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Modelling Energy Systems
- A Study on Power System Reserves in South Africa

Master Thesis in Mathematical Modelling and Computation

DTU

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Preface

This thesis was prepared at the department of Management Engineering, the Technical University of Denmark in fulfilment of the requirements for acquiring an M.Sc. in Mathematical Modelling and Computation. The thesis was developed in cooperation with the Danish consulting company Ea Energy Analyses. Professor Jesper Larsen from Management Engineering, DTU and Lars Bregnbæk, Ea Energy Analyses has been supervisors for the thesis.

The thesis deals with the study of power system reserves in South Africa using mathematical modelling to represent imbalances and regulation.

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Abstract

An energy system refers to the complex world of generating heat and electricity and transmitting this to end consumers. Today, energy systems are constantly subjected to imbalances in form of e.g. fluctuations in electricity demand or failures on power plants.

In this thesis a study on reserves in the South African power system is performed. Reserves constitutes the possibilities of compensating for imbalances in the system by e.g. regulating generation or transmission of electricity. Mathematical modelling is used to formulate the reserves and these are implemented into the Balmorel model. The Balmorel model is a partial equilibrium model formulated in GAMS and is used to represent entire energy systems. The model is applied to the South African power system and this is used to analyse the implementation of reserves.

An analysis is performed on the imbalances of the South African power system in form of fluctuations in wind power generation and electricity demand along with forced outages, i.e. an unexpected loss of generation capacity due to failure on generation units. This is done to estimate the magnitude of imbalances needed to be compensated by reserves. The magnitude of the imbalances are calculated using a pragmatic approach to estimate forecast errors by simulations.

Additionally, a tool to generate forced outages is described and developed

in MATLAB. This tool is based on a two state Markov process and uses statistical distributions to simulate the occurrences of failure and repair times. Furthermore, the tool is also used to generate planned outages. The planned outages are time periods where generation units are shut down for service and maintenance.

The implementation of the reserves and the calculation of the imbalances were analysed by examining results from the Balmorel model. In order to guide this thesis research questions were defined and answered based on these results. The chosen methodology was proved competent to answer the research questions and yielded a reasonable estimate of the economic costs and effects of reserves in a power system.

The GAMS code of the Balmorel model used in this thesis is provided by Ea Energy Analyses and may not be copied for commercial use.

Finally, this thesis was written simultaneously with research on reserves performed by Ea Energy Analyses in relation to the research project ENSYMORA. Through this collaboration and knowledge sharing on the modelling of reserves has occurred.

Resumé

Et energisystem refererer til den komplekse verden af el- og varmeproduktion og transmission ud til forbrugere. Energisystemer er i dag konstant udsat for ubalancer, i form af fx udsving i el forbrug eller nedbrud på kraftværker.

I dette speciale er der udført en undersøgelse af reserver i det sydafrikanske elsystem. Reserver betegner mulighederne for at kompensere for ubalancer i systemet, ved fx at regulere produktion eller ved transmission af el. Matematisk modellering er brugt til at formulere reserver og disse er implementeret i Balmorel modellen. Balmorel modellen er en partiel ligevægtsmodel, formuleret i GAMS, og bruges til at repræsentere større energisystemer. Modellen er anvendt på det sydafrikanske elsystem og dette er brugt til at analysere implementeringen af reserver.

Der er foretaget en analyse af ubalancer i det sydafrikanske elsystem, i form af udsving i vindkraft og elforbrug samt nedbrug på produktionsanlæg, hvilket vil sige, et uventet tab af produktionskapacitet, grundet fejl på produktionsanlæg. Dette er gjort, for at vurdere størrelsesordenen af ubalancer, som skal opvejes af reserver. Størrelsesorden af disse ubalancer beregnes ved hjælp af en pragmatisk tilgang til at estimere prognosefejl ved hjælp af simuleringer.

Yderligere er et værktøj til at generere nedbrud på produktionsanlæg

beskrevet og udviklet i Matlab. Dette værktøj er baseret på Markovprocesser og anvender statistiske fordelinger, til at simulere forekomster af nedbrud og reparationstider. Derudover er værktøjet også brugt til at generere planlagte udetider. Planlagte udetider er perioder, hvor produktionsanlægget er lukket ned til service og vedligeholdelse.

Implementering af reserver og beregning af ubalancer, er analyseret ved at undersøge resultater fra Balmorel modellen. For at retlede dette speciale, er en række forskningsspørgsmål blev defineret og besvaret på grundlag af disse resultater. Metodevalget vidste sig at være brugbart til at besvare de opstillede forskningsspørgsmål, og var grundlag for et rimeligt estimat af de økonomiske omkostninger og effekter af reserver i et elsystem.

GAMS koden for Balmorel modellen, som anvendes i dette speciale er leveret af Ea Energianalyse A/S og må ikke kopieres til kommercielt brug.

Specialet er skrevet sideløbende med forskning af reservemodellering udført af Ea Energianalyse A/S, dette i forbindelse med forskningsprojektet ENSYMORA. Gennem denne proces, har der indtruffet samarbejde og videndeling om modellering af reserver.

Acknowledgements

I would like to thank my supervisors Jesper Larsen and Lars Bregnbæk, for guidance and support during the creation of this thesis. Furthermore, a thanks goes to all the employees at Ea Energy Analyses for their advice and support. Finally, a special thanks goes to my friends Anders Therkelsen for helping me by proofreading the thesis and Rasmus Elken for graphical assistance.

Contents

Chapter 1

Introduction

Since the dawn of Man the power to generate energy has always been subject to great fascination. Whether it be the discovery of fire in 770,000 B.C., the invention of the steam engine in the late 1700s or any number of technological advancements through time that constitutes the basis of modern day energy systems. But what is an energy system? Energy is usually defined as the ability to do work. This is an anthropocentric and utilitarian perspective of energy. However, it is a useful definition for engineering, where the aim of machines is to convert energy to work [16]. The term *Energy System* is used in many contexts e.g. biology or mechanical engineering and generally defines a closed system in which energy of some form is converted into movement. In this thesis an energy system denotes the large scale world of generating heat and electricity which, through transmission and distribution, can supply a consumer with the ability of turning on a light switch or radiator.

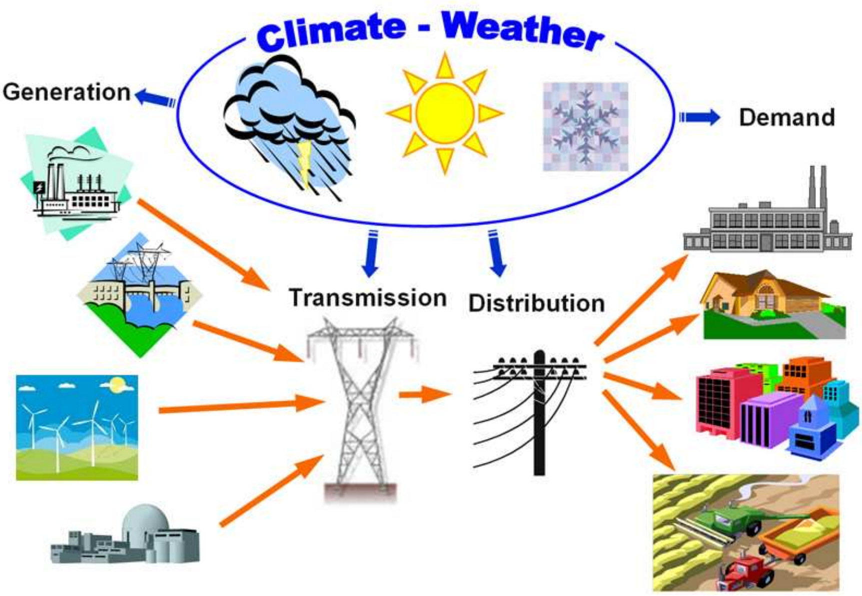

Figure 1.1: Illustration of a simple energy system. *Source:* [4]

Today energy systems are complex, intricate systems involving numerous stakeholders. The different technical solutions of generating heat and electricity combined with the many types of consumers, may it be private residents, public transportation or industrial sectors, create the need for an energy system providing an increasing level of performance. In recent years, the focus on the energy sector has been growing due to topics like scarcity of fossil fuels (e.g. coal or oil) and a heightened interest in the environment as a consequence of increasing emissions of greenhouse gases. This has not only meant an immense interest in innovation and development in renewable energy forms (e.g. wind and solar energy) but also in the governing of the existing energy systems. The complex nature of an energy system provides endless possibilities in every day operations. When should heat or electricity (power) be generated? Where should this be done? Which fuel type should be used? Where should it be transmitted? and so on. It is difficult to find the best possible solution without having some form of tool to govern these decisions.

1.1 Energy System Models

Energy system models play an important role in energy planning today. An increasing number of stakeholders in the energy sector rely on mathematical models to help govern daily generation of heat and power, predict future development, analyse economics, etc. In recent years mathematical modelling has proven an essential tool in decision making for the stakeholders as a consequence of e.g. increased focus on environmental policies. In order to ensure best possible results with regards to economics, certainty in energy supply or decisions in operational strategy, "business as usual" thinking has stepped aside giving more room for a quantitative approach. Many different types of mathematical models exists. Most designed to a rather specific and limited purpose like predicting electricity demand or forecasting wind generation while other models try to represent a broader perspective. Models like Balmorel [33], OptGen [29], EMPS [14] and ReEDS [28] constitutes a selection of rather complex models used to model energy systems of larger geographic areas on a detailed level.

When modelling energy systems there are many paths to consider. Representation of an energy system can take various forms. A model can be intuitive and rely on the past, thus letting history dictate a predicted way of the future. Forecasting broad terms like sustainable energy policies and fuel prices can be based on historical knowledge and the use of practical reasoning and very little mathematics. When predicting the future of energy systems this form of practical models was previously common in the world of energy analysis. People with years of experience in the energy sector were inclined to use "best guess" models when the need for future predictions arose. However, the potential of mathematics is vast when dealing with modelling energy systems. Topics like forecasting, time series analysis and operations research give way to an enormous amount of possibilities. The combination of theoretical mathematics and software programming is essential for stakeholders in energy analysis today[7].

The preferred tool in modelling energy systems is obviously dictated by the specific need. The combinations of mathematics and software are numerous whether the discipline be linear programming, econometrics, network modelling or statistical analysis. Thus, it is important to realize exactly what possibilities are present and how each option will fit a certain need. One of the more common choices in modelling entire energy systems is linear programming. The constraints and complexity of a whole system of generation units, transmission lines and end users fit well into linear programming representation. Furthermore, linear programming provides optimization rather than strictly arbitrary results as seen in some Microsoft Excel based models e.g. the *STREAM* model [31]. Often GAMS [22] or CPLEX [23] are used to represent the linear (or mixed integer) programming formulation. In a report made by *ATEsT* a collection of many of the tools and models used in energy analysis and energy planning in present day is described [5].

1.2 Purpose of the Thesis

The general field of this thesis is the modelling of an entire energy system. The representation of generation of heat and power and the continued supply to consumers are the driving forces in this thesis. Since large models of energy systems already exits, it was chosen to focus on a smaller part of modelling energy systems within an existing model. For this purpose the Balmorel model was chosen. The Balmorel model is a partial equilibrium model used on energy systems on a large geographical scale. A partial equilibrium model is used to represent a market in equilibrium considered in isolation from other product or input markets. The model uses GAMS to provide a LP or MIP formulation of the entire energy system and seeks an optimal solution of generation of heat and power (called *dispatch*) to satisfy energy demand while minimizing the socio-economic costs. A more thorough explanation of this as well as a description of the model can be found in chapter 4. The Balmorel model was chosen because of its relevance in energy analysis today being used in projects by renowned companies like Vestas or governments all across the world. Furthermore, the mathematical approach applied by the model creates an environment that welcomes individuals without extensive energy background to model energy systems.

In this thesis the Balmorel model will be the basis of modelling *reserves* in the South African power system. The model and data representing the South African power system is described in chapter 6. Reserves denote an amount of generation capacity that must be available in an energy system at all times, in order to help regulate imbalances in the system. These imbalances constitute the *reserve requirement* and are determined by:

- Wind power fluctuations
- Electricity demand fluctuations
- Forced outages
- Transmission outages
- Other renewable energy fluctuations (Solar power, hydro power etc.)

Wind power fluctuation denotes the variation from the forecast in wind power generation. The wind speeds might be faster than the forecast in the model predicts thus creating a surplus of power in the system. This surplus must be counteracted by a *downregulating reserve* i.e. an entity in the system that can reduce power generation to restore balance e.g. a power plant that shuts down. Conversely, if wind speed are lower than forecast predicts then an *upregulation reserve* must compensate for this deficit of electricity. This could be in form of increased generation on a unit. Electricity demand fluctuations are the variations from the forecast in electricity demand used in the model. If the electricity demand is higher than the forecast predicts then an upregulating reserve must react to this deficit. This might again be a power plant which increases generation or by an increase in electricity transmission from another region in the system. Forced outages denote the loss of generation units due to sudden failure leading to a sudden deficit in generation capacity. Transmission outages are the sudden loss of a transmission line (used to transmit electricity) due to failure. Reserves are very important to ensure that all consumers are provided with heat and electricity at all times, this is called *security of supply*. In a world, where renewable energy is becoming an increasing part of the total generation capacity, reserves are growing more important. Because of the fluctuations of solar and wind power a increased need of regulation exists to compensate for imbalances. Governing reserves is a rather difficult discipline. The economic consequence of committing too much capacity to regulate imbalances can be extensive but conversely too little can result in a breach in the security of supply.

In this thesis it is assumed that the imbalances are only represented by outages, fluctuations in wind power generation or from fluctuations in electricity demand. In reality transmission outages and fluctuations in solar and hydro power will also add imbalances to the system. These are however not included in this thesis since the chosen imbalances will be sufficient to represent the modelling of reserves as well as to limit the scope of this thesis. Each of the imbalances will be described and implemented into the Balmorel model and an analysis will be performed to demonstrate the effects of the imbalances. A version of the Balmorel model representing the South African power system will be used for this. Outages are the loss of generation capacity either by sudden failure, called *forced outages*, or planned service and maintenance of generation units, called *planned outages*. This is an important topic when dealing with reserves. Thus, a tool to simulate the forced and planned outages of generation units will be created.

Chapter 2

Methodology

In the following chapter the ideas for the approach and methodology to determine the reserves are presented as well as the questions and tools needed to perform an analysis. Each element of the imbalances forming the reserve requirements will be explained.

2.1 Reserves

The reserves are formed by fluctuations in wind power generation and electricity demand along with forced outages. As mentioned, each imbalance can contribute to either an up- or downregulating reserve. The reserves are viewed in separate geographical areas, thus it is possible to have a need for an upregulating reserve in one region while another has a need for downregulating reserves. The upregulating reserves denotes the combined opportunities to regulate a deficit in energy. These are defined as:

- Increase generation on already generating units
- Start up new units
- Unload from heat or electricity storages or reduce amount loaded into storages
- Transmission of electricity from another region

Conversely, the downregulating reserves are used to regulate a surplus of energy. These are defined as:

- Decrease generation on generating units or completely shut down
- Load into storages if storage capacity allows it
- Transmission of electricity to another region

Combined the up- and downregulating reserves must be available to regulate the imbalances that form the reserve requirement. In the following the contributions to the reserve requirement are described.

2.1.1 Wind

Due to the fluctuating nature of wind speeds, wind power generation has a high impact on the reserve requirement in an electricity system, where wind power capacity is significant. Especially in future energy systems, the imbalances from wind power generation will constitute an increasing contribution to the reserve requirement. In figure 2.1 the wind power generation in relation to total electricity demand can be seen for the Danish energy system to demonstrate the increase in wind power in recent years. Furthermore, most predictions on the future of energy dictates that generation on fossil fuels will be replaced with renewable energy like wind or solar power. According to a report made by *Klimakommissionen* wind power generation in Denmark will constitute 60-80% of electricity consumption in 2050 [24].

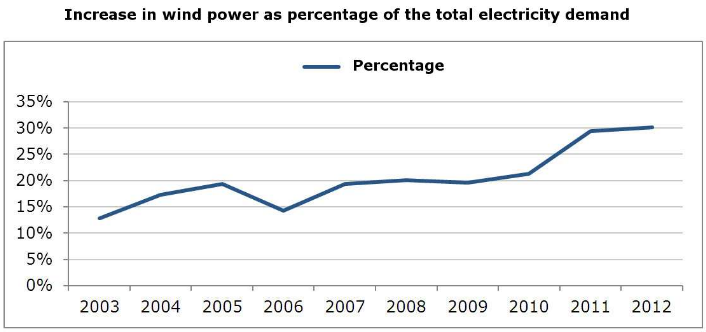

Figure 2.1: Wind power generation as percentage of total electricity demand in Denmark.

In the Balmorel model, electricity from wind power is determined by a variation profile for wind power generation and a number of *full load hours*. Full load hours are a convenient notion expressing the number of hours which multiplied with the installed capacity will give the generation during one year. It is used to define the maximum wind power generation in the model since a wind turbine can choose to shut down if a surplus of electricity in the system exists. This is called curtailment. Full load hours are given for an installed amount of wind power given in megawatt (MW) in a specific geographical area. This means that wind power generation is not modelled as a number of single wind turbines but as a combined group. In a given geographical area it is assumed that all wind turbines are the same and yields a total capacity with a related profile and full load hours. This can, if necessary, be divided into smaller areas if the need of modelling a variety of different wind turbine types in the same geographical area exist. The wind profiles used in the Balmorel model are found using historical measurements of wind speeds and consequently provide a realistic input to the model. Full load hours are calculated for a wind turbine type in an geographical area by using *power curves*. Power curves are used to describe the power output from a wind turbine at different wind speeds since the ratio between wind speeds as power output depends on the type of wind turbine. A study on this was performed by Ea Energy Analyses in the report "Paths towards a fossil-free energy supply" [13] and has provided a very good estimate for wind power generation in the Balmorel model.

The discipline of estimating wind power generation in a deterministic model is quite difficult. When providing a model with full information on hourly generation and asking the model to react accordingly this will typically lead to better results than the system will actually perform. There are many ways of addressing this problem and the task of modelling wind power generation is in itself a topic drawing large focus worldwide. A stochastic approach as e.g. used by the WILMAR model [35] will normally provide a more realistic result as the uncertainty of wind speeds will be taken into account. Much work is also done on predicting wind power generation using a probabilistic forecasting approach. For instance on DTU where wind power forecasting has become a research field of its own dealing with various topics like:

- Point forecasting of wind power (for horizons from few minutes to several days ahead)
- Spatio-temporal modelling of wind generation at the level of a region or a country (as well as the forecast uncertainty)
- Probabilistic forecasting of wind power (up to few days ahead): quantile forecasting, prediction intervals and density forecasts, or alternatively scenarios
- Skill forecasting, indicating the confidence to have in provided forecasts

Source: [10]

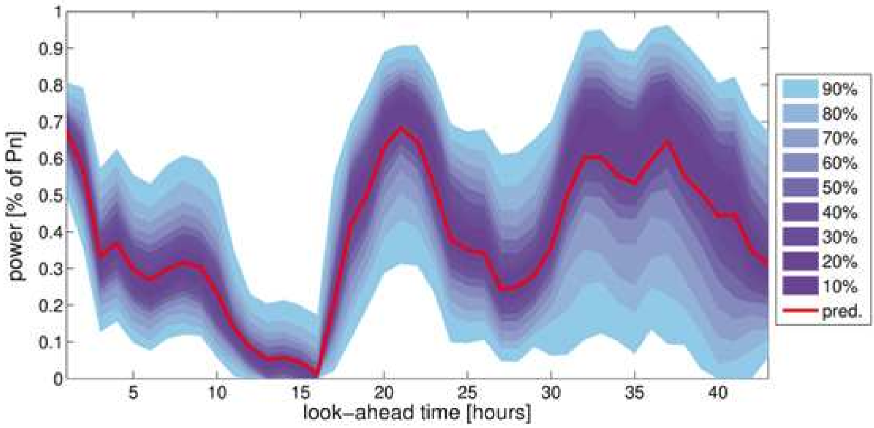

Figure 2.2: Forecasts of wind power generation from DTU forecast research. *Source: [10]*

As figure 2.2 shows the uncertainty of the prediction becomes large over a small period of time. Thus, the methods of forecasting wind power generation as researched by e.g. DTU could also be implemented in the Balmorel model. By running the model several times and forcing the model to stick to previous decisions on e.g. electricity generation on a number of units in relation to the wind power forecast, and then taking a step forward in time and running again using a new forecast could yield a more realistic and less optimistic result. This method is called rolling horizon rescheduling. An article describing rolling horizon rescheduling can be found in [20]. This type of solution will result in a vast number of model runs and will accordingly cause excessive run-times. Another way could be to include the uncertainties surrounding the prediction as seen in figure 2.2. However, this will start approaching stochastic programming and experience with the WILMAR model has shown that this can also result in large run-times. On that basis, it is concluded that the approach using historical data as a forecast for wind power generation is sufficient for this thesis and a complete analysis of forecasting wind power generation and related implementation will also be out of scope.

In regards to the calculation of the reserve requirements imbalances in wind power generation will produce both the need for an up- and downregulating reserve. At a given time the wind profile will determine a specific electricity output, ignoring curtailment for now, and to calculate the need for reserves at that time, one of three scenarios will occur in relation to the real actual wind speed. Assuming that generation output lies between 0 and maximum capacity, wind speeds will either be higher, lower or the same as predicted by the given wind profile. If wind speeds are higher (thus producing more electricity than forecast predicts) this will present a need for a downregulating reserve to regulate the surplus of electricity generated by wind power and conversely an upregulating reserve if wind speeds are lower. If the wind speed equals the prediction then no reserve is needed. Now, since it is impossible to predict the exact wind speed on a hourly basis (or less) for a long time period as seen in figure 2.2 this means that to calculate a realistic reserve requirement both up- and down regulation are always needed with some probability. Here two special cases exist. If the wind power generation is at a maximum then obviously no downregulation is needed since a higher wind speed than predicted will not result in higher generation output. This is a technological limit of wind turbines yielding an upper limit of wind power output. In the same way if wind power generation is 0 then no upregulating reserve is needed since negative wind speeds and negative wind power generation does not exist. Wind power generation can also be used as reserve capable of regulating other imbalances. Wind turbines can decrease generation or be shut down to be used as a downregulating reserve. Conversely, if curtailment is present meaning that wind turbines are generating less than wind speed actually allows then the turbines can increase generation to be used as an upregulating reserve.

2.1.2 Electricity Demand

The electricity demand is defined as the nett electricity need in a geographical area. This may be the need of a distribution center supplying private consumers or industrial need etc. In Balmorel the electricity demand is defined by an annual electricity demand in a region and a corresponding profile describing the hourly variation. The profiles are found using historical data from energy agencies such as Energinet.dk [15] or ENTSOE [18]. The prediction of the electricity demand is very dependent on temperature and, like wind speeds, very hard to predict over a long time period. Much work is done on forecasting electricity demand. Statistical approaches like multivariate regression as described in the article "Modelling Sector-Wise Demand For Electricity In Sri Lanka Using A Multivariate Regression Approach" [30] or forecasting on shorter time periods using univariate methods like an $ARMA$ model as seen in "A Comparison of Univariate Methods for Forecasting Electricity Demand Up to a Day Ahead" [32]. In the same way as described with wind power generation, these types of methods could be implemented using rolling horizon rescheduling. However, since results from the Balmorel model are normally analysed over a large time period the historical data will perform quite well and will yield a reasonable estimate for the variation in electricity demand. When using historical data as a forecast then it is important to be aware of the potential forecast errors. Work forecasting from the articles mentioned above showed a mean absolute percentage error (MAPE) around 1.5%, see figure 2.3. Obviously, using a historical variation profile as a forecast for the model can not be directly compared to forecast methods as described in [30] or [32]. However, as seen in figure 2.3 the MAPE seems to stabilize over large time periods. On this basis it is concluded that it will be reasonable to use a historical profile as a forecast with the knowledge of a possible forecast error.

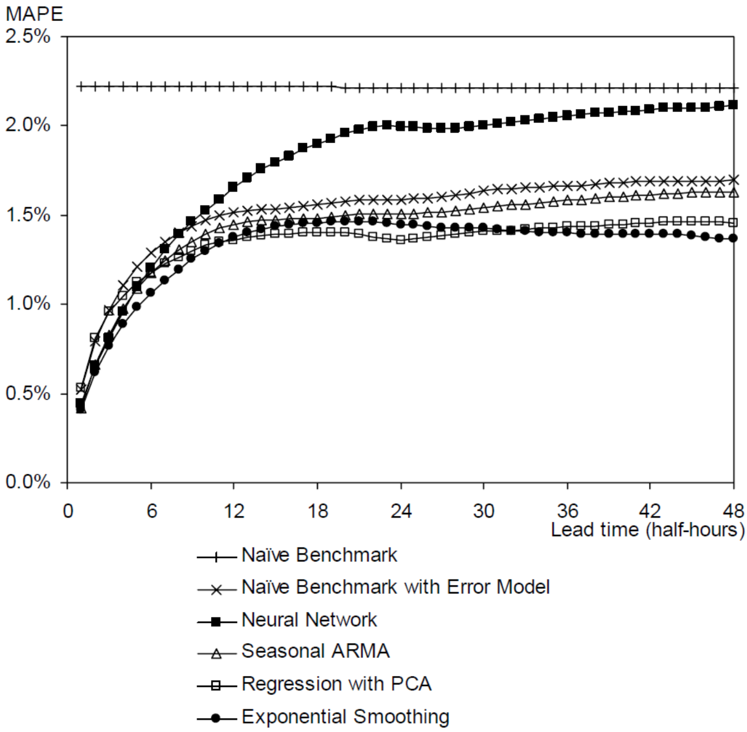

Figure 2.3: Forecast errors of electricity demand over time using univariate methods. *Source: [32] p.27*

When calculating the reserve requirements from electricity demand, the uncertainty of the prediction will create the need for both up- and downregulating reserves. The need of electricity in an area could be greater than predicted and thus produce a need for a upregulating reserve and conversely lower demand will result in the need for a downregulating reserve.

2.1.3 Outages

Outages are defined as a loss in generation capacity and are divided into two parts: *Forced outages* and *Planned outages*. Forced outages are the unforeseen sudden loss of generation capacity on a unit due to failure. Typically a mechanical issue of some sort leading to a halt in generation. The variety of problems for e.g. a coal power plant is extensive due to mechanical complexity of the unit. Planned outages represents a known loss of capacity due to service and maintenance at a planned time interval. In a modelling perspective is it assumed that only the forced outages will have an impact on the reserves. The planned outages are implemented as a known quantity of available generation capacity and will thus not be subject to uncertainty. Obviously, the forced outages will present a negative effect on available generation capacity, thus only the need for a upregulating reserve exists when a unit suddenly fails. No downregulating reserve is needed since no unit will suddenly start generating by mistake.

To determine the reserve requirement from outages a statistical approach must be chosen. A given unit will fail with some probability depending on the type of unit. This is often given as a Forced Outage Rate (FOR). A way of modelling the forced outages is discussed in chapter 3. Here a tool to produce an outage profile for a unit is described. The profiles for the different units will be independent from each other and the profiles will be an important asset in the modelling of reserves.

In chapter 5 the ways of calculating and estimating the magnitude of the imbalances are described. The mathematical approach chosen in order to produce a reserve requirement to the Balmorel is presented along with a representation of the actual modelling of the reserves.

2.2 Method

In this section the method of analysing the reserve requirement is described. Furthermore, the tools used to analyse each imbalance in a economic context are described as well as how to analyse the effects of the reserves in a modelling perspective.

The main analysis in this thesis will be based on Balmorel model runs, showing the impact of the imbalances on the behaviour of the energy system. Additionally, the impact of each separate reserve requirement, and the effects on the need for reserves will be shown. In order to clarify the analysis performed in this thesis a number of research questions are presented along with a solution methodology. These are presented in table 2.1. Firstly the model runs needed to form the methodology i.e. the needed circumstances to be able to answer the research questions are shown. In order to investigate the impact of each imbalance model runs both with and without reserve requirements are performed. Performing model runs with reserve requirements from each imbalance will provide a way of establishing the actual cost/benefits separately.

