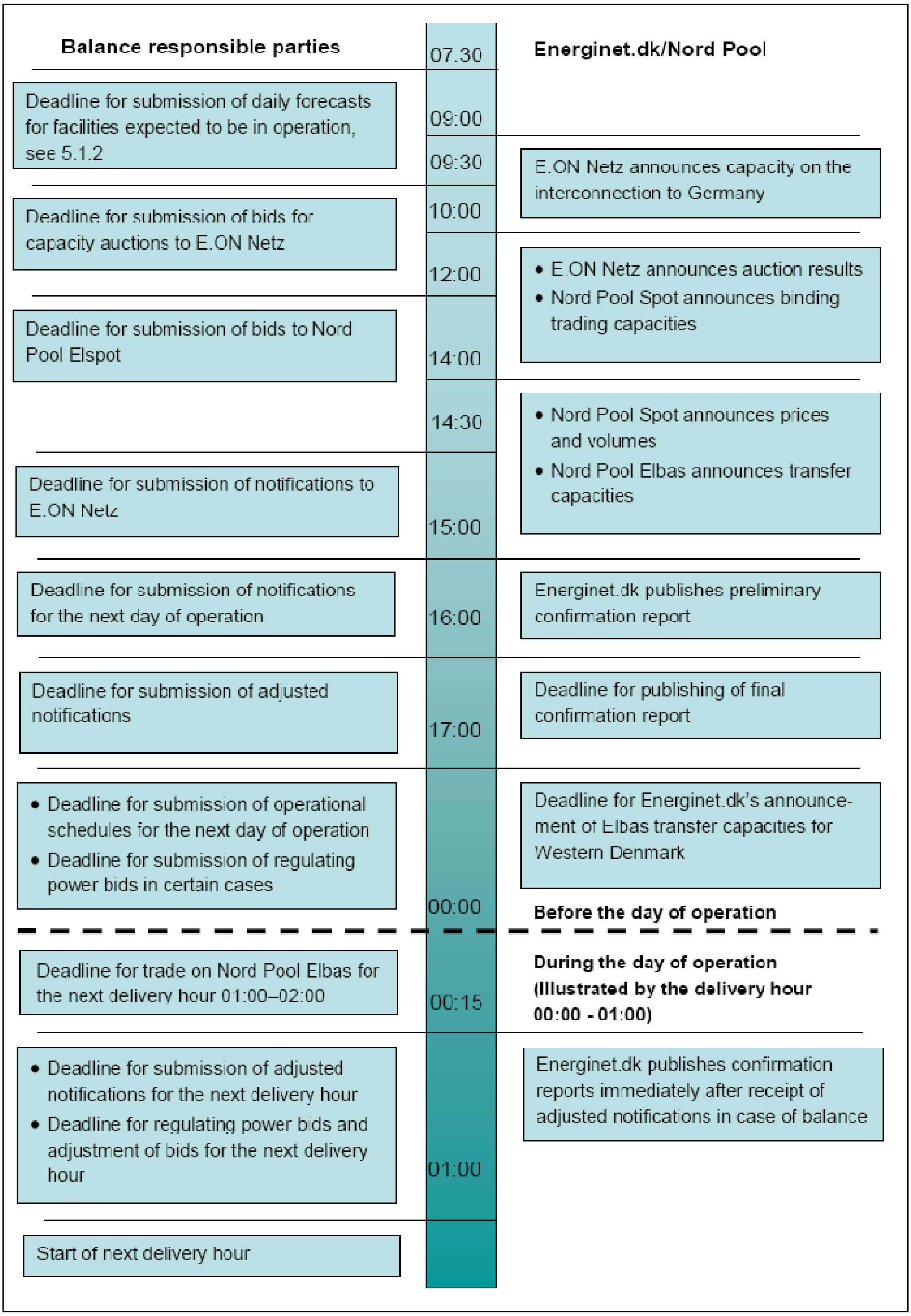


Figure 2.22 - The phases of the power market (detailed). Source: "Regulation C3 - Handling of notifications and schedules - daily procedures", Energinet.dk

2.3 - Power Plants

When the pool is built, bids for demand and offer are aggregated in two curves. Figure 2.23 shows the supply curves according to the type of power plant.

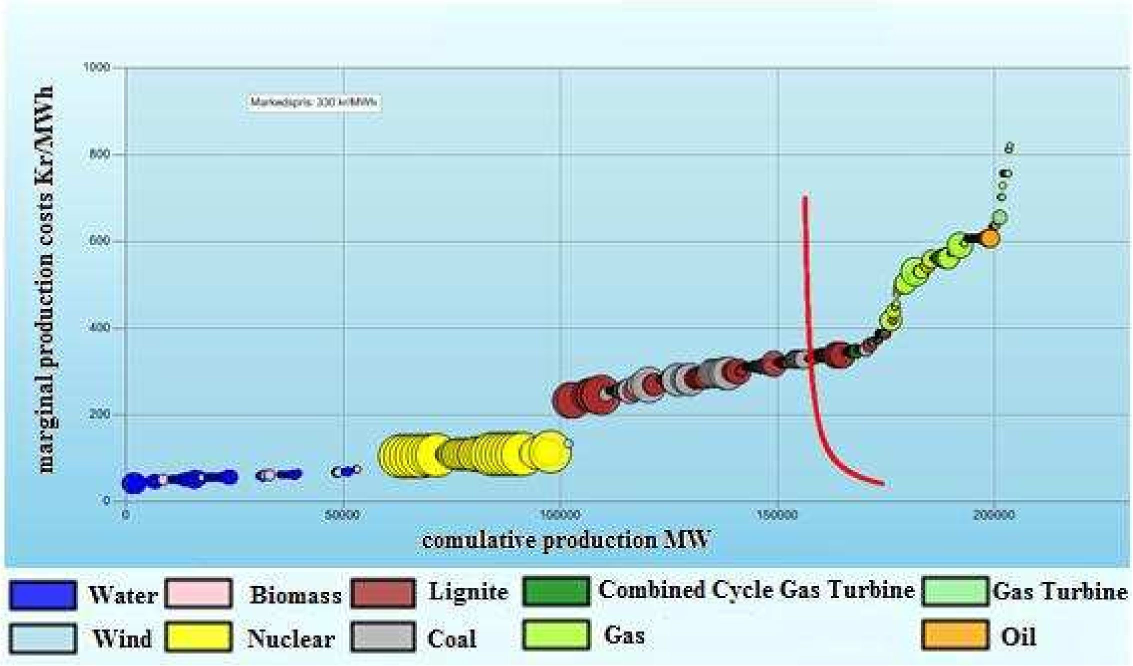


Figure 2.23 – The power market in the Nordic countries. Source: *"Summer School Power 2009", Flemming Nissen (adapted).*

In the pool model the supply curve is organized by prices starting by the cheapest to the more expensive. So the first players to be chosen are the wind power in Denmark and the Hydropower in Sweden and Norway. Wind power and hydro power are the cheapest ways of production.

After comes the nuclear power in Germany, Sweden and Finland followed by the coal fired units in Denmark. The most expensive, and by consequence the last choose by the pool, are the Gas and Oil power plants.

If we look to the Danish system independently (Figure 2.24) this is how the pool looks.

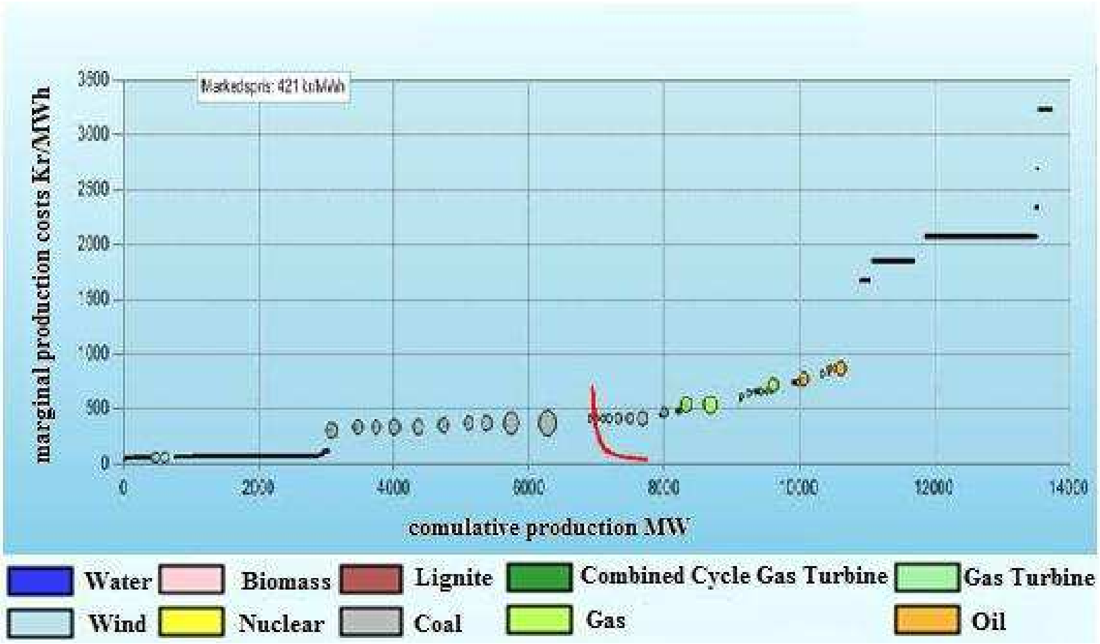
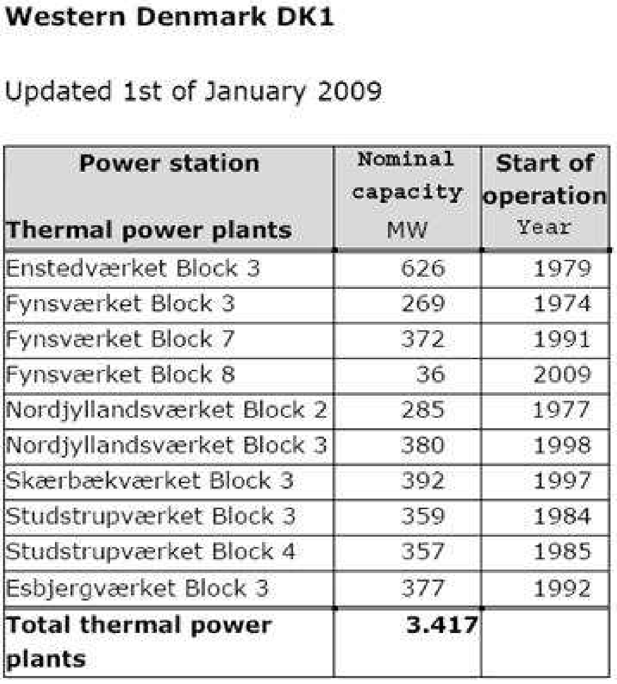


Figure 2.24 – The power market in Denmark. Source: *"Summer School Power 2009", Flemming Nissen (adapted).*

Looking at Figure 2.24, in the Danish system we can only find wind power, coal fire units, Gas Turbines and Oil units. The most relevant units in the system will be presented next.

2.3.1. Central Power Plants

Central Power Plants (also known as Centralized power plants) are coal fired units and are the most important producers of electricity in the Danish System. In DK-West there are 6 Central Power Plants split in theirs several units. Figure 2.25 gives a description of these several units and their nominal capacity.



Western Denmark DK1

Updated 1st of January 2009

Power station Thermal power plants	Nominal capacity MW	Start of operation Year
Enstedværket Block 3	626	1979
Fynsværket Block 3	269	1974
Fynsværket Block 7	372	1991
Fynsværket Block 8	36	2009
Nordjyllandsværket Block 2	285	1977
Nordjyllandsværket Block 3	380	1998
Skærbækværket Block 3	392	1997
Studstrupværket Block 3	359	1984
Studstrupværket Block 4	357	1985
Esbjergværket Block 3	377	1992
Total thermal power plants	**3.417**	

Figure 2.25 – List of Central Power Plants in DK-West. Source: Energinet.dk

In DK-West there are only two companies with central power plants. Dong Energy and Vattenfal.

Dong Energy owns Ensted, Esbjeg, Skærbæk and Studstrup Power Station. Fyens and Nordjylland belong to Vattenfall.

Figure 2.26 – Ensted Power Station. Source: Dong Energy

Central Power Station like Ensted (Figure 2.26) used coal as fuel, but also oil and natural gas are common fuels. Figure 2.27 illustrates a simple description how this units run.

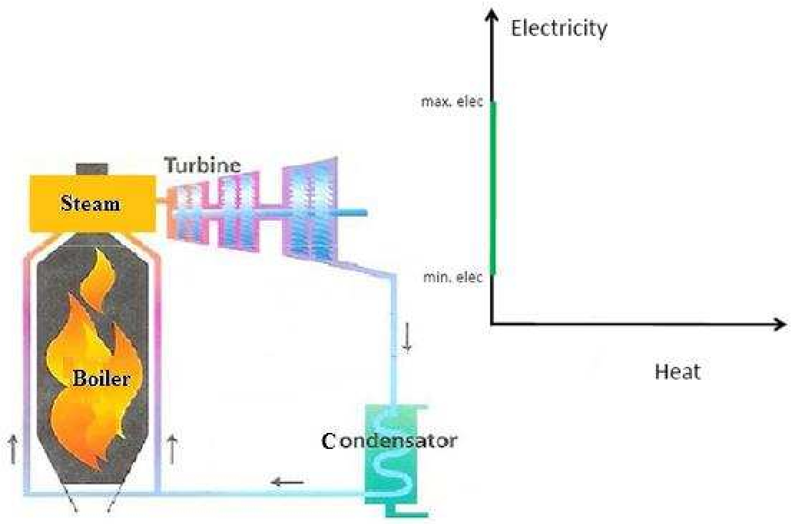


Figure 2.27 – Condensation plant. <u>Source</u>: *"De vigtigste komponenter og beslutninger i energisystemet"*.

In this type of plant showed in Figure 2.27 after the fuel is introduced into the boiler, steam is produced and used in the electricity-generating turbine. After that the steam is cooled and condensed into water, this water is then sent back to the boiler repeating the cycle.