- R1: Basis model run without reserves requirements
- R2: Model run with total reserve requirement
- R3: Model run without wind power imbalances
- R4: Model run without electricity demand imbalances
- R5: Model run without forced outage imbalances

These model runs will generate results used to answer the research questions stated below. The analysis performed in this thesis will primarily focus on economic results i.e. system operation costs. The tools or result criteria needed for this are also presented below.

Research Questions	**Methodology**
What are the cost and effects of introducing reserves?	R2-R1: Comparing the cost of R2 and R1, the cost of reserves can be calculated.
What are the cost and effects of introducing imbalances from wind power generation?	R3-R2: Comparing the cost of R2 and R3.
What are the cost and effects of introducing imbalances from electricity demand?	R4-R2: Comparing the cost of R2 and R4.
What are the cost and effects of introducing imbalances for forced outages?	R5-R2: Comparing the cost of R2 and R5.

Table 2.1: Research questions and Methodology.

These questions are chosen to motivate the purpose of this thesis. In order to answer these questions a mathematical formulation of reserves must be made along with an implementation in the Balmorel model. Furthermore, the reserve requirement must be calculated. The research questions provide a perspective on how to analyse reserves in a energy system and why this is important.

The total system cost will be calculated for each model run. The total system cost are perceived in a socio-economic context meaning that these are the total combined cost from all generation, transmission, taxes etc. determined by the solution found in the model run. When minimizing socio-economic costs then the costs of the system are perceived as a whole and consequently the model will seek to find a solution that creates the most economical result for "all". Here "all" is a combination of every stakeholder represented in the model: Power companies, transmission agencies, government (tax collectors), consumers. In reality different stakeholders are separately liable for individual costs and will try to optimize own economic gain. However, this approach will in general provide the most economical solution to the end consumer by minimizing all combined costs. To analyse the total system costs the following attributes are utilized:

- Variable Operation and Maintenance (O&M) costs
- Fixed O&M costs
- Fuel costs
- Emission costs
- Start-up costs

The variable O&M costs are the operating cost on a generation unit (Power plant, gas turbine etc.) per unit of energy generated. Fixed O&M costs are included regardless of the energy generated and are annual costs of having a unit installed. Fuel costs are the costs of fuel used to generate energy, coal on a power plant, natural gas on a gas turbine etc. Fuel costs are normally paid per gigajoule (GJ). Emission costs are the taxes (or penalties) paid for producing greenhouse gases (CO_2, SO_2, N_2O, etc.) which is commonly a side effect of generating energy using fossil fuel. Start-up costs are the costs of bringing a unit "on-line". When e.g. large power plants starts up from being turned off or inactive the costs of starting generation can be rather significant. It can sometimes be a more economical decision to remain active and generate at minimal capacity even though the system has no need for the energy rather than shutting completely down and having to restart later on. When introducing the imbalances of the reserve requirement these can create unrealistic results where a unit constantly turns on and off if the start-up costs are not regarded in the model.

These attributes will determine the economic effects and help analyse the crucial financial pit falls when implementing reserves and running the model. Providing economic tables along with graphical representation of e.g. generation on significant units at certain times will form the most important tools for analysing the effects of the reserve requirements in the model.

Chapter 3

Outages

When planning the dispatch of heat and electricity many uncertainties comes into play. Uncertainties from nature like wind speed and temperature have great influence on the wind power generation, heat demand and thus also electricity demand since heat and electricity generation is strongly correlated. However, another important factor in energy planning is of course available generation capacity, i.e. the subset of units ready to generate at a given time. When a unit is unavailable for generation it is assumed that this is caused by one of two things: *Forced outages* or *Planned outages*, other reasons like fuel shortages, strikes or natural disasters are disregarded in this thesis. Forced outages describes the unanticipated failure of a unit. This is when a unit for some reason is unavailable for generation. The cause for this breakdown is often of technical nature but can be the result of various failures. Planned outages describes a scheduled time period where a unit is unavailable due to repairs, alterations or upgrades to the unit. Planned outages play an important role in almost all generation contexts. Planned service and maintenance help prevent forced outages that are often more costly, thus there is a considerable economic incentive to optimize planned outages.

In the following a mathematical approach to modelling forced outages will be explained. By the use of a statistical distribution it will be possible to model the forced outages of a unit in a time period by a number of given parameters. The work done in this chapter is based on the articles "Overview of Power System Reliability Assessment Techniques" [34] and "WP3: Prototype development for operational planning tool" [26].

3.1 Modelling Forced Outages

Looking at a unit a state diagram can be established:

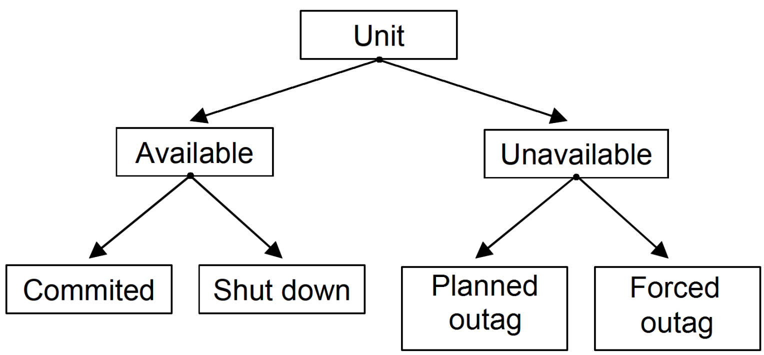

Figure 3.1: State diagram for a generation unit.

A unit can either be available or unavailable. If a unit is available then it can be committed i.e. generating or it can be shut down. In the other case where a unit is unavailable this can either be because of a planned outage or a forced outage. Consequently, this can be used to formulate a *Markov model* [27]. Markov models or Markov chains are used to describe a transition from one state t to another Δt where the new state is dependent on the previous state but not on earlier states. This applies well on the modelling of availability of a unit. Using a two state Markov process for availability, this will produce the two states "available" and "unavailable" with the transitions or state changers *time to failure* (TF) and *time to repair* (TR). These transitions will determine the rates of change in the process and can be shown by the *mean failure time* (MFT) and *mean repair time* (MRT):

$$\lambda = \frac{1}{MFT} \tag{3.1}$$

$$\mu = \frac{1}{MRT} \tag{3.2}$$

Where λ is the failure rate and μ is the repair rate. Assuming that the transition rates are exponentially distributed then they will be constant and independent of the time period. The exponential distribution is given by the probability density function (PDF):

$$f(t, \lambda) = \lambda \cdot e^{-\frac{1}{\lambda}} \tag{3.3}$$

Here given for the TF. Assuming that the unit is available at time $t = 0$, then the state probabilities can be formulated. The probability that the unit is available $P_A(t)$ and the probability that the unit is unavailable $P_U(t)$ are:

$$P_A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t} \tag{3.4}$$

$$P_U(t) = \frac{\lambda}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t} \tag{3.5}$$

Letting the transition $t \to \infty$ the long term probabilities will become

$$P_A = \frac{\mu}{\lambda + \mu} \tag{3.6}$$

$$P_U = \frac{\lambda}{\lambda + \mu} \tag{3.7}$$

which are independent of the initial conditions. Using 3.1 then the following can be formulated:

$$P_A = \frac{MFT}{MFT + MRT} \tag{3.8}$$

$$P_U = \frac{MRT}{MFT + MRT} \tag{3.9}$$

Looking at 3.9 this is equivalent to what is normally called the *Forced Outage Rate* (FOR). This is usually defined as the number of *Forced Outage Hours* (FOH) compared to all hours in the time period:

$$FOR = P_U = \frac{\text{Forced Outage Hours}}{\text{Total Hours}} \tag{3.10}$$

After establishing the FOR then the MFT can now be calculated by rearranging 3.1

$$MFT = MRT \cdot \frac{1 - FOR}{FOR} \tag{3.11}$$

Thus, a relation between MFT and MRT can be determined by a FOR. One reason for the importance of this is that the FOR is a commonly used property of a generation unit.

Over a given time period this can be used to give an estimate of the probability of the forced outages, still under the assumption of exponential distribution. When modelling failure then the exponential distribution is often used. The same way as the Poisson distribution is for e.g. arrivals. The independence of events and the shape of the exponential distribution will in general produce a realistic occurrence of events i.e. failures. However, when looking at repair times then the long tail of the exponential distribution will lead to unrealistic results. When modelling the repair time a bell-shaped distribution will perform more realistically. Therefore, the two-parameter *Weibull* distribution is investigated. The *Probability Density Function* (PDF) for the Weibull distribution [25] is given as:

$$f(t, \lambda, \beta) = \frac{\beta}{\lambda} \cdot \frac{t}{\lambda}^{\beta - 1} \cdot e^{-\frac{t}{\lambda}^{\beta}} \tag{3.12}$$

Here given for the TF. Where β is the shape factor. It can be seen that $\beta = 1$ will actually produce the exponential distribution and furthermore the functionality of the Weibull distribution is that when $\beta \approx 3.5$ the distribution becomes more bell shaped. The size of $\beta > 1$ will determine a skewness of the distribution. Examples of the Weibull distribution can be seen in figure 3.2 with exponential distribution with $\beta = 1$.

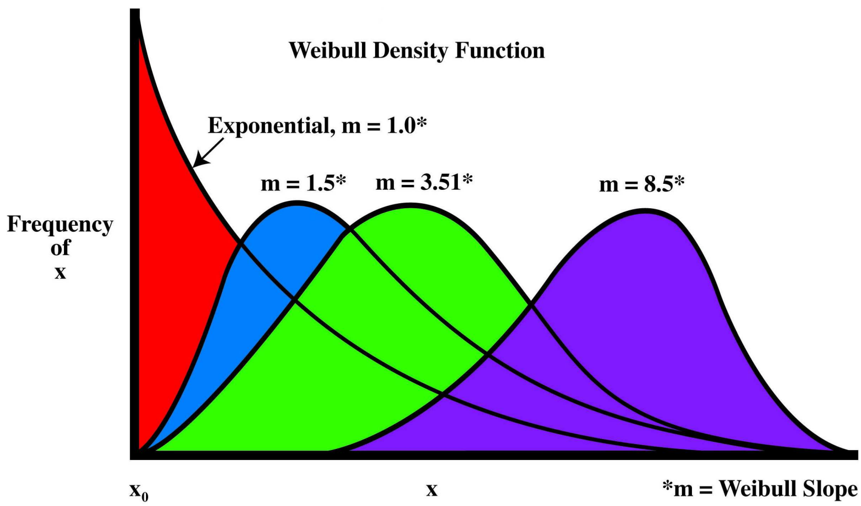

Figure 3.2: Examples of the Weibull distribution. *source:*[1]

When using non-exponential distributions for one or more of the transitions then a Semi-Markov process is used. The Semi-Markov process has the functionality of having state changing times from different distributions given by random variables.

To produce a valid estimate of the FOR for generation units, some statistical analysis of historical data for outages must be done. Here the project "Markedsgørelse af forsyningssikkerhed" (written in Danish) can be mentioned, where data from NordPool Spot [1] in the form of UMMs (Urgent

[1] www.nordpoolspot.com/

Market Message) analyse the occurrence of forced outages. Based on the historical data key figures for estimation of forced outages are calculated. In similar way this could be done to find an expected FOR. However, this is considered to be out of scope for this thesis. Instead other sources are used to give a reasonable estimate for a FOR.

Now an algorithm can be described to create forced outages for a unit by Semi-Markov processes.

3.1.1 Algorithm for Generating Outages

The theoretical background found above can be formulated into an algorithm. The algorithm will produce a forced outage profile over a given time period for a unit based on a MRT and FOR. It is obvious that the MRT must be given relative to the time period. The algorithm is described in the following.

1. Firstly the availability state of the unit must be determined to start the Semi-Markov process. This is done by generating a random number z and comparing it to the FOR. If $z \leq FOR$ then the unit is unavailable. If $z > FOR$ then the unit is considered as available.
2. In the case where the unit is started as *available* then a TF is found using the exponential distribution with a λ corresponding to the unit.
   If the unit is started as *unavailable* then a TR is found using the Weibull distribution with μ corresponding to the unit and a suitable shape factor β.
3. When the transition time e.g. time of a state change is found, then a jump forward to this time is performed and the availability of the unit is changed. If the unit was available then the *Time of failure* determines the transition and conversely for the *Time of repair*.
4. Generate successive TF and TR until the whole time period is covered, typically a full year.

5. Now the resulting FOR can be calculated as defined by 3.10. The algorithm is then restarted until the resulting FOR equals the given FOR with some tolerance ϵ., if this option is chosen.

The algorithm is implemented using Matlab and can be seen in A.2.1

3.1.2 Implementation

Using the algorithm a tool was created to generate forced outages for a number of units. The algorithm and theory about forced outages has been implemented using MATLAB. Firstly, a function to generate the forced outages for one unit over a given time period is created using the algorithm stated above. The function `outagesSA(MRT,FOR,HIY)` takes a mean time of repair, a forced outage rate and a time period to produce the forced outages for a unit. To create the TF and RT the MATLAB function `wblrnd(`λ`,`β`)` is used. This function produces a random number from the Weibull distribution with the scale parameter λ and the shape factor β. The scale parameter is given as the mean time of repair. The shape factor must be chosen such that the Weibull distribution fits the overall distribution of the mean repair times. In figure 3.3 a histogram of the MRTs of 163 units from the South African power system is shown. The data for these were provided by Ea Energy Analyses [11] in terms of planned outage times. Studies from the WILMAR [35] model has shown that a MRT of 60 hours was reasonable. Where the MRTs are given in relation to a time period of a full year. Based on this the MRTs were calculated for each unit by using the corresponding planned outage times. It is assumed that these will give a fair representation of the length of the MRTs.

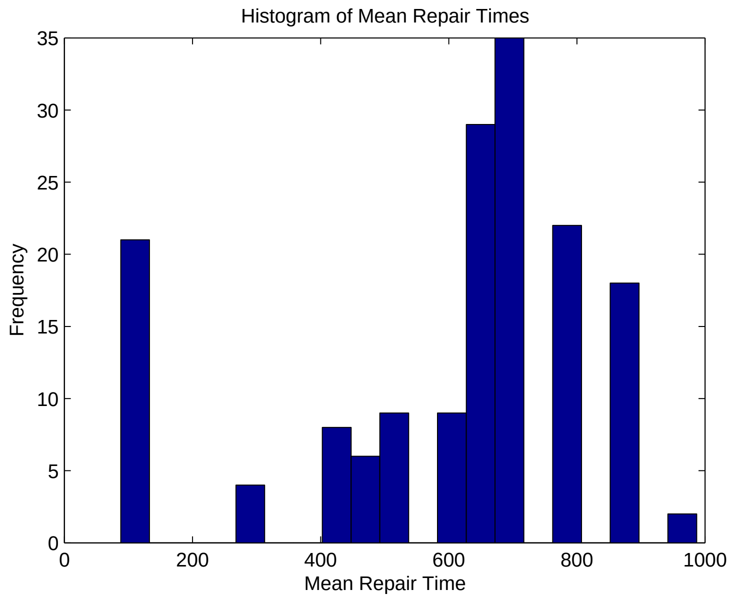

Figure 3.3: Mean repair times of 163 units from the South African power system.

The implementation of the function can be seen in appendix A.2.1.

Now a corresponding shape factor for the Weibull distribution must be found. A statistical analysis could be performed to try to find the shape factor β that best suits mean repair times. The MATLAB function `weifit()`[2] is used to fit the mean repair times and produces the shape factor $\beta = 2.716$. This can be seen in figure 3.4 where the Weibull distribution has been normalized to fit the histogram of the mean repair times.

[2] http://www.mathworks.se/help/stats/wblplot.html

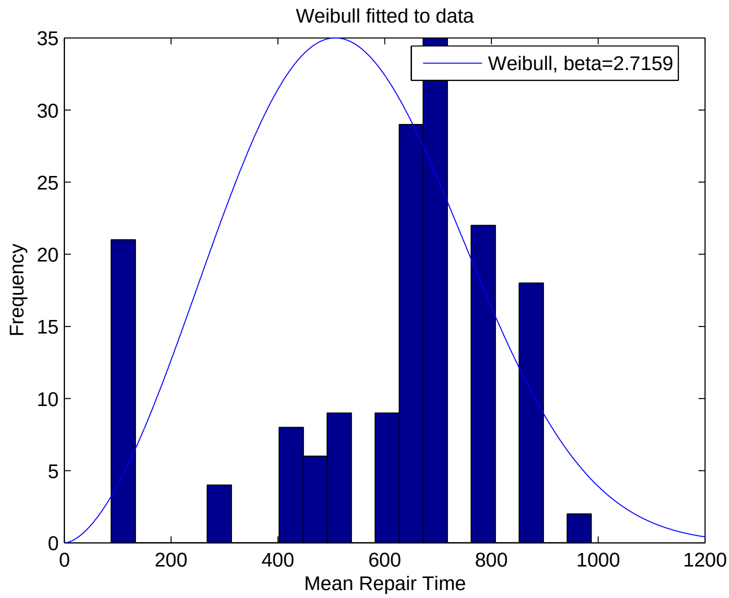

Figure 3.4: Weibull fit of mean repair times with $\beta = 2.716$

Since the histogram shows a small skewness to the left of the average then the fit using a shape factor of $\beta = 2.716$ seems to fit the data reasonably well. Obviously, 163 units are not a large amount of data to fit. However, to demonstrate the functionality of the MATLAB function they will suffice in ensuring a realistic shape factor for the Weibull fit. Furthermore, the generation units are of different type. Among others wind turbines, coal fuelled power plant and nuclear power plant are represented in the data. On that basis, it might be give a better estimate if the forced outages were simulation for each unit group with a corresponding β. However, this problem is addressed by adding a tolerance on the simulated FOR. More on this in the following.

The MATLAB function now has the needed parameters to produce forced outages. In figure 3.5 some examples on forced outages are shown. The graphs demonstrate forced outages in terms of the percentage of available capacity over a year. This is shown for the following three units.

Name	Type	MRT	FOR	FOR*
Camden1	Condensing coal unit	69.8	0.1699	0.1408
Koeberg1	Nuclear power plant	98 .5	0.0871	0.1242
Amakhala	Windmill farm	8.8	0.01	0.0087

Table 3.1: Mean repair times, FOR and the simulated FOR*.

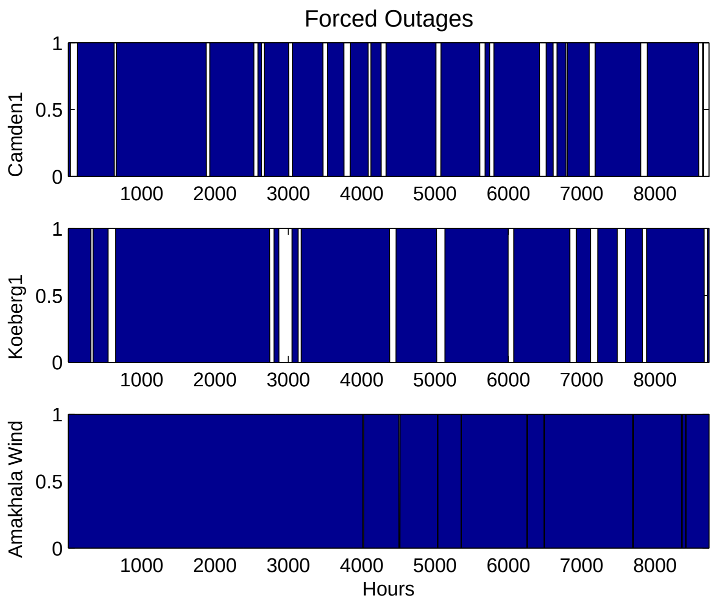

Figure 3.5: Forced outages.

Figure 3.5 shows forced outages profiles that suit the data given for the three units well. The Camden unit has a high FOR and this unit has several forced outages resulting in FOH=1230. The Koeberg unit has a lower FOR and a higher MRT than Camden, this correspond to the figure, where fewer outages are seen but with longer duration. The Amakhala windmill farm has a low FOR and as expected has few occurrence of forced outages. The low MRT also leads to short outage times, resulting in a FOH=76. Simulations for other units can be seen in A.1. Analysing the forced outages of several units had lead to conclude that the algorithm provides a good representation of forced outages.

In cases where the shape factor β is not representative of all units because of large variation in the FOR and MRT data. The possible of correcting a forced outages profile has been developed. It was created such that the algorithm dictates that the MATLAB function will keep running until a suitable simulated FOR* is found. This is determined by a chosen tolerance ϵ in FOR* = FOR $\pm\epsilon$.

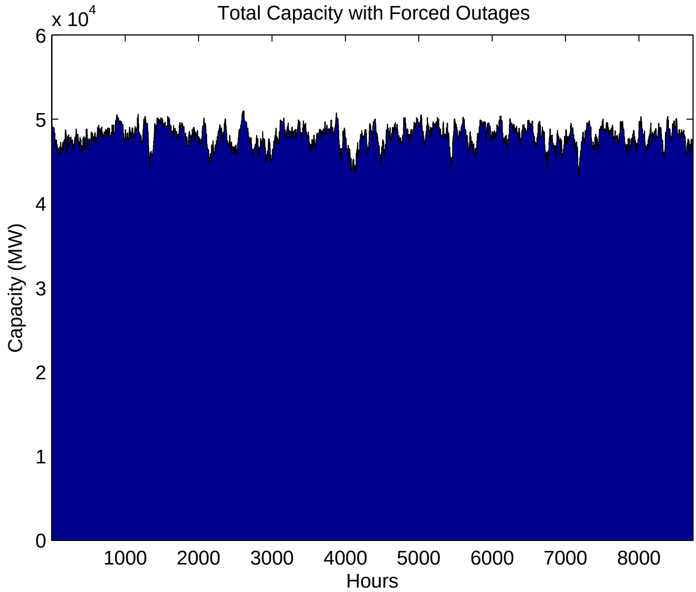

Figure 3.6: Total capacity with forced outages for a year

The MATLAB code be seen in appendix A.2.

3.2 Modelling Planned Outages

Planned outages has a significant effect on the available generation capacity of the energy system. Normally the maintenance and service of the units are planned in collaboration with a governing energy agency e.g. ESKOM [19]. The purpose of this is to ensure security of supply such that energy demand can always be met with some margin. So to be able to model planned outages information on maximum unavailable capacity over the full time period (here a year) is needed. This information can either be sought out from the governing energy agency in charge of planning outages or can be derived from energy consumption data.

The process of planning outages is done differently from country to country and no universal solution exist. However all solutions share the constraint of security of supply. Thus, a rather simply solution to planning outages is chosen in this thesis. Given a set of units with a corresponding outage time an algorithm is developed as seen below.

- Firstly, a maximum unavailable capacity (MUC) is found for each time step over the time period.
- Starting with the first given unit. This is chosen to be *unavailable* from time 1 until the outage time has expired and the unit is then set to be *available*. An indication that the unit has been out is set to 1 and the capacity of the unit is added to a sum of unavailable capacity (SUC) in the corresponding time steps.
- The next unit is chosen to be *unavailable* from the next time step if:
  - The unit capacity + SUC does not exceed the MUC. If this is the case, then a jump to the next time step is performed
  - The unit has not been out before. If it has, then a jump to the next unit is performed
  - The next time step does not exceed the time period. If this is the case, then a jump to the first time period is performed.

  At a given time step, if the outage time will exceed the time period then a shift is performed "to the left" such that the outage time will end at the last time step.
- This is repeated until all units have been out exactly once.

This is implemented in a MATLAB script. The MATLAB code be seen in appendix A.2.2. In figure 3.7 the planned outages of four units can be seen.

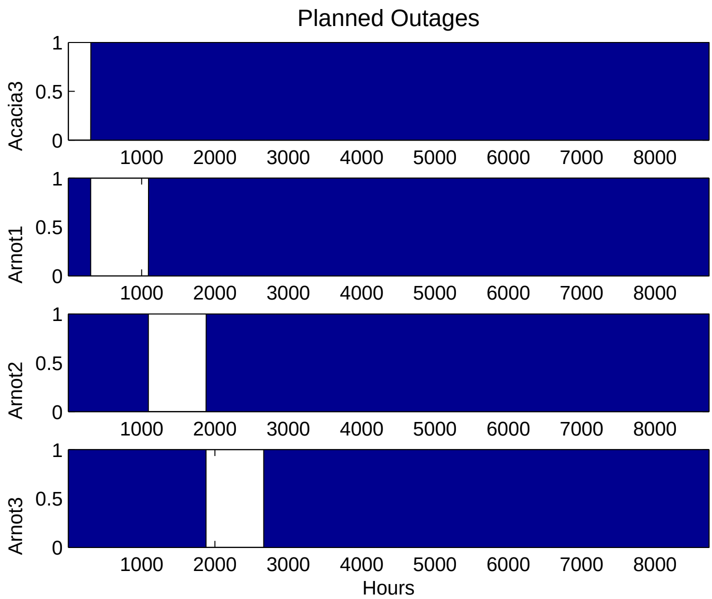

Figure 3.7: Planned outages for 4 units.

Introducing the MUC will create a constraint for the algorithm such that the simple unit by unit outages seen in figure 3.7 will not repeat for all units. In figure 3.8 the MUC graph is seen for the South African system. This is based on historical weekly data for maximum unavailable capacity and using MATLABs `polyfit` a polynomial is found as a function of time. In the winter time (week 22-34) the electricity demand is at its highest and thus no planned outages are allowed in order to satisfy electricity demand.

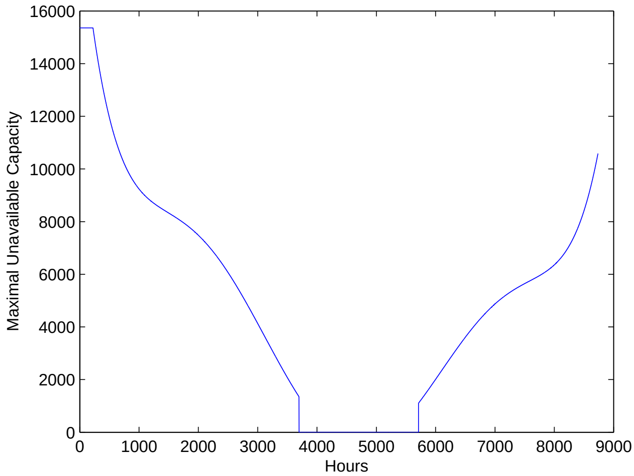

Figure 3.8: MUC graph for one year.

Using the algorithm with this MUC constraint to produce planned outages for all 163 units will generate the following image of the total planned outages, see figure 3.9.

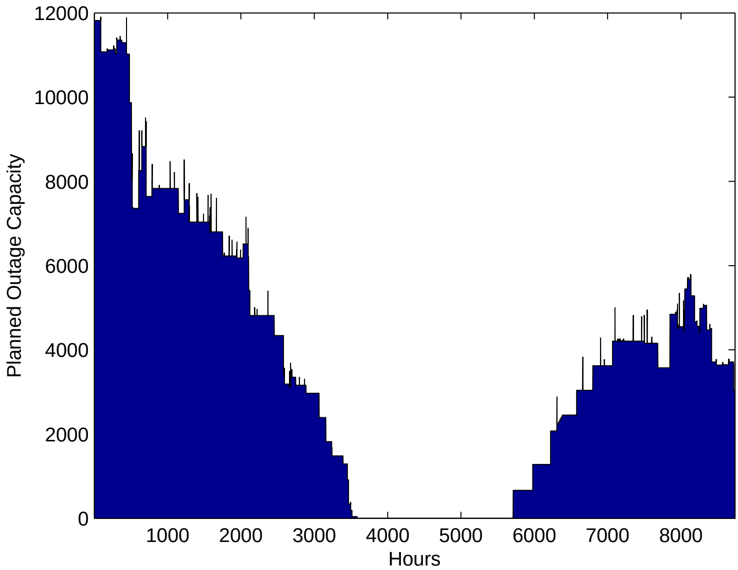

Figure 3.9: Planned outage capacity.

The jagged course of the figure is a result of the very variable size of both capacity and outage time of the units. The reason not many unit are planned to be out at the end of the time period is caused by the size of the outage time. Since the algorithm dictates that all planned outages must be within the time period, then not many can lie at the end of the year because the outage time would exceed this time period. In reality this will not be the case since planning will not be limited to fit completely into a year. Since the process of planning outages will most likely never be done by a generic software program, this solution to planned outages is assumed to be sufficient for this thesis. Additional planned outage profiles can be seen in appendix A.2 In figure 3.10 the total available capacity with effect of the loss of capacity by planned outages can be seen. In appendix

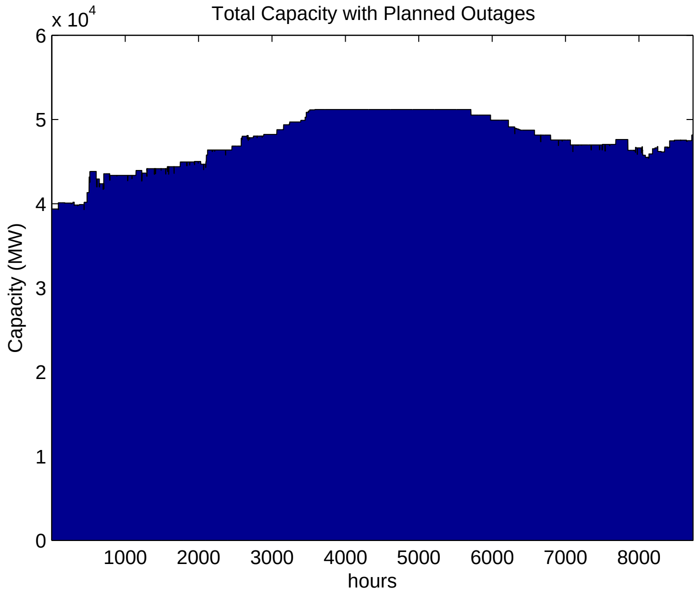

Figure 3.10: Total available capacity with planned outages.

3.3 Total Outages

Now combining the forced and planned outages will give a realistic image of the total available capacity during the time period. When combining the two, it is assumed that the forced and planned outages are independent. Meaning, that if a unit has just been out of commission for a planned outage then this will not have an effect on the probability of a forced outage in the near future. It could be argued that a unit will probably be less likely to fail after a planned extensive service and maintenance. However, it will not eliminate the probability of failure and since the forced outages is assumed to follow a Markov chain representation, in relation to independence of time steps, then it is decided that assuming independence between forced and planned outages will be a reasonable assumption. Furthermore, in the case where the forced and planned outages occur in same time steps, meaning that a forced outage occurs while the unit is out for maintenance, this will not change the total outage i.e. the forced outage will be ignored. The total outage percentage of a unit will thus be the product of the forced and planned outages using a boolean indication at each time step. In figure 3.11 the forced, planned and total outages can been seen for one unit, here the Duvha power station, unit number 6.

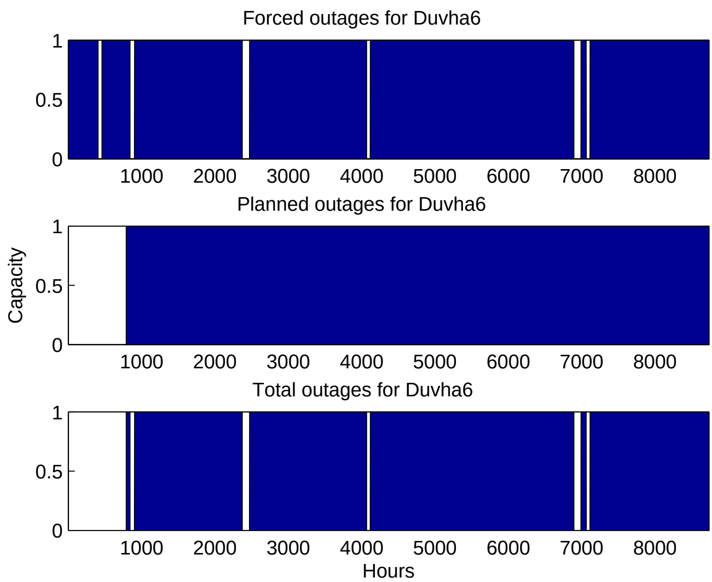

Figure 3.11: Forced, planned and total outages for Duvha, unit no. 6.

Combining the forced and planned outages for all 163 units in the South African model will produce the total available capacity in the time period, see figure 3.12.

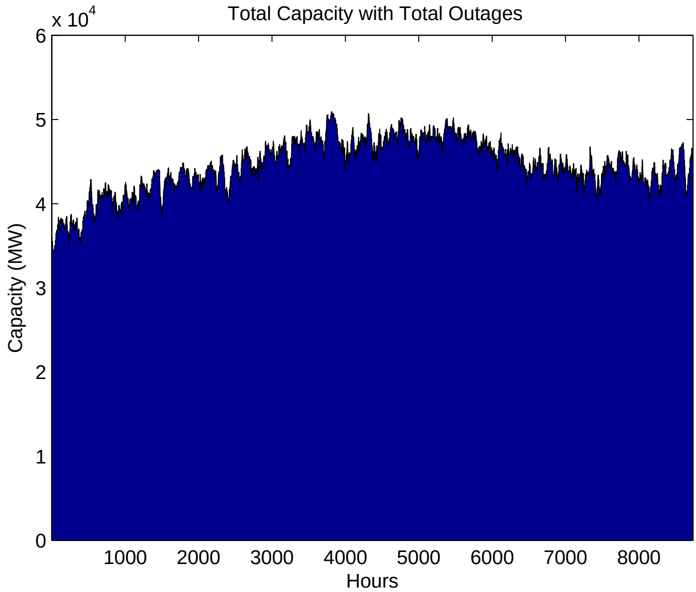

Figure 3.12: Total available capacity with planned outages.

Here it is shown how much of the 51195 MW total capacity is actually available during the year.

3.4 Summary

In this chapter it was shown how a tool to produce forced and planned outages was developed. The tool was used to produce outages for the units in the South African model. Looking at the total outages in figure 3.12 on average 87% of the capacity is available in a time step. This gives a good indication of the importance of the outages in an energy system. When using deterministic models like e.g. the Balmorel model, where full information is assumed i.e. all data for demand, wind generation etc. is known. Then, providing a realistic result for the available capacity over the time period can have a rather large impact on the operational solution in a model run. Here operational solution means the solution in which the model chooses units to generate over the time period in order to satisfy the demand. The economic cost of loosing units of large capacity, due to forced or planned outages, at times where demand is high can be significant. The downside of modelling outages in this fashion and implementing them in a deterministic model is, due to the random nature of the modelling, that the possibility of time segments where it is impossible to satisfy energy demand exists. With that said, the tool provided to create forced and planned outages will help ensure a more realistic result for deterministic models as well as being able to predict a theoretical operational pattern for an energy system based on few key figures for the units. Finally, this tool can provide FORs and MRTs for calculation of reserve requirements. More on this will follow.

Chapter 4

The Balmorel Model

In this thesis the Balmorel model is used as a tool for modelling energy systems. This chapter introduces the model and gives an overview of the mechanisms used to provide a mathematical representation of an energy system. Many developments (add-ons) have been done on the Balmorel model to meet needs for specific energy related analysis. Due to the vast number of possibilities thus resulting in equations, parameters, variables etc. when using the model, only the essential parts of the model will be explained in this chapter. Further information and documentation can be found at [2] and [3].

4.1 Introduction

The Balmorel Model started development in 1999 as a tool for analysis of the electricity and combined heat and power (CHP) sectors in the Baltic Sea Region. The purpose of the Balmorel project was the construction of a partial equilibrium model covering the sectors in the countries around the Baltic Sea suited for the analysis of relevant policy questions to the extent that these contain substantial international aspects. The Balmorel project was supported by the Danish Energy Research Program and institutions involved. The project was a collaboration between the following:

- Elkraft System, Denmark: Hans F. Ravn (project manager), Magnus Hindsberger, Mogens Petersen, Rune Schmidt, Rasmus Bøg.
- Risø National Laboratory, Denmark: Poul Erik Grohnheit, Helge V. Larsen.
- AKF, Institute of Local Government Studies, Denmark: Jesper Munksgaard, Jacob Ramskov.
- Stockholm Environment Institute, Estonia: Markko-Raul Esop.
- Institute of Physical Energetics, Latvia: Gaidis Klavs.
- Lithuanian Energy Institute, Lithuania: Arvydas Galinis.
- PSE International, Poland: Robert Paprocki, Marek Wawrzyszczuk.
- Kaliningrad State University, Russia: Alexander Gloukhov.

Source: [6]

However, since the original development of the model, many new actors has joined in and applied the model for further development and usage. Users of the Balmorel model include research institutions, consulting companies, energy authorities, transmission system operators and energy companies. Among these Ea Energy Analyses A/S [11] has played an essential role and moreover, been helpful in providing model development, data for the model and analysis tools for this thesis.

Today the model plays an important role in a variety of analysis for long range planning as well as shorter time operational analysis. The model is used on a large geographical scale including projects in Denmark, Norway, Estonia, Latvia, Lithuania, Poland, Germany, Austria, Ghana, Mauritius, Canada and China. It has been used for analyses of i.e. security of electricity supply, the role of flexible electricity demand, hydrogen technologies, wind power development, the role of natural gas, development of international electricity markets, market power, heat transmission and pricing, expansion of electricity transmission, international markets for green certificates and emission trading, electric vehicles in the energy system and environmental policy evaluation. [33]

4.2 GAMS

The model is implemented in the GAMS (General Algebraic Modeling System) modelling language. GAMS is a high-level modelling system for mathematical programming and optimization. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modelling applications, and allows the development of large maintainable models that can be adapted quickly to new situations [22]. The syntax of GAMS, where an optimal solution given an objective function is sought subject to a number of constraints, suits the discipline of representing an energy system mathematically well. The model uses LP (Linear Programming) or MIP (Mixed Integer Programming) to formulate and solve the problem. This presents some problems when real life problems are in fact not linear e.g. the combined generation of heat and electricity on a CHP unit. However, linearization of these problems provides a satisfying approximation in most cases. A general formulation of the model is given as:

$$Z^* = \min_x f(\alpha; x) \tag{4.1}$$

s.t.

$$g(\alpha; x) \leq \gamma \tag{4.2}$$

$$h(\alpha; x) = \eta \tag{4.3}$$

Where Z^* is an optimal solution (but not necessarily the only one) subject to the constraints g and h given by the parameters γ and η and the coefficients α. It should be mentioned that when dealing with model runs of the full model, the complexity and large amount of data sometimes require a slack on the optimal solution ($Z^* = Z \pm \epsilon$) due to run time issues or failing to converge to a solution. A more theoretical description of the LP (or MIP) implementation can be found at [3], chapter 11.

4.3 The model

The Balmorel model is a partial equilibrium model which essentially seeks a solution minimizing costs while ensuring the demand for electricity and heat given the technical constraints of an energy system. To further explain the equations of the model a terminology must be presented. To be able to represent a mathematical formulation and still be able to recognize parameters, variables and sets in the Balmorel model it was chosen to use superscript for naming. This means that for e.g. $G^{kfx}_{y,a,g}$ then kfx are not indexes but name abbreviations from the Balmorel model indicating "capacity fixed" for the model parameter `GKFX(Y,A,G)`. In the following the terminology is given:

Sets:

- C: Countries, with elements c
- R: Regions
- A: Areas
- G: Technologies
- F: Fuel
- T: Time period
- Y: Years

Indexes:

- $r \subset R$, with subset
  - R_c, the regions r in country c
- $a \subset A$, with subsets
  - A_c, the areas a in country c
  - A_r, the areas a in region r

- $g \subset G$, with subset
  - G_a, the technologies (generation unit type) g in area a
- $f \subset F$, the subset of fuels in F
- $t \subset T$, the time steps t in time period T [1], with subset
  - T_y, the time steps t in year y
- $y \subset Y$, the subset of years in Y

Parameters:

- D_r^e, Annual electricity demand in region r in MWh
- D_a^h, Annual heat demand in area a in MWh
- $D_{r,t}^{evart}$, Variation in electricity demand in area a in time step t
- $D_{a,t}^{hvart}$, Variation in electricity demand in area a in time step t
- X_{r_1,r_2}^{cap}, The electricity transmission capacity x between region r_1 and region r_2 in MW
- X_{r_1,r_2}^{loss}, Loss in electricity on transmissions between region r_1 and region r_2
- $X_{r_1,r_2}^{kderate}$, Factor (representing outages) to reduce electricity transmission capacity between region r_1 and region r_2
- X_{r_1,r_2}^{cost}, Cost of electricity transmission between region r_1 and region r_2 \$/MW [2]
- $G_{y,a,g}^{kfx}$, Exogenous generation capacity in year y in area a on technology g in MW

[1] In Balmorel the time period is actually divided into season and time step to be able to model seasonal storage and hydro power, where weekly cycles are used. However, for the sake of simplicity only one time index is used in the representation.

[2] \$ - refers a chosen currency.

- $G_{a,g,t}^{kderate}$, Factor representing reduced generation capacity in area a on technology g at time step t [3]
- $G_{y,a,f}^{fmax}$, Maximum fuel use of fuel f in area a in year y in GJ
- $G_{y,a,f}^{fmin}$, Minimum required fuel use of fuel f in area a in year y in GJ
- $G_{a,g}^{OMVCOST}$, Variable operation and maintenance cost in an area a for a technology g in \$/MWh
- $G_{a,g}^{OMFCOST}$, Annual fixed operation and maintenance cost in an area a for a technology g in \$/MW
- $F_{a,f}^{kpot}$, Restricted fuel potential or maximum fuel use of fuel f in area a in MW
- $F_{y,a,f}^{price}$, Fuel price in a year y for an area a for a fuel f in \$/GJ
- $M_g^{CO_2}$, CO_2 emission coefficient for technology g
- $M_g^{SO_2}$, SO_2 emission coefficient for technology g
- $M_g^{NO_x}$, NO_x emission coefficient for technology g
- $TAX_c^{CO_2}$, CO_2 emission tax for country c in \$/ton
- $TAX_c^{SO_2}$, SO_2 emission tax for country c in \$/ton
- $TAX_c^{NO_x}$, NO_x emission tax for country c in \$/kg
- $TAX_{c,f}^{f}$, Fuel tax for fuel f in country c in \$/GJ

Variables:

- $V_{a,g,t}^{e}$, Electricity generation in area a on unit g in time step t
- $V_{a,g,t}^{h}$, Heat generation in area a on unit g in time step t

[3] $G_{a,g,t}^{kderate}$ was previously used to de-rate generation capacity on units to represent both forced and planned outages as scalar saying that only 90% was available at all time steps. However, this has now been redefined to represent only planned outages on a hourly basis generated by the tool described in chapter 3.

- $V^f_{a,g,t}$, Fuel consumption in area a on unit g in time step t
- $V^x_{r_1,r_2,t}$, Electricity transmission from region r_1 to region r_2 in time step t
- $V^{estoloadt}_{a,t}$, Loading volume into an electricity storage in area a at time step t

These sets, parameters and variables will be used to present the essential mechanics of the Balmorel model and also help illustrate how the complex world of energy modelling can be constructed into a mathematical formulation.

4.3.1 Geography

When modelling energy systems it is important to be able to create a realistic representation of the geography of the area that is being considered. In the Balmorel model geography is determined by three entities: area, region and country. A country can be divided into regions, which again can be divided into areas, see figure 4.1.

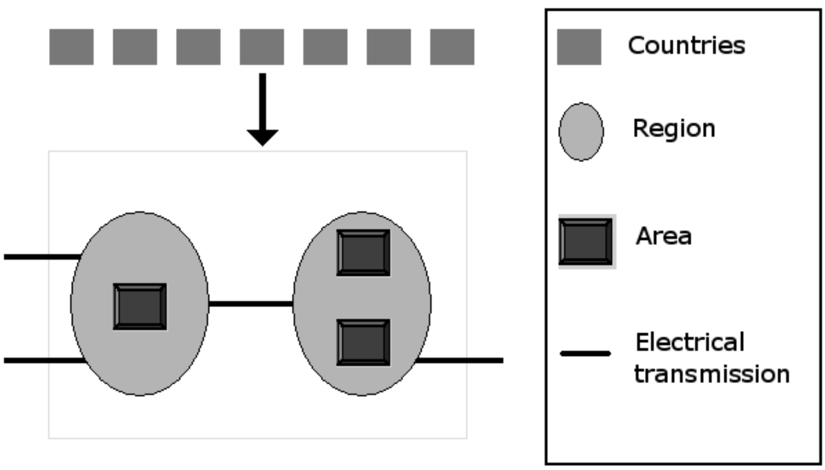

Figure 4.1: The geographical entities used in the Balmorel model.

This geographical division helps differentiate the input data. Meaning that some modelling can be done on a small geographical scale and other on a larger scale. In this way, electricity transmission can occur from region to region, restrictions on CO_2 emissions can be defined for countries and so on. Transmission of energy is also possible in the model. Electricity can be transmitted from one region to another through transmission lines. The transmission (distribution) grid is represented in the model by maximum amount of electricity in MW that can be transmitted from one region to another.

4.3.2 Representation of Energy Technical Properties

In the following the energy technical properties of the model will be shown and briefly explained. This is done to provide a general introduction to the attributes of fuel types, generation unit etc., that help formulate the physical entities in an energy system.

4.3.2.1 Technologies

Generation of electricity and heat i.e. conversion of energy fuels to heat and electricity, is performed on generation units or technologies. A technology is defined by a set of criteria, in Balmorel terminology this set is called GDATASET:

- Generation type, (see below)
- Fuel type, the fuel type used to generate electricity and/or heat
- C^v value, (see below)
- C^b value, (see below)
- f^e value, fuel efficiency i.e. the relation between input (fuel) and output (energy)
- Degree of desulphoring, determines the SO_2 emission

- NO_x-factor, emission of nitrogen oxides (mg/MJ)
- CH_4-factor, emission of methane (mg/MJ)
- Variable operating and maintenance (O&M) costs ($/MWh)
- Annual O&M costs (1000$/MW)

Combined these characteristics can be used to define a very specific technology. The fuel type and generation type is the main attributes to differentiate between technologies. A generation type is given by one of the following

- Condensing, only electricity generation
- Back pressure, CHP unit
- Extraction, CHP unit
- Heat-only boilers
- Heat pumps
- Heat storage
- Electricity storage
- Wind power
- Solar voltaic
- Solar heat
- Wave power

Condensing Unit
A condensing unit only generates electricity. Fuel is converted to steam and through a turbine and a generator, electricity is generated as seen in figure 4.2.

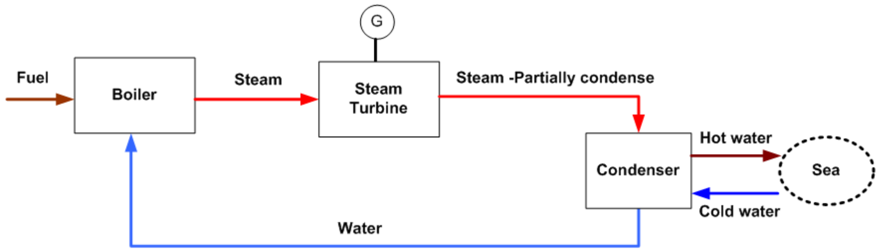

Figure 4.2: The process of a condensing unit. *Source*: [21]

Back Pressure Unit

A back pressure unit is a CHP unit meaning that both electricity and heat can be generated as shown in figure 4.3. Through a condenser the generated heat is then forwarded to a district heating (DH) system as steam.

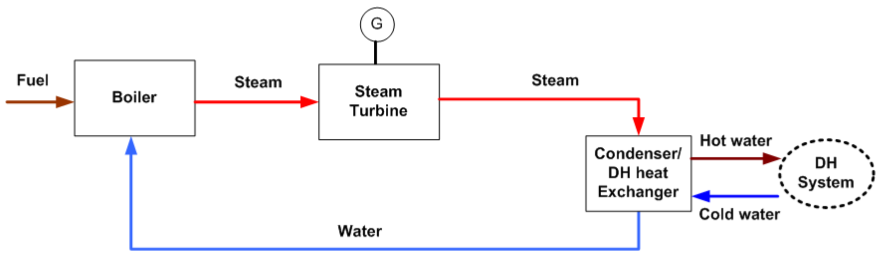

Figure 4.3: The process of a back pressure unit. *Source*: [21]

As shown in figure 4.3 a back pressure unit will have a fixed relation between heat and electricity. This relation is called the C^b value and is defined as $V^e = C^b \cdot V^h$, where V^e is generated electricity and V^h is heat.

Extraction Unit

An extraction unit is a flexible CHP unit. The process with a steam turbine is shown in figure 4.4.

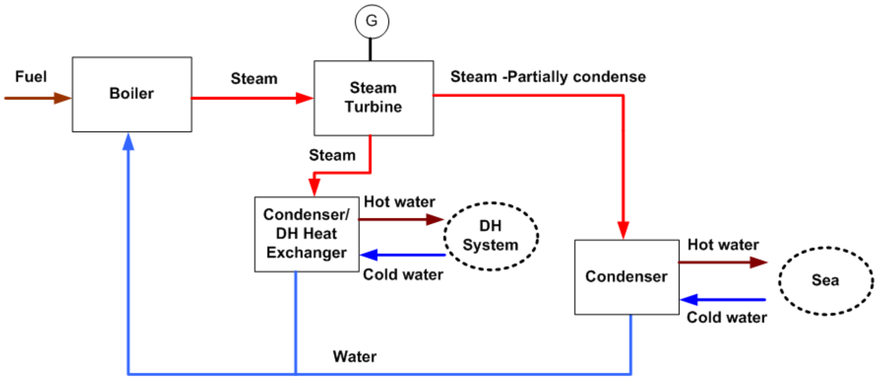

Figure 4.4: The process of a extraction unit. *Source*: [21]

In an extraction unit the steam can be extracted from the turbine and through a condenser continued to a DH system. If steam is not extracted then the unit will function as a condensing unit and only generate electricity. This flexible relationship between generated electricity and heat means that a unit at a given time can generate at a point defined by figure 4.5

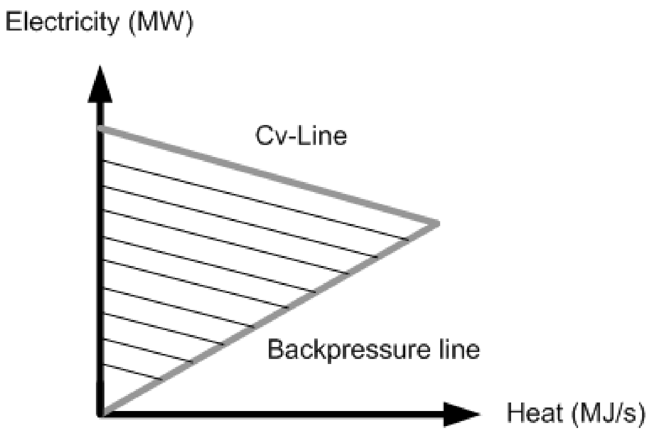

Figure 4.5: The generation area of an extraction unit.

The generation point can be chosen within the area limited by the top C^v-line with a slope $-C^v$ and the bottom back pressure line with slope C^b.

The C^b value represents the maximum electricity generation in the CHP unit divided by the maximum heat generation. The C^v value represents the maximum electricity at full CHP generation. The lines parallel to the C^v-line illustrates that fuel used for generation is the same for all points along one of these lines. This means that heat and electricity is at first generated at a fixed relationship defined by the C^b line, however if more electricity is needed then the generated heat can be exchanged to electricity with a relation given by the C^v value.

Other Generation Types

The remaining generation types are quite self explanatory. Wind power is generated from wind on wind turbines, solar power from the sun on solar panels, called photovoltaics and heat or electricity storage is the storage of energy to be used at a later point in time. It is, however, worth mentioning that the Balmorel model has been used to model a number of other technologies. Furthermore, the modelling of the technologies above is actually used to represent a variety of other technologies with similar mechanics, here mechanics is meant in a mathematical modelling perspective.

4.3.2.2 Fuel Types

The fuel type determines the energy form used to generate electricity or heat (or both). Additionally, the fuel type helps differentiate how the output results are calculated in the Balmorel model. Two generation types might work exactly the same but use different fuel types (speaking in a modelling perspective). The fuel types used to define the technologies are seen below, these form the fuel set F:

- Nuclear
- Natural gas
- Coal
- Lignite
- Fuel oil

- Light oil
- Shale
- Peat
- Municipal waste
- Biomass, given as
  - Straw
  - Wood
  - Straw pellets
  - Wood pellets
  - Wood waste
- Biogas
- Heat, used as a fuel for heat storages

Again more fuels are in some cases modelled for special versions of the Balmorel model. In the model, the set F also includes renewable fuels like wind or sun as a fuel for the respective renewable technologies; wind turbines or solar power etc.. This is done to provide a more generic modelling set up and generalize input. Each fuel is differentiated by the following attributes, called FDATASET:

- CO_2 emission in kg/GJ fuel, equivalent to $M_g^{CO_2}$
- SO_2 emission in kg/GJ fuel, equivalent to $M_g^{SO_2}$
- N_2O emission in kg/GJ fuel
- Share of renewable energy

These attributes presents the possibility of calculating the different emissions from each fuel and the contributions to the renewable energy equation in the energy system. This is included not only to analyse the emissions of greenhouse gases in a economic perspective but is also used to add the possibility of emission constraints in the model.

Using the sets given above it is possible to define a technology g by the set GDATASET where the fuel type in GDATASET corresponds to a fuel f defined by FDATASET. This will be denoted $g \sim f$, stating that a equation exposed to this relation will only apply for technologies g using fuel f. This relation stems from functionality in the Balmorel model where it is formulated as `GDATA(g,'GDFUEL')=FDATA(g,'FDNB)'`.

4.3.3 Model Constraints

In the following section some of the main constraints of the model will be presented. Because of the vast number of applications of the Balmorel model many more constraints exist in the original version. Some to help satisfy a certain need for a specific type of analysis. Others simply to help formulate a physical property of the energy system that in a mathematical representation is somewhat complex. Mostly the model is created to be as generic as possible, so that the constraints in one field e.g. fuel consumption, will cover as many of the technical entities as widely possible. However, the difference in technical mechanics will sometimes create the need for more specific constraints to handle a certain fuel type or generation unit type.

4.3.3.1 Supply

Given a heat and electricity demand by D_r^e and D_a^h the model seeks to find an optimal combination of generation on available technologies g to supply the demand. This is represented in the following:

$$\sum_{a \in A_r} \sum_{g} V_{a,g,t}^{e} - V_{a,t}^{estoloadt} - \sum_{r_2} V_{r,r_2,t}^{x} + \sum_{r_2} V_{r_2,r,t}^{x} = D_r^e \cdot D_{r,t}^{evart}, \qquad \forall r, t \tag{4.4}$$

Saying that all electricity generation in the areas of a region minus the amount that is stored at electricity storages combined with what is transmitted to and from other regions must be equal to the electricity demand at a given time step for all regions in the model.

Assuming that heat transmission is ignored the supply and demand equation is given below. Heat transmission is ignored since the value of analysing heat transmission is minimal compared to the entire system.

$$V^h_{a,g,t} = D^h_a \cdot D^{hvart}_{a,t}, \qquad \forall a, t \tag{4.5}$$

Saying that all heat generation in an area must be equal to the heat demand at a given time step for all areas in the model. In The Balmorel model the technology set g is divided into several subsets due to the mechanics of calculating heat generation on different technology types. For the sake of simplicity this is ignored here. The same is also true for electricity generation.

The transmission of electricity is possible between regions. This is limited by a maximum capacity of each transmission line, $X^{cap}_{r_1,r_2}$. In the model this is defined as:

$$V^x_{r_1,r_2,t} \leq X^{cap}_{r_1,r_2} \cdot X^{kderate}_{r_1,r_2} \qquad \forall (r_1, r_2) \in R, t \tag{4.6}$$

The $X^{kderate}_{r_1,r_2}$ factor is used to represent transmission outages as an approximation by downscaling transmission capacity. Normally this is around 90%. This method is often used to represent outages in the deterministic Balmorel model. Before this thesis this was also used to represent forced and planned outages.

4.3.3.2 Fuel

The fuel consumption of a technology is presented as a variable $V^f_{a,g,t}$ and is defined as

$$V^f_{a,g,t} = V^e_{a,g,t} f^e_g + \frac{V^g_{a,g,t} C^v}{f^e_g} \qquad \forall a, g, t \tag{4.7}$$

saying that the fuel consumption is equal to the electricity generation multiplied with the fuel efficiency added to the heat contribution given as the heat generation times the C^v value over the fuel efficiency.