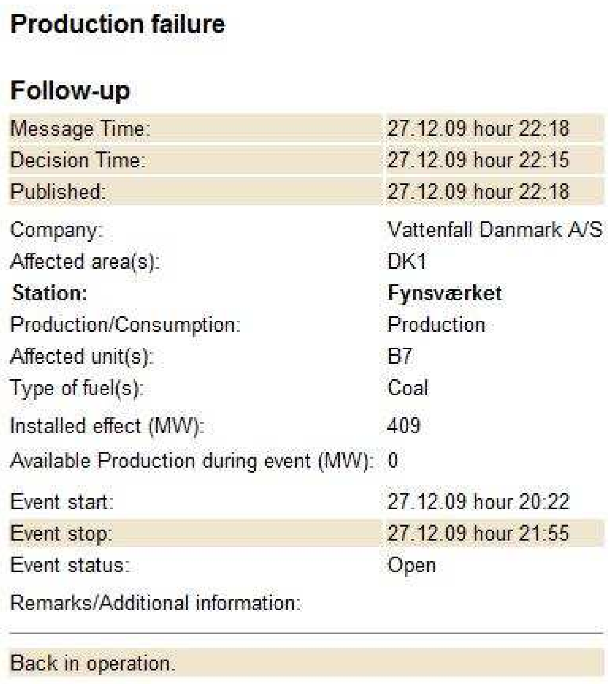
Being the most significant component on the side of generation, when one of these power plants fails to deliver the capacity planned by result of the pool market the TSO must be informed, in order to respond to the imbalance using reserves of energy. The Urgent Market Messenger (UMM) is a tool that BRP have to inform the TSO and the Market about failures or other disturbances that affect the well-being of the system.

2.3.1.1. Urgent Market Messages (UMM)

In general terms UMMs are a tool for producers report to the TSO and Nord Pool for planned outages, unplanned outages (failures) and updates when the failures are solves.

For unplanned outage, the UMMs shall describe available transmission capacities and changes in such available transmission capacities within and connected to the Nordic electricity market. UMM shall be sent as soon as possible and not later than 60 minutes after the decision or failure time, including information about the reason for the outage if possible. If information about reason is not available it may be published in a follow-up as soon as it is available.

Figure 2.28 shows an example of a UMM.



Production failure

Follow-up

Message Time:	27.12.09 hour 22:18
Decision Time:	27.12.09 hour 22:15
Published:	27.12.09 hour 22:18
Company:	Vattenfall Danmark A/S
Affected area(s):	DK1
Station:	**Fynsværket**
Production/Consumption:	Production
Affected unit(s):	B7
Type of fuel(s):	Coal
Installed effect (MW):	409
Available Production during event (MW):	0
Event start:	27.12.09 hour 20:22
Event stop:	27.12.09 hour 21:55
Event status:	Open
Remarks/Additional information:	

Back in operation.

Figure 2.28 – Example of an Urgent Market Message (UMM). Source: Nord Pool

These UMMs will be very important data source for the model to be built has it will be explain more ahead in this paper.

2.3.2. Local Power Plants

Local Power Plants (also known as decentralized power plants) have an important role in the Danish system and in the market where they are included. They are normally associated with CHP production (Combined Heat and Power). CHP power plants bid for the heat market, but because they combine the production of heat and power they are also included in the market for electricity. The heat market is not relevant for this project but the electricity they produce, even though it’s more reduced that in the big central power plants, are also included in the model. The efficiency of these local power plants is very high (95%).

Cogeneration is a type of technology considered one of the most efficient and environmentally friendly energy way of producing both electricity and heat. This concept has been developed through the years and is associated with District Heating. In few words District Heating it’s a public heat supply to deliver heat to the consumers.

When referring to Cogeneration in Denmark various technologies can be pointed, either can use natural gas, coal furnaces or even boiling water.

District Heating is produced either in CHP power plants or in heat-only-boiler’s.

Heat only boiler’s are the simplest heat plants present in the Danish heat system. A heat-only boiler station generates thermal energy in the form of hot water to be used in district heating applications. Unlike combined heat and power installations which produce thermal energy as a by-product of electricity generation, heat-only boiler stations are exclusive dedicated to generating heat.

A CHP power plant can produce both heat and electricity. This brings the advantage of reducing by about 30% the fuel consumption when compared to the separate production of heat and electricity.

Figure 2.29 and Figure 2.30 illustrate two types of technology associated with this genre of power plant.

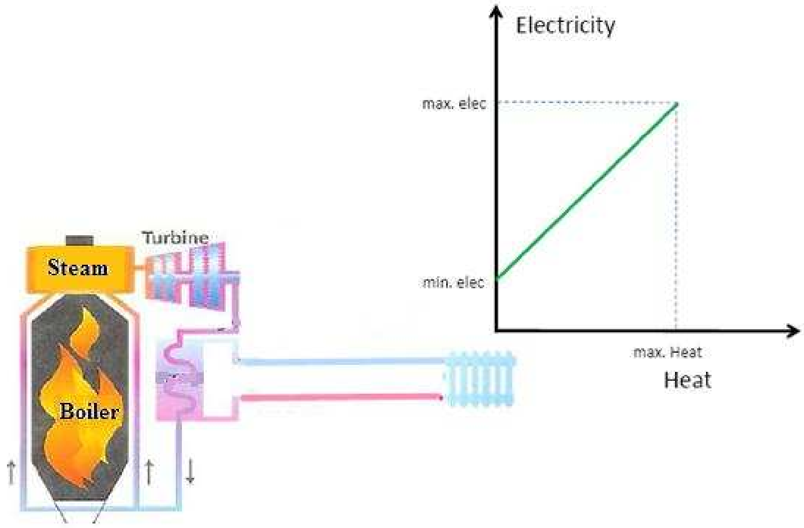


Figure 2.29 – Backpressure plant. Source: *"De vigtigste komponenter og beslutninger i energisystemet".*

In the power plants described in Figure 2.29, after the fuel has been introduced into the boiler, steam is produced and used in the electricity-generating turbine and before being cooled it's used to heat cool district heating water via a heat exchanger. After that it's condensed into water and goes back to the boiler

In practice terms these power plants don't produce only heat. Heat production is always associated electricity production. However, these power plants are designed to meet the heat demand, so the heat production is the key factor for the use of these plants. For this reason the relation between heat and electricity is a fixed ratio like the one showed in Figure's 2.29 graphic.

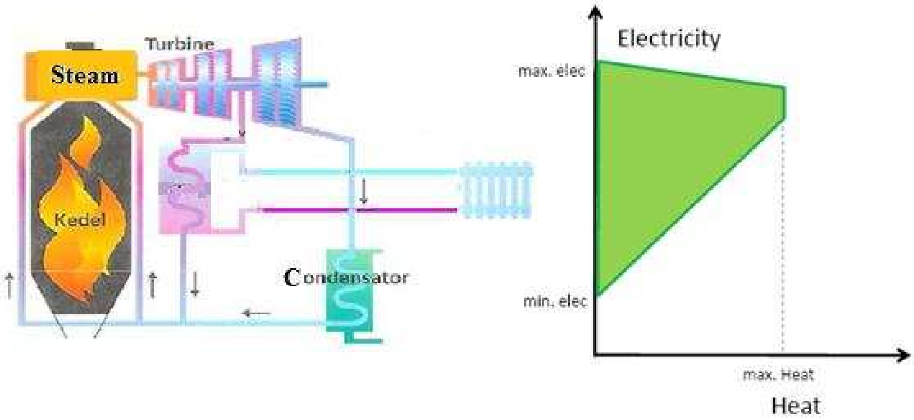


Figure 2.30 – Extraction plant. <u>Source</u>: *"De vigtigste komponenter og beslutninger i energisystemet"*.

Figure 2.30 shows the most common and flexible CHP plant. The steam produced in the boiler is used in the electricity-generating turbine and after that it's used to heat cool district heating water via a heat exchanger. This way the water is heated and the steam cooled and condensed into water, which is fed back to the boiler, where it becomes high-pressure steam once more. The water is heated around 100-120ºC and it distributed via pipelines.

These power plants are the most flexible ones allowing a wide range and different operational scenarios as it's shown in the graphic.

Chapter 3

Modelling the problem

In this chapter the model will be presented and discussed.

Firstly, a description of the model, the purpose and background behind it, and finally the main goals.

Secondly the description of the variables involved. The assumptions, choices and sources will be topic of discussion.

Finally the results will be presented and discussed.

3.1 - Model

Denmark is part of the Nord Pool Market. This market is well optimized and power plants are operated in the most optimized way to fulfill the consumption needs.

All the power plants selected to be in operation are expected to be fully available but contingencies occur so the TSO should have a backup plan to avoid the loss of load. That's the reason why reserves are an important item in the system and the study of its requirements should be a topic of discussion and appreciation.

In the Danish power system, as mentioned before, there are 3 types of reserves: *Primary*, *secondary* and *tertiary* reserves.

For this model the mains focus will be the so called "Operational Reserves".

Reminding at was described in section 2.1, the primary reserve is performed by the regulating units automatically, within seconds, in order to restore the system frequency in case of an imbalance. The secondary reserves will take over the remaining frequency and power deviation after 15 to 30 seconds in order to restore the system frequency and the levels of the primary reserve. If there's still a surplus of consumption the tertiary control is activated. The tertiary reserves are manual regulated reserves activated together with other regulating bids (from the NOIS list) within 15 minutes after the imbalance. The TSO reserves

680MW capacity hourly for this tertiary control and if still not enough the TSO makes use of the bids in the NOIS list. These 680MW are called "Operational Reserves"

The development of the model will lead to results that will show the number of hours that these Operational Reserves were not enough to satisfy the deficit of power and therefore the TSO had to import reserves using the NOIS list. Another result will be the maximum amount imported for reserves.

Then, new scenarios affecting the wind will be tested and new results will be obtained for the numbers of hours that the Operational Reserves were not enough to cover the imbalance. Again also the maximum amount of imported reserves will be found.

Afterwards, by matching the results, a new number for the requirements of this Operational Reserves will be presented as well as conclusions regarding this decision.

The concept created for this project is described in Figure 3.1

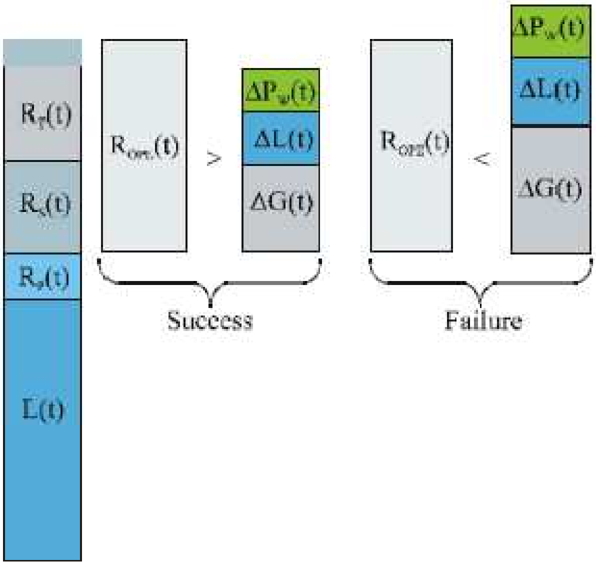


Figure 3.1 – Operational reserves adequacy evaluation. Source: *"Dealing with intermittent generation in the long-term evaluation of system adequacy and operational reserve requirements in the Iberian Peninsula", Peças Lopes, M.A. Matos, Gomes Cabral, Sampaio Ferreira, Fidalgo Martins, Artaiz Wert, Soto Martos, López Sanz, M. Rosa, R. Ferreira, Leite da Silva, Warlley Sales, Leonidas Resende, Luiz Manso.*

The variables are described in a simple form as follow:

L(t) - Load at period t

R_P(t) - Primary Reserve at period t

R_S (t) – Secondary Reserve at period t

R_T(t) - Tertiary Reserve at period t

R_{OPE}(t) - Operational Reserve at period t

ΔG(t) - Loss of generation in period t

$\Delta L(t)$ - Unexpected load variation in period t

$\Delta P_W(t)$ - Unexpected wind power variation in period t

t - period time

With the real historical data collected, this model calculates the number of hours in which the Operational Reserves were enough to bridge the gaps in DK-West supply due to Unexpected Deficit of Power (UDP).

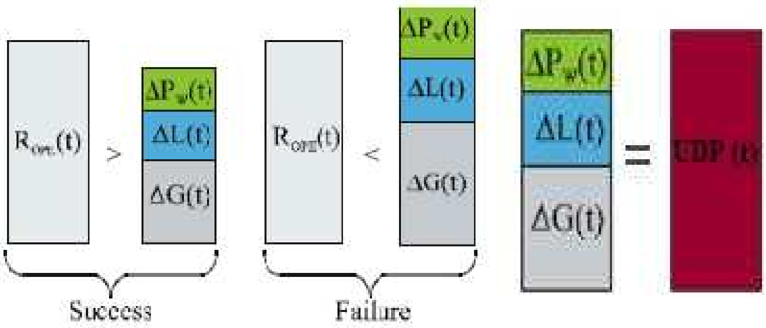


Figure 3.2 – Operational reserves adequacy evaluation (simplified).

UDP (t) - Unexpected Deficit of Power in period t

UDP (Figure 3.2) is the total amount of the unpredictable loss of load due to deviation in win power predictions **$\Delta P_W(t)$**, deviation between forecasted and real consumption **$\Delta L(t)$** and loss of generation due to a contingency in a planned unit **$\Delta G(t)$**.

When the Operational Reserve (R_{OPE}) is greater than UDP the system is considered healthy, meaning that DK-West it's not depending on its neighboring countries to manage the system fails. If the Operational Reserve it's not enough to meet the UDP there's a need to up regulate the supply using the NOIS list and therefore depending on the neighboring systems.

$$R_{OPE}(t) \geq \Delta P_W(t) + \Delta L(t) + \Delta G(t) \rightarrow Success \tag{3.1}$$

$$R_{OPE}(t) < \Delta P_W(t) + \Delta L(t) + \Delta G(t) \rightarrow Failure \tag{3.2}$$

For every hour the model will calculate the UDP and will add the number of hours where the equation 3.2 was true and show as a result the number of hours where the Operational Reserve was not enough to respond to the imbalance.

In this model all the variables that contribute for UDP are only considered if they require a need for up-regulation in the system and therefore make use of the available reserves.

3.2 - Variables

The variables are:

- **t -** period time

Nord Pool only started publishing the wind power forecasts from 14-09-2009 so the period considered for this model was 6 months starting from that day. So the data goes from 00h00 14-09-2009 until 23h00 13-03-2010 with a total of 3864 hours (the total number of hours should be 4344 but in 480 of those Nord Pool fail to deliver the predictions for wind or consumption).

- **R_{OPE}(t) -** Operational Reserve at period t:

"Operational Reserve" is the selected term for "manual reserves" and it's the available reserves that the TSO can use before going to the NOIS list. In our present's days, the **Operational Reserve is 680MW**.

- **ΔP_W(t) -** Unexpected wind power variation in period t

It's the difference between forecast and real wind production. The data was extracted from Nord Pool wind power report. Nord Pool makes prediction for the wind power production and publishes them on the day before the day of operation in order for the players to make use of it if they want. The real data was extracted from the TSO (energinet.dk) production report. The two values were compared for every hour and the deviation was calculated using the equation:

$$\Delta P_W(t) = P_W\, forecast(t) - P_W\, product(t) \tag{3.3}$$

$$\Delta P_W(t) > 0 \rightarrow up - regulation$$

$$\Delta P_W(t) < 0 \rightarrow down - regulation$$

Only the need for up regulation is considered valid for this variable. Table 3.1 shows how this variable is calculated.

Table 3.1 — Model [$\Delta P_W(t)$].

Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) ΔP_w (t) = forec - product
14-09-2009	0	549,0	548,7	**0,30**
14-09-2009	1	517,0	517,8	**-0,80**
14-09-2009	2	490,0	509,1	**-19,10**
14-09-2009	3	476,0	523,3	**-47,30**
14-09-2009	4	472,0	552,3	**-80,30**
14-09-2009	5	488,0	598,5	**-110,50**
14-09-2009	6	524,0	632,6	**-108,60**
14-09-2009	7	580,0	652,3	**-72,30**
14-09-2009	8	675,0	679,8	**-4,80**
14-09-2009	9	816,0	798,8	**17,20**
14-09-2009	10	957,0	1008,9	**-51,90**
(...)	(...)	(...)	(...)	(...)
13-03-2010	12	1779,0	2065,8	**-286,80**
13-03-2010	13	1821,0	2140,4	**-319,40**
13-03-2010	14	1842,0	2156,4	**-314,40**
13-03-2010	15	1844,0	2158,8	**-314,80**
13-03-2010	16	1839,0	2128,1	**-289,10**
13-03-2010	17	1798,0	2140,6	**-342,60**
13-03-2010	18	1746,0	2120,3	**-374,30**
13-03-2010	19	1715,0	2082,5	**-367,50**
13-03-2010	20	1686,0	2028,7	**-342,70**
13-03-2010	21	1640,0	1998,3	**-358,30**
13-03-2010	22	1595,0	1954,4	**-359,40**
13-03-2010	23	1538,0	1797,1	**-259,10**

Only the up-regulation is considered for the UDP meaning that when the forecast exceeds the real value produced, there's a need for up-regulate to maintain the expected levels of production, so the positive values (red boxes) represent the ΔPW(t) in the period considered.

Down-regulation is not an option because wind power is one of the cheapest way of production, therefore is not rational to decrease the wind power production. Also the technology behind wind power is not well prepared to low the levels of production so the solution would be shut down some of the wind turbines and in a market perspective it's not a valid option.

- **ΔL(t) -** Unexpected load variation in period t

It's the difference between forecast and real gross consumption. The data was extracted from Nord Pool consumption report. Nord Pool also makes these predictions and publishes them one day before the day of operation. The real consumption was also extracted from

Nord Pool data base and the values were compared for every hour and the deviation was calculated using:

$$\Delta L(t) = Lconsumpt\,(t) - Lforecast\,(t) \tag{3.4}$$

$$\Delta L(t) > 0 \rightarrow up - regulation$$

$$\Delta L(t) < 0 \rightarrow down - regulation$$

Only the need for up regulation is considered valid for this variable. Table 3.2 shows how this variable is calculated.´

Table 3.2 — Model [ΔL(t)].

Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) ΔP_w (t) = forec - product	DK-West: Gross consumption forecasting Nord Pool	DK-West: Gross consumption Nord Pool	Consumption deviation (need for up-regulation) ΔL (t) = consump - forec
14-09-2009	0	549,0	548,7	**0,30**	1565,0	1560,0	**-5,0**
14-09-2009	1	517,0	517,8	**-0,80**	1516,0	1507,0	**-9,0**
14-09-2009	2	490,0	509,1	**-19,10**	1520,0	1510,0	**-10,0**
14-09-2009	3	476,0	523,3	**-47,30**	1528,0	1527,0	**-1,0**
14-09-2009	4	472,0	552,3	**-80,30**	1582,0	1578,0	**-4,0**
14-09-2009	5	488,0	598,5	**-110,50**	1764,0	1756,0	**-8,0**
14-09-2009	6	524,0	632,6	**-108,60**	2162,0	2224,0	**62,0**
14-09-2009	7	580,0	652,3	**-72,30**	2605,0	2638,0	**33,0**
14-09-2009	8	675,0	679,8	**-4,80**	2765,0	2800,0	**35,0**
14-09-2009	9	816,0	798,8	**17,20**	2785,0	2744,0	**-41,0**
14-09-2009	10	957,0	1008,9	**-51,90**	2826,0	2838,0	**12,0**
(...)	(...)	(...)	(...)	(...)	2876,0	2839,0	**-37,0**
13-03-2010	12	1779,0	2065,8	**-286,80**	2374,0	2271,0	**-103,0**
13-03-2010	13	1821,0	2140,4	**-319,40**	2319,0	2242,0	**-77,0**
13-03-2010	14	1842,0	2156,4	**-314,40**	2249,0	2268,0	**19,0**
13-03-2010	15	1844,0	2158,8	**-314,80**	2237,0	2269,0	**32,0**
13-03-2010	16	1839,0	2128,1	**-289,10**	2292,0	2333,0	**41,0**
13-03-2010	17	1798,0	2140,6	**-342,60**	2521,0	2542,0	**21,0**
13-03-2010	18	1746,0	2120,3	**-374,30**	2686,0	2616,0	**-70,0**
13-03-2010	19	1715,0	2082,5	**-367,50**	2587,0	2535,0	**-52,0**
13-03-2010	20	1686,0	2028,7	**-342,70**	2415,0	2330,0	**-85,0**
13-03-2010	21	1640,0	1998,3	**-358,30**	2272,0	2218,0	**-54,0**
13-03-2010	22	1595,0	1954,4	**-359,40**	2141,0	2082,0	**-59,0**
13-03-2010	23	1538,0	1797,1	**-259,10**	2008,0	1950,0	**-58,0**

Only the need of up-regulation (red boxes) is considered for the UDP meaning that when the forecast misses by defect the real value, there's a need for up-regulate in order to insure that all the demand is satisfied. The need to down-regulation (blue boxes) is not included independently but it might influence the value of ΔL(t).

The positive values (red boxes) represent the ΔL(t) in the period considered, but when the forecast exceeds the real value of consumption (negative values: blue box) there's a need to down-regulate the supply. And, even though the down-regulation is not considered in the model, if for the same period *t* there's a need to up-regulate the Wind Power and for the same hour there's a need for down-regulate the consumption then this down-regulated power will be deduced to the wind power up-regulation, in a way that there's a balance in the system and the down regulation of the consumption compensates the up regulation in the wind production. Table 3.3 summarizes the options behind this assumption.

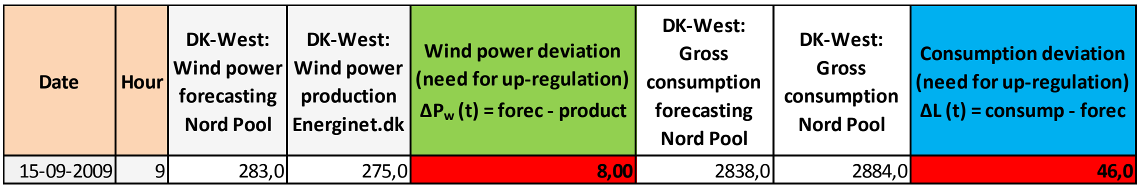
Table 3.3 — [ΔL(t)] assumptions.

ΔP_W	ΔL	UDP	
> 0	> 0	$\Delta P_W + \Delta L$	
< 0	< 0	0	
< 0	> 0	ΔL	
> 0	< 0	se $(\Delta PW + \Delta L) > 0$	$(\Delta PW + \Delta L)$
		se $(\Delta PW + \Delta L) < 0$	0

Deduct the down-regulation for wind power in the up-regulation of the consumption is not considered because, once again, it's not an option to reduce the production in the wind turbines.

To make it clear, examples are given:

Example 1



Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) ΔP_w (t) = forec - product	DK-West: Gross consumption forecasting Nord Pool	DK-West: Gross consumption Nord Pool	Consumption deviation (need for up-regulation) ΔL (t) = consump - forec
15-09-2009	9	283,0	275,0	8,00	2838,0	2884,0	46,0

In this case both **ΔP_W(t)** and **ΔL(t)** are considered because there's a need for up-regulation for both wind power production and consumption:

$$\Delta P_W(t) + \Delta L(t) = 8{,}00 + 46{,}0 = 54{,}00 MW$$

Example 2

Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) $\Delta P_w(t)$ = forec - product	DK-West: Gross consumption forecasting Nord Pool	DK-West: Gross consumption Nord Pool	Consumption deviation (need for up-regulation) $\Delta L(t)$ = consump - forec
03-10-2009	9	1290,0	1320,4	**-30,40**	2105,0	1898,0	**-207,0**

In this case none of the variables are considered:

$$\Delta P_W(t) + \Delta L(t) = 00{,}00 + 00{,}0 = 00{,}00MW$$

Example 3

Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) $\Delta P_w(t)$ = forec - product	DK-West: Gross consumption forecasting Nord Pool	DK-West: Gross consumption Nord Pool	Consumption deviation (need for up-regulation) $\Delta L(t)$ = consump - forec
02-10-2009	13	473,0	513,6	**-40,60**	2576,0	2589,0	**13,0**

In this case only **ΔL(t)** is in need for up-regulation therefore:

$$\Delta P_W(t) + \Delta L(t) = 00{,}00 + 13{,}0 = 13{,}00MW$$

Example 4

Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) $\Delta P_w(t)$ = forec - product	DK-West: Gross consumption forecasting Nord Pool	DK-West: Gross consumption Nord Pool	Consumption deviation (need for up-regulation) $\Delta L(t)$ = consump - forec
02-10-2009	9	421,0	386,8	**34,20**	2908,0	2898,0	**-10,0**

In this case only **$\Delta P_W(t)$** is in need for up-regulation but the consumption has the opposite sign so the value should be deduced to the Wind Power deviation.

$$\Delta P_W(t) + \Delta L(t) = 34{,}20 - 10{,}0 = 24{,}20MW$$

Example 5

Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) $\Delta P_w(t)$ = forec - product	DK-West: Gross consumption forecasting Nord Pool	DK-West: Gross consumption Nord Pool	Consumption deviation (need for up-regulation) $\Delta L(t)$ = consump - forec
12-10-2009	1	913,0	889,2	**23,80**	1659,0	1604,0	**-55,0**

In this case only **$\Delta P_W(t)$** is in need for up-regulation but the consumption has the opposite sign so the value should be deduced to the Wind Power deviation and it's enough to compensate the up-regulation in the wind power, so for the model:

$$\Delta P_W(t)+\Delta L(t)=23{,}80-55{,}0=-31{,}20\rightarrow 00{,}0MW$$

- **ΔG(t) -** Loss of generation in period t

It consists on the unexpected loss of generation. This data was extracted from Nord Pool Urgent Market Messages (UMMs) regarding failures in DK-West power plants for the selected period and also from Energinet.dk production report.

The loss of generation is divided in two plots (Figure3.3): *Local generation* **$\Delta G(t)_{local}$** and *Central generation* **$\Delta G(t)_{central}$**. The central generation is the most significant portion of the loss of generation obviously related with the volumes of capacity involved. Production in the big central power units is way more representative then in the local CHPs.

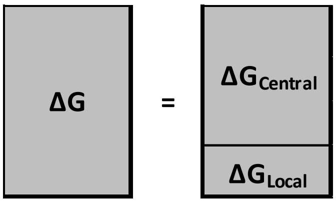


Figure 3.3 - ΔG(t)

The Loss of generation **ΔG(t) is** then determined using the equation:

$$\Delta G(t)=\Delta G_{Local}(t)+\Delta G_{Central}(t) \qquad (3.5)$$

The local generation refers to production from local CHPs (Decentralized power plants) in Western Denmark (**$G_{CHP}(t)$**). The level of efficiency of these types of power plants is higher so severe failures are not expected. For this reason it's considered a failure rate of 5% in every period t. For every hour:

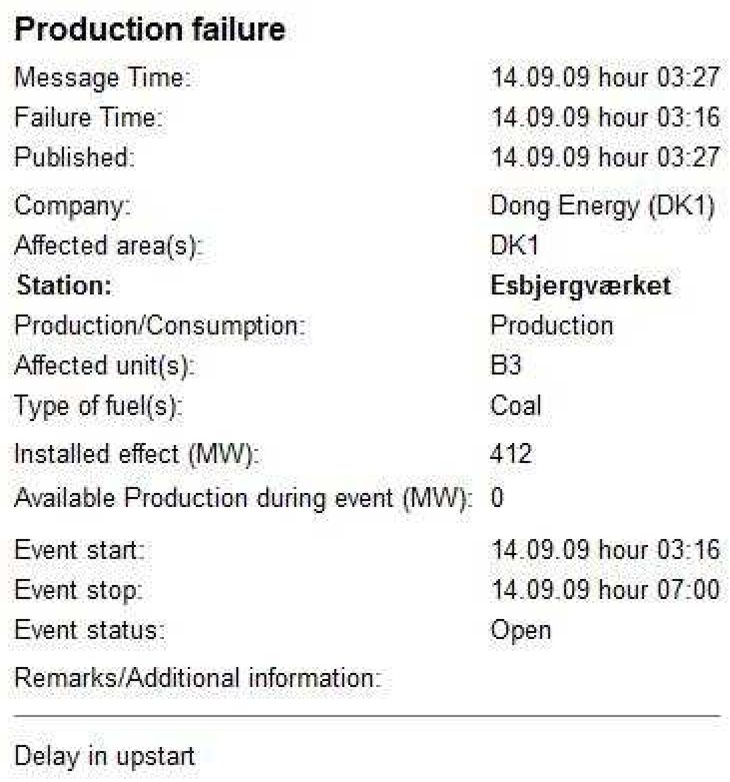
$$\Delta G_{Local}(t) = G_{CHP}(t) \times 5\% \tag{3.6}$$

The central generation refers to production in the big coal power (centralized power plants) plants in DK-West. The values considered for this variable are based on Nord Pool Urgent Market Message (UMM's) reports. Some assumptions were made during the analysis of these UMM's:

1. If the message is sent before 13h00, the failure is considered until the end of the day of operation with the value of the capacity unavailable for that period.
    - **1.1.** The value of the capacity is updated if changes occurred in the power plant status during the day of operation. If the capacity is fully restore then no loss of generation is considered from one hour after the recovery message.