Restriction when modelling energy systems are often the amount of available fuel e.g. biomass or coal, meaning that an area, a region or country can only use a certain fuel potential. There are several ways of implementing this restriction into the model. It could be done by limiting the usable fuel amount in GJ. Another way is to limit the installed generation capacity of technologies that use the fuels in question. In the Balmorel model these two method are combined to provide the opportunity to restrict some fuel use in GJ, typically biomass or biogas, or in capacity (MW) which is often done for renewable or nuclear energy i.e.. cheap technologies that most likely will generate as much as possible.

The restricted fuel potential in capacity (MW) is represented as:

$$G^{kfx}_{y,a,g} \leq F^{kpot}_{a,f}, \qquad \forall y, a, (g, f) \in \{g \sim f\} \tag{4.8}$$

For all years in the simulation the installed capacity of a technology using fuel f in an area must be less than or equal to the potential of a technology using f. Furthermore, the fuel consumption in GJ can be forced or restricted by the parameters $G^{fmin}_{y,a,f}$ and $G^{fmax}_{y,a,f}$:

$$\sum_{g \in \{g \sim f\}, t \in T_y} V^{f}_{a,g,t} \geq G^{fmin}_{y,a,f} \qquad \forall y, a, f \in \{g \sim f\} \tag{4.9}$$

$$\sum_{g \in \{g \sim f\}, t \in T_y} V^{f}_{a,g,t} \leq G^{fmax}_{y,a,f} \qquad \forall y, a, f \in \{g \sim f\} \tag{4.10}$$

It should be mentioned that the exact same method is used when it comes to restricting emissions. Only the fuel consumption is multiplied with the emission factor for each type of emission e.g. CO_2.

4.3.4 Objective Function

In the sections above some of the more important constraints of the Balmorel model is described. In the following the significant parts of the objective function will be presented. These are the driving forces in determining the best solution to supplying heat and electricity to consumers under the constraints and costs of an energy system. The Balmorel model seeks to find a solution that minimizes the socio-economic costs of the system, such that the entire system perform as efficiently as possible generating and transmitting heat and electricity at the lowest cost. With socio-economics is meant that the costs are not differentiated from each stakeholder. This means that e.g. the fuel costs on a power plant and transmission to the consumer which is normally paid by different stakeholders will be included in the total costs, which the model will try to minimize. The objective function is stated below:

$$\sum_{g,f}(F^{price}_{y,a,f} \cdot \sum_{t} V^{f}_{a,g,t}) \tag{4.11}$$

$$+\sum_{a,g}(G^{OMVCOST}_{a,g} \cdot \sum_{t} V^{e}_{a,g,t}) \tag{4.12}$$

$$+\sum_{a,g} G^{OMFCOST}_{a,g} \cdot G^{kfx}_{y,a,g} \tag{4.13}$$

$$+\sum_{r_1,r_2}(X^{cost}_{r_1,r_2} \cdot \sum_{t} V^{x}_{r_1,r_2,t}) \tag{4.14}$$

$$+\sum_{c}\sum_{a\in A_c,g}(\sum_{t}(3.6 \cdot M^{CO_2}_{g} \cdot V^{f}_{a,g,t}) \cdot TAX^{CO_2}_{c}) \tag{4.15}$$

$$+\sum_{c}\sum_{a\in A_c,g}(\sum_{t}(3.6 \cdot M^{SO_2}_{g} \cdot V^{f}_{a,g,t}) \cdot TAX^{SO_2}_{c}) \tag{4.16}$$

$$+\sum_{c}\sum_{a\in A_c,g\in\{g\sim f\}}(\sum_{t}(3.6 \cdot M^{NO_x}_{g} \cdot V^{f}_{a,g,t}) \cdot TAX^{NO_x}_{c}) \tag{4.17}$$

$$+\sum_{c,f\in\{g\sim f\},t}(\sum_{a\in A_c,g\in\{g\sim f\}} 3.6 \cdot TAX^{f}_{c,f} \cdot V^{f}_{a,g,t}) \tag{4.18}$$

$$\tag{4.19}$$

The first term 4.11 constitutes the fuel cost. This is the fuel price for the simulated year multiplied with the total fuel consumption of each unit.

The next term 4.12 is the total variable operation and maintenance cost. This is the sum of all costs of the variable O&M at each unit multiplied with the total generation. The "variable" means that, as seen, the cost is determined by the amount of generation on the unit.

In 4.13 the contribution from the fixed O&M is shown. This is the annual cost of a unit independent of the generated energy. Thus, this is a unit costs that must be paid whether or not the unit actually is in use.

Transmission cost is shown in 4.14. This is the cost of transmitting electricity from one region to another. This is sought to be minimized not only to cut costs but also to ensure that electricity is not passed around the transmission system unnecessarily.

The emission taxes can be seen in 4.15, 4.16 and 4.17. This is the the total emission, given by fuel consumption multiplied with emission factor, times the emission tax.

Lastly, in 4.18 the fuel tax contribution to the objective function can be seen. This is the fuel tax multiplied with the fuel consumption.

4.4 Summary

In this chapter the governing dynamics of the Balmorel model was described. In order to understand how the Balmorel model is used to formulate the complexity of an energy system, the most important parts of the constraints and objective function were shown. It was demonstrated how physical attributes of fuel types and generation units can be formulated in the form of parameters. Furthermore, a general introduction to how the model is built, in terms of time segments and geographical division. It must be mentioned, that an important function of the Balmorel model is the functionality of adding investments in new generation capacity to the model runs. This is a very important feature that makes it possible to create model runs that help predict the future of the energy system based on forecasts in demand, emission regulation, fuel prices etc. This functionality plays a key role in the application of the Balmorel model and is the basis of many projects using the Balmorel model to analyse the future of energy. However, since no simulations of the future of the South African power system are performed in this thesis, the effects on the constraints and objective function from the investments functionality is ignored in the sections above.

Chapter 5

Modelling Reserves

In the following chapter the calculation of the reserve requirement and the modelling of the reserves are described. The contributions to the reserve requirement from each imbalance entity are explained and how this is implemented into the model. Furthermore, the mathematical formulation of how the reserves are represented and implemented into the Balmorel model is shown.

5.1 Reserve Requirement

In this section each contribution of the imbalances to the reserve requirement are described. As previously stated, the imbalances originates from wind power generation, electricity demand and forced outages. To represent the imbalances in the system each contribution to the reserve requirement is calculated as an amount of electricity in MW. The imbalances produced by wind power generation, electricity and forced outages are convoluted into the total reserve requirement for the system. The contributions to the total reserve requirement are based on the imbalances in relation to the forecasts used in the Balmorel model. For electricity demand and wind power generation the imbalances are presented in form of forecast errors. The imbalances from forced outages are derived from outage probability in terms of failure rates on units assumed committed (on-line). Since reserves are examined on an hourly basis the reserve requirement is seen as imbalances within an hour, meaning imbalances from the planned dispatch at time step t_i to the forecast in time step t_{i+1}. This is done using an Microsoft Excel Spreadsheet to calculate the hourly imbalances for the entire system and made to produce an exogenous input to the Balmorel model. The Excel Spreadsheet was developed in collaboration with Ea Energy analyses.

The purpose of the Excel Spreadsheet is to generate a reserve requirement to help analyse the implementation of reserves in the Balmorel model. The method described below is chosen as a pragmatic way of calculating the reserve requirement. By using random simulations the reserve requirement is found as a reasonable estimate for an otherwise unknown imbalance size. The simulations for each imbalance entity are performed to estimate probability functions. Since each entity will have different distributions in relation to estimation of imbalances, the simulations will provide the possibility of combining each contribution to form the reserve requirement. The ambition of the Excel Spreadsheet is not to perform a thorough mathematical method of forecasting imbalances in the system. But rather a simplified way of providing a reserve requirement that will be reasonable in magnitude and able to demonstrate the effects of each imbalance contribution for the further implantation of reserves in the Balmorel model.

To produce an amount of reserve requirement a number of different probability points are chosen. These are called *quantiles* and are represented as selected probability points in which an amount of regulating reserve is calculating with a corresponding probability. This is seen in figure 5.1:

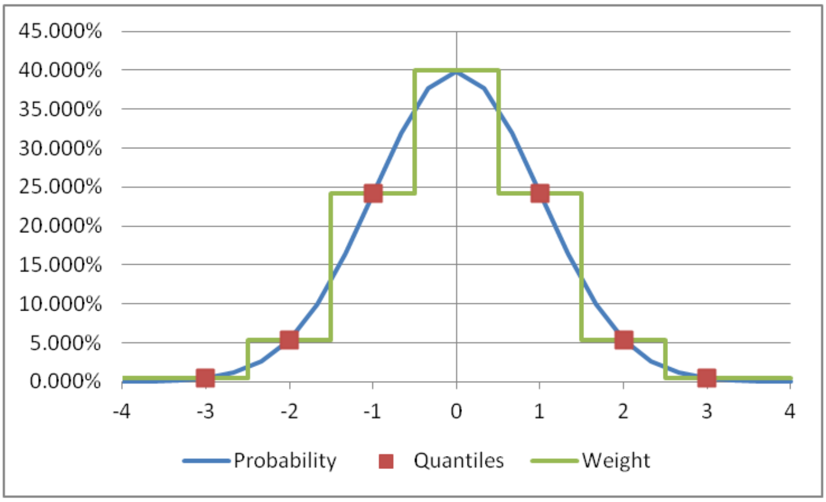

Figure 5.1: Quantiles with corresponding probability mass.

The weight is calculated so that the probability mass between two points is divided in half. This is done to represent the upregulating reserves (above 0) and the downregulating reserves (below 0). Thus, these can be described by a quantile with a corresponding probability for each imbalance entity. The chosen quantiles are $q = \{q_1, q_2, ..., q_6\}$ with the probability mass $P(q) = \{0.15\%, 2.25\%, 15.85\%, 84.15\%, 97.75\%, 99.85\%\}$ corresponding to the midpoints in between ± 3 standard deviation in the Normal Distribution $\mathcal{N}(\mu, \sigma^2)$. Assuming that 50% is the actual forecast, where no forecast error exist the quantiles then represents the up- and downregulating reserve requirement with a corresponding probability mass.

5.1.1 Electricity Demand

Electricity demand is given as an annual consumption and a variation profile for each region in the model. By adding the demand from each region in every time step, then a variation profile for the system as a whole can be found for each time step. The variation profile consequently acts as a forecast on the demand given as μ_{demand}. Then it is assumed that the electricity demand will vary from the predicted value μ_{demand} seen as a demand forecast error. It is assumed that the demand forecast error is normally distributed with a normalized standard deviation σ. This assumption of normal distribution is based on a "best guess" under guidance from Ea Energy Analyses [11] as well as the article "The Half-Normal distribution method for measurement error: two case studies" [8]. This is likely a reasonable assumption, though obviously the error must be truncated such that a forecast error will newer result in negative demand. From the article an estimate of the size of the normalized standard deviation is produced by a relation between the assumed MAPE = 1.9%(shown in figure 2.3) and the normally distributed standard deviation as:

$$MAPE = \sqrt{\frac{2}{\pi}}\sigma \Leftrightarrow \sigma = MAPE \cdot \sqrt{\frac{\pi}{2}}\sigma = 1.5\% \cdot \sqrt{\frac{\pi}{2}} = 1.9\% \qquad (5.1)$$

Future work could implement a more scientific analysis on the behaviour on demand forecast errors. However, it was decided for the purpose of this thesis that assuming a normally distributed forecast error will be adequate. In figure 5.2 the electricity demand is presented with ± 3 standard deviation as $\mu_{demand} + X\sigma, \quad X = \{-3, -2, ..., 3\}$:

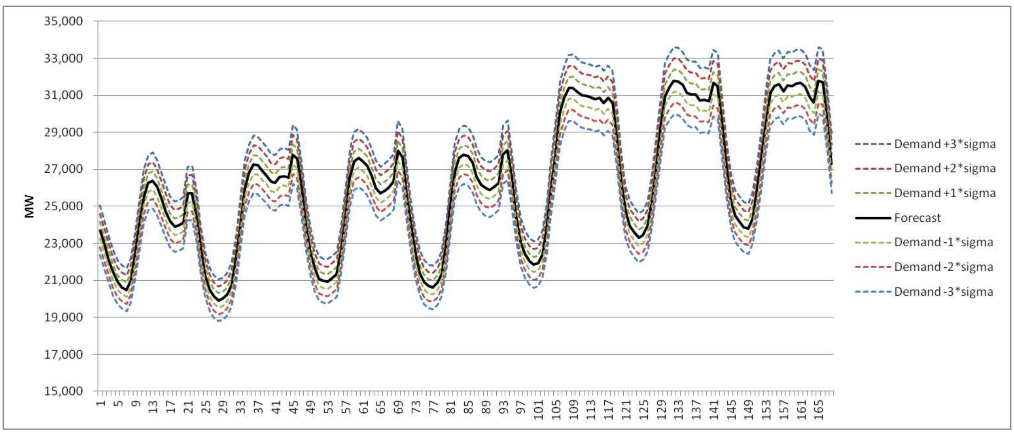

Figure 5.2: Hourly forecast on electricity demand $\pm 3\,\sigma$ for one week.

As previously stated the fluctuations in electricity demand create the need for both an up- and downregulation reserve. The imbalance contribution to each are presented by forecast errors. To estimate the imbalances from electricity demand it was chosen to generate 4000 random numbers X_z to simulate the forecast error from the normal distribution with $\mu = 0$ and $\sigma = 1.9\%$, meaning that $X_z \in \mathcal{N}\{0, 1.9\%\}$. The sample size of 4000 is chosen for all simulation to be able to combine the imbalances from each contribution. The amount of imbalance in MW X_z^d at a time step t is then given as $X_z^d = X_z \cdot D_t^e, \forall t$ where D_t^e is the forecast of total electricity demand. By performing this type of simulation it is possible to estimate the fluctuations that form the reserve requirement from electricity demand. It must be mentioned that this is a very pragmatic approach to estimate the forecast errors. A more mathematical solution to represent the probability function of the forecast error could be chosen. However, empirical studies showed that a sample size of 4000 randomly generated numbers worked well to represent the forecast errors.

Ultimately, it is possible to generate the reserve requirement X_q^d from electricity demand using the simulated randomly generated forecast errors X_z^d for the chosen quantiles q by the probabilities $P(q)$ equivalent to the amount of the forecast errors in each quantile. This is done for every time step. In figure 5.3 this can be seen for a week:

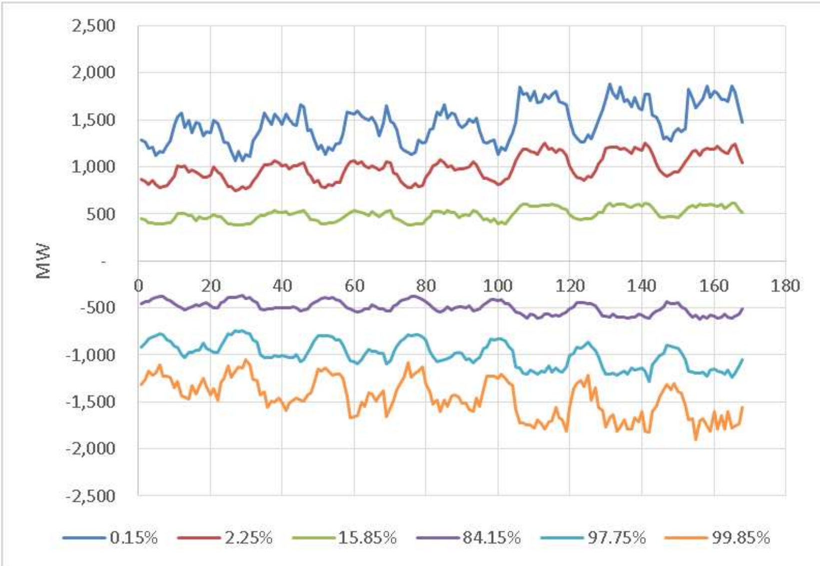

Figure 5.3: Generated quantiles for the imbalances from electricity demand forecast error in one week.

5.1.2 Wind Power

The predicted wind power generation is given as installed capacity with a corresponding variation profile for each area at every time step. In the same way as described with electricity demand above the forecast wind power generation is calculated for the whole system in all time steps. A study on the historical data [1] for forecast errors on wind power generation has showed the following relation between forecast error and normalized generation:

[1] Historical data for forecast errors on wind power generation was provided by Energinet.dk [15]

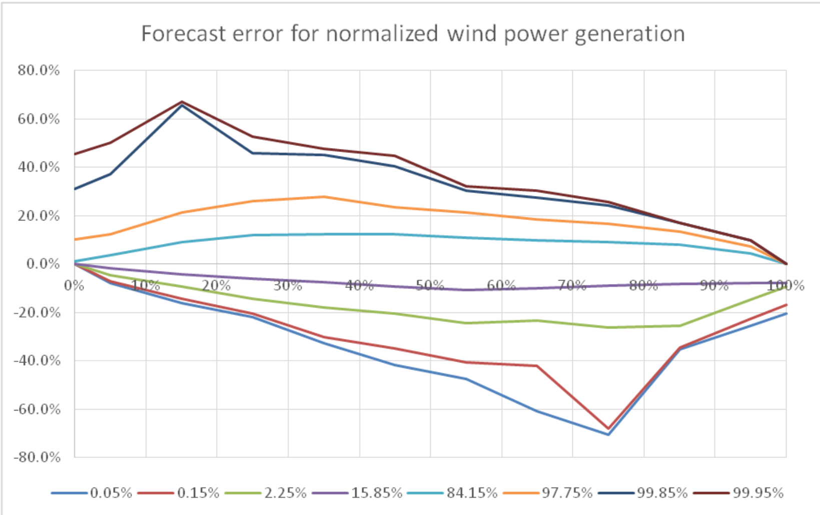

Figure 5.4: Relation between forecast error and forecast normalized by installed wind power capacity.

This shows a logical asymmetry on the forecast error as a function of the forecast level of wind power generation. As wind power generation approached 100% of maximum capacity the likelihood of more generation is negligible while the likelihood of less possible power is considerable. In other words, if forecast predicts maximum generation then a forecast error ultimately resulting in an upregulating is non existing. Conversely, as the forecast is close to 0 (no generation) there is disappearing likelihood of less generation and considerable likelihood of more. In table 5.1 the relation between forecast errors and the normalized forecast in wind power generation is shown. The table is based on 2.5 years of data (44561 data points) from NordPool Spot of the realized wind power generation and forecast errors in Denmark. The forecast errors are divided into quantiles described the magnitude in relation to realized generation:

q \ Forecast	**100%**	**85%**	**65%**	**45%**	**25%**	**5%**	**0%**
0.15%	-16.7%	-34.6%	-42.1%	-34.7%	-20.5%	-7.3%	0.0%
2.25%	-9.2%	-25.5%	-23.3%	-20.4%	-14.3%	-4.5%	0.0%
15.85%	-7.8%	-8.1%	-10.0%	-9.4%	-6.2%	-1.8%	0.0%
4.15%	0%	8.0%	10.0%	12.3%	12.1%	3.8%	1.1%
97.75%	0%	13.2%	18.3%	23.5%	25.9%	12.2%	10.2%
99.85%	0%	17.0%	27.5%	40.5%	45.7%	37.3%	30.9%

Table 5.1: Relation between forecast error and normalized forecast in wind power generation.

This is used to generate an estimate for a probability function for wind power forecast error. Given a forecast dictated by the wind variation profile in a time step this can be viewed as a normalized forecast in relation to total installed capacity. Comparing this to table 5.1 a estimated probability function can be made by interpolation. It must be mentioned that this a done as a pragmatic approach to estimate the forecast error distribution and is not a complete statistical solution of finding a mathematical expression for wind power forecast errors. Using the quantiles as seen in table 5.1 for forecast errors a discretization is constructed to generate the hourly probability function divided into each quantile. Thus, a normalized forecast can in relation to the forecast error seen in 5.4 be used to create a discrete probability function for the related forecast error.

Again a sample size of 4000 point are randomly generated in order to simulate the imbalances from wind power generation by the forecast errors. Using the discrete probability function for the forecast at each time steps the simulations are divided into the quantiles q with the probabilities $P(q)$ thus producing an amount of imbalanced wind power generation X_q^w representing the contribution to the reserve requirement. Assuming the forecast represents the 50% quantile the reserve requirements from wind power generation can now be seen as:

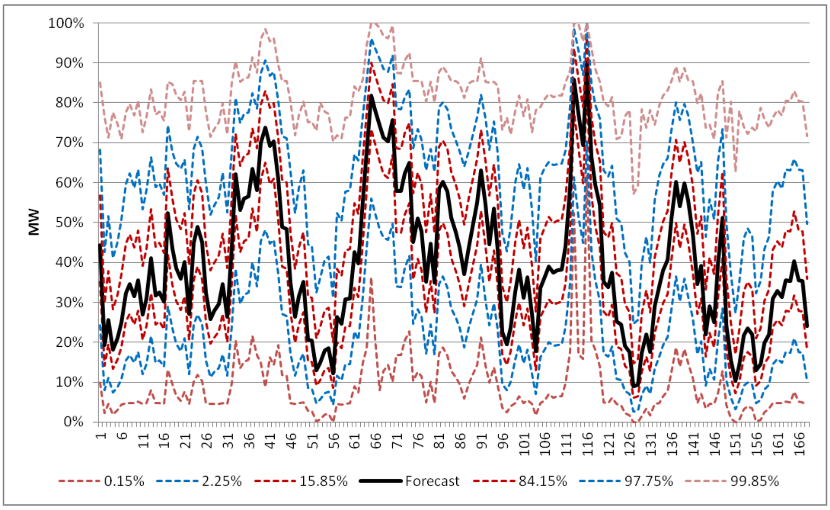

Figure 5.5: Hourly wind power forecast and forecast errors in one week.

Figure 5.5 shows how the magnitude of the forecast error is inversely proportional to the normalized wind generation as expected based on the relation shown in figure 5.4. Furthermore, in figure 5.6 the reserve requirement from wind power generation is shown in MW.

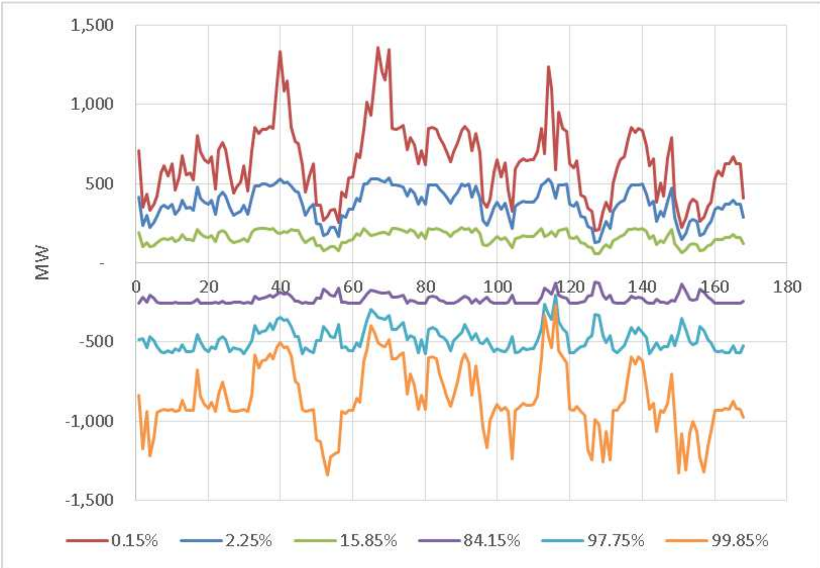

Figure 5.6: Generated quantiles for the imbalances from wind power generation forecast error in one week.

5.1.3 Forced Outages

The imbalance of the generation units by forced outages arrives from the likelihood of the cumulated loss of generation capacity from all units. In a time step the imbalance is represented by the loss of generation capacity of units that are actually generating power i.e. units that are not on-line will not create the need for an upregulating reserve. Thus, to be able to estimate the imbalances from forced outages some assumption on the on-line units in a time step must be made. In a time step a certain forecast of electricity demand exist as described above. For each time step the electricity demand must be covered by generation units and wind generation (assuming storage and other technologies are ignored). This is done in an Excel spreadsheet where a number of units are estimated to be on-line in a time step in order to be able to satisfy electricity demand. Firstly, the units are chosen such that the cheapest unit is committed first. In cheapest is meant the unit with lowest short term marginal cost in form of variable O&M and fuel price.

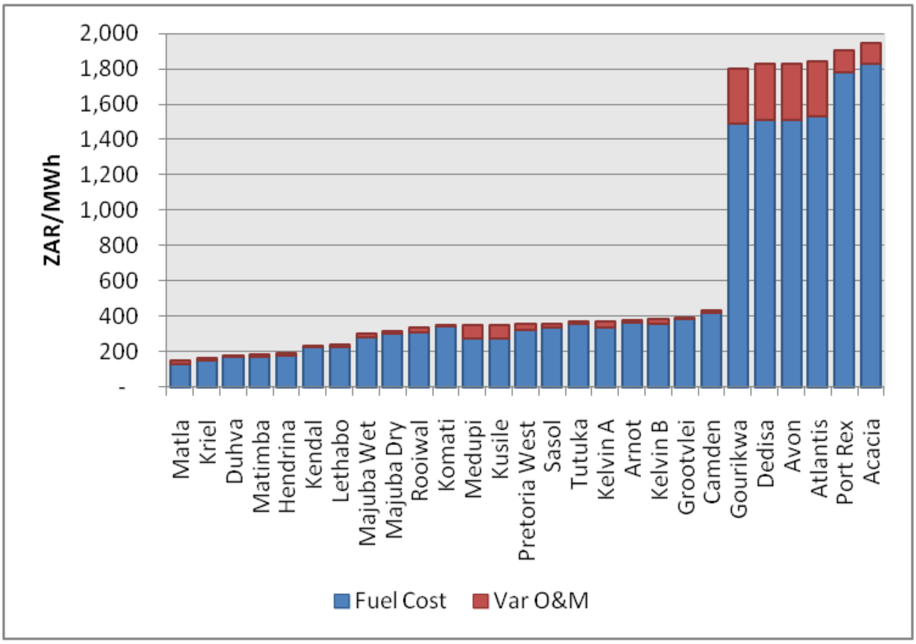

Figure 5.7: Short term marginal costs in 2009 Rands (South African currency) of generation for regulating units.

The data for each unit can be seen in appendix A.4.1. If a unit can not satisfy demand then another unit is committed with the second lowest marginal cost and so on. Secondly, the demand needed to be satisfied by the committed units is not the complete electricity demand. Since wind power exist in the system then the wind generation in the time step will help satisfy some of the demand. However, though the forecast on wind power generation predicts an amount of wind power it is not certain that this will be the realized generation. Thus, it is chosen to only subtract 50% of wind power generation from the electricity demand to represent the uncertainty of wind power generation. This might seem extreme in relation to the forecast error of around 2% but in a system where wind power does not constitute a majority as in the South African power system it is more likely to commit a surplus of capacity in order to regulate the smaller imbalances of wind power generation. Furthermore, in relation to real life dispatch this is an expected conservative attitude in the dispatch centres. In the South African electricity 2055 MW of wind power exist in a system of 54 GW of generation capacity. This can be formulated as:

$$\sum_{a,g^{bal}} (G^{kfx}_{y,a,g^{bal}}) \geq \sum_{r} (D^{evart}_{r,t} \cdot D^{e}_{r}) - \sum_{a,g^{wnd}} V^{forecast}_{a,g^{wnd},t} \qquad \forall y, t \qquad (5.2)$$

where g^{bal} are the units needed to satisfy the right hand side, g^{wnd} are wind power technologies and $V^{forecast}_{a,g^{wnd},t}$ is the forecast in generation capacity for g^{wnd} in area a at time step t. Thus, a number of units is chosen in each time step to be committed. These are the units from which the imbalances from forced outages are estimated.

To represent the imbalances from forced outages in a time step the loss of generation capacity is given by the cumulative probability of forced outage on each unit in that time step. This is done to produce an estimated (discrete) probability function for the forced outages.