2. If the message is sent after 13h00, the failure it's considered until the end of the day after the day of operation with the value of the capacity unavailable for that period. This assumption is made because the affected power plant could be already included in the next day of operation since the failure starts after the volumes and prices announcement by Nord Pool for the day of operation.
    - **2.1.** The value of the capacity is updated if changes occurred in the power plant during the day of operation or the day after. If the capacity is fully restore then no loss of generation is considered from one hour after the recovery message.

Figure 3.4 shows an example of an UMM:



Production failure

Message Time:	14.09.09 hour 03:27
Failure Time:	14.09.09 hour 03:16
Published:	14.09.09 hour 03:27
Company:	Dong Energy (DK1)
Affected area(s):	DK1
Station:	**Esbjergværket**
Production/Consumption:	Production
Affected unit(s):	B3
Type of fuel(s):	Coal
Installed effect (MW):	412
Available Production during event (MW):	0
Event start:	14.09.09 hour 03:16
Event stop:	14.09.09 hour 07:00
Event status:	Open

Remarks/Additional information:

Delay in upstart

Figure 3.4 – Urgent Market Message (UMM). Source: Nord Pool

For this example on 14-09-2009 from t ε $[3;7]$ 412MW should be considered in the variable **$\Delta G(t)_{central}$**.

These UMMs are sent to Nord Pool by the units in operation but, in fact, these UMMs are not clear. In an UMMs, there’s the information regarding the installed capacity and the available production. But it’s not sure that all the capacity was traded on the market. It’s even possible that this unit was not selected in the pool market. But because this information is not available to common users this assumption is made: every unit that reports to Nord Pool are supposed to be in operation by result of the pool market with is total capacity.

Table 3.4 shows how this variable is calculated.

Table 3.4 — Model [ΔG(t)].

Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) $\Delta P_w(t)$ = forec - product	DK-West: Gross consumption forecasting Nord Pool	DK-West: Gross consumption Nord Pool	Consumption deviation (need for up-regulation) $\Delta L(t)$ = consump - forec	DK-West: Local production Energinet.dk	Loss of Generation $\lvert\Delta G(t)\rvert_{local}$	Loss of Generation $\lvert\Delta G(t)\rvert_{central}$	$\lvert\Delta G(t)\rvert$
14-09-2009	0	549,0	548,7	**0,30**	1565,0	1560,0	**-5,0**	216,9	10,8	0,0	**10,8**
14-09-2009	1	517,0	517,8	**-0,80**	1516,0	1507,0	**-9,0**	215,9	10,8	0,0	**10,8**
14-09-2009	2	490,0	509,1	**-19,10**	1520,0	1510,0	**-10,0**	215,2	10,8	0,0	**10,8**
14-09-2009	3	476,0	523,3	**-47,30**	1528,0	1527,0	**-1,0**	215,3	10,8	412,0	**422,8**
14-09-2009	4	472,0	552,3	**-80,30**	1582,0	1578,0	**-4,0**	214,5	10,7	412,0	**422,7**
14-09-2009	5	488,0	598,5	**-110,50**	1764,0	1756,0	**-8,0**	217,9	10,9	412,0	**422,9**
14-09-2009	6	524,0	632,6	**-108,60**	2162,0	2224,0	**62,0**	286,5	14,3	412,0	**426,3**
14-09-2009	7	580,0	652,3	**-72,30**	2605,0	2638,0	**33,0**	514,2	25,7	412,0	**437,7**
14-09-2009	8	675,0	679,8	**-4,80**	2765,0	2800,0	**35,0**	701,1	35,1	0,0	**35,1**
14-09-2009	9	816,0	798,8	**17,20**	2785,0	2744,0	**-41,0**	734,7	36,7	0,0	**36,7**
14-09-2009	10	957,0	1008,9	**-51,90**	2826,0	2838,0	**12,0**	733,9	36,7	0,0	**36,7**
(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)
13-03-2010	12	1779,0	2065,8	**-286,80**	2374,0	2271,0	**-103,0**	678,5	33,9	0,0	**33,9**
13-03-2010	13	1821,0	2140,4	**-319,40**	2319,0	2242,0	**-77,0**	628,8	31,4	0,0	**31,4**
13-03-2010	14	1842,0	2156,4	**-314,40**	2249,0	2268,0	**19,0**	608,2	30,4	0,0	**30,4**
13-03-2010	15	1844,0	2158,8	**-314,80**	2237,0	2269,0	**32,0**	562,3	28,1	0,0	**28,1**
13-03-2010	16	1839,0	2128,1	**-289,10**	2292,0	2333,0	**41,0**	551,0	27,6	0,0	**27,6**
13-03-2010	17	1798,0	2140,6	**-342,60**	2521,0	2542,0	**21,0**	636,2	31,8	0,0	**31,8**
13-03-2010	18	1746,0	2120,3	**-374,30**	2686,0	2616,0	**-70,0**	734,5	36,7	0,0	**36,7**
13-03-2010	19	1715,0	2082,5	**-367,50**	2587,0	2535,0	**-52,0**	745,6	37,3	0,0	**37,3**
13-03-2010	20	1686,0	2028,7	**-342,70**	2415,0	2330,0	**-85,0**	726,3	36,3	0,0	**36,3**
13-03-2010	21	1640,0	1998,3	**-358,30**	2272,0	2218,0	**-54,0**	661,6	33,1	0,0	**33,1**
13-03-2010	22	1595,0	1954,4	**-359,40**	2141,0	2082,0	**-59,0**	648,4	32,4	0,0	**32,4**
13-03-2010	23	1538,0	1797,1	**-259,10**	2008,0	1950,0	**-58,0**	600,6	30,0	0,0	**30,0**

When $\mathbf{\Delta G(t)}_{central}$.=0 means that for that hour *t* any failure or force outage in the central power plants were affecting the system.

- **UDP(t) -** Unexpected Deficit of Power in period *t*

The Unexpected Deficit of Power it's the total amount of power that has to be replaced due to the unforeseen reasons previously described.

$$UDP(t) = \Delta P_W(t) + \Delta L(t) + \Delta G(t) \tag{3.7}$$

Table 3.5 shows how this variable is calculated.

Table 3.5 — Model [UDP(t)].

Date	Hour	DK-West: Wind power forecasting Nord Pool	DK-West: Wind power production Energinet.dk	Wind power deviation (need for up-regulation) $\Delta P_w(t)$ = forec - product	DK-West: Gross consumption forecasting Nord Pool	DK-West: Gross consumption Nord Pool	Consumption deviation (need for up-regulation) $\Delta L(t)$ = consump - forec	DK-West: Local production Energinet.dk	Loss of Generation $\|\Delta G(t)\|_{local}$	Loss of Generation $\|\Delta G(t)\|_{central}$	$\|\Delta G(t)\|$	UDP
14-09-2009	0	549,0	548,7	0,30	1565,0	1560,0	-5,0	216,9	10,8	0,0	10,8	10,8
14-09-2009	1	517,0	517,8	-0,80	1516,0	1507,0	-9,0	215,9	10,8	0,0	10,8	10,8
14-09-2009	2	490,0	509,1	-19,10	1520,0	1510,0	-10,0	215,2	10,8	0,0	10,8	10,8
14-09-2009	3	476,0	523,3	-47,30	1528,0	1527,0	-1,0	215,3	10,8	412,0	422,8	422,8
14-09-2009	4	472,0	552,3	-80,30	1582,0	1578,0	-4,0	214,5	10,7	412,0	422,7	422,7
14-09-2009	5	488,0	598,5	-110,50	1764,0	1756,0	-8,0	217,9	10,9	412,0	422,9	422,9
14-09-2009	6	524,0	632,6	-108,60	2162,0	2224,0	62,0	286,5	14,3	412,0	426,3	488,3
14-09-2009	7	580,0	652,3	-72,30	2605,0	2638,0	33,0	514,2	25,7	412,0	437,7	470,7
14-09-2009	8	675,0	679,8	-4,80	2765,0	2800,0	35,0	701,1	35,1	0,0	35,1	70,1
14-09-2009	9	816,0	798,8	17,20	2785,0	2744,0	-41,0	734,7	36,7	0,0	36,7	36,7
14-09-2009	10	957,0	1008,9	-51,90	2826,0	2838,0	12,0	733,9	36,7	0,0	36,7	48,7
(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)	(...)
13-03-2010	12	1779,0	2065,8	-286,80	2374,0	2271,0	-103,0	678,5	33,9	0,0	33,9	33,9
13-03-2010	13	1821,0	2140,4	-319,40	2319,0	2242,0	-77,0	628,8	31,4	0,0	31,4	31,4
13-03-2010	14	1842,0	2156,4	-314,40	2249,0	2268,0	19,0	608,2	30,4	0,0	30,4	49,4
13-03-2010	15	1844,0	2158,8	-314,80	2237,0	2269,0	32,0	562,3	28,1	0,0	28,1	60,1
13-03-2010	16	1839,0	2128,1	-289,10	2292,0	2333,0	41,0	551,0	27,6	0,0	27,6	68,6
13-03-2010	17	1798,0	2140,6	-342,60	2521,0	2542,0	21,0	636,2	31,8	0,0	31,8	52,8
13-03-2010	18	1746,0	2120,3	-374,30	2686,0	2616,0	-70,0	734,5	36,7	0,0	36,7	36,7
13-03-2010	19	1715,0	2082,5	-367,50	2587,0	2535,0	-52,0	745,6	37,3	0,0	37,3	37,3
13-03-2010	20	1686,0	2028,7	-342,70	2415,0	2330,0	-85,0	726,3	36,3	0,0	36,3	36,3
13-03-2010	21	1640,0	1998,3	-358,30	2272,0	2218,0	-54,0	661,6	33,1	0,0	33,1	33,1
13-03-2010	22	1595,0	1954,4	-359,40	2141,0	2082,0	-59,0	648,4	32,4	0,0	32,4	32,4
13-03-2010	23	1538,0	1797,1	-259,10	2008,0	1950,0	-58,0	600,6	30,0	0,0	30,0	30,0

3.3 - Results

After UDP calculation for every hour the model calculates the number of hours that the Operational Reserve was not enough to cover the Unexpected Deficit of Power. The results are shown in table 3.6 and illustrated by the graphic in 3.5.

Table 3.6 — Model Results.

		Ratio
UDOP > R_{OPE} (h)	51,0	1,32%
Max UDOP (MW)	1076,635	63,16%
	680	
	R_{OPE} (MW)	

These results will be the "reference" for the upcoming scenarios.

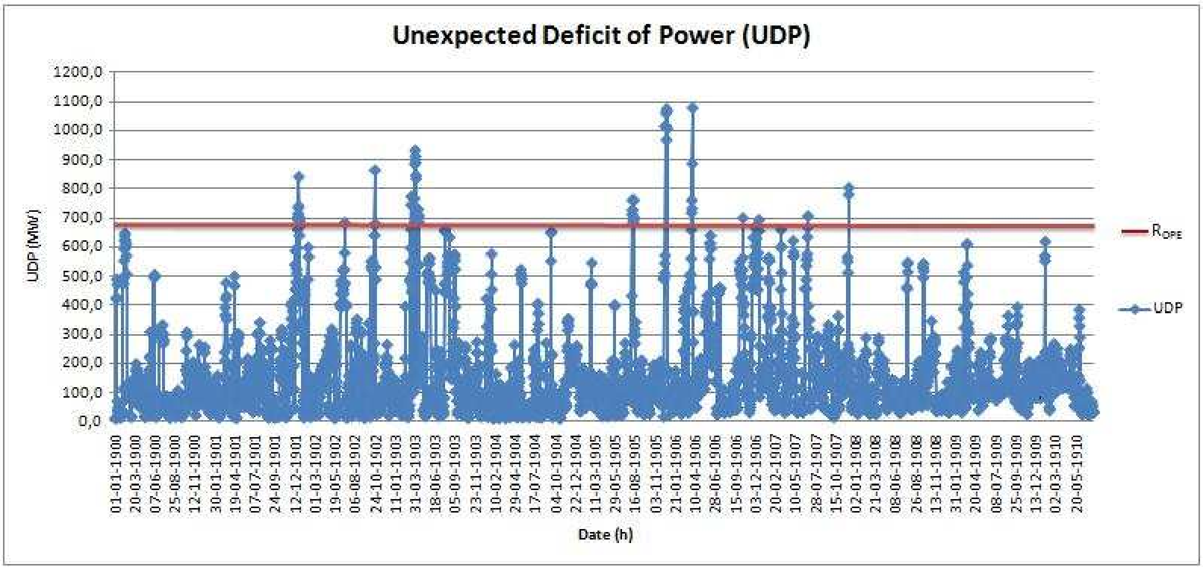


Figure 3.5 – Unexpected Deficit of Power vs Operational Reserve: Baseline Scenario

The results show that in 51 hours of the total period (3864h) the Operational Reserve was not enough to cover the Unexpected Deficit of Power and therefore there was a need to buy reserves, meaning that on those 51 hours Denmark was not self-sufficient and was forced to import reserves using the NOIS list. In percentage, the number of hours of failure correspond to 1,32% of the total period considered.

Another result it's obtained by the model: the maximum Unexpected Deficit of Power (max UDP). This value is relevant when is taken into perspective the total amount of power that the TSO buys from the NOIS list. This value represents the max amount of reserves imported. In percentage, the Operational Reserve was only enough to cover 63,16% of the maximum UDP.

3.4 - Conclusions

In this chapter the model, assumptions and procedures were presented and described. The assessment of the Operational Reserves will be topic of discussion in the next chapter were new scenarios will be implemented.

The model here described, looks at DK-West system as an independent system. The model only includes production, consumption and generation units running in Western Denmark. Therefore this should always be taken into perspective during the building of the model and the scenarios featured ahead in this report.

The results obtain in this chapter will be the "baseline results" that will be compared with some new results based on two new scenarios, where the wind power contribution will be affected.

The next Chapter is devoted to applying and testing the model to new scenarios in order to withdraw new results and conclusion.

Chapter 4

Adjusting to new scenarios

It was already mentioned in this report that in a near future the renewable energy will gain more relevance than ever. Putting into numbers, the energy policy of the Danish governments set a goal aiming for an increasing of the wind power capacity in Denmark to a production volume corresponding to 50 % of Danish electricity consumption in 2025.

The idea behind these new scenarios is to simulate this increase of wind power and come up with new results, conclusions and new values for Operational Reserves (R_{OPE}).

Two scenarios will be tested. In both scenarios the wind will be affected exactly the same way. The difference will reside in the assumptions made for the generation's units.

With the results obtain conclusions will be made and a new values for the Operational Reserves will be presented.

4.1 - Scenario 1: "Full Operation"

The challenge for this first scenario is to double the wind power in the system, by affecting the variable **$\Delta P_W(t)$,** maintaining the same conditions for the other variables.

The option for simulating the rising of the wind power was to duplicate the value of **$\Delta P_W(t)$** for every hour. The idea behind the model is to use real data instead of making deterministic or probabilistic approaches to find new values, so instead of forecast new values for the wind production it's assumed that the forecasting error remain the same but duplicated, so the Unexpected wind power variation will be double.

After this modification the model will one more time calculate the number of hours that the Operational Reserve was not enough to cover the Unexpected Deficit of Power as well as the new maximum UDP.

$\Delta P_W(t)$ was the only variable affected in this scenario. The other variables were not affected.

Since the 80's until our present days the energy consumption has remained almost unchanged and its assumed that it will not change significantly also in the future ahead, so the variable ΔL(t) will not be affected. Also the forecasting techniques are very accurate when forecasting consumption, so even though the consumption might increase the deviations will remain low as in the baseline scenario.

It's difficult to say what will happen to the generation units in the future. It's fair to expect that some will reach their lifetime and, under an economic point of view, might not be advantageous for the owner to renew or built a new one and therefore they will be closed. Besides that, invest in wind farms or wind turbines is subsided in order to stimulate the rising of the wind power. Knowing that the first bids to be accepted in the pool are the ones from the wind power this means that the increase of wind power units will lead to a scenario where the central power plants take the risk of not being selected by the pool due to higher prices then the wind turbines.

To avoid this risk, the owners of these power plants will be forced to reduce the cost of the offers in order to reduce this risk. However, they can't reduce it to values lower than the marginal costs of production, otherwise it's not profitable to bid in this market. In other words, it's not profitable to keep these units in operation.

All these factors might lead to a decrease of these units in Denmark. But, on the other hand, Denmark is part of a Nordic market where energy is traded without borders. In this perspective even with an increase of the wind production these central power plants will still have place in the market. These coal/natural gas central power plants that exist in DK-West are more expensive than wind farms or hydropower from Norway or Sweden but compared to coal units in Germany they are cheaper and therefore they can find profit by staying in the market.

Besides, primary, secondary and tertiary control is performed by these units, not by wind turbines. So, if Denmark wants to keep its levels of dependency regarding reserves, these units should be running as well. Also Voltage Control and Reactive Power are assured by some of these units.

Taking all this factors into account, for this scenario, it's assumed that the same number of units will continue running and consequently the same loss of generation (ΔG(t)) will be considered.

The results are shown in table 4.1 and illustrated by the graphic in 4.1.

Table 4.1 — Model Results: Scenario 1.

		Ratio
UDOP > R_{OPE} (h)	122,0	3,16%
Max UDOP (MW)	1546,335	43,97%
	680	
	R_{OPE} (MW)	

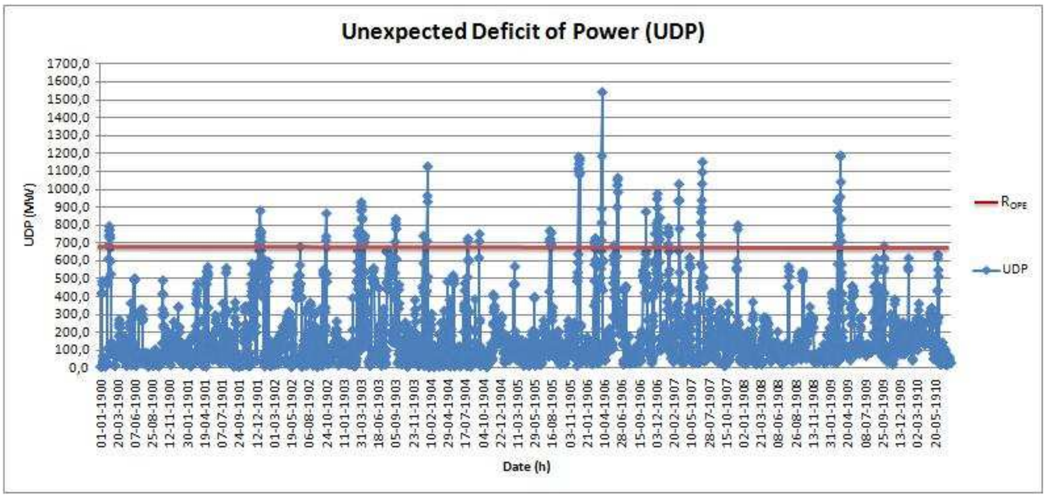


Figure 4.1 – Unexpected Deficit of Power vs Operational Reserve: Scenario 1

As expected, doubling the wind contribution maintaining the value of the other variables, will lead to an increase of the number of hours where the Operational Reserve was not enough to cover the value of UDP. The new number is 122 hours.

The next step is to determinate which should be the new value for the Operational Reserve to maintain the same number of hours as the baseline scenario. The results are presented in Table 4.2

Table 4.2 — New Operational Reserve: Scenario 1.

	Baseline Scenario	Scenario 1	New value R_{OPE} (MW)
UDOP > R_{OPE} (h)	51,0	122,0	815
Max UDOP (MW)	1076,635	1546,335	977

Two values were found for the Operational Reserve.

If the goal is to restore the number of hours as it was in the baseline scenario than R_{OPE} should be re-adjusted to 815 MW. This represents an increase of 135MW to the previous value.

If the objective is to keep the same ratio between R_{OPE} and the maximum UDP, then the value is 977 MW. This represents an increase of 297 MW.

4.2 - Scenario 2: “Technical Minimum”

This scenario differs from Scenario 1 in the assumption made for the Unexpected Loss of Generation (**ΔG(t)**).

Instead of assuming that the central power plants will continue in the market at full operation, in this scenario it’s assumed that the owners will run their units at the technical minimum, and bid the remaining capacity in the regulating market or in the intra-day market if necessary. With this choice, the suppliers decrease the risk of not being selected by the pool because they are offering lower levels of capacity and because they are running at their technical minimum they can increase production and sell this capacity in the intra-day market.

Taking these reasons into account, for this scenario, it’s assumed that the same number of units will continue running but at their technical minimum, so in every hour that there was a failure in generation the capacity unavailable is the minimum capacity of the unit.

The technical minimum for these units it’s **20% of the Nominal Capacity**.

The results are shown in table 4.3 and illustrated by the graphic in 4.2.

Table 4.3 — Model Results: Scenario 2.

		Ratio
UDOP > R_{OPE} (h)	**46,0**	**1,19%**
Max UDOP (MW)	**1209,735**	**56,21%**
	680	
	R_{OPE} (MW)	

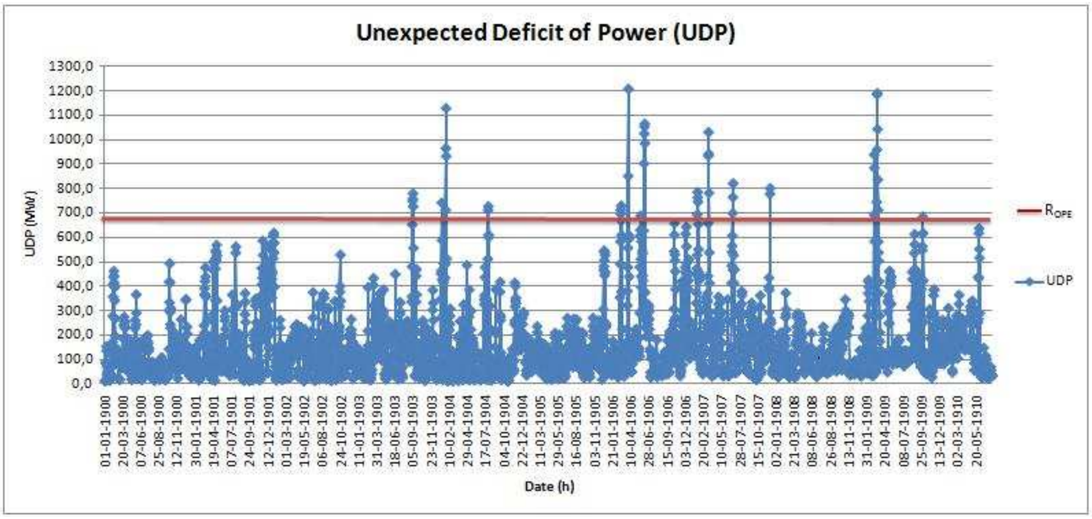


Figure 4.2 – Unexpected Deficit of Power vs Operational Reserve: Scenario 2

The results obtain with this new assumption show that the number of hours has, in fact, been reduced (46 hours), even though the max UDP is still bigger than in the baseline scenario.

So with these results two new values can be calculated for R_{OPE}. They are presented in Table 4.4

Table 4.4 — New Operational Reserve: Scenario 1.

	Baseline Scenario	Scenario 1	New value R_{OPE} (MW)
UDOP > R_{OPE} (h)	51,0	46,0	645
Max UDOP (MW)	1076,635	1209,735	765

The number of hours is lower in this scenario which is not a bad consequence. So the value of R_{OPE} can remain the same or it can be reduced to 645MW to match the baseline scenario.

If the goal is to keep the same ratio between R_{OPE} and the maximum UDP, then the new value should be 765 MW. This represents an increase of 85 MW.

4.3 - Conclusions

In this chapter the main results of the model were presented, in two different scenarios.

The idea behind this project was to built and run a model inspired by [1] but with real data instead of making a deterministic or probabilistic approaches to the variables.

Knowing this, work with real data and try to built a bridge for a future scenario using the same values can raise some doubts on the results but they are still valid and should be taken into appreciation.

This model is focused on the Western Danish System. These results were obtained making the assumption that DK-West runs as an independent system when in fact that doesn't happen. DK-West is part of a European market and DK-West is connected to his neighboring countries. Still the results obtained can be an indicator for all the Nordic countries to review their levels of Operational Reserves.

Some of the assumptions made for the variables should also be target of reflection.

ΔPW(t) reflects the difference between forecast and what was actually produced in the day of operation. The forecast values are published by Nord Pool on the day before the day of operation, but in fact, these values are internally updated. But because these updates are not published, the values considered for the model were the first predictions available on Nord Pool wind power report. Then, as previously stated, the increase of wind power production was made by doubling the difference between forecasts and actual production. Another way to simulate this scenario would be, for example, to make a prediction for these values or add a certain degree of uncertainty, to the values from the baseline scenario, by implementing a model calculation based on probabilities or deterministic associated with the variables.

Likewise, ΔL (t) could have been determined by making new predictions, but consumption has a predictable behaviour, so even if there is an increase or decrease in the consumption, the forecasted values will remain with a similar deviations.

Regarding the Loss of Generation **ΔG(t)**, in both scenarios the assumption made was that all the units continue in operation and the losses were considered in the same periods as the baseline scenario. Logically the failures in the future will not occur in same hours and with the same values, but in this model the idea was to simulate the same scenario as the “baseline scenario” but doubling the wind. Add some uncertainty or probability to the losses in generation could also be a way of simulating losses in a future event, but these imbalances in generation will be always present in the system, despite the instant were it occurs, so for the purpose of this project it’s valid to accept that this variable remains with the same values.

One consideration about the Urgent Market Message’s (UMMs). These messages were interpreted as reports of failures in the central power units operating only in DK-West. It’s a fact that these units are located in DK-West area but it’s not granted that these units are providing the DK-West system with its capacity. Once again, DK-West is part of a European market and also these units, so the unavailable capacity reported in these messages might not be integrated in DK-West system, but still this data can contribute in a way that, even if it’s other units supplying DK-West system, failures in generation occur when it’s least expected.

The loss of generation in Local production considered was 5% of the total production in every hour. This low percentage was assumed because, even though sometimes it might be bigger or lower or even null, the efficiency of these CHP units is very high so these losses represent the smaller share of **ΔG(t)**.

Finally, the time period considered (6 moths), it’s enough to withdraw conclusions but is short. 1 or 2 years of historical data would give extra consistency to the results obtained. But the data was only available for this period.

Looking now to the results, Scenario 1 revealed two new values for “Operational Reserve”. In TSO perspective, if it’s more relevant to keep the same number of hours that the operational reserves (R_{OPE}) were enough to cover the unexpected deficit of power (UDP) the new value for R_{OPE} should be 815 MW. On the other hand, if it’s more important to keep the same ratio between R_{OPE} and the maximum UDP, then the R_{OPE} should be re-adjusted to 765 MW.