When viewing the imbalances between forecast and realised dispatch on an hourly basis then the probability of a forces outage on a unit is equal to the failure rate as described in chapter 3 and from 3.1 and 3.11 the failure rate λ is given as:

$$\lambda = \frac{FOR}{MRT \cdot (1 - FOR)} \qquad (5.3)$$

Furthermore, the estimated forced outage capacity in a time step must be the sum of the probability of forced outage given by λ multiplied with the corresponding capacity. In total 145 units exist in the South African power system that are considered able to regulate imbalances. Some generation type are not included. These are nuclear power plants, hydro power plants, wind power and solar photovoltaic. The reason for this is that hydro and solar power generation is dictated by the climate and thus not used to regulate imbalances because of their fluctuation nature. Nuclear power plants are slow in regulation and start up and well as expensive hence these will newer be used to regulate imbalances in the system. Wind power imbalances are handled separately as described above. The 145 balancing units can however be reduced into grouped units. Most of the units are actually units in the same plant e.g. different turbines on a power plant. These have identical (or very similar) technological attributes e.g. capacity, FOR and marginal operation cost.

Hence, these can be modelled as a group of units rather than singular units. In figure 5.8 the grouped units needed to satisfy the demand - 50% of wind generation are shown.

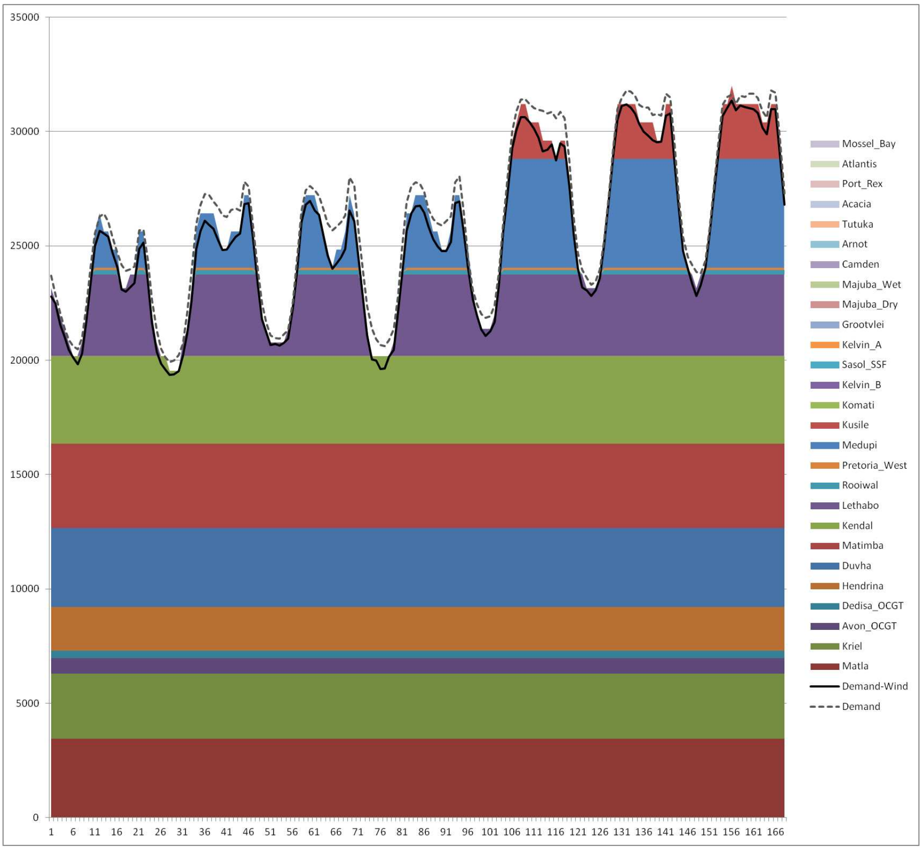

Figure 5.8: Hourly committed units to satisfy demand minus 50% wind power in one week.

When grouping units the possibility of a forced outage from grouped units can be found using the binomial distribution $X_n \sim B(n, f_r)$ where X_n follows the Binomial Distribution for n units with failure rate f_r. For each group of units the probability of k failures are given as:

$$P(X_n = k) = \binom{n}{k} p^k (1-p)^{n-k} \tag{5.4}$$

Consequently, to estimate the probable amount of loss in capacity in a time step by the sum of probabilities of failure for all committed units (or grouped units) in a time step. By simulating this for each hour with a sample size of 4000 an amount of loss in capacity due to forced outages X_q^o can be found for the quantiles q with the probability $P(q)$ constituting the reserve requirements from forced outages. As previously stated, forced outages does not create the need for a downregulating reserve. Correspondingly, no sample will generate a negative amount of loss in capacity. Again, 50% relative to the quantiles represent no imbalance, then only q_1, q_2 and q_3 will constitute the reserve requirement from forced outages. In figure 5.9 the reserve requirements are shown for a week for the quantiles q:

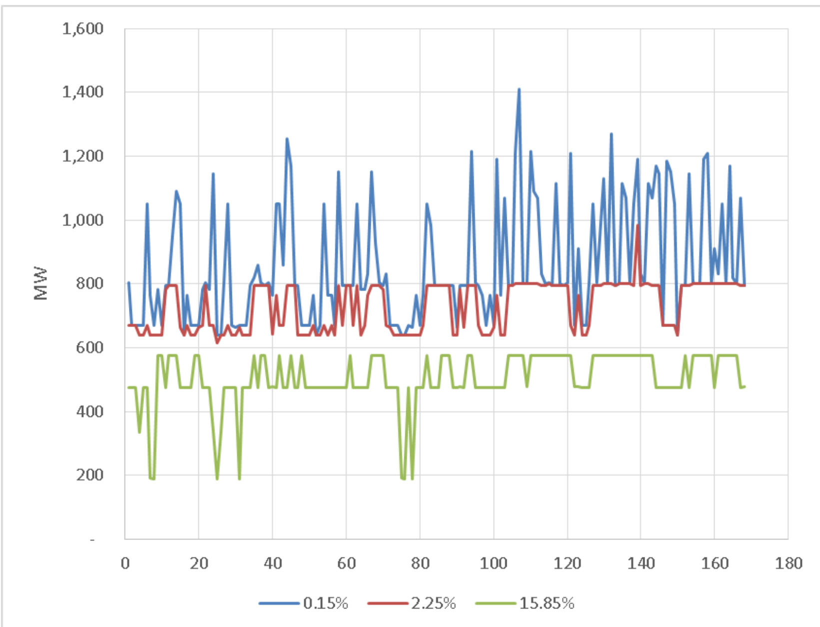

Figure 5.9: Hourly reserve requirements for forced outages in one week.

This shows that there will always be a need for an upregulation reserve. With the presented probability there is no time step where forced outage capacity is 0. This is a consequence of having a large number of units. If fewer units existed the probability of no forced outages would be higher.

5.1.4 Total Reserve Requirement

Above the contribution from each imbalance was described. To find the total reserve requirement the same approach is used to express an amount of up- and downregulating reserve by quantiles q with a probability $P(q)$. Again assuming that 50% is seen as the mean where no reserve requirement is needed i.e. no forecast error exist and no forced outages occur it is possible to calculate the reserve requirement by the combined pragmatically estimated probability functions for each imbalance contribution. As seen above the sample size of 4000 randomly generated occurrences of imbalance is chosen. The total reserve requirement is given as the amount of imbalances from each of the contributions $X_z^{res} = X_z^d + X_z^w + X_z^o$ where X_z^{res} is the total reserve requirement for a simulated random event of imbalances in the system. Now, the occurrence of an imbalance can originate from any one of wind power, demand or forced outages or as a sum of several imbalances. Thus, one of the sample points to represent the total imbalance is given as the sum of a sample point from each of the three imbalances wherein a reserve requirement from wind power generation might be positive while the reserve requirement from demand is negative and no forced outages exits. The sample size of 4000 randomly generated occurrences gives a reasonable representation of possible combinations of total imbalances. This is done for all time steps and divided into the the quantiles q with the probability $P(q)$. In figure 5.10 and figure 5.11the total reserve requirement are shown for one quantile to demonstrate the contributions from each imbalance.

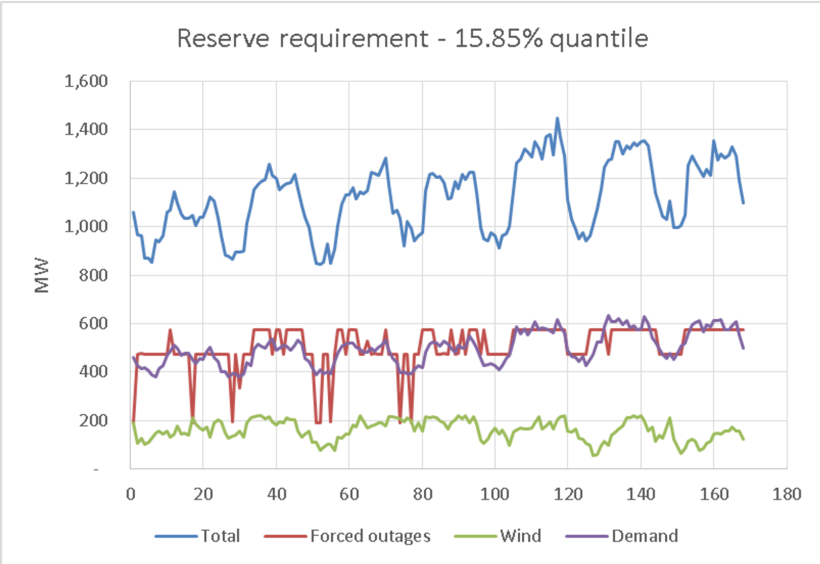

Figure 5.10: Hourly reserve requirements for one week in quantile q_3.

Here the reserve requirements for the most probable upregulating reserve requirement quantile q_3 with probability $P(q_3) = 15.85\%$ is demonstrated. It can be seen that the fluctuations on demand and the forced outages produce the largest contribution to the reserve requirement whereas wind power generation is not an equally large source of imbalance. This is obviously a consequence of the limited capacity of wind power in the South African system. In the future the amount of renewable energy capacity is growing which will lead to a larger contribution of reserve requirement from wind power.

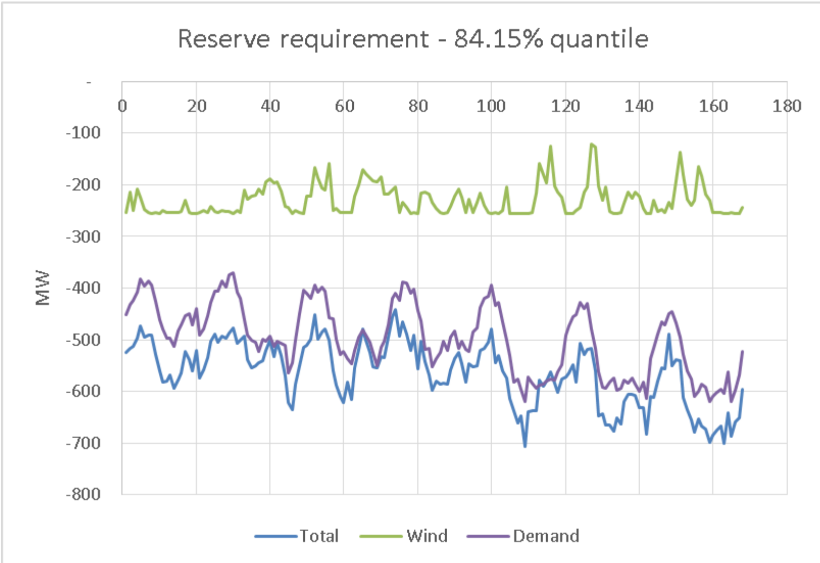

Figure 5.11: Hourly reserve requirements for one week in quantile q_4.

Here the downregulating reserve requirement quantile q_4 with probability $P(q_4) = 84.15\%$ is shown. Here the demand clearly dictated the majority of the reserve requirement. The reason the sum each contribution does not add up to the sum of the total reserve requirement is the this the combined probability of an imbalance in each quantile not the sum on the quantiles from each contribution. The total reserve requirement in MW for all quantiles are presented in figure 5.12:

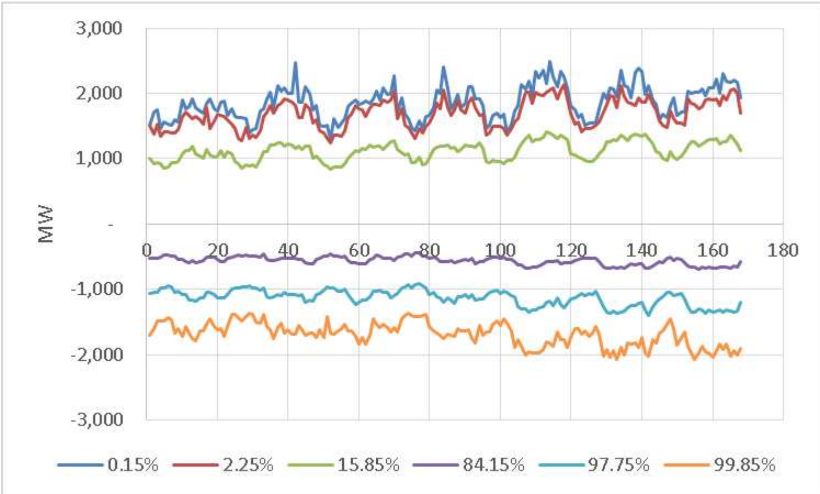

Figure 5.12: Hourly total reserve requirement for one week in quantiles.

This is the total reserve requirement for the entire power system in one week. In it seen that there is little difference between the 0.15% (q_1) and 2.25% (q_2) quantile. Meaning that in the most extreme cases the upregulating reserve requirement is not subject to massive increase as could be feared. On the other hand, the downregulation reserve seems to grow considerately in the most improbable cases.

The reserve requirements were calculated for the entire system. The reason for this is the pragmatic approach to calculating the reserve requirement. Using randomness to estimate probability of imbalance with a sample size of 4000 for both wind power, demand and forces outages in 168 time step is computational hard for the Excel Spreadsheet. To give an even better estimate of the reserve requirements this should be done for each region and not the entire system. Thereby producing a more statistical viable estimate by the units, demand and wind power capacity in the system. Due to the time consuming task of generating 4000 random point for 3 imbalances in 168 time steps for 52 weeks and 9 regions resulting in a minimum of 900 million computations is was chosen to calculate the imbalances for the system as a whole. Furthermore, if it was chosen to calculate reserve requirement on a regional level, then the probability of imbalance from each region should also be combined. To create an input to the Balmorel model for the reserve requirement on a regional level a way of dividing the total reserve requirements must be chosen. The upregulation reserve requirements for each region is based on the percentage of installed regulation capacity in relation to the entire system. This is done based on figure 5.10 where the forced outages seemed to represent a major part of the reserve requirement. This is an assumption which seems fair in relation to the uncertainty of the imbalances since is impossible to predict the exact location and size of the imbalances but possible to estimate the total magnitude. The downregulation reserve requirements are divided into regions based on their demand as figure 5.11 showed that demand forecast errors constituted the majority of the imbalance cause.

5.2 Reserves Equations

In chapter 5 the entities of the up- and downregulation reserves were stated. These are implemented into the Balmorel model to satisfy the reserve requirement described above. In order to formulate the equations of reserve modelling in the model a terminology must be presented:

Sets:

- g^{bal}, Technologies able to regulate imbalances, $g^{bal} \subset G$
- g^{wnd}, Wind technologies able to regulate imbalances, $g^{wnd} \subset G$ and $g^{wnd} \subset g^{bal}$
- q, Quantiles, used for representing reserve requirement

Parameters:

- Q_q^{prob}, Probability of quantile q
- ACT_q^{prob}, Activation probability for quantile q, the likelihood that a reserve is activated with-in a time step
- $RESREQ_{r,t,q}^{up}$, Upregulating reserve requirement in region r at time step t for quantile q in MW

- $RESREQ^{down}_{r,t,q}$, Downregulating reserve requirement in region r at time step t for quantile q in MW
- $WND^{var}_{a,t}$, Variation profile for wind power generation in area a at time step t
- WND^{flh}_{a}, Full load hours for wind power generation in area a
- G^{kesto}_{a} Electricity storage loading capacity in area a in MW

Variables:

- $V^{xup}_{r_1,r_2,t,q}$, Upregulating reserve capacity from region r_1 to r_2 in time step t for quantile q in MW
- $V^{xdown}_{r_1,r_2,t,q}$, Downregulating reserve capacity from region r_1 to r_2 in time step t for quantile q in MW
- $V^{resup}_{a,g^{bal},t,q}$, Upregulating reserves available in area a at time step t for quantile q in MW
- $V^{resdown}_{a,g^{bal},t,q}$, Downregulating reserves available in area a at time step t for quantile q in MW

These sets, parameters and variable in help formulate the equations of the reserve formulation.

5.2.1 Model Constraints

The reserves needed to satisfy the reserve requirement described above is presented in the following.

Transmission of electricity between regions can act as reserve to compensate for imbalances in the system. If an upregulating reserve is needed in a region then an increase in transmission of electricity from another region can be used as a reserve or a decrease of planned transmission out of the region ($V^{x}_{r_1,r_2,t}$) where the imbalance exist can also act as a reserve. The contribution to the upregulating reserves from transmission from one region to another is given as a variable $V^{xup}_{r_1,r_2,t,q}$ and is defined as

$$(X^{cap}_{r_1,r_2} \cdot X^{kderate}_{r_1,r_2}) - V^{x}_{r_1,r_2,t} + V^{x}_{r_2,r_1,t} \geq \sum_q V^{xup}_{r_1,r_2,t,q}, \qquad \forall (r_1, r_2) \in R, t \tag{5.5}$$

saying that the total transmission capacity from a region to another (derated by $X^{kderate}_{r_1,r_2}$) minus the planned transmission out of the region plus the planned transmission into the region will define the upper limit for the upregulating reserve between to regions for each quantile q.

Conversely, the downregulating reserve that can help regulate a surplus in a region. The planned transmission out of the region can be increased or the planned transmission into the region can be decreased limited by the total transmission capacity.

$$(X^{cap}_{r_1,r_2} \cdot X^{kderate}_{r_1,r_2}) + V^{x}_{r_1,r_2,t} - V^{x}_{r_2,r_1,t} \geq \sum_q V^{xdown}_{r_1,r_2,t,q}, \qquad \forall (r_1, r_2) \in R, t \tag{5.6}$$

In time steps where curtailment exist wind power generation can also act as a upregulating reserve by increasing generation. The maximum generation of wind power in an area is determined by the variation profile and the full load hours. The term $\frac{WND^{var}_{a,t}}{\sum_t WND^{var}_{a,t}} \cdot WND^{flh}_{a}$ is an expression for the maximum wind power generation in a time step. Norming the profile multiplied with the full load hours in a time step will produce the actual possible wind power generation for installed wind power capacity in the area. By subtracting the planned generation of wind power the contribution to the upregulating reserves in an area at a time step is found.

$$G^{kfx}_{y,a,g^{wnd}} \cdot \frac{WND^{var}_{a,t}}{\sum_t WND^{var}_{a,t}} \cdot WND^{flh}_{a} - V^{e}_{a,g^{wnd},t} \geq \sum_q V^{resup}_{a,g^{wnd},t,q}, \qquad \forall a, g^{wnd}, t \tag{5.7}$$

In the model GAMS has the ".up" functionality that can be used to represent the upper limit on a variable. In the implementation this is used to represent the upper limit for wind power generation $V^{e}_{a,g^{wnd},t}$

instead of the formulation described above. This can be done since the maximum wind power generation formulation already exist in the "main" of the Balmorel model constraints.

Wind power generation can also act as a downregulating reserve. If a surplus of electricity exist then wind power generation can be shut down. Thus, the planned wind power generation $V^{e}_{a,g^{wnd},t}$ can contribute to the downregulating reserves as:

$$V^{e}_{a,g^{wnd},t} \geq \sum_{q} V^{resdown}_{a,g^{wnd},t,q}, \qquad \forall a, g^{wnd}, t \tag{5.8}$$

The main contribution to the reserves is represented by the generation units. The regulations in generation are crucial to counteract the imbalances. For the upregulating reserve these are units that can increase generation or start up. These combined with upregulating capacity from electricity storages contributes to the upregulation reserves $V^{resup}_{a,g^{bal},t,q}$ as seen below:

$$G^{kfx}_{y,a,g} \cdot G^{kderate}_{a,g,t} - V^{e}_{a,g,t} + G^{kesto}_{a} + V^{estoloadt}_{a,t} \geq \sum_{q} V^{resup}_{a,g,t,q} \qquad \forall a, g \in \{g^{bal} \setminus g^{wnd}\}, t \tag{5.9}$$

stating that the amount of upregulating reserves is determined by the difference between maximum generation capacity and planned generation for each unit in an area plus the storage loading capacity plus the planned loading into storage. The Balmorel model does not offer a storage chronology. This means that the amount of regulation from storage is expressed by hours it takes to load or unload to the storage. This is a reasonable simplification but not entirely accurate and thus leading to a reduced reserve regulation capacity from electricity storage.

The downregulation reserve contribution from generation units and storage is seen as

$$V^{e}_{a,g,t} + G^{kesto}_{a} - V^{estoloadt}_{a,t} \geq \sum_{q} V^{resdown}_{a,g^{bal},t,q} \qquad \forall a, g^{bal} \wedge \not g^{wnd}, t \tag{5.10}$$

stating the downregulating reserves are limited by the planned generation plus the storage loading capacity minus the amount loaded into storage.

Here all contributions are combined to create the total upregulating reserves needed to satisfy the upregulating reserve requirements:

$$\sum_{r_1} V^{xup}_{r_1,r,t,q} - \sum_{r_2} V^{xup}_{r,r_2,t,q} + \sum_{a \in A_r, g^{bal}} V^{resup}_{a,g^{bal},t,q} = RESREQ^{up}_{r,t,q}, \qquad \forall r,t,q \tag{5.11}$$

stating that upregulating reserves by transmission into the region minus upregulating reserves by transmission out the region plus the upregulation reserves from units within the region must satisfy the upregulation reserve requirement in the region. This applies for all regions at all time step for each quantile.

In the same way, this is also done for the downregulation reserves:

$$\sum_{r_1} V^{xdown}_{r_1,r,t,q} - \sum_{r_2} V^{xdown}_{r,r_2,t,q} + \sum_{a \in A_r, g^{bal}} V^{resdown}_{a,g^{bal},t,q} = RESREQ^{down}_{r,t,q}, \qquad \forall r,t,q \tag{5.12}$$

stating that downregulating reserves by transmission into the region minus downregulating reserves by transmission out the region plus the downregulating reserves from units within the region must satisfy the downregulating reserve requirement in the region. Again for all regions at all time step for each quantile.

These constraints are implemented in the Balmorel model and can be seen in appendix A.3.

5.2.2 Reserve Costs

The balancing technologies that form the reserves needed to satisfy the reserve requirement are as any other technologies in the model subject to operation costs, taxes etc. Thus, the costs of generation on reserve technologies g^{bal} must be added to the objective function. These are the same cost as earlier described in the objective function in chapter 4 in 4.11 through 4.18.

- Fuel price

- Variable O&M costs
- Fuel taxes
- Emissions taxes (CO_2, SO_2, N_2O)
- Transmission costs

However, the fixed O&M as seen in 4.13 has already been paid for all installed units. Since the reserve requirement are given as an amount with a corresponding probability for each quantile, then obviously the costs will also be subject to the corresponding activation probability. Thus, the costs are added to the objective function for both the up- and downregulating variables $V^{resup}_{a,g^{bal},t,q}$ and $V^{resdown}_{a,g^{bal},t,q}$ here given in simplified terms:

$$\sum_{g^{bal},f,q} \eta_{g^{bal},f} \cdot (V^{resup}_{g^{bal},q} - V^{resdown}_{g^{bal},q}) \cdot ACT^{prob}_{q} \tag{5.13}$$

Where η represents the short run marginal generation costs per MWh mentioned above. The implementation can be seen in appendix A.3.

5.3 Summary

Above the modelling of reserves were formulated. It was described how the imbalances were expressed as a reserve requirement and the reserves needed to satisfy these were formulated. It was shown how to combine imbalances produced by different estimated probability function to form a reserve requirement for the model. A reserve requirement needed to be able to perform model runs as described in chapter 7.

The implementation into the Balmorel model was done in GAMS. It should be mentioned that the equations above are not only reformulated into GAMS syntax but the representation of some terms in the equations are modified to suit the terminology and mechanics of the Balmorel model.

Chapter 6

The South African Power System

To help analyse the implementation of the reserves and reserve requirement the South African power system was chosen as a case. In this chapter the South African electricity system will be briefly explained. All data to represent the South African electricity system was provided by Ea Energy Analyses [11].

The Balmorel model was created such that changes in geographical location will not have an impact on model constraints, objective function, terminology etc. Only input data in form of geographical sets; areas, regions, countries and data used to represent generation units, transmission, demand, taxes, restrictions on emissions and so on will define the South African power system. Even though the Balmorel model is typically used in a CHP system it presents no difficulties or faults in only representing an electricity system.

The South African power system (SAPS) was chosen to represent the modelling of reserves because of the simplicity of the model set-up. In energy systems with CHP units the combined generation of heat and electricity on individual units will in the complexity of the whole system sometimes lead to "mysterious" results, interesting as they are, they might remove focus from the effects of the reserve modelling and make it difficult to differentiate between effects of the different entities in the model. Additionally, the generation unit catalogue of the SAPS is somewhat limited meaning that most unit types are similar within each fuel type. This leads to a model set-up that will work well in analysing new implementation.

In South Africa the climate does not create the need for a district heating system. All heating is done using electricity or locally, disconnected from the system. So no reserve requirements exist for heat generation in South Africa.

The model data representing South Africa is divided into 9 regions. These can be seen in figure 6.1.

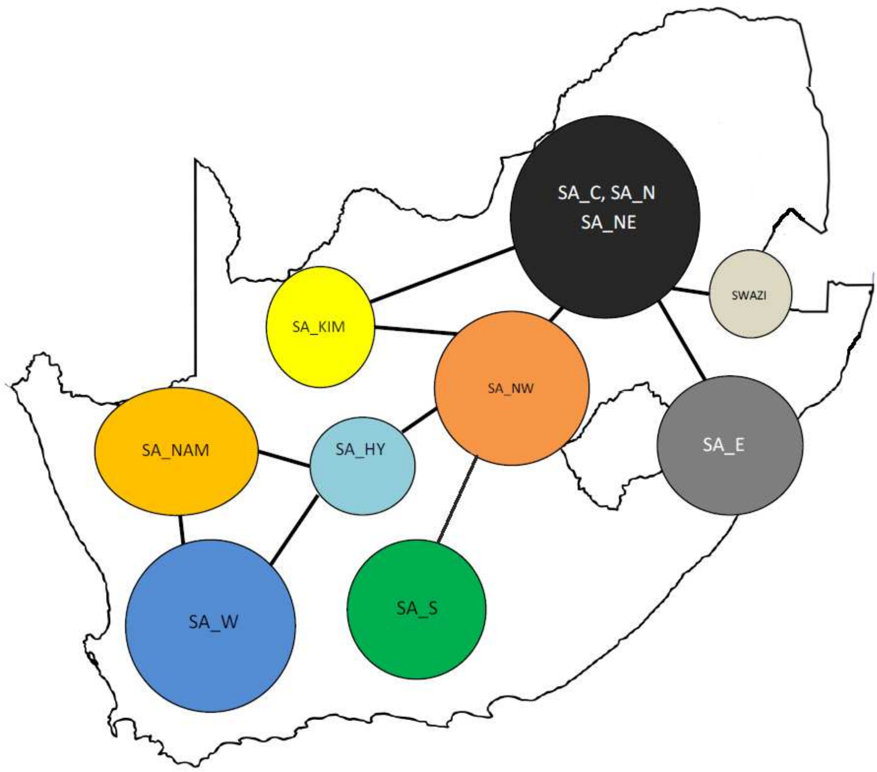

Figure 6.1: Illustration of regions of the South African power system in the Balmorel model.

The lines between regions represent the transmission lines available in the model. Transmission capacity and cost between regions can be seen in appendix A.4.1.

The electricity demand is given for each region and can be seen here:

Region	Electricity demand (TWh)
SA_NAM	1.0
SA_KIM	5.4
SA_NW	12.2
SA_S	14.1
SA_W	28.5
SA_E	45.2
SA_N	45.7
SA_NE	54.7
SA_C	69.8
Total	276.6

Table 6.1: Annual electricity demand by region in TWh.

To satisfy this demand the installed capacity is given in terms of fuel type as:

Region	Coal	Diesel	Nuclear	Hydro	Wind	Solar
SA_C	4926					
SA_E	3843	670				
SA_HY				360		
SA_N	7660					206
SA_NE	26913					
SA_S		506		305	1431	361
SA_W		2115	1800		624	86
SA_KIM						781
SA_NAM				24		129
SA_NW				10		183
Total	43342	3291	1800	699	2055	1746

Table 6.2: Installed capacity by fuel in MW.

In appendix A.4.1 a list of all technologies can be found. The majority of the SAPS consists of condensing coal power plants. The fuel prices can be seen here:

Fuel type	Rand/GJ
Nuclear fuel	90.0
Wood chips	150.0
Coal_Matla	256.6
Coal_Kriel	300.5
Coal_Hend	308.3
Coal_Duvha	321.2
Coal_Matim	335.9
Coal_New	420.8
Coal_Kenda	432.3
Biogas	433.3
Coal_Rooiv	440.9
Coal_Pret	440.9
Coal_Letha	442.6
Coal_KelA	470.2
Coal_Arnot	471.0
Coal_Komat	484.0
Coal_Sasol	492.6
Coal_KelB	512.4
Coal_Groot	577.0
Coal_Majub	589.0
Coal_Camde	651.0
Coal_Tutuk	745.7
Natural gas	1106.1
Fuel oil	1293.7
Diesel	2281.7

Table 6.3: Fuel price in Rand/GJ.

The different coal prices are used for the individual plants. In South Africa each power plant normally has an agreement with a coal supplier. The fuel price is then dictated by transport length, quality of fuel and cost of mining.

Unit Commitment

The model uses unit commitment meaning the activation of binary variable. This is done as an activation variable stating when a unit is committed. The reason for this is to represent start up costs and to formulate a minimum capacity. When a unit is committed it has a minimum amount of generation. The data for the unit commitment is shown in appendix A.4.1.

In appendix A.4.1 more data used to represent the SAPS can be found. For a more thorough description of the representation of the SAPS in the Balmorel model, see [12] where a project performed by Ea Energy Analyses called "Costs and benefits of implementing renewable energy policy in South Africa" demonstrated the use of the Balmorel model on the South African power system.

Chapter 7

Analysis

In the following chapter the results from the model runs are presented in order to answer the research questions asked to analyse the implementation of reserves.

The data for the South African power system was used as model set-up for the Balmorel model. It was chosen to create model runs for the year 2016 since Ea Energy Analyses provided an elaborate data foundation for this year. The model runs were performed for all hours, 8736 hours in total, for each model run R1-R5 as described in chapter 2. In order to calculate the start-up costs and represent minimum generation capacity for committed unit, it was chosen to use unit commitment in the Balmorel model. This requires the solution to be found using MIP. However, when running the model the with 8736 time steps this proved computational difficult and run times were too excessive. For that reason, it was chosen to run the model using Relaxed Mixed Integer Programming (RMIP). The RMIP is the same as the MIP problem in all respects except all the integer restrictions are relaxed. This is a source of misrepresentation of the commitment of units and must be considered as a possible error in the results.

The results from each model run will be shown below in relation to the research questions shown in table 2.1. All economic result are given in Euro 2011 currency unless other information is given. The results are presented for the entire system for each model run to illustrate the costs and effects. The model runs R1-R5 are repeated below to enhance readability of this chapter:

- R1: Basis model run without reserves requirements
- R2: Model run with total reserve requirement
- R3: Model run without wind power imbalances
- R4: Model run without electricity demand imbalances
- R5: Model run without forced outage imbalances

In the following each research question, seen in table 2.1, will be examined and answered based on the results from the model runs and the experiences from estimating the reserve requirement.

7.1 Basis Model Run

Firstly, the basis model run is briefly presented. This is the basis model run, where the reserve requirement is not included nor the representation of reserve. The basis model run is used to analyse the economic effects of adding a reserve requirement to the Balmorel model. To demonstrate the effects of introducing reserves in the Balmorel model, some general results from the basis run R1 are presented.

As stated previously, the electricity demand must be satisfied in each region by generation, electricity storage and transmission. In figure 7.1 the annual electricity generation is shown.

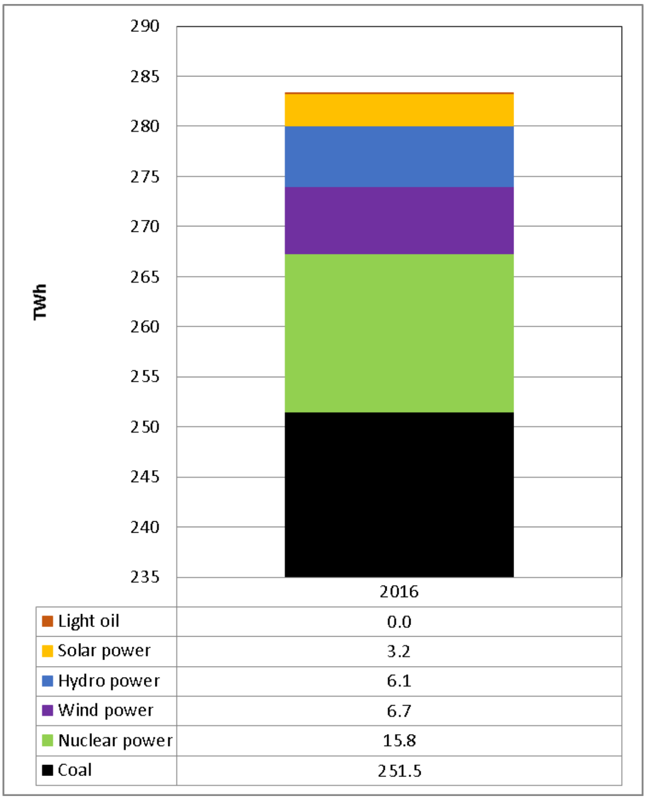

Figure 7.1: R1: Annual electricity generation in TWh by fuel.

As seen, coal fuelled power plants and nuclear power provides the majority of the electricity generation. The coal fuelled power plants are all regulation units g^{bal}. The hourly electricity generation for coal fuelled power plants are showed in figure 7.2 for one week.

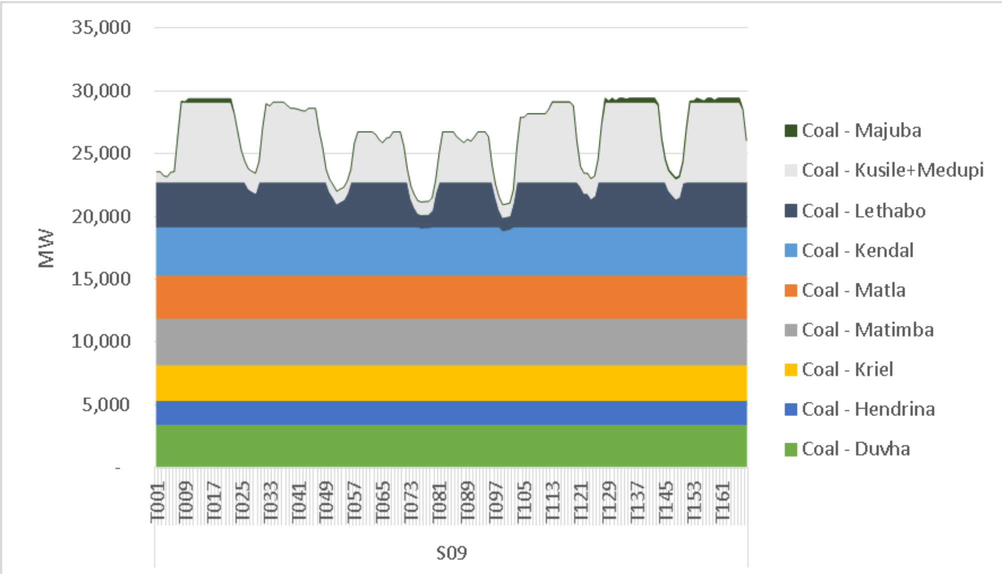

Figure 7.2: R1: Electricity generation in MW for coal fuelled power plants in one week.

It can be seen that the generating units in this week are units with low short term marginal cost, which corresponds with figure 5.7. As expected the units with low short term marginal costs will be committed first.

The total annual costs of the entire South African power system is shown in table 7.1.

	R1: Basis model run
Fixed O&M	26506
Variable O&M	6568
Fuel Costs	53566
Start-up Costs	4.94
Total costs	86645

Table 7.1: R1: Total annual cost in million Euro.

Previously, it was stated that emission costs would apply to the total costs. In present day, no taxes exist for emissions in South Africa. However, emission taxes for CO_2 will soon be introduced into the South African Power System. More on this in the following. Dividing results seen in table 7.1 with the annual electricity generation will produce the system operations costs, see table 7.2.

Per MWh	R1	R2	R3	R4	R5
Fixed O&M	76.5	76.3	76.3	76.4	76.3
Variable O&M	23.1	23.2	23.2	23.2	23.2
Fuel Costs	173.8	174.5	174.4	174.3	174.4
Start-up Costs	0.02	0.02	0.02	0.02	0.02
Total costs	273.5	274.0	274.0	273.9	274.0

Table 7.2: Total operational costs for all model runs in million Euro/MWh.

The system operations costs shows very little difference between the model runs R2-R5 and the basis model run R1. This is expected since the installed generation units are the same for all. Furthermore, this indicates that the magnitude of the reserve requirement does not inflict a radical change in the behaviour of the system. Thus, it can be assumed that reserves needed to compensate for the reserve requirement does not inflict a major influence the planned dispatch.

7.2 What are the Costs and Effects of Introducing Reserves?

In the R2 model run reserves are implemented into the Balmorel model along with the total reserve requirement. To analyse the economic costs of reserves the total costs are shown:

	R1: Basis model run	R2: All RR	Difference
Fixed O&M	26506	26506	0.00
Variable O&M	6568	6593	24.76
Fuel Costs	53566	53605	39.57
Start-up Costs	4.94	4.97	0.04
Total costs	86645	86709	64.4

Table 7.3: R2: Total annual costs in million Euro.

Table 7.3 shows an increase of 64.4 million Euro when introducing the reserve requirement to the system. Thus, the need for upregulating reserves has a larger impact on the total economics than the downregulating reserves, since the downregulating reserve requirement could lead to minimized costs. In table 7.4 the annual operation costs of up- and downregulating reserves are shown. These are weighted by the probabilities $P(q)$ for each quantile q.

	R2: All RR
Fuel costs Up	0.9
Fuel costs Down	-3.8
Variable O&M Up	0.1
Variable O&M Down	-1.4

Table 7.4: R2: Annual cost of up- and downregulating reserves in million Euro.

This shows the cost of satisfying the need for upregulation is larger than the potential savings of downregulation.

To demonstrate the effects of introducing reserves, the hourly balancing reserves g^{bal} are shown for one week. The upregulation reserves can be seen in 7.3

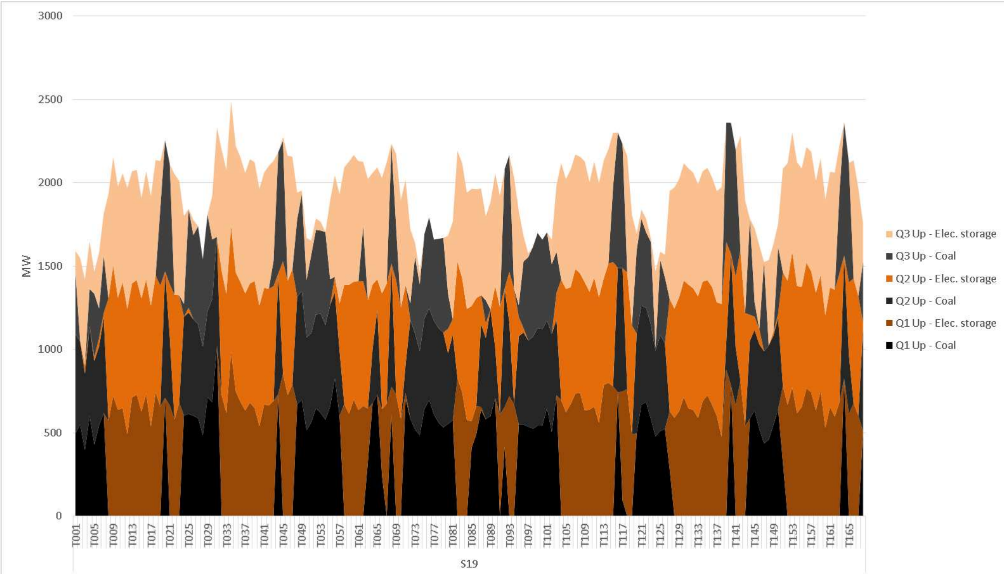

Figure 7.3: R2: Upregulating reserves for quantiles in MW in one week.

All regulation from units consists of coal fuelled power plants or from electricity storages. In the South African power system a significant amount of electricity storages are installed. The results show that these are important when the need for upregulation exists. Storages can only be used to regulate imbalances if storage volume allows this. If the storages are used as an upregulating reserve, then obviously the storage needs an electricity volume to do this. The model solution chooses to uses electricity storages to satisfy upregulation needs. This is due to the fact that electricity can be generated at times, where e.g. the electricity demand is low and consequently more units of low short time marginal costs will be available. Generation from these units can then be loaded into storages and uses for upregulation at a later time. The Balmorel model is a deterministic model, running under full information, this gives a further incentive for storages since the model solution (if an optimal solution is found) will always choose the best economic time to load into storages. In reality, at a planning time it is difficult to know if storage loading is the best economic decision because of the uncertainties of future events, as shown in the calculations of the reserve requirement in chapter 5. In a power system where the amount of electricity storages is limited, the generation units would play a more significant role. Comparing this to figure 7.2 it can be seen that the model switches between using coal fuelled power plant and electricity storages in relation to the increase in electricity generation. This is exactly as expected, since the increase in generation is causes by an increase in electricity demand. Analysing the time steps it can be seen, that in the day time where consumption is greater, more power plants are committed to satisfy demand. At night demand is lower (people are asleep), thus more units are planned to generate on minimum capacity or to be shut down. This means, that units with low short time marginal cost are available. These units are then used to generate electricity to load onto storage, which can be used during the day. Consequently, electricity is constantly generated at units with lowest short time marginal costs. The best economic solution is to load onto storage at night time instead of shutting down, which would result in a payment of start-up cost the following day. This result is a good indication of validity of the reserves implementation. This behaviour should be expected in a system, where the operational costs are minimized.

In figure 7.4 the downregulating reserves are shown.

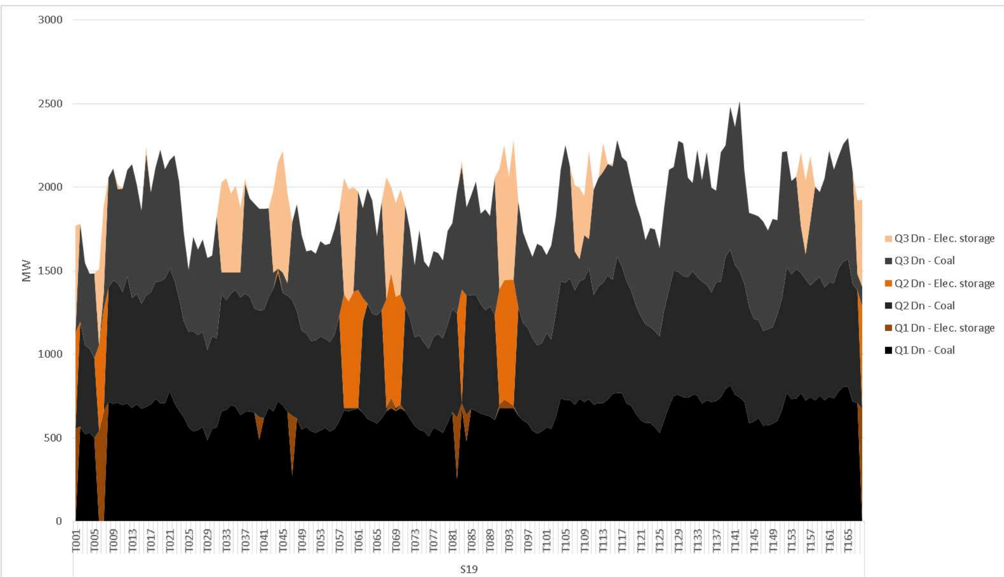

Figure 7.4: R2: Downregulating reserves for quantile in MW in one week.

Figure 7.4 shows that most of the downregulation is carried out on the coal fuelled power plants. However, this does not conclude that downregulating generation is typically the most economical decision. Actually, as figure 7.5 demonstrates the storage capacity limits the amount of downregulation from electricity storages. This figure demonstrates the unloading of the storages in the day time, leaving the possibility of loading at night time. Again, electricity storages constitutes a significant part of regulation.

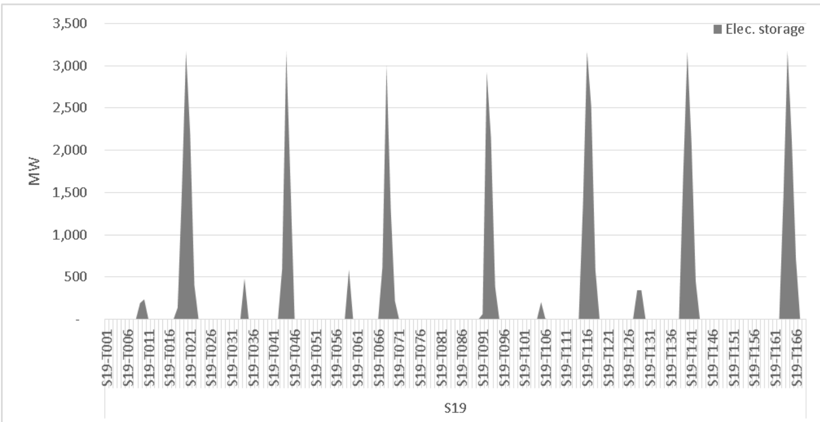

Figure 7.5: R2: Unloading electricity storages in MW in one week.

7.3 What are the Costs of Introducing Imbalances?

In the section above the effects of introducing reserves were analysed. The model runs R3-R5 constitutes the model runs with reduced reserve requirement. However, the implantation of the reserves remains the same. It is the same conditions that drive the supply of reserves to compensate for the reserve requirement. In that way the economic costs of the imbalances can be calculated from the total costs of R2. Table 7.5 shows the individual total economic cost from R3-R5:

	R2	R3-R2	R4-R2	R5-R2
Fixed O&M	21618	0	0	0
Variable O&M	6560	-1.18	-8.56	-1.79
Fuel Costs	49409	-8.89	-78.26	-15.59
Start-up Costs	5	-0.001	0.001	-0.002
Total costs	77592	-10	-87	-17

Table 7.5: The economic cost of each imbalance in million Euro.

R3-R2 represents the costs of not including the contribution of wind power generation to the reserve requirement. The results of the model run indicates that imbalances in wind power generation can have an economic effect of 10 million Euro in total operational costs. This means that better forecasting of wind generation, in relation to the method demonstrated in this thesis, or better use of reserves to compensate for the imbalances can potentially save upwards of 10 million Euro if performed optimally.

R4-R2 represents the costs of not including the contribution of electricity demand to the reserve requirement. The economic effect were calculated to be 87 million Euro when ignoring the fluctuations of electricity demand.

R4-R2 shows that imbalances from forced outages are 17 million Euro.

Based on these results it must be concluded that electricity demand is the greatest source of imbalances in a economic context. Obviously, this is subject to several assumptions on the calculations of the reserve requirement, data provided for the generation units, the catalogue of installed capacity and so on.

Ea Energy Analyses is has been commissioned to write a proposal for renewable energy policies for South Africa. In this project, the effects of introducing a tax on CO_2 emissions will be studied using the Balmorel model. In South Africa it has already been decided that the CO_2 tax will be phased in between 2015 and 2020. Based on this proposal an estimate of a CO_2 tax for 2016 is given as 9 Euro/ton CO_2. Using results for CO_2 emissions from the model runs the following costs could be added to the total system costs described above:

	R1	R2	R3	R4	R5
Total CO_2 emission costs	2221.2	2228.1	2227.9	2225.7	2227.7
Increase in CO_2 emission cost	-6.93	-	-0.28	-2.41	-0.48

Table 7.6: Total CO_2 emission cost in million Euro and the difference in relation to R2.

This demonstrates an additional system costs of the imbalances, if the planned energy policy on CO_2 is decided. It is only interesting to note, that implementing reserves result in an emission tax of 7 million Euro.

7.4 Discussion

Above the results of the model runs were presented. By analysing these results, conclusions were made in relation to the research questions. The effects of the imbalances were described in chapter 5, where the magnitude of each imbalance was estimated. This, combined with the results for the behaviour of the reserves was chosen as sufficient answers for the "effect" part of the research questions. In order to perform a more thorough analysing on the validity of the reserve requirement and results of the behaviour of reserves, historical data should be examined. This would produce a viable study of the results and lead to a more complete analysis. Unfortunately, it was not possible to acquire such data. However, no results in the sections above has lead to a disbelief in the methods applied in this thesis.

The "costs" part of the research questions were analysed as total annual costs for each model runs. These demonstrated the economic costs of each imbalance contribution. The results are subject to several assumptions and uncertainties and should be viewed as estimates rather than exact results. However, the magnitude of the costs seems reasonable and help verify the modelling of the reserves and reserve requirement.

The fluctuations of hydro and solar power were not included as imbalances in this thesis. In the South African power system these does not constitute a large share of total generation, hydro power generated 2.1%

and solar power 1.1%. On this basis, it is conclude that the reserve requirements found in this thesis will be reasonable as estimates of the reserve requirement in the South African power system.

Transmission outages were ignored in this thesis. It could be argued that these will not add a significant contribution to the reserve requirement based on [12] p. 17. Here it is suggested that new renewable energy capacity could replace investments in transmission capacity. Thereby, possibly downgrading the importance of the transmission lines in the future. However, this is probably a crude assumption and transmission outages should be examined to estimate a complete reserve requirement. Despite of this, is was chosen not to include transmission outages in order to limit the extent of this thesis.

When examining the start-up costs they are small relative to other system costs. It should be mentioned that the Balmorel model uses weekly cycles, such at the last hour of a week is not joined with the first hour of the next. In order not to pay start-up costs for the first hour of every week, the start-up costs are ignored for this hour. This is a simplification in the Balmorel model, which possibly leads to smaller start-up costs than the total dispatch actually entails. Furthermore, the RMIP solution might also have a negative impact on start-up costs. However, the magnitude of these relative to other system costs might suggest that the RMIP solution provides a good result without errors on integer restrictions, but this is optimistic to conclude.

CHAPTER 8

Future work

In the following chapter future work in modelling reserves in a energy system will be discussed. Moreover, some of the additional possibilities in the discipline of reserve modelling will be presented.

The future of energy systems will be increasingly renewable. The scarcity of fossil fuels combined with environmental issues will lead to energy system mainly consisting of renewable energy forms. Many of the renewable energy technologies are dependent of nature in form of wind, water, solar and so on. This will breed energy systems, where uncertainty of generation is increasing due to the difficult task of forecasting renewable generation. Thus, reserves will play an important role in the energy systems of the future. This will probably lead to a never ending demand for a better and more efficient way of governing reserves and estimating the reserve requirement. In this thesis a step was taken in that direction. However, future work could still be done in modelling reserves.

In this thesis it was chosen only to focus on imbalances produced by wind power generation, electricity demand and forced outages. In future work transmission outages should also be represented in the model. These are outages of transmission lines transmitting electricity between regions. When considering transmission outages the same type of approach could be chosen, as seen in chapter 3 on modelling forced outages based on forced outage rates and mean repair times. This must be related to historical data for transmission outages. Here NordPool Spot could be used as a source. The more difficult task arrives when trying to represent a probabilistic formulation of loss in transmission capacity. The loss of a transmission line will only have an effect on the reserve requirement if electricity is actually transmitted at that time. Furthermore, if other transmission lines exist these might be able to compensate completely for the outage. However, these might also fail. This creates a system of independent occurrences that will be very dependent on each other in relation to the contribution of imbalances in the system. Some work has already been done in this field using methods like cluster theory or maximum likelihood estimates as seen in the article "The probability, identification, and prevention of rare events in power systems" written by Qiming Chen [9]. Presently Ea Energy Analyses is performing a study on transmission outages by combining historical data with a stochastic approach using Markov chains.

The fluctuations of solar and hydro power should also be examined. Solar power is similar to wind power and in the same way as described in chapter 5 by analysing the forecast and forecast errors, the imbalances could be estimated. Hydro power consists of different types of technologies. Some are Run-of-river and their power output is directly causes by water flow. Others have a reservoir and are able to store water to generate power at the best possible times during the day. This makes the estimation of imbalances of hydro power more complicated. However, a similar approach as seen in this thesis for wind power could be basis for reasonable representation of imbalances from hydro power.

In chapter 3 a tool to generate forced was developed. Though analysis this showed reasonable results in terms of FORs and MRTs. A more thorough study on historical data for forced outages for individual unit type could be performed to validate the generation of forced outages. Furthermore, the choices of using the Weibull distribution for MRTs and the exponential distribution for MFTs could be questioned by analysing other distributions.

Throughout this thesis reserves are thought of as hourly imbalances and regulations. This is a fair way of analysing reserves on a longer time horizon. However, when dealing with a shorter time horizon, smaller time steps should be used to represent the reserves needed to compensate for imbalances. In a dispatching context, analysing daily operation the time step and modelling should be refined. The operating reserves for a system operator is typically divided into different categories. Some are used to react instantaneously, others within 10-15 minutes or over longer time periods. To model reserves in order to analyse operational strategy for dispatch or estimating the reserve requirement for system operators more work should be performed to provide a representation of reserves that can react faster. ENSYMORA (Energy systems modelling, research and analysis) is a research project supported by the Danish Council for Strategic Research under the Danish Agency for Science, Technology and Innovation[17]. In this project Ea Energy Analyses has been involved in modelling reserves using smaller time steps to represent the operational reserves in the Balmorel model. The project has been running simultaneously with this thesis and experiences and knowledge has been shared. In additional work of modelling reserves for the Balmorel model, future publications from the ENSYMORA should be examined.

Chapter 9

Conclusion

In this thesis a study of modelling reserves in a power system was performed. A tool to produce forced and planned outages for a generation unit was developed to provide input to deterministic energy models. This tool was proved to generate reasonable simulations for forced outages based on few key figures of generation units. The imbalances in an energy system was explained and an estimate of imbalances from wind power generation, electricity demand and forces outages was calculated to represent the reserve requirement for the South African power system. Furthermore, the reserves constituting the entities able to compensate for the imbalances in form of the reserve requirement was explained and implemented into the Balmorel model.

To guide this thesis research questions was made. The answers to these questions was provided in an economic and operational context and yielded estimations of the costs of reserves in the South African power system. The estimation on the magnitude of the imbalances from wind power generation, electricity demand and forced outages,described in chapter 5, helped show the effects of introducing reserve modelling to the Balmorel model.

An analysis was performed to validate the implementation of the reserves and reserve requirement. In the analysis the validity of the methods applied in this thesis was discussed.

Even though simplifications were made in both the estimation of the reserve requirement and in the formulation of the reserves. The produced results of this thesis was plausible and help shown the inner mechanics of the reserves. It was found that the implementation of reserves in the Balmorel model was a reasonable tool to analyse reserves on a longer time horizon.

Appendix A

Appendix

A.1 Units and Abbreviations

CHP	combined heat and power
CO2	carbon dioxide
DH	District Heating
FOH	Forced Outage Hours
FOR	Forced Outage Rate
GJ	Gigajoule
GW	gigawatt
GWh	gigawatt hours
kW	kilowatt
kWh	kilowatt hours
LP	Linear Programming
MFT	Mean failure time
MIP	Mixed Integer Programming
MUC	Maximum Unavailable Capacity
MRT	Mean repair time
MW	megawatt
MWe	megawatt, electric
MWh	megawatt hours
NOx	nitrogen oxides
PDF	Probability Density Function
PJ	petajoule
RE	Renewable Energy
RES	Renewable Energy Sources
SAPS	South African Power System
SO2	sulphur dioxide
SUC	Sum of Unavailable Capacity
TJ	terajoule
toe	ton of oil equivalent
TWh	terawatt hours
OMONEY	Currency in Balmorel for the specific geographical area
Conversion factors	
1 GWh	3600 GJ
1 toe	41.86 GJ
Unit prefixes	
k	kilo, 10^3
M	Mega, 10^6

G	Giga, 10^9
T	Tera, 10^{12}
P	Peta, 10^{15}
E	Exa, 10^{18}

A.2 Forced Outages

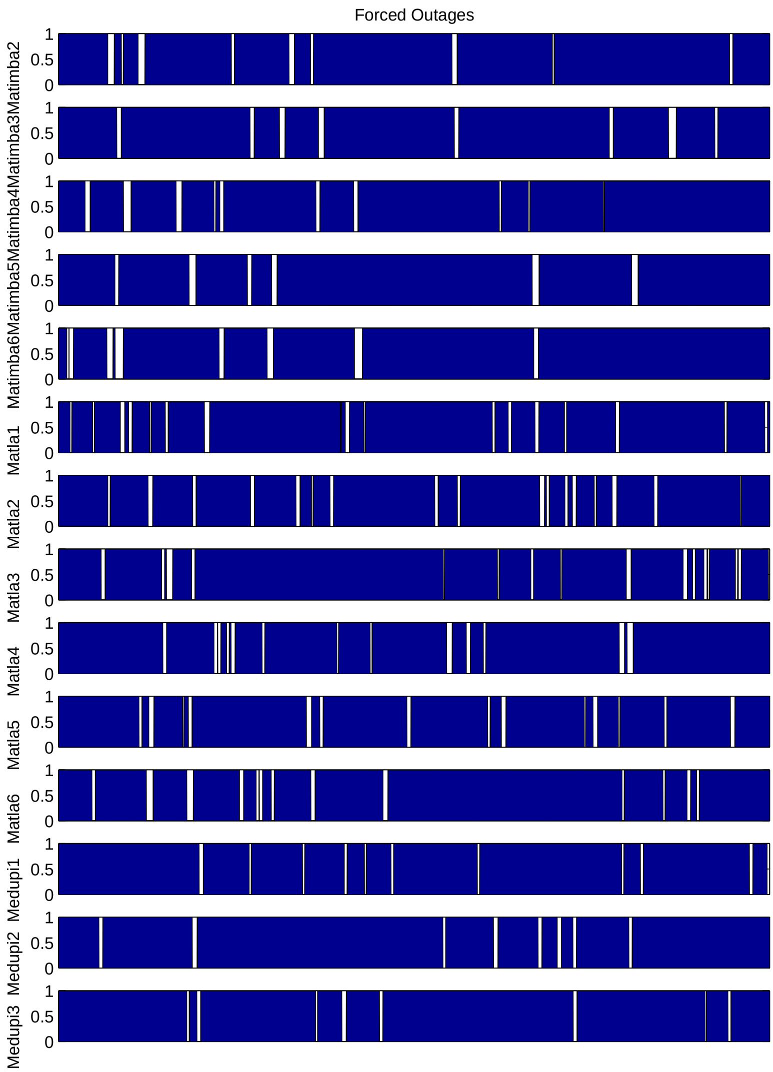

Figure A.1: Forced outages.

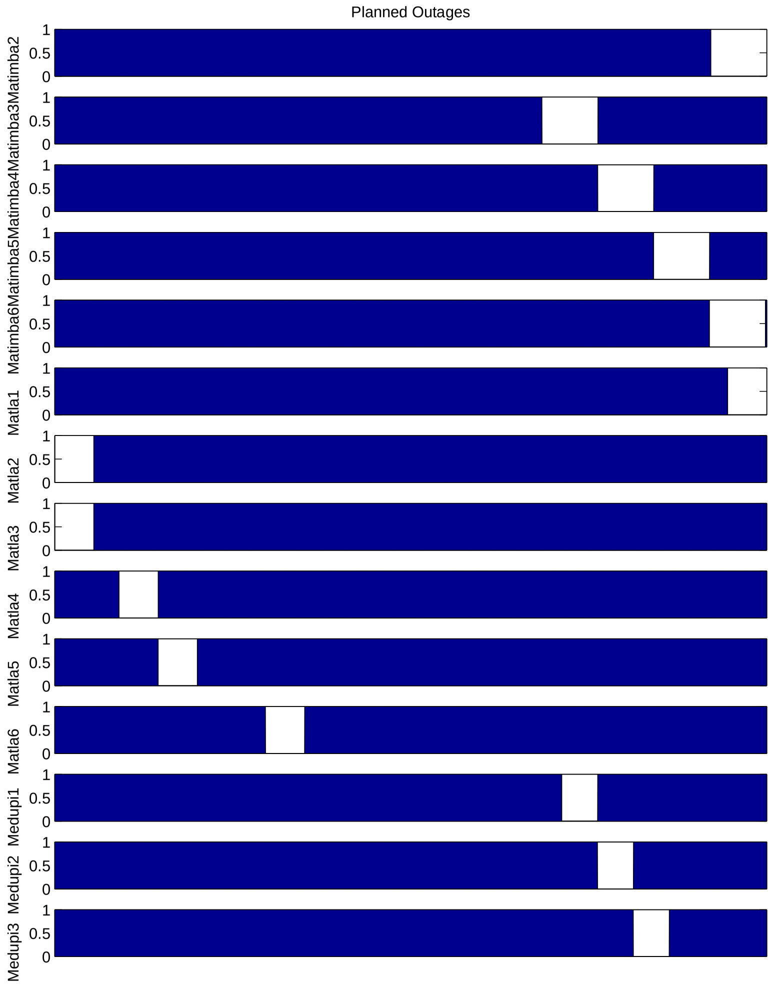

Figure A.2: Planned outages.

A.2.1 `outagesSA.m` (Function to generate forced outages)

```
function [outag, FORhat]=outagesSA(MTR,FOR,HIY,betaHat)
MTF=MTR*((1-FOR)/FOR);
my=1/MTR;
lamb=1/MTF;
betaF=1;
betaR=betaHat;
toll=FOR*0.2;
FORhat=0;
outag=zeros(HIY,1);
% Add possible of tollerance on FOR
% while (FORhat>FOR+toll || FORhat<FOR-toll)
timeToRepair=0;
timeToFailure=0;
for i=1:HIY
    if (i<timeToRepair || i<timeToFailure)
        outag(i)=outag(i-1);
        continue
    elseif timeToFailure==i
        outag(i)=0;
        wblnmb=round(wblrnd(MTR,betaR));
        wblnmb=max(wblnmb,1);
        timeToRepair=i+wblnmb;
        continue
    elseif timeToRepair==i
        outag(i)=1;
        expnmb=round(wblrnd(MTF,betaF));
        expnmb=max(expnmb,1);
        timeToFailure=i+expnmb;
        continue
    else
        rndnmb=rand;
        if rndnmb<=FOR
            outag(i)=0;
            wblnmb=round(wblrnd(MTR,betaR));
            wblnmb=max(wblnmb,1);
            timeToRepair=i+wblnmb;
        end
```

```
        if rndnmb>FOR
            outag(i)=1;
            expnmb=round(wblrnd(MTF,betaF));
            expnmb=max(expnmb,1);
            timeToFailure=i+expnmb;
        end
    end

end

FOH=length(find(outag==0));
FORhat= FOH/HIY;

%  end
```

A.2.2 runTotalOutagesSA.m (Script to generate planned and total outages)

```
clear, close all,
clc

%Balmorel time steps
HIY=52*168;
hours=1:HIY';
halfHIY=round(HIY/2);

%Load units and attributes
[name,cap,outHour,FOR] = textread('SAOutagData.csv','%s%n%
   n%n','delimiter',';');

name=char(name);
correctTime=365/364;
outHour=round(outHour*correctTime);
FOR=FOR*correctTime;
m=mean(outHour);
%Number of units
n=length(name);
```

```
totalCap=sum(cap);
% Mean repair time from WILMAR
meanRT=60;
% Using planned outage time for MRT
MRT = outHour./mean(outHour).*meanRT;

% Number of generations without wind or solar. Option to
   exclude
%n = 164;

%Fitting data to produce beta
paramHat = wblfit(MRT(1:n));
betaHat = paramHat(2)

forcedOutages=zeros(HIY,n);
FORhat=zeros(n,1);

%Generating forced outagesw
for i=1:n
    [forcedOutag, FORha]= outagesSA(MRT(i),FOR(i),HIY,
       betaHat);
    forcedOutages(:,i) = forcedOutag;
    FORhat(i)=FORha;
end

%Weibull analysis
% for i=1:1000
% weib1(i)=wblrnd(m,1);
% end
% for i=1:1000
% weib2(i)=wblrnd(m,betaHat);
% end

%The Weibull distribution
x=[1:1:1200];
W = (betaHat/m)*((x/m).^(betaHat-1)).*exp(-((x/m).^betaHat
   ));
```

```
 figure
hist(outHour,20);
title('Histogram of Mean Repair Times')
xlabel('Mean Repair Time')
ylabel('Frequency')

 figure
hist(outHour,20);
title('Histogram of Mean Repair Times')
xlabel('Mean Repair Time')
ylabel('Frequency')

% figure
hold on
hist(outHour,20);
title('Weibull fitted to data')
xlabel('Mean Repair Time')
N=max(hist(outHour,20));
W=W./max(W)*N;
p2=plot(W);
legend(p2,['Weibull, beta=',num2str(betaHat)], 'Location',
   'Best')

% figure
% hist(weib1,50);
% title('Weibull distribution with beta=1')
% figure
% hist(weib2,50);
% title('Weibull distribution with beta=2.5')

% Loading time steps
[timeStep] = textread('timestep.csv','%s','delimiter',';')
   ;
timeStep=char(timeStep);
```

```
%MUC curve based on historical data. Given in weeks.
x=hours;
t=[1 5.333 9.666 13.999 18.332 22.665 26.998 31.331 35.664
    39.997 44.33 48.663 52];
t1=t/52*HIY;
s=[6300 4000 2900 2400 2000 0 0 0 400 2000 2200 2500
   4200];
P=polyfit(t1,s,6);
MUCCurve=P(1).*x.^6 + P(2).*x.^5 + P(3).*x.^4 + P(4).*x.^3
    + P(5).*x.^2 +P(6).*x + P(7);



%Correcting curve to SA system. In week 22-34 planned
   outages must be 0.
k=find(x>22/52*HIY & x<34/52*HIY);
m=find(MUCCurve>6000);
MUCCurve(m)=6000;
MUCCurvehat=MUCCurve;
MUCCurvehat(k)=0;

% Normalizing curve
MUCCurvehat=MUCCurvehat/max(MUCCurvehat);
% Maximal 30% of total cap can be out
MUCCurvehat=MUCCurvehat*sum(cap)*0.3;


%allocating space
isOut=zeros(n,1);
plannedOutages=ones(n,HIY);
sumOut=zeros(1,HIY);
i=1;
% Planned outages algorithm
while sum(isOut)<n
    for j=1:n
        outTime=i+outHour(j);
        if outTime > HIY
           i=HIY-outHour(j);
```

```
        outTime=HIY;
    end
    minUC=min(MUCCurvehat(i:outTime));
    maxUC=max(sumOut(i:outTime)+cap(j));
    if (maxUC<=minUC && isOut(j)==0 && outTime<HIY)
        plannedOutages(j,i:outTime)=0;
        sumOut(i:outTime)=sumOut(i:outTime)+cap(j);
        isOut(j)=1;
        i=outTime;
    elseif (maxUC<=minUC && isOut(j)==0 && outTime==
       HIY)
        plannedOutages(j,i:outTime)=0;
        sumOut(i:outTime)=sumOut(i:outTime)+cap(j);
        isOut(j)=1;
        i=1;
    elseif (maxUC>minUC && outTime<=HIY && outTime>
       halfHIY && isOut(j)==0)
        for i=halfHIY:HIY
            outTime=i+outHour(j);
            if outTime > HIY
                break
            end
            minUC=min(MUCCurvehat(i:outTime));
            maxUC=max(sumOut(i:outTime)+cap(j));
            if (maxUC<=minUC)

                plannedOutages(j,i:outTime)=0;
                sumOut(i:outTime)=sumOut(i:outTime)+
                   cap(j);
                isOut(j)=1;
                i=outTime;
                break
            else
            end
        end
    elseif (maxUC>minUC && outTime<=HIY && isOut(j)
       ==0)
        for i=1:HIY
```

```
                outTime=i+outHour(j);
                if outTime > HIY
                    break
                end
                minUC=min(MUCCurvehat(i:outTime));
                maxUC=max(sumOut(i:outTime)+cap(j));
                if (maxUC<=minUC)
                    plannedOutages(j,i:outTime)=0;
                    sumOut(i:outTime)=sumOut(i:outTime)+
                       cap(j);
                    isOut(j)=1;
                    i=outTime;
                    break
                else
                end
            end
        elseif outTime>HIY
            i=1;
         elseif isOut(j)==0
            i=i+1;
        else
            i=i+1;
        end
        sum(isOut);
    end
end


plannedOutages=plannedOutages';
totalOutages=forcedOutages.*plannedOutages;


%MUC graph
figure
plot(x,MUCCurvehat)
ylabel('Maximal Unavailable Capacity')
xlabel('Hours')
```

```
% Choose which units to show in graphs
chooseUnits=[18,67,149];

% Forced Outage Hours
for i=1:length(chooseUnits)
unit=name(chooseUnits(i),:)
FOH=length(find(forcedOutages(:,chooseUnits(i))==0))
end

%Forced Outages
figure
subplot(3,1,1)
area(hours,forcedOutages(:,chooseUnits(1)))
ylabel(name(chooseUnits(1),:))
title('Forced Outages','Fontsize',12)
subplot(3,1,2)
area(hours,forcedOutages(:,chooseUnits(2)))
ylabel(name(chooseUnits(2),:))
subplot(3,1,3)
area(hours,forcedOutages(:,chooseUnits(3)))
ylabel(name(chooseUnits(3),:))
xlabel('Hours')

%Planned Outages
figure
subplot(3,1,1)
area(hours,plannedOutages(:,chooseUnits(1)))
ylabel(name(chooseUnits(1),:))
title('Planned Outages','Fontsize',12)
subplot(3,1,2)
area(hours,plannedOutages(:,chooseUnits(2)))
ylabel(name(chooseUnits(2),:))
subplot(3,1,3)
area(hours,plannedOutages(:,chooseUnits(3)))
ylabel(name(chooseUnits(3),:))
xlabel ('Hours')

%Total Outages
```

```
figure
subplot(3,1,1)
area(hours,totalOutages(:,chooseUnits(1)))
ylabel(name(chooseUnits(1),:))
title('Total Outages','Fontsize',12)
subplot(3,1,2)
area(hours,totalOutages(:,chooseUnits(2)))
ylabel(name(chooseUnits(2),:))
subplot(3,1,3)
area(hours,totalOutages(:,chooseUnits(3)))
ylabel(name(chooseUnits(3),:))
xlabel ('Hours')

%Planned Outages
figure
subplot(4,1,1)
area(hours,plannedOutages(:,1))
ylabel(name(1,:))
title('Planned Outages','Fontsize',12)
subplot(4,1,2)
area(hours,plannedOutages(:,2))
ylabel(name(2,:))
subplot(4,1,3)
area(hours,plannedOutages(:,3))
ylabel(name(3,:))
subplot(4,1,4)
area(hours,plannedOutages(:,4))
ylabel(name(4,:))
xlabel ('Hours')

% Tool to analyse planned outages
l=100:113;
figure
for i=l
    subplot(length(l),1,i-l(1)+1)
    area(hours,plannedOutages(:,i))
    ylabel(name(i,:))
     set(gca, 'XTickLabelMode', 'Manual')
```

```
     set(gca, 'XTick', [])
     if i==min(l)
         title('Planned Outages','Fontsize',10)
     end
end

% Tool to analyse forced outages
figure
for i=l
    subplot(length(l),1,i-l(1)+1)
    area(hours,forcedOutages(:,i))
    ylabel(name(i,:))
     set(gca, 'XTickLabelMode', 'Manual')
     set(gca, 'XTick', [])
     if i==min(l)
         title('Forced Outages','Fontsize',10)
     end
end

%Choose a figure
% chooseUnit=37;
%
% figure
% subplot(3,1,1)
% area(hours,forcedOutages(:,chooseUnit))
% title(['Forced outages for ' name(chooseUnit,:)])
% subplot(3,1,2)
% area(hours,plannedOutages(:,chooseUnit))
% title(['Planned outages for ' name(chooseUnit,:)])
% ylabel('Capacity')
% subplot(3,1,3)
% area(hours,totalOutages(:,chooseUnit))
% title(['Total outages for ' name(chooseUnit,:)])
% xlabel('Hours')
%
% figure
% area(hours,cap'*forcedOutages');
% title('Total Capacity with Forced Outages')
```

```
% ylabel('Capacity (MW)')
% xlabel('Hours')
%
% figure
% area(hours',cap'*plannedOutages')
% title('Total Capacity with Planned Outages')
% ylabel('Capacity (MW)')
% xlabel('Hours')
% %
% figure
% area(hours,plannedOutages)
% title('Total Planned Outages')
% ylabel('Capacity (MW)')
% xlabel('Hours')
%
% figure
% area(hours,cap'*totalOutages');
% title('Total Capacity with Total Outages')
% ylabel('Capacity (MW)')
% xlabel('Hours')
%
% figure
% area(hours,sumOut(hours));
% ylabel('Planned Outage Capacity')
% xlabel('Hours')

forcedOutageRate=mean(forcedOutages)';
meanforcedOutageRate=mean(mean(forcedOutages))'
totalPlannedRate=mean(plannedOutages)';
meantotalPlannedRate=mean(mean(plannedOutages))'
totalOutageRate=mean(totalOutages)';
meantotalOutageRate=mean(mean(totalOutages))'

%Write to file

fid=fopen('outagesSA.inc','w');
fprintf(fid,'\t');
for i=1:n
```

```
    fprintf(fid,'\t');
    fprintf(fid,'%s',name(i,:));
end
fprintf(fid,'\n');

for i=1:size(plannedOutages,1)
   fprintf(fid, '%s',timeStep(i,:));
   fprintf(fid,'\t');
   fprintf(fid, '%d\t\t\t', plannedOutages(i,:));
   fprintf(fid,'%15','');
   fprintf(fid, '\n');
end
fclose(fid);
```

A.3 GAMS Code

A.3.1 Reserve Constraints

```
* Reserves add-on to Balmorel.
* See the documentation for details and inspiration.

* Equations
*==========================================



EQUATION  QRESTRANSUP(RRR,RRR,S,T)          'Upwards
   balancing reserves transmission limited by transmission
    capacity and already existing transmission';
EQUATION  QRESTRANSDOWN(RRR,RRR,S,T)        'Downwards
   balancing reserves transmission limited by transmission
    capacity and already existing transmission';
EQUATION  QRESPRODUP(AAA,GGG,S,T)           'Upregulating
   reserves limited by thermal existing production';
EQUATION  QRESPRODDN(AAA,GGG,S,T)           '
   Downregulating reserves limited by thermal existing
   production';
EQUATION  QRESWINDUP(AAA,G,S,T)             'Wind
   Upregulating reserves limited by resources, capacity
   and planned production';
EQUATION  QRESWINDDN(AAA,G,S,T)             'Wind
   Downregulating reserves limited by resources, capacity
   and planned production';
EQUATION  QRESBALANCE_UP(RRR,S,T,QUANTILES)   'Balance
   between reserves import, reserves export and availible
   upwards balancing reserves';
EQUATION  QRESBALANCE_DOWN(RRR,S,T,QUANTILES) 'Balance
   between reserves import, reserves export and availible
   downwards balancing reserves';
$ifi %UnitComm%==yes    EQUATION  QRESRAMPU(AAA,GGG,S,T)
          'Reserves availible limited by ramp up';
$ifi %UnitComm%==yes    EQUATION  QRESRAMPD(AAA,GGG,S,T)
          'Reserves availible limited by ramp down';
```

```
*============================================


* Transmission up
QRESTRANSUP(IRE,IRI,IS3,T)$(IXKINI_Y(IRE,IRI) OR IXKN(IRI,
   IRE) OR IXKN(IRE,IRI)) ..
*        Transmission capacity from area ire to iri (
   including invested capacity*)
          (IXKINI_Y(IRE,IRI) + VXKN(IRE,IRI)$(IXKN(IRE,IRI)
              OR IXKN(IRI,IRE)))*XKDERATE(IRE,IRI,IS3)
*        Planned transmission from area ire to iri (
   positive or negative)
          - VX_T(IRE,IRI,IS3,T)
          + VX_T(IRI,IRE,IS3,T)$(IXKINI_Y(IRI,IRE) OR IXKN(
             IRI,IRE) OR IXKN(IRE,IRI))
          =G=
*        Sum of the necessary margin of transmission
   capacity from area ire to iri in to supply reserves
   upwards in interval QUANTILES
         SUM(QUANTILES,VX_UP(IRE,IRI,IS3,T,QUANTILES))
;

* Transmission down
QRESTRANSDOWN(IRE,IRI,IS3,T)$(IXKINI_Y(IRE,IRI) OR IXKN(
   IRI,IRE) OR IXKN(IRE,IRI)) ..
*        Planned transmission from area ire to iri (
   positive or negative)
          VX_T(IRE,IRI,IS3,T)
          - VX_T(IRI,IRE,IS3,T)$(IXKINI_Y(IRI,IRE) OR IXKN(
             IRI,IRE) OR IXKN(IRE,IRI))
*        Transmission capacity from area ire to iri (
   including invested capacity*)
         + (IXKINI_Y(IRI,IRE) + VXKN(IRI,IRE)$(IXKN(IRI,IRE
             ) OR IXKN(IRE,IRI)))*XKDERATE(IRI,IRE,IS3)
          =G=
```

```
*        Sum of the necessary margin of transmission
   capacity from area ire to iri in to supply reserves
   downwards in interval QUANTILES
        SUM(QUANTILES,VX_DOWN(IRE,IRI,IS3,T,QUANTILES))
;
* Wind power:
QRESWINDUP(IA,IGWND,IS3,T)$(IAGK_Y(IA,IGWND) or IAGKN(IA,
   IGWND)) ..
* Possible generation by existing wind power:
*      ((IGKVACCTOY(IA,IGWND)+IGKFX_Y(IA,IGWND))*WND_VAR_T(
   IA,IS3,T)/IWND_SUMST(IA)*WNDFLH(IA))$IAGK_Y(IA,IGWND)
* Use .UP fuctionality instead
     VGE_T.up(IA,IGWND,IS3,T)$IAGK_Y(IA,IGWND)

* Possible generation by new wind power:
      +(VGKN(IA,IGWND)*WND_VAR_T(IA,IS3,T)/IWND_SUMST(IA)*
         WNDFLH(IA))$IAGKN(IA,IGWND)

* Less planned generation
     - VGE_T(IA,IGWND,IS3,T)$IAGK_Y(IA,IGWND)
     - VGEN_T(IA,IGWND,IS3,T)$IAGKN(IA,IGWND)
         =G=
*        The regulation of technology ige need in area ia
   upwards in interval QUANTILES
    SUM(QUANTILES, VRES_UP(IA,IGWND,IS3,T,QUANTILES))
;

QRESWINDDN(IA,IGWND,IS3,T)$(IAGK_Y(IA,IGWND) or IAGKN(IA,
   IGWND)) ..
       VGE_T(IA,IGWND,IS3,T)$IAGK_Y(IA,IGWND)
     + VGEN_T(IA,IGWND,IS3,T)$IAGKN(IA,IGWND)
         =G=
*        The regulation of technology ige need in area ia
   downwards in interval QUANTILES
       SUM(QUANTILES, VRES_DOWN(IA,IGWND,IS3,T,QUANTILES))
;
```

```
*      Limitation on upregulation reserve supplied by
   technology.
QRESPRODUP(IA,IGE,IS3,T)$((IAGK_Y(IA,IGE) or IAGKN(IA,IGE)
   ) and IGEBAL(IGE) and IGNOTETOH(IGE) and (not IGWND(IGE
   )) and (not IGCOMB2(IGE))) ..
* Upregulation on generation technologies are limited by
   possible generation minus planned generation.

* Possible generation on other dispatchable generation
   technologies
     ((IGKVACCTOY(IA,IGE)+IGKFX_Y(IA,IGE))*GKDERATE(IA,IGE
        ,IS3,T)*(1+(-1+1/GDATA(IGE,'GDSTOHUNLD'))$IGESTO(
        IGE)) )$IAGK_Y(IA,IGE)
                           + (VGKN(IA,IGE)*GKDERATE(IA,IGE
                              ,IS3,T)*(1+(-1+1/GDATA(IGE,'
                              GDSTOHUNLD'))$IGESTO(IGE)) )
                              $IAGKN(IA,IGE)
*       The production of technology ige need in area ia
       -(VGE_T(IA,IGE,IS3,T))$IAGK_Y(IA,IGE)
       -(VGEN_T(IA,IGE,IS3,T))$IAGKN(IA,IGE)
* Add storage loading (which can be reduced) if storage is
    present in the area (NB: will fail if more than one
   electricity storage is present in the area.
       +VESTOLOADT(IA,IS3,T)$IGESTO(IGE)
         =G=
*       The regulation of technology IGE need in area IA
   upwards in interval QUANTILES
                 SUM(QUANTILES, VRES_UP(IA,IGE,IS3,T,
                    QUANTILES))
;


*      Limitation on downregulation reserve supplied by
   technology.
QRESPRODDN(IA,IGE,IS3,T)$((IAGK_Y(IA,IGE) or IAGKN(IA,IGE)
   ) and IGEBAL(IGE) and IGNOTETOH(IGE) and (not IGCOMB2(
   IGE))) ..
*       The production of technology ige need in area ia
```

```
          (VGE_T(IA,IGE,IS3,T))$IAGK_Y(IA,IGE)
          +(VGEN_T(IA,IGE,IS3,T))$IAGKN(IA,IGE)
* Option to increase storage loading.
          +(((IGKVACCTOY(IA,IGE)+IGKFX_Y(IA,IGE))*GKDERATE(
             IA,IGE,IS3,T)/GDATA(IGE,'GDSTOHLOAD'))$IAGK_Y(
             IA,IGE)
             +(VGKN(IA,IGE)*GKDERATE(IA,IGE,IS3,T)/GDATA(
                IGE,'GDSTOHLOAD'))$IAGKN(IA,IGE)
            - VESTOLOADT(IA,IS3,T)
           )$IGESTO(IGE)
         =G=
*        The regulation of technology ige need in area ia
   downwards in interval QUANTILES
                SUM(QUANTILES, VRES_DOWN(IA,IGE,IS3,T,
                   QUANTILES))
;

*        Balance up
QRESBALANCE_UP(IR,IS3,T,QUANTILES)  ..
*         Reserves capacity for transmission from IR to IRI
            SUM(IRI$(IXKINI_Y(IR,IRI) OR IXKN(IRI,IR) OR
               IXKN(IR,IRI)), VX_UP(IRI,IR,IS3,T,QUANTILES)
               )
*         Reserves capacity for transmission from IRE to IR
          - SUM(IRE$(IXKINI_Y(IRE,IR) OR IXKN(IR,IRE) OR
             IXKN(IRE,IR)), VX_UP(IR,IRE,IS3,T,QUANTILES))
*         The production of technology ige in area ia
          + SUM((IA,IGE)$(RRRAAA(IR,IA) and (IAGK_Y(IA,IGE)
              or IAGKN(IA,IGE)) and IGEBAL(IGE)),VRES_UP(IA
             ,IGE,IS3,T,QUANTILES))
*         Penalty
          + VQRESBALANCE_UP(IR,IS3,T,QUANTILES)
          =E=
*         Regulation need in area IR
          RES_REQ_UP(IR,IS3,T,QUANTILES)
;

*        Balance down
```

```
QRESBALANCE_DOWN(IR,IS3,T,QUANTILES) ..
*        Reserves capacity for transmission from IR to IRI
           SUM(IRE$(IXKINI_Y(IRE,IR) OR IXKN(IR,IRE) OR
              IXKN(IRE,IR)), VX_DOWN(IRE,IR,IS3,T,
              QUANTILES))
*        Reserves capacity for transmission from IRE to IR
         - SUM(IRI$(IXKINI_Y(IR,IRI) OR IXKN(IRI,IR) OR
            IXKN(IR,IRI)), VX_DOWN(IR,IRI,IS3,T,QUANTILES)
            )
*        The production of technology ige in area ia
         + SUM((IA,IGE)$(RRRAAA(IR,IA) and (IAGK_Y(IA,IGE)
             or IAGKN(IA,IGE)) and IGEBAL(IGE)),VRES_DOWN(
            IA,IGE,IS3,T,QUANTILES))
*        Penalty
         +VQRESBALANCE_DOWN(IR,IS3,T,QUANTILES)
         =E=
*        Regulation need in area IR
         RES_REQ_DOWN(IR,IS3,T,QUANTILES)
;

$ifi %UnitComm%==yes    QRESRAMPU(IA,IGE,IS3,T)$(GDATAUC(
   IGE,'GDUCRAMPU') and IGEBAL(IGE) and (IAGK_Y(IA,IGE) or
    IAGKN(IA,IGE))) ..
$ifi %UnitComm%==yes    SUM(QUANTILES,VRES_UP(IA,IGE,IS3,T
   ,QUANTILES))  =L=  GDATAUC(IGE,'GDUCRAMPU');

$ifi %UnitComm%==yes    QRESRAMPD(IA,IGE,IS3,T)$(GDATAUC(
   IGE,'GDUCRAMPD') and IGEBAL(IGE) and (IAGK_Y(IA,IGE) or
    IAGKN(IA,IGE))) ..
$ifi %UnitComm%==yes    SUM(QUANTILES,VRES_DOWN(IA,IGE,IS3
   ,T,QUANTILES))  =L=  GDATAUC(IGE,'GDUCRAMPD');
```