In scenario 2, the results show that the value of the operational reserve can be, in fact, reduced. This means that, in this scenario, the increase of wind power in DK-West is beneficial for the system, and the TSO can in fact maintain or even reduce the amount of operational reserves.

In a market perspective the decrease of the operational reserve could lead to lower prices in some specifics periods and areas.

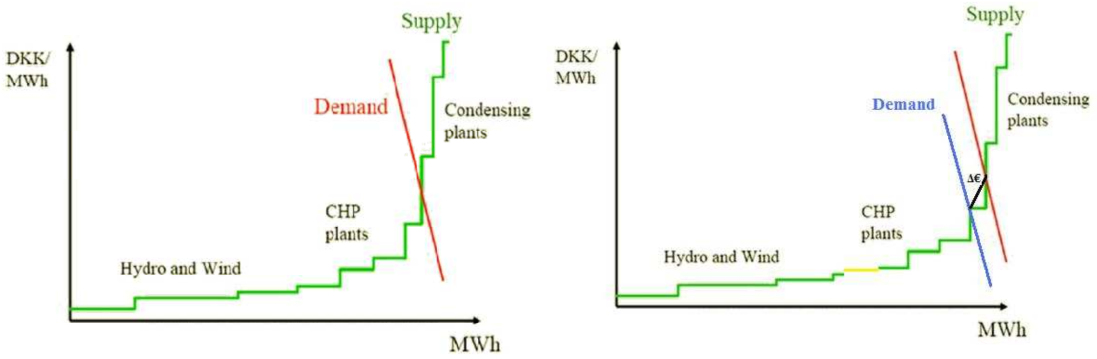


Figure 4.3 – Scenario 2: A market perspective

Those 35MW of reserves that can be reduced for the operational reserve will be added to the market and, because normally they should be purchased from the cheapest units, this will lead, in some situations, to a decrease (**Δ€**) of the price of the area like is illustrated in Figure 4.3.

In the future the share of wind production in the system will become even more relevant, reaching levels of production around 6000MW. Knowing the instable behavior of the wind, that 200MW can be lost within moments, 680MW of operational reserves may be short to solve a situation of failure in the generation. This is also one of the reasons why the requirements should be reviewed.

Finally, it's also fair to make the question: just because the number of hours has increased for the double justifies that the TSO should buy 100MW or 200MW extra reserves for the all 3864 hours? Maybe the economical answer is "no" but to help answering this question the next step should be to perform a common study between all the TSOs and this study would definitely bring new results and challenges for operational reserves in a future context where renewable energies will become one of the bigger shares in production.

Chapter 5

Conclusions and future work

This Chapter will summarize the previously drawn conclusions, when the main results in Chapter 4 were analyzed, in a context of assessment if the objectives proposed for this thesis were attained. Will also reflect the overall report and then some guidelines to continue and improve the work on this thesis will be detailed.

5.1 - Objectives achieved

In this thesis a new model was presented in order to evaluate the requirements for the reserves and at the same time study the dependency of the Danish system on their neighbors (by making use of the NOIS list).

First an overview on the Danish system was presented, namely the structure and background with special focus on the operational reserves, explaining their meaning and role in the system. Then a close looks into the energy market, how it operates and how reserves can be included as well in a market context. This overview was made as an useful background trough the Danish system and the energy market focusing on the operational reserves that make possible to understand the ideas and purposes behind the model developed in this report.

Built a model that could help understanding the new paradigms for the requirements of reserves was one of the main objectives. That objective was achieved and the model presented help bring some new answers and predictions on how the requirements for reserves can evolve in the near future.

The results show that, despite all the assumptions, the requirements of reserves should be target of reflection in the near future. The requirements for reserves are defined by agreements between the European TSOs not by an individual TSO. However, the results presented in this thesis can be source of reflection for all the TSOs in their areas to also perform case studies in this subject in order to review these requirements.

To sum up in this thesis it was proved that the requirements for reserves are efficient but should be target of future reflection in order to maintain a system optimized and ready for the new challenges that the renewable energies will bring into the power system.

5.2 - Future work

The results of the work developed in this thesis may be the inspiration for other research studies. Therefore a list of possible studies that can be made is now presented:

- Improve the model by increasing the timeline, adding new variables, include all forms of renewable sources and extend the model to all Nordic region;
- Apply the model to other areas and see if these regions should also reflect on their requirements for reserves;
- It will be also interesting to perform studies to see how the power plants should react to the increase of wind power production in order to avoid being closed or lose their place in the market.

References

[1] Manuel Matos, João Peças Lopes, Mauro Rosa, Ricardo Ferreira, Armando Leite da Silva, Warlley Sales, Leonidas Resende, Luiz Manso, Pedro Cabral, Marco Ferreira, Nuno Martins, Carloz Artaiz, Fernando Soto, Rubén López. “Probabilistic Evaluation of reserve requirements of generating systems with renewable power sources: the Portuguese and Spanish cases”, 16th Power Systems Computation Conference, PSCC Glasgow Scotland, July 14-18, 2008.

[2] “Energy in Denmark 2008”, ENTSO-E. Available in http://www.ens.dk/en-US/Info/FactsAndFigures/Energy_statistics_and_indicators/Annual%20Statistics/Documents/Energy%20in%20Denmark%202008.pdf. Access in July 2010.

[3] “Danish Energy Policy 1970-2010 – Vision: 100% independence of fossil fuels”, Danish Energy Agency. Available in http://www.ens.dk/en-US/Info/news/Factsheet/Documents/DKEpol.pdf%20engelsk%20til%20web.pdf. Access in July 2010

[4] Joana Rasmussen, Arne Hejde Nielsen. “Phasor measurement of wind power plant operation in Eastern Denmark.

[5] “UCTE Operational Handbook”, ENTSO-E. Available http://www.entsoe.eu/index.php?id=57. Acess in July 2010

[6] Preben Nyeng, Knud Ole Helgesen Pedersen, Jacob Østergaard. “Ancillary services from distributed energy resources – perspectives for the Danish power system”. 2007

[7] “Nord Pool Spot Annual Report 2009”, Nord Pool. Available http://www.nordpoolspot.com/en/about/Annual_reports/. Access in July 2010

[8] “Description of Balance Regulation in the Nordic Countries”, ENTSO-E. Available in http://www.entsoe.eu/fileadmin/user_upload/_library/publications/nordic/market/080331_entsoe_nordic_DescriptionBalanceRegulationNordicCountries.pdf. Access July 2010

[9] “Regulation C2 - Balancing Market”, Energinet.dk. Available in http://www.energinet.dk/NR/rdonlyres/EDCF7811-2288-4F73-B646-727466B098DA/0/RegC2Thebalancingmarketandbalancesettlement.pdf. Access in July 2010

[10] “Regulation C3 – Handling of notifications and schedules”, Energinet.dk. Available in http://www.energinet.dk/NR/rdonlyres/145C8F46-832E-4B37-BEC9-618F3693EF85/0/RegC3_Handlingofnotificationsandschedules.pdf. Access in July 2010

[11]Henning Parbo. “The Power Market in Denmark”, Energinet.dk. Available in http://www.dispowergen.com/std/der/meetings/fredericia_2008-02/ws/1.1%20Energinet%20HP.pdf. Access in July 2010

[12]“Nordel Annual Report 2008”, ENTSO-E. Available in http://www.entsoe.eu/fileadmin/user_upload/_library/publications/nordic/annualreport/Annual%20report%202008.pdf. Access in July 2010

[13]“Agreement regarding operation of the interconnected Noridc power system - System Operation Agreement”, ENTSO-E. Available in http://www.entsoe.eu/fileadmin/user_upload/_library/publications/nordic/operations/060613_entsoe_nordic_SystemOperationAgreement_EN.pdf. Access in July 2010.

[14]Flemming Nissen. “Summer School 2009”, August 2009

[15]Flemming Nissen. “De vigtigste komponenter og beslutninger i energisystemet”.

[16]“Regulation A: Principles for the electricity market”. Energinet.dk. Available in http://www.energinet.dk/NR/rdonlyres/9AC19440-3D21-40BD-8234-16B1E05623D5/0/16591507_v3_RegulationAPrinciplesfortheelectricitymarketdoc.pdf. Access in July 2010

Appendix 1 - Glossary

Ancillary Services

Ancillary Services are Interconnected Operations Services identified as necessary to effect a transfer of electricity between purchasing and selling entities and which a provider of Transmission services must include in an open access transmission tariff.

Availability

Availability is a measure of time during which a generating unit, transmission line, ancillary service or another facility is capable of providing service, whether or not it actually is in service.

Balance responsible player (BRP)

A player approved by and party to an agreement with Ener-ginet.dk regarding balance responsibility. The player is financially liable for discrepancies between the submitted notifications and schedules and the actual consumption/production. A BRP can be balance responsible for production, consumption and/or trade.

Balancing market

Deviations from submitted notifications and schedules attributable to BRPs cause imbalances in the entire electricity sys-tem. The transmission system operator maintains balance by buying regulating power. The costs of buying regulating power are distributed among the BRPs relative to their individual purchase or sale of balancing power. The term "balancing market" stands for the purchase of regulating power as well as the purchase/sale of balancing power.

Balancing power

Imbalances incurred by a BRP are covered by buying from or selling to the BRP. Energy traded in this way is called balancing power.

Capacity

Capacity is the rated continuous load-carrying ability of generation, transmission, or other electrical equipment, expressed in megawatts (MW) for Active power or megavolt-amperes (MVA) for Apparent Power.

Congestion (bottleneck)

Transfer constraint in the electricity grid. The transmission system operator is committed to preventing transactions that may lead to overload or may otherwise jeopardize operational reliability.

Contingency

Contingency is the unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, switch, or other electrical element. A CONTINGENCY also may include multiple components, which are related by situations leading to simultaneous component outages.

Demand {Consumption}

Demand is the rate at which electric power is delivered to or by a system or part of a system, generally expressed in kilowatts (kW) or megawatts (MW), at a given instant or averaged over any designated interval of time. “Demand” should not be confused with “Load”.

Downward regulation

In case of surplus energy in the system, the transmission system operator neutralizes the surplus by activating bids for downward regulation on the regulating power market. As a consequence, the player will reduce his production or in-crease his consumption and buy the equivalent volume from the transmission system operator.

Load

Load means an end-use device or customer that receives power from the electric system. Load should not be confused with Demand, which is the measure of power that a load receives or requires. Load is often wrongly used as a synonym for Demand

N-1 Criterion

The N-1 Criterion is a rule according to which elements remaining in operation after failure of a single network element (such as transmission line / transformer or generating unit) must be capable of accommodating the change of flows in the network caused by that single failure.

Regulating power market

To maintain balance in the delivery hour the transmission system operator buys upward or downward regulation re-serves on the regulating power market.

Reliability

Reliability describes the degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired. Reliability on the transmission level may be measured by the frequency, duration, and magnitude (or the probability) of adverse effects on the electric supply / transport / generation.

Reserve capacity market

The transmission system operator enters into agreements on reserve capacity to ensure that sufficient reserve capacity is available. Players concluding reserve capacity agreements receive an availability payment for offering capacity to the regulating power market.

System Frequency

System Frequency is the electric frequency of the system that can be measured in all network areas of the Synchronous Area under the assumption of a coherent value for the system in the time frame of seconds (with minor differences between different measurement locations only).

System price

The market price for electricity on the common Nordic market, without taking into consideration congestions in the grid.

Transmission System Operator (TSO)

A Transmission System Operator is a company that is responsible for operating, maintaining and developing the transmission system for a Control Area and its Interconnections.

Upward regulation

In case of a deficit of energy in the system, the transmission system operator neutralizes the deficit by activating bids for upward regulation on the regulating power market. As a consequence, the player will increase his production or reduce his consumption and sell the equivalent volume to the transmission system operator.

Appendix 2 - "Probabilistic Evaluation of reserve requirements of generating systems with renewable power sources: the Portuguese and Spanish cases" Article

PROBABILISTIC EVALUATION OF RESERVE REQUIREMENTS OF GENERATING SYSTEMS WITH RENEWABLE POWER SOURCES: THE PORTUGUESE AND SPANISH CASES

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Abstract — **This paper presents an application of probabilistic methodologies to evaluate the reserve requirements of generating systems with large amounts of renewable energy sources. The idea is to investigate the behavior of reliability indices, including those from the well-being analysis, when the major portion of the renewable sources comes from the wind power. Renewable in this work mainly comprises hydroelectric, mini-hydroelectric and wind power sources. Case studies on configurations of the Portuguese and Spanish generating systems are presented and discussed.**

Index Terms: **Power system reliability, Generating system adequacy, Operating reserve, Monte Carlo simulation, Renewable energy sources.**

I. INTRODUCTION

THE increased use of electricity produced from renewable energy sources constitutes an important part of the package of measures needed to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Renewable energy source is defined as any energy resource naturally regenerated over a short time scale that is derived directly from the sun (such as solar thermal and photovoltaic), indirectly from the sun (such as wind, hydropower and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and ocean energy) [1]. Renewable energies can play a major role in tackling the twin challenge of energy security and global warming because they are not depletable and produce less greenhouse-gas emissions than fossil fuels. The promotion of this type of electricity has a high priority in many countries, in particular, in the European Union.

In the last few years, several discussions among European governments and associations have been carried, and in March 2007, Europe's Heads of States agreed to a binding target of 20% renewable energy by 2020 [2], [3]. This decision gives a strong signal for Europe's future energy policy as well as for the further expansion of the European renewable energy industry, which includes the development of new ways of operating and planning power systems.

While contributions from renewable energy sources for electricity production is small, with the exception of hydro, their market penetration is growing at a much faster rate than any other conventional source. Although there are still many potential hydro sites in the world, severe restriction based mainly on environmental aspects have limited their exploitation.

Wind has become a popular source of *green* electricity around the world [4]. At the end of 2005, the worldwide capacity of wind-powered generators was 59 GW; in Spain, about 10GW of installed capacity has produced more than 8% of its total energy needs, and in Portugal, about 1GW of installed capacity has produced almost 4% of its needs. At the end of 2006, the global capacity of wind-powered generators reached almost 74GW; Spain and Portugal have the second and nineth largest installed capacity in the world.