A.3.2 Contributions to Objective Function

```
* Reserves add-on
* Contribution to objective function
```

```
* Restricts unnecessary reserves
  + SUM((IA,IGEBAL,IS3,T,QUANTILES)$(IAGK_Y(IA,IGEBAL) or
     IAGKN(IA,IGEBAL)),1*VRES_UP(IA,IGEBAL,IS3,T,QUANTILES
     ) + 1*VRES_DOWN(IA,IGEBAL,IS3,T,QUANTILES))

*-------------------------------------------
* Penalty for unsatisfied reserves
    + PENALTYQ*SUM((IR,IS3,T,QUANTILES),VQRESBALANCE_UP(IR
       ,IS3,T,QUANTILES))
    + PENALTYQ*SUM((IR,IS3,T,QUANTILES),VQRESBALANCE_DOWN(
       IR,IS3,T,QUANTILES))
*-------------------------------------------


$ifi %CASEID%==ReserveNoCosts $goto no_res_costs
* Upregulating costs
  + SUM(QUANTILES,
    ACTIVATION_PROB(QUANTILES)*(

* Cost of fuel consumption during the year---:
* Therefore each cost element proportional to fuel use is
   gathered in this stage.
     +SUM((IA,IGE,FFF)$((IAGK_Y(IA,IGE) or IAGKN(IA,IGE))
        and IGEBAL(IGE) AND IGF(IGE,FFF)),
* Fuel price
        (IFUELP_Y(IA,FFF)
* --- Emission taxes, Fuel taxes + More fuel taxes on
   technology types.
         +SUM(C$ICA(C,IA), IOF0001*ITAX_CO2_Y(C)*IM_CO2(
            IGE) + IOF0001*ITAX_SO2_Y(C)*IM_SO2(IGE) +
            IOF0000001*ITAX_NOX_Y(C)*GDATA(IGE,'GDNOX') +
            TAX_F(FFF,C) + ITAX_GF(IA,IGE))
         )* IOF3P6 * SUM((IS3,T), IHOURSINST(IS3,T) * (
         GEFFDERATE(IA,IGE)/GDATA(IGE,'GDFE')*(VRES_UP(IA,
            IGE,IS3,T,QUANTILES)- VRES_DOWN(IA,IGE,IS3,T,
            QUANTILES))$IGNOTETOH(IGE))))
```

```
* Variable operation and maintainance cost:
    + SUM((IA,IGE)$((IAGK_Y(IA,IGE) or IAGKN(IA,IGE)) and
       IGEBAL(IGE)),
        GOMVCOST(IA,IGE) * SUM((IS3,T), IHOURSINST(IS3,T)
           *(
            +(VRES_UP(IA,IGE,IS3,T,QUANTILES)-VRES_DOWN(IA
               ,IGE,IS3,T,QUANTILES))$IGNOTETOH(IGE))))

* Transmission costs
    + SUM((IRI,IR,IS3,T)$((IXKINI_Y(IR,IRI) OR IXKN(IRI,IR
       ) OR IXKN(IR,IRI))),
        XCOST(IRI,IR)*(VX_UP(IRI,IR,IS3,T,QUANTILES)+
           VX_DOWN(IRI,IR,IS3,T,QUANTILES)))

* Electricity generation taxes (and subsidies).
    + SUM((C,IR,IA,IGE)$(IGEBAL(IGE) AND (IAGK_Y(IA,IGE)
       or IAGKN(IA,IGE)) and ITAX_GE(IA,IGE) AND CCCRRR(C,
       IR) AND RRRAAA(IR,IA) and IGNOTETOH(IGE)),
          SUM((IS3,T),ITAX_GE(IA,IGE)*IHOURSINST(IS3,T)  *
              (VRES_UP(IA,IGE,IS3,T,QUANTILES)-VRES_DOWN(
             IA,IGE,IS3,T,QUANTILES))))

))
$label no_res_costs
```

A.4 Data for South African Power System

A.4.1 Grouped Units to Regulate Imbalances (g^{bal})

Units	MW	# units	Failure rate	Marg Euro/MW	Cum Cap
Matla	575	6	0.100%	268	3450
Kriel	475	6	0.125%	310	6300
Avon OCGT	670	1	0.082%	314	6970
Dedisa OCGT	335	1	0.077%	314	7305
Hendrina	190	10	0.127%	318	9205
Duvha	575	6	0.056%	325	12655
Matimba	615	6	0.059%	343	16345
Kendal	640	6	0.050%	437	20185
Lethabo	593	6	0.075%	452	23743
Rooiwal	51	4	0.068%	461	23947
Pretoria West	25	4	0.073%	462	24047
Medupi	794	6	0.060%	473	28811
Kusile	800	6	0.067%	473	33611
Komati	101	9	0.225%	487	34520
Kelvin B	51	3	0.093%	491	34673
Sasol SSF	52	10	0.051%	509	35193
Kelvin A	25	3	0.094%	533	35268
Grootvlei	190	6	0.245%	582	36408
Majuba Dry	617	3	0.085%	597	38259
Majuba Wet	664	3	0.073%	604	40251
Camden	190	8	0.279%	659	41771
Arnot	410	6	0.103%	663	44231
Tutuka	585	6	0.021%	754	47741
Acacia	57	3	0.165%	2400	47912
Port Rex	57	3	0.099%	2406	48083
Atlantis	575	9	0.086%	2596	53258
Mossel Bay	475	5	0.055%	2596	55633

Table A.2: Tabel of units with data for: capacity, number of grouped units, failure rate, marginal costs and cumulated capacity.

A.4.2 Fuel Data

Fuel	FDNB	FDCO2 kg/GJ	FDSO2 kg/GJ	FDN2O kg/GJ	FDRE
Nuclear	1	0	0	0	0
Natural gas	2	56.1	0	0.001	0
Coal	3	96.25	0.714	0.003	0
Light oil	6	74	0.023	0.002	0
Wind	14	0	0	0	1
Solar	16	0	0	0	1
Elec. storage	17	0	0	0	0
Biogas	23	-29	0	0.001	1
Coal - Grootvlei	101	96.25	0.714	0.003	0
Coal - Komati	102	96.25	0.714	0.003	0
Coal - Arnot	103	96.25	0.714	0.003	0
Coal - Camden	104	96.25	0.714	0.003	0
Coal - Duvha	105	96.25	0.714	0.003	0
Coal - Kendal	106	96.25	0.714	0.003	0
Coal - Hendrina	107	96.25	0.714	0.003	0
Coal - Kriel	108	96.25	0.714	0.003	0
Coal - Lethabo	109	96.25	0.714	0.003	0
Coal - Majuba	110	96.25	0.714	0.003	0
Coal - Matimba	111	96.25	0.714	0.003	0
Coal - Matla	112	96.25	0.714	0.003	0
Coal - Tutuka	113	96.25	0.714	0.003	0
Coal - KelvinA	114	96.25	0.714	0.003	0
Coal - KelvinB	115	96.25	0.714	0.003	0
Coal - PretoriaW	116	96.25	0.714	0.003	0
Coal - Rooiwal	117	96.25	0.714	0.003	0
Coal - Sasol	118	96.25	0.714	0.003	0
Coal - New	119	96.25	0.714	0.003	0

Table A.3: Data for fuel: Fuel number, emission factor for CO_2,SO_2 and N_2O, share of renewable energy.

A.4.3 Generation units

Unit	Cap. MW	Fuel	Fuel eff. %	Min. gen. %	Start up cost Euro/MW	Fixed O&M kEuro/MW	Var. O&M Euro/MWh
Acacia3	57	Diesel	28%	20%	200	79	118.4
Arnot1	410	Coal	32%	30%	580	368	11.7
Arnot2	380	Coal	32%	30%	580	368	11.7
Arnot3	380	Coal	32%	30%	580	368	11.7
Arnot4	380	Coal	32%	30%	580	368	11.7
Arnot5	380	Coal	32%	30%	580	368	11.7
Arnot6	380	Coal	32%	30%	580	368	11.7
Atlantis1	147	Diesel	33%	20%	200	76	314.1
Atlantis2	147	Diesel	33%	20%	200	76	314.1
Atlantis3	147	Diesel	33%	20%	200	76	314.1
Atlantis4	147	Diesel	33%	20%	200	76	314.1
Atlantis5	147	Diesel	33%	20%	200	76	314.1
Atlantis6	147	Diesel	33%	20%	200	76	314.1
Atlantis7	147	Diesel	33%	20%	200	76	314.1
Atlantis8	147	Diesel	33%	20%	200	76	314.1
Atlantis9	147	Diesel	33%	20%	200	76	314.1
Avon_OCGT	670	Diesel	33%	-	-	76	314.1
Camden1	190	Coal	28%	30%	580	149	8.2
Camden2	190	Coal	28%	30%	580	149	8.2
Camden3	190	Coal	28%	30%	580	149	8.2
Camden4	190	Coal	28%	30%	580	149	8.2

Camden5	190	Coal	28%	30%	580	149	8.2
Camden6	190	Coal	28%	30%	580	149	8.2
Camden7	190	Coal	28%	30%	580	149	8.2
Camden8	190	Coal	28%	30%	580	149	8.2
Colleywobbles	42	Hydro	100%	-	-	134	4.2
CSP_Bokpoort	50	Solar	100%	-	-	497	0.0
CSP_KaXuSolarOne	100	Solar	100%	-	-	497	0.0
CSP_KhiSolarOne	50	Solar	100%	-	-	497	0.0
Darling	5	Wind	100%	-	-	13	121.6
Dedisa_OCGT	335	Diesel	33%	-	-	76	314.1
Duvha1	575	Coal	35%	30%	580	198	3.5
Duvha2	575	Coal	35%	30%	580	198	3.5
Duvha3	575	Coal	35%	30%	580	198	3.5
Duvha4	575	Coal	35%	30%	580	198	3.5
Duvha5	575	Coal	35%	30%	580	198	3.5
Duvha6	575	Coal	35%	30%	580	198	3.5
Gariep1	90	Hydro	100%	-	-	135	4.2
Gariep2	90	Hydro	100%	-	-	135	4.2
Gariep3	90	Hydro	100%	-	-	135	4.2
Gariep4	90	Hydro	100%	-	-	135	4.2
Grootvlei1	190	Coal	27%	30%	580	239	5.1
Grootvlei2	190	Coal	27%	30%	580	239	5.1
Grootvlei3	190	Coal	27%	30%	580	239	5.1
Grootvlei4	190	Coal	27%	30%	580	239	5.1
Grootvlei5	190	Coal	27%	30%	580	239	5.1

Grootvlei6	190	Coal	27%	30%	580	239	5.1
Hendrina1	190	Coal	32%	30%	580	411	9.4
Hendrina10	190	Coal	32%	30%	580	411	9.4
Hendrina2	190	Coal	32%	30%	580	411	9.4
Hendrina3	190	Coal	32%	30%	580	411	9.4
Hendrina4	190	Coal	32%	30%	580	411	9.4
Hendrina5	190	Coal	32%	30%	580	411	9.4
Hendrina6	190	Coal	32%	30%	580	411	9.4
Hendrina7	190	Coal	32%	30%	580	411	9.4
Hendrina8	190	Coal	32%	30%	580	411	9.4
Hendrina9	190	Coal	32%	30%	580	411	9.4
Hydro_Neusberg	10	Hydro	100%	-	-	0	0.0
Hydro_Stortemelk	4	Hydro	100%	-	-	0	0.0
HydroPlant	20	Hydro	100%	-	-	0	0.0
Kelvin_A1	25	Coal	25%	-	-	435	21.1
Kelvin_A2	25	Coal	25%	-	-	435	21.1
Kelvin_A3	25	Coal	25%	-	-	435	21.1
Kelvin_B1	51	Coal	26%	-	-	354	21.1
Kelvin_B2	51	Coal	26%	-	-	354	21.1
Kelvin_B3	51	Coal	26%	-	-	354	21.1
Kendal1	640	Coal	35%	30%	580	143	4.7
Kendal2	640	Coal	35%	30%	580	143	4.7
Kendal3	640	Coal	35%	30%	580	143	4.7
Kendal4	640	Coal	35%	30%	580	143	4.7
Kendal5	640	Coal	35%	30%	580	143	4.7

Kendal6	640	Coal	35%	30%	580	143	4.7
Klipheuwel	3	Wind	100%	-	-	13	121.6
Koeberg1	900	Nuclear	30%	20%	10000	488	11.7
Koeberg2	900	Nuclear	30%	20%	10000	488	11.7
Komati1	101	Coal	26%	30%	580	219	3.1
Komati2	101	Coal	26%	30%	580	219	3.1
Komati3	101	Coal	26%	30%	580	219	3.1
Komati4	101	Coal	26%	30%	580	219	3.1
Komati5	101	Coal	26%	30%	580	219	3.1
Komati6	101	Coal	26%	30%	580	219	3.1
Komati7	101	Coal	26%	30%	580	219	3.1
Komati8	101	Coal	26%	30%	580	219	3.1
Komati9	101	Coal	26%	30%	580	219	3.1
Kriel1	475	Coal	36%	30%	580	349	9.4
Kriel2	475	Coal	36%	30%	580	349	9.4
Kriel3	475	Coal	36%	30%	580	349	9.4
Kriel4	475	Coal	36%	30%	580	349	9.4
Kriel5	475	Coal	36%	30%	580	349	9.4
Kriel6	475	Coal	36%	30%	580	349	9.4
Kusile1	800	Coal	37%	25%	580	533	52.0
Kusile2	800	Coal	37%	25%	580	533	52.0
Kusile3	800	Coal	37%	25%	580	533	52.0
Lethabo1	593	Coal	35%	30%	580	151	9.4
Lethabo2	593	Coal	35%	30%	580	151	9.4
Lethabo3	593	Coal	35%	30%	580	151	9.4

Lethabo4	593	Coal	35%	30%	580	151	9.4
Lethabo5	593	Coal	35%	30%	580	151	9.4
Lethabo6	593	Coal	35%	30%	580	151	9.4
Majuba_Dry1	617	Coal	35%	-	-	157	8.2
Majuba_Dry2	617	Coal	35%	-	-	157	8.2
Majuba_Dry3	617	Coal	35%	-	-	157	8.2
Majuba_Wet1	664	Coal	38%	-	-	105	15.2
Majuba_Wet2	664	Coal	38%	-	-	105	15.2
Majuba_Wet3	664	Coal	38%	-	-	105	15.2
Matimba1	615	Coal	35%	30%	580	234	7.0
Matimba2	615	Coal	35%	30%	580	234	7.0
Matimba3	615	Coal	35%	30%	580	234	7.0
Matimba4	615	Coal	35%	30%	580	234	7.0
Matimba5	615	Coal	35%	30%	580	234	7.0
Matimba6	615	Coal	35%	30%	580	234	7.0
Matla1	575	Coal	35%	30%	580	220	11.7
Matla2	575	Coal	35%	30%	580	220	11.7
Matla3	575	Coal	35%	30%	580	220	11.7
Matla4	575	Coal	35%	30%	580	220	11.7
Matla5	575	Coal	35%	30%	580	220	11.7
Matla6	575	Coal	35%	30%	580	220	11.7
Medupi1	794	Coal	37%	25%	580	533	52.0
Medupi2	794	Coal	37%	25%	580	533	52.0
Medupi3	794	Coal	37%	25%	580	533	52.0
Medupi4	794	Coal	37%	25%	580	533	52.0

Medupi5	794	Coal	37%	25%	580	533	52.0
Mossel_Bay1	147	Diesel	34%	-	-	79	314.1
Mossel_Bay2	147	Diesel	34%	-	-	79	314.1
Mossel_Bay3	147	Diesel	34%	-	-	79	314.1
Mossel_Bay4	147	Diesel	34%	-	-	79	314.1
Mossel_Bay5	147	Diesel	34%	-	-	79	314.1
OnshoreWind	749	Wind	100%	-	-	327	38.6
Port_Rex1	57	Diesel	28%	-	-	83	124.2
Port_Rex2	57	Diesel	28%	-	-	83	124.2
Port_Rex3	57	Diesel	28%	-	-	83	124.2
Pretoria_West1	25	Coal	24%	-	-	817	21.1
Pretoria_West2	25	Coal	24%	-	-	817	21.1
PV_Aries	10	Solar	100%	-	-	471	0.0
PV_Aurora	9	Solar	100%	-	-	471	0.0
PV_Boshof	60	Solar	100%	-	-	471	0.0
PV_DeAar	48	Solar	100%	-	-	471	0.0
PV_Dreunberg	70	Solar	100%	-	-	471	0.0
PV_Droogfontein	48	Solar	100%	-	-	471	0.0
PV_Greefspan	10	Solar	100%	-	-	471	0.0
PV_Herbart	20	Solar	100%	-	-	471	0.0
PV_Jasper	75	Solar	100%	-	-	471	0.0
PV_Kalkbult	72	Solar	100%	-	-	471	0.0
PV_Kathu	75	Solar	100%	-	-	471	0.0
PV_Konkoonsies	10	Solar	100%	-	-	471	0.0
PV_Lesedi	64	Solar	100%	-	-	471	0.0

PV_Letsatsi	64	Solar	100%	-	-	471	0.0
PV_Linde	37	Solar	100%	-	-	471	0.0
PV_MuliloDeAar	10	Solar	100%	-	-	471	0.0
PV_Prieska	20	Solar	100%	-	-	471	0.0
PV_RustMo1	7	Solar	100%	-	-	471	0.0
PV_SishenSolar	74	Solar	100%	-	-	471	0.0
PV_SolarCapDeAar	75	Solar	100%	-	-	471	0.0
PV_SolCapDeAar3	75	Solar	100%	-	-	471	0.0
PV_Soutpan	28	Solar	100%	-	-	471	0.0
PV_Swartland	5	Solar	100%	-	-	471	0.0
PV_Touwsrivier	36	Solar	100%	-	-	471	0.0
PV_UpingtonSolar	9	Solar	100%	-	-	471	0.0
PV_Vredendal	9	Solar	100%	-	-	471	0.0
PV_Witkop	30	Solar	100%	-	-	471	0.0
Rooiwal1	51	Coal	26%	30%	580	282	19.9
Rooiwal2	51	Coal	26%	30%	580	282	19.9
Rooiwal3	51	Coal	26%	30%	580	282	19.9
Rooiwal4	51	Coal	26%	30%	580	282	19.9
Sasol_SSF1	52	Coal	26%	-	-	162	16.4
Sasol_SSF10	52	Coal	26%	-	-	162	16.4
Sasol_SSF2	52	Coal	26%	-	-	162	16.4
Sasol_SSF3	52	Coal	26%	-	-	162	16.4
Sasol_SSF4	52	Coal	26%	-	-	162	16.4
Sasol_SSF5	52	Coal	26%	-	-	162	16.4
Sasol_SSF6	52	Coal	26%	-	-	162	16.4

Sasol_SSF7	52	Coal	26%	-	-	162	16.4
Sasol_SSF8	52	Coal	26%	-	-	162	16.4
Sasol_SSF9	52	Coal	26%	-	-	162	16.4
Sere	101	Wind	100%	-	-	331	38.6
SolarPower	496	Solar	100%	-	-	471	0.0
Tutuka1	585	Coal	38%	30%	580	149	8.2
Tutuka2	585	Coal	38%	30%	580	149	8.2
Tutuka3	585	Coal	38%	30%	580	149	8.2
Tutuka4	585	Coal	38%	30%	580	149	8.2
Tutuka5	585	Coal	38%	30%	580	149	8.2
Tutuka6	585	Coal	38%	30%	580	149	8.2
Umtata1falls	6	Hydro	100%	-	-	134	4.2
Umtata2falls	17	Hydro	100%	-	-	134	4.2
Vanderkloof1	120	Hydro	100%	-	-	135	4.2
Vanderkloof2	120	Hydro	100%	-	-	135	4.2
WI_Amakhala	138	Wind	100%	-	-	327	38.6
WI_Chaba	21	Wind	100%	-	-	327	38.6
WI_Cookhouse	135	Wind	100%	-	-	327	38.6
WI_Dassiesklip	26	Wind	100%	-	-	327	38.6
WI_Dorper	97	Wind	100%	-	-	327	38.6
WI_Gouda	135	Wind	100%	-	-	327	38.6
WI_Grassridge	60	Wind	100%	-	-	327	38.6
WI_Hopefield	65	Wind	100%	-	-	327	38.6
WI_JefferysBay	134	Wind	100%	-	-	327	38.6
WI_Kouga	78	Wind	100%	-	-	327	38.6

WI_Metrowind	26	Wind	100%	-	-	327	38.6
WI_Noblesfontein	73	Wind	100%	-	-	327	38.6
WI_Tsitsikamma	95	Wind	100%	-	-	327	38.6
WI_WestCoast1	91	Wind	100%	-	-	327	38.6
WI_Waainek	23	Wind	100%	-	-	327	38.6

Table A.4: Technology data: Installed capacity, fuel type, fuel efficiency, minimum generation capacity, start up cost, fixed and variable O&M.

A.4.4 Transmission Data

Region	SA_C	SA_E	SA_HY	SA_KIM	SA_N	SA_NAM	SA_NE	SA_NW	SA_S	SA_W	SWAZI
SA_C	0	7600	0	600	INF	0	INF	6000	600	0	0
SA_E	7600	0	0	0	0	0	0	0	400	0	0
SA_HY	0	0	0	0	0	725	0	6000	1000	2175	0
SA_KIM	1000	0	0	0	0	600	0	485	0	0	0
SA_N	INF	INF	0	0	0	0	INF	0	0	0	1250
SA_NAM	0	0	1000	600	0	0	0	0	0	725	0
SA_NE	INF	0	0	0	INF	0	0	0	0	0	0
SA_NW	INF	0	4000	485	0	0	0	0	0	0	0
SA_S	1000	400	2000	0	0	0	0	0	0	0	0
SA_W	0	0	3000	0	0	1000	0	0	0	0	0

Table A.5: Electricity transmission capacity between regions in MW, INF represents no upper limit on transmission.

	SA_C	SA_E	SA_N	SA_NE	SA_NW	SA_S	SA_W	SA_NAM	SA_HY	SA_KIM
SA_C	0	0.320	0.320	0.320	0.320	0.330	0	0	0.165	0
SA_E	0.320	0	0.320	0.320	0.320	0	0	0	0	0
SA_N	0.320	0.320	0	0.320	0.320	0	0	0	0	0
SA_NE	0.320	0.320	0.320	0	0.320	0	0	0	0	0
SA_NW	0.320	0.320	0.320	0.320	0	0	0	0	0	0
SA_S	0.330	0	0	0	0	0	0	0	0.165	0
SA_W	0	0	0	0	0	0	0	0	0.166	0
SA_NAM	0	0	0	0	0	0	0	0	0.165	0.165
SA_HY	0.165	0	0	0	0	0.165	0.166	0.165	0	0
SA_KIM	0	0	0	0	0	0	0	0.165	0	0

Table A.6: Electricity transmission cost between regions in Euro/MWh, existing transmission lines not shown here are given a transmission cost of 0.001.

Bibliography

[1] *Auto weibull for the weibull distribution function.* www.autoweibull.com/.

[2] *The Balmorel model - model structure.* http://www.eabalmorel.dk/files/download/TheBalmorelModelStructure-BMS302.pdf.

[3] *The Balmorel model - theoretical background.* http://www.eabalmorel.dk/files/download/The%20Balmorel%20Mode%20Theoretical%20Background.pdf.

[4] ARGONNE, *Decision and information sciences.* www.dis.anl.gov/news/WECC_ClimateChange.html.

[5] ATEST HOMEPAGE, *Analysing transition planning and systemic energy planning tools for the implementation of the energy technology information system.* www.cres.gr/atest/pdf/D_2_1_Models_Characterisation_Report.pdf.

[6] BALMOREL HOMEPAGE, *A model for analyses of the electricity and chp markets in the baltic sea region.* www.eabalmorel.dk/files/download/Balmorel%20A%20Model%20for%20Analyses%20of%20the%20Electricity%20and%20CHP%20Markets%20in%20the%20Baltic%20Sea%20Region.pdf.

[7] BEMBook Homepage, *History of building energy modeling.* www.bembook.ibpsa.us/index.php?title=History_of_Building_Energy_Modeling.

[8] J. M. Bland, *The half-normal distribution method for measurement error: two case studies*, Department of Health Sciences, University of York.

[9] Q. Chen, *The probability, identification, and prevention of rare events in power systems.* www.pserc.wisc.edu, 2004.

[10] DTU Informatics, *Wind power forecasting.* www.imm.dtu.dk/English/Research/Mathematical_Statistics/Research/time-series_analysis/wind.aspx.

[11] Ea Energy Analyses. www.eaea.dk.

[12] Ea Energy Analyses Homepage , *Costs and benefits of implementing renewable energy policy in south africa.* www.ea-energianalyse.dk/reports/1132_costs_benefits_of_implementing_re_in_south_africa.pdf, 2012.

[13] Ea Energy Analyses Homepage, *Paths towards a fossil-free energy supply.* www.ea-energianalyse.dk/reports/1010_Paths_towards_a_fossil_free_energy_supply.pdf, 2010.

[14] Energinet.dk, *Samkøringsmodellen.* www.energinet.dk/DA/El/Udvikling-af-elsystemet/Analysemodeller/Sider/Samkoeringsmodellen.aspx.

[15] Energinet.dk Homepage. www.energinet.dk.

[16] Energy Systems. http://telstar.ote.cmu.edu/environ/m3/s3/all_ene_sys.htm.

[17] ENSYMORA Homepage, *Energy systems modelling, research and analysis.* www.ensymora.dk/.

[18] ENTSOE Homepage, *European network of transmission system operators for electricity.* www.entsoe.eu/.

[19] ESKOM homepage. www.eskom.co.za/live/index.php.

[20] J. Fang and Y. Xi, *A rolling horizon job shop rescheduling strategy in the dynamic environment*, (1997).

[21] E. Friis-Jensen, *Modeling of the combined heat and power system of greater copenhagen.* http://ea-energianalyse.dk/reports/student-reports/modelling_of_the_combined_heat_and_power_system_of_greater_copenhagen.pdf.

[22] GAMS (General Algebraic Modeling System). www.gams.com.

[23] IBM ILOG CPLEX Optimizer. www-01.ibm.com/software/integration/optimization/cplex-optimizer/.

[24] Ingeniøren, *Hovedpunkter i klimakommissionens rapport.* http://ing.dk/artikel/hovedpunkter-i-klimakommissionens-rapport-112432, September 2010.

[25] R