The previous values put system operators and planners under a huge pressure to come up with solutions bearing in mind these new technologies. The main reason is that the number of random variables and system complexities greatly increase, when renewable energy sources are added to the system, due to the *fluctuating* capacity levels of these sources. New computational models and tools have to be developed to deal with these new *variables*, particularly those related with wind power. A huge number of technical works have recently been published in this area: see, for instance [5]-[12].

From the planning point of view, deterministic based approaches have very attractive characteristics such as simple implementation, easy understanding, assessment and judgment by planners in relation to severe conditions like network outages and system peak load. Unfortunately, the perception of many planning engineers that past experience in addition to some known critical situations is enough to assess system risk conditions is not valid. In addition, past experience with renewable sources like wind power is very limited. However, the principles of some deterministic standards (e.g. "N-1" criterion) must be recognized as attractive.

Conversely, methodologies based on probability concepts can be extremely useful in assessing the performance of power systems [13]. They have been successfully applied to many areas including generation and transmission capacity planning, operating reserve assessment, distribution systems, etc. The proper measure of risk can only be achieved by recognizing the probabilistic nature of power system parameters.

A new framework, named *system well-being analysis* [14]-[16], has been built combining the deterministic perception with probability concepts. This new framework reduces the gap between deterministic and probabilistic approaches by providing the ability to measure the *degree of success* of any operating system state. In a well-being analysis, success states are further split into *healthy* and *marginal* states, using the previously mentioned engineers' perception as the criterion. Well-being analysis has been applied in the last decade to areas such as generating systems, operating reserve assessment, and composite generation and transmission systems. Chronological or sequential Monte Carlo simulation has been used for generating system well-being analysis, considering the loss of the largest available unit in the system as the deterministic criterion. These concepts can be extremely useful for dimensioning the reserve capacities considering renewable resources [17]-[24].

This paper presents an application of chronological Monte Carlo simulation (MCS) to evaluate the reserve requirements of generating systems, considering renewable energy sources. The idea is to study the behavior of reliability indices (conventional and well-being), when a major portion of the energy sources is renewable. Renewable comprises mainly hydro, wind, mini-hydro power sources, although other sources such as solar are present in much lesser amounts.

Case studies with the Portuguese and Spanish generating systems are presented and discussed. The work was developed in the framework of a RTD project financed by the TSO of Portugal and Spain (REN and REE, respectively) within their activities related to MIBEL (the Iberian electricity market), with the aim of maximizing the integration of renewable energy.

II. PROPOSED METHODOLOGY

The estimates of reliability indices are based on two distinct representations: state space and chronological modeling. State enumeration and non-sequential MCS methods are examples of state space based algorithms, where Markov models are usually used for both equipment and load state transitions. Therefore, states are selected and evaluated without considering any time connection. Conversely, sequential simulation can perceive all chronological aspects and, hence, it is able to correctly represent equipment aging process, time varying loads, spatial and time correlation aspects, etc. Chronological modeling, however, implies that two consecutive state samples differ from each other on only one state component and so, it requires considerably more computational effort. A method named pseudo-chronological MCS has also been proposed [25], which preserves the efficiency of the non-sequential MCS and the modeling ability of the chronological simulation.

Chronological MCS is very suitable due to its flexibility, as it allows the representation of non-exponential residence times, useful when dealing with chronological processes. Moreover, as dealing with renewable energy sources and their natural uncertainties, due to hydrologic inflow sequences, wind speed variations etc., chronological MCS seems to be the most effective way to adequately model and solve these difficulties.

A. Chronological Monte Carlo Simulation

The operation history of system states, for a simulation period T, is based on stochastic models of the components and on the load model. The initial operating state is sampled from the probability distributions of the generating equipment. After evaluating each state, performance indices are estimated using test-functions G(t):

$$E(G) = \frac{1}{T}\int_0^T G(t)dt \ . \qquad (1)$$

Each performance index can be estimated using a suitable test-function. The failure probability, for instance, corresponds to the expected value of an indicator function where G(t)=1 if the system associated with time t is a failure state; otherwise G(t)=0. Another way of estimating the expected value of G(t) is shown as follows:

$$\tilde{E}(G) = \frac{1}{NY}\sum_{k=1}^{NY} G(y_k) \qquad (2)$$

where NY is the no. of simulated years and y_k is a sequence of system states in year k. For instance, the energy not supplied will be the summation of unsupplied energy associated with each interruption of a simulated year. The uncertainty around the estimated indices is given by the variance of the estimator:

$$V(\tilde{E}(G)) = \frac{V(G)}{NY} \qquad (3)$$

where V(G) is the variance of the test-function. The convergence of the simulation process is tested using the *coefficient of variation* β [25].

$$\beta = \sqrt{V(\tilde{E}[G])} \Big/ \tilde{E}[G] \ . \qquad (4)$$

1) Modeling of Thermal Units

A two-state Markov model is used for modeling the up/down cycle of all thermal generating units. They are specified through their failure (λ) and repair (μ) rates. Clearly, any non-Markovian model could be used if the necessary parameters are available. Fig. 1a shows the well known two-state Markov model [13]. The generating capacity of the thermal units are fixed and pre-specified.

2) Modeling of Hydroelectric Units

The capacities of the hydro units will be defined for each month, according to the corresponding hydrological series. These series are defined for each hydraulic basin based on historical data and aim at capturing the historical inflows, reservoir volumes and type of operation. Mathematical polynomials convert the monthly storage volume of each reservoir into available power capacity for the month. In the case of hydro power plants with pumping capacity, some additional evaluations are carried out. Historical yearly series of volumes per power plant and per month have to be provided.

3) Modeling of Wind Units

Usually, in a wind power site, there are several generating units and they will be grouped into an equivalent multi-state Markov model, as shown in Fig. 1b. Only two stochastic parameters are necessary: unit failure and repair rates. Parameter N represents the number of generating units of the wind farm. If C is the unit capacity, the amount of power associated with the k^{th} state is given by $C_k = (N\text{-}k)\times C$, $k=0,\ldots,N$. The cumulative probability P_k (from 0 to k) associated with this state can be easily calculated. In order to reduce the number of these states during the chronological MCS, a simple truncation process sets the desired order of accuracy. Therefore, instead of $N+1$ states, a much smaller number up to the capacity C_L will limit this model; e.g. $1\text{-}P_L \leq$ tolerance.

The productions of the wind generating units will be defined for each hour, according to the hourly wind series for each geographic region. The wind series try to capture the wind speed and power conversion characteristics. Historical yearly series of per unit capacity fluctuations per hour have to be provided.

4) Modeling of Mini-Hydro

Mini-hydro units are modeled similarly to the hydro generating units from the hydrological point of view, but they are grouped into multi-state units of Fig. 1b to simplify the modeling processing. Due to the lack of specific data in relation to the hydrological basin where they are located, an equivalent reservoir is used to model the capacity variations with time. Obviously, if specific data are available, they can be properly considered.

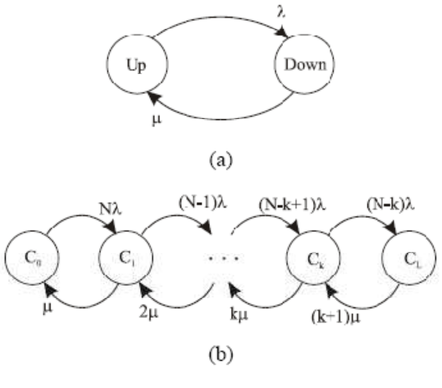

Figure 1: (a) Two-state; (b) Multi-states Markov models.

One has always to balance the benefits in terms of accuracy and the cost in terms of computing effort and levels of model detail.

5) Modeling of Co-Generation

Co-generating units are modeled similarly to the thermal units, but like in the previous case, they are clustered as well by using multi-state units of Fig. 1b.

Moreover an hourly utilization factor is specified, which models the actual co-generation power used by the system. This factor varies during the year following the tariff attractiveness and/or the industry production cycle

6) Maintenance Aspects

A certain amount of power generation will be specified per month in order to capture the maintenance activities along the year. In order to deal with that, the proposed chronological MCS algorithm, according to the generating power on maintenance, adequately increases the hourly load curve. This simplified model is particularly useful for planning purposes, since it is difficult to accurately specify the exact period for generating unit maintenance activities. For some nuclear power generators, due to its peculiarities, it is possible to detail this period and the chronological simulation should account for that.

7) Load Characteristics

A standard chronological load model containing 8760 levels, corresponding to each hour, is used. The chronological MCS will sequentially follow these load steps during the simulation process. Two uncertainty levels, representing short and long-term load forecasting deviations can be simulated through the MCS process. Gaussian or any other distribution can be used.

B. Conventional Reliability Indices

The conventional reliability indices are: LOLP = loss of load probability; LOLE = loss of load expectation; EPNS = expected power not supplied; EENS = expected energy not supplied; LOLF = loss of load frequency; LOLD = loss of load duration; LOLC = loss of load cost [13], [20], [24] and [25].

C. Well-being Indices

The well-being indices are [14]-[16] and [24]: E_H = expected healthy hours, which is the expected number of hours in a period (e.g. year) the system will stay in healthy states; E_M = expected marginal hours, which is the expected number of hours in a period (e.g. year) the system will stay in marginal states; F_H and F_M = expected frequency associated with healthy and marginal states, respectively; D_H and D_M = expected duration of system residing in healthy and marginal states, respectively. The deterministic criterion used to differentiate between healthy and marginal states may be the specified value for the secondary reserve, but the loss of the largest available unit in the system can also be used.

D. Operating Reserve Assessment

All previous risk indices are based on the following power balance equation:

$$G - L < 0 \tag{5}$$

where G represents the system available generation and L is the total system load. The random variable G depends on the equipment availabilities and on the capacity *fluctuations* due to, for instance, hydrology and wind variations, etc. The random variable L depends on the short and long-term uncertainties and also on the hourly variations.

In order to assess the performance of the operating reserve, new variables have to be defined as shown in Fig. 2. In this work, the primary (or regulation) and secondary (or spinning) reserves are pre-defined values. Obviously, the spinning reserve amount can always be redefined, in case its associated performance is below a pre-established acceptable value. The tertiary reserve (non-spinning) is composed by those generators that can be synchronized within 1 hour. This reserve is the most relevant in the present study.

The following power balance equation is set to assess the risk indices associated with the operating reserve:

$$R_{OPE} = R_S + R_T < \Delta L + \Delta P_W + \Delta G \tag{6}$$

where ΔL represents the short term load deviation at hour "t"; ΔP_W represents the possible wind power capacity variation at hour "t"; and ΔG represents the generating capacity variation due to forced outages at hour "t". From Fig. 2, one can observe an extra amount of capacity at the top of the tertiary reserve. This is due to the discrete effect of unit generating capacities.

Equation (6) describes the risk of changes in the load, wind power capacity and generating outages not being duly covered by the amount of spinning reserve, and also by those generators that can be synchronized within 1 hour. Therefore, the same traditional and well-being indices can be evaluated with this risk equation.

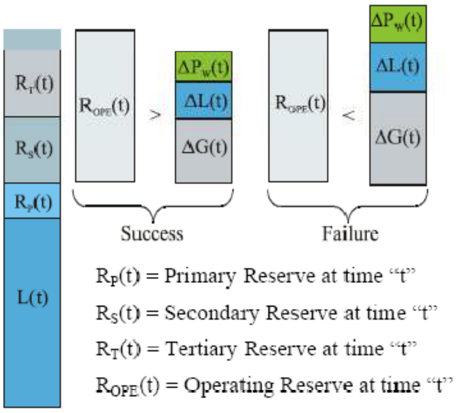

Figure 2: Operating reserve assessment.

Although there are many reference values for LOLP or LOLE indices (in capacity analysis studies), within the framework of generation planning, there are no reference values for the well-being indices nor for the operating reserve proposed framework.

E. Computational Program Characteristics

The implementation of the previous models is carried out through a Fortran (calculation mode) and VBasic (user interactive mode) algorithm. The convergence process is tracked through a coefficient of variation specified for the EENS index. Usually, once ensuring the convergence of EENS index, the others will have converged as well. The probability distributions of all, conventional and well-being, reliability indices are also evaluated.

III. APPLICATION RESULTS

The proposed algorithm has been tested under several conditions with different systems. A case using the Portuguese and Spanish Generating System (PGS and SGS, respectively) will be discussed as follows. The case will show the results using the PGS and SGS configurations for the year 2005. The idea is to evaluate these configurations to establish certain reliability parameters or standards for the years to come. Further studies will address *potential* configurations for the years 2010-2020.

A. Portuguese and Spanish Systems

For the year 2005, the PGS had 1035 units with a total installed capacity of 12.59 GW, distributed as follows: 4.38 GW (Hydro); 5.43 GW (Thermal); 0.98 GW (Wind); 0.34 GW (Mini-hydro); and 1.46 GW (Co-generation). The annual peak load occurred in January and it was approximately 8.53 GW. Also, the amount of renewable power in the system is 45% of the total capacity.

For the year 2005, the SGS had 8150 units with a total installed capacity of 70.2 GW, distributed as follows: 15.17 GW (Hydro); 37.1 GW (Thermal); 9.54 GW (Wind); 0.79 GW (Mini-hydro); and 7.6 GW (Co-generation). The annual peak load occurred in January and it was approximately 43.14 GW. Also, the amount of renewable power in the system is 36% of the total capacity.

In 2005, there were 35 hydro power plants in Portugal and 174 in Spain. In this study, 6 hydrological basins in Portugal and also 6 in Spain were considered, and 16 years of monthly hydrological conditions were used (1990–2005). Figure 3 shows the hydro production variations (Dry, Average and Wet conditions) for Portugal. The driest year was 2005 for Portugal and 1992 for Spain, and the wettest year was 1996 for Portugal and 2003 for Spain. These monthly variations must be duly captured by the MCS-based reliability assessment proposed algorithm.

In 2005, there were 8 thermal power plants in Portugal and 74 in Spain (not including co-generation). About 655 wind-generating turbines (units) were in the PGS and 6365 in the SGS. Bearing in mind the wind series, Portugal was divided into 7 regions and Spain into 18 regions. In 2005, for the SGS, the day with the highest peak capacity was August 8th, and the day with the lowest peak capacity was April 8th. Figure 4 shows these two days, and also the average value of the annual wind series. In order to model the deviation ΔP_W in (6), it was assumed a forecasting error by persistence. The error was then estimated by comparing the wind power availability in subsequent hours.

The actual 2005 hourly load curves were used for both PGS and SGS. Uncertainty of the short-term forecasting (i.e. expression ΔL in Eq. 6) was simulated using a Gaussian distribution. Sensitivity analyses were preliminarily carried out to validate the distribution parameters used in Portugal and Spain.

Several other data involving mini-hydro and co-generation units, maintenance, etc. have also to be processed. These data are not shown or discussed in this paper due to the lack of space, but they represent relevant information and also sources of variations, which had to be carefully considered.

B. Results

The proposed MCS algorithm is being tested with several possible configurations of the PGS and SGS. The idea is to determine the required amount of system generating reserve capacity to ensure an adequate power supply, bearing in mind not only the uncertainties from the equipment availabilities, but also the uncertainties due to the renewable power sources capacity variations. This study is being carried out considering a horizon of 20 years (2005-2025). Different scenarios involving not only hydro and wind unfavorable conditions, but also co-generation usage and maintenance strategies are being analyzed.

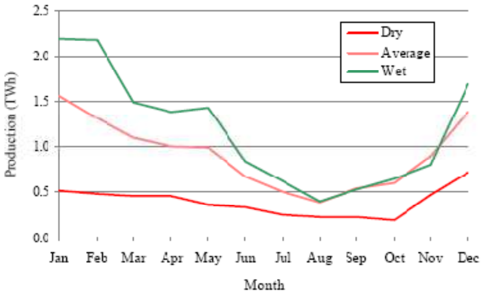

Figure 3: Hydro production, 1990-2005 (Portugal).

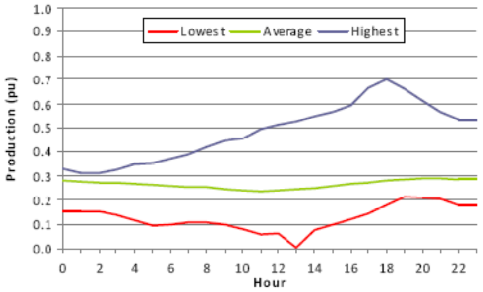

Figure 4: Wind power typical fluctuations, 2005 (Spain).

1) *Analysis for the 2005 Configuration*

In order to define reliability standards for the PGS and SGS, the *2005 Configuration* was used. Although several operating conditions or cases were tested, only some of them will be discussed. For the Base case, all historical hydrological and wind series were simulated with the *2005 Configuration* for both systems. In the H^+ case, the wettest hydrological year was considered, and in the H^- case, the driest hydrological was simulated. The HWM case considers that driest hydrological condition occurs simultaneously with all observed wind series having their capacities reduced by 50%. Also, the usual amount of power on maintenance was increased by 20%. Certainly, this is a very severe scenario.

Table 1 shows the traditional reliability indices for Portugal. As it can be seen from this table, the PGS configuration (2005) is extremely robust. As it could be expected, the worst condition occurs for "HWM", resulting in indices like: $LOLE_{CA}$ = 0.023 hours/year and the $LOLE_{OPE}$ = 0.032 hour/year. Under these "HWM" conditions, the performance can be considered perfectly acceptable.

Table 2 shows the well-being reliability indices, for Spain. One can provide the following interpretation for this system, if everything goes wrong (i.e. HWM case) with the 2005 configuration. Bearing in mind the capacity analysis, the SGS will stay, in average per year, 8754 hours in healthy states, 3.814 hours in marginal states, and 2.596 hours in risk states. Bearing in mind the operating reserve, the SGS will stay, in average, 8741 hours in a healthy state, 16.20 hours in a marginal state and 2.832 hours in risk states.

These are indeed very low values for that particular stressing scenario.

Case	LOLE (hours)	EENS (MWh/y)	LOLF (occ./y)	LOLD (hours)
Capacity Analysis				
Base	0.006	0.915	0.006	1.036
H^+	0.001	0.240	0.002	0.870
H^-	0.012	1.704	0.011	1.057
HWM	0.023	3.784	0.021	1.076
Operating Reserve				
Base	0.036	3.760	0.044	0.817
H^+	0.147	12.66	0.190	0.773
H^-	0.017	2.542	0.016	1.092
HWM	0.032	5.304	0.031	1.026

Table 1: Reliability indices – Portugal 2005.

Case	E_H (hours)	F_H (occ./y)	E_M (hours)	F_M (occ./y)
Capacity Analysis				
Base	8760	0.147	0.153	0.144
H^+	8760	0.000	0.001	0.000
H^-	8758	1.068	1.107	0.994
HWM	8754	3.568	3.814	3.455
Operating Reserve				
Base	8756	6.914	4.188	6.909
H^+	8758	1.914	1.169	1.917
H^-	8751	12.12	7.508	12.19
HWM	8741	24.68	16.20	24.60

Table 2: Well-being indices – Spain 2005.

It has to be pointed out that the "HWM" scenario impacts more on the Spanish system than on the Portuguese system, since the SGS depended much more on wind sources in 2005: 13.6% of the installed capacity in Spain, against 7.8% in Portugal. In conclusion, both systems had very robust composition for the year 2005. Moreover, the proposed simulation algorithm properly captured the performance of both capacity analysis and operating reserves.

The convergence criterion β was set to 5% in all tests for the EENS index, and a maximum of 3000 years were simulated. All simulations were carried out in a PC with 2.8GHz. The CPU time was, in average, 0.4 hours for the PGS and 7 hours for the SGS. These huge CPU times indicated that convergence was difficult, due to lack of risk states in the simulation, which means that both systems were extremely reliable.

2) *Analyses for Future Configurations*

Initially, some sensitivity analyses were carried out with the 2005 configurations, by increasing the peak load of both systems in order to measure the capacity slackness in these configurations. Figure 5 shows the results for the index LOLE associated with the capacity analysis of the SGS ($LOLE_{CA}$). Similar sensitivity tests were carried with the $LOLE_{OPE}$ indices.

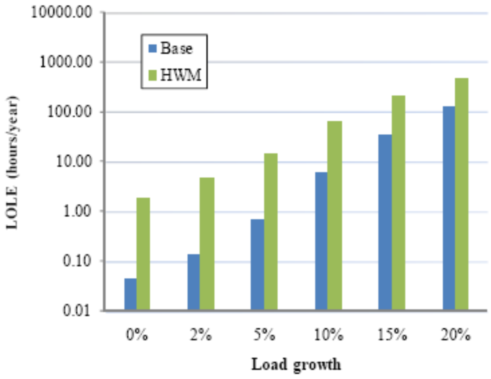

Figure 5: Sensitivity analyses – $LOLE_{CA}$ (hours/year)

In order to assess the risks associated with both capacity analysis and operating reserves in the period 2010-2025, the chronological MCS based algorithm is now being run for both the PGS and SGS.

IV. FINAL REMARKS

Renewable energy technologies will take a greater share of the electricity generation mix in order to minimize the dependence on oil and the emission of CO_2. While contributions from renewable energy sources for electricity production is small, with the exception of hydro, their market penetration is growing at a much faster rate than any other conventional source. More renewable power sources cause, however, an increase in the number of random variables and operation complexities in the system, due to the *fluctuating* production levels of these sources. Therefore, the determination of the required amount of system capacity (both capacity analysis and operating reserves) to ensure an adequate supply becomes a very important aspect of generating capacity expansion analyses.

The dimensioning of operating reserve, spinning and non-spinning, plays an important role in systems with high penetration levels of renewable sources, mainly those from wind power, due to its natural volatility. Although there are many reference values for LOLE indices related with capacity analysis (e.g. 0.1 day/year [13], 10 hours/year [24]), there are no such standards for well-being indices or for operating reserves.

By testing recently operated generation arrangements, one can provide some preliminary values for the establishment of future standards. However, most generating systems, including the Portuguese and Spanish, have today a smaller amount of *fluctuating* capacity sources, like wind power, than they will have in the future; even considering that Spain has the second largest wind power capacity installed in the world.

Discussions on innovative criteria (e.g. the system has simultaneously to survive the worst hydrological and wind conditions), operation strategies and assessment tools will be the new insights of generating capacity expansion planning considering renewable power sources for the years to come.

REFERENCES

[1] EREC – European Renewable Energy Council, "EREC's Position on the framework directive for renewable energy sources", 1/10/2007, EREC website (access through: http://www.erec-renewables.org/fileadmin/erec_docs/ Documents/ Position_Papers/EREC_Position_Framework_Directive.pdf.

[2] Presidency Conclusions of the Brussels European Council (8/9 March 2007), Reference: DOC/07/1, Date: 09/03/2007, Europa website (access through: http://europa.eu/rapid/pressReleasesAction.do?reference=DOC/07/1.

[3] EU Commission Communication of 10 January 2007: "Renewable energy road map - renewable energies in the 21st century: building a more sustainable future", Europa website (through: http://europa.eu/scadplus/leg/en/lvb/l27065.htm).

[4] S. Rahman, "Green Power: What is it and where can we find it?", IEEE Power and Energy Magazine, Vol. 1, No. 1, pp. 30-37, Jan./Feb. 2003.

[5] N. Hatziargyriou and A. Zervos, "Wind power development in Europe", *Proceedings of the IEEE*, Vol. 89, No. 12, pp. 1765-1782, Dec. 2001.

[6] R. Ramakumar, J.G. Slootweg, L. Wozniak, "Guest Editorial: Introduction to the special issue on wind power", *IEEE Trans. on Energy Conversion*, Vol. 22, No. 1, pp. 1-3, Mar. 2007.

[7] L. Söder, L. Hofmann, A. Orths, H. Holttinen, Y. Wan and A. Tuohy, "Experience from wind integration in some high penetration areas", *IEEE Trans. on Energy Conversion*, Vol. 22, No. 1, pp. 4-12, Mar. 2007.

[8] B.C. Ummels, M. Gibescu, E. Pelgrum, W.L. Kling and A.J. Brand, "Impacts of wind power on thermal generation unit commitment and dispatch", *IEEE Trans. on Energy Conv.*, Vol. 22, No. 1, pp. 44-51, Mar. 2007.

[9] G. Strbac, A. Shakoor, M. Black, D. Pudjianto and T. Bopp, "Impact of wind generation on the operation and development of the UK electricity systems", *Electric Power Systems Research*, Vol. 77, No. 9, pp. 1214-1227, July 2007.

[10] M. O'Malley and J.J. Sanches-Gasca, "Guest Editorial: Special section on wind energy", *IEEE Trans. on Power Systems*, Vol. 22, No. 3, pp. 899, Aug. 2007.

[11] R.G. Almeida and J.A. Pecas Lopes, "Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation", *IEEE Trans. on Power Systems*, Vol. 22, No. 3, pp. 944-950, Aug. 2007.

[12] P. Sørensen, N.A. Cutululis, A. Vigueras-Rodriguez, L.E. Jensen, J. Hjerrild, M.H. Donovan and H. Madsen, "Power fluctuations from large wind farms", *IEEE Trans. on Power Systems*, Vol. 22, No. 3, pp. 958-965, Aug. 2007.

[13] R. Billinton and R.N. Allan, "*Reliability Evaluation of Power Systems*", Plenum Press, New York, 1996.

[14] R. Billinton and M. Fotuhi-Firuzabad, "A basic framework for generating system operating health analysis", *IEEE Trans. on Power Systems*, Vol.9, No. 3, pp.1610-1617, Aug. 1994.

[15] R. Billinton and R. Karki, "Application of Monte Carlo simulation to generating system well-being analysis", *IEEE Trans. on PWRS*, Vol. 14, No. 3, pp. 1172-1177, Aug. 1999.

[16] A.M. Leite da Silva, L.C. Resende, L.A.F. Manso and R. Billinton, "Well-being analysis for composite generation and transmission systems", *IEEE Trans. on Power Systems*, vol. 19, no. 4, pp. 1763-1770, Nov. 2004.

[17] X. Wang, H. Dai and R.J. Thomas, "Reliability modeling of large wind farms and electric utility interface systems", *IEEE Trans. on PAS*, Vol. 103, No. 3, pp. 569-575, Mar. 1984.

[18] C. Singh and A.L. Gonzalez, "Reliability modeling of generation systems including unconventional energy sources", *IEEE Trans. on PAS*, Vol. 104, No. 5, pp. 1049-1056, May 1985.

[19] G. Desrochers and M. Blanchard, "A Monte Carlo simulation for the economical assessment of the contribution of wind energy to power systems", *IEEE Trans. on Energy Conv.*, Vol. 1, No.4, pp. 50-56, 1986.

[20] A.M. Leite da Silva, A.C.G. Melo and S.H.F. Cunha, "Frequency and duration method for reliability evaluation of large-scale hydrothermal generating systems", *IEE Proc.-C*, Vol.138, No.1, pp.94-102, Jan. 1991.

[21] R. Billinton and A.A. Chowdhury, "Incorporating of wind energy conversion systems in conventional generating capacity adequacy assessment", *IEE Proc.-C*, Vol. 139, No. 1, pp. 45-56, Jan. 1992.

[22] R. Billinton, H. Chen and R. Ghajar, "A sequential simulation technique for adequacy evaluation of generating systems including wind energy", *IEEE Trans. on Energy Conv.*, Vol. 11, No. 4, pp. 728-734, 1996.

[23] F.C. Sayas and R.N. Allan, "Generation availability assessment of wind farms", *IEE Proc.-C*, Vol. 143, No. 5, pp. 507-518, Sept. 1996.

[24] A.M. Leite da Silva, L.A.F. Manso, W.S. Sales, L.C. Resende, M.J.Q. Aguiar, M.A. Matos, J.A. Peças Lopes and V. Miranda, "Application of Monte Carlo Simulation to Generating System Well-Being Analysis Considering Renewable Sources, *European Transactions on Electrical Power*, Vol. 17, No. 4, pp. 387-400, Jul.-Aug. 2007.

[25] A.M. Leite da Silva, L.A.F. Manso, J.C.O. Mello, R. Billinton, "Pseudo-chronological simulation for composite reliability analysis with time varying loads", *IEEE Trans. on Power Systems*, Vol. 15, No. 1, pp. 73-80, Fev. 2000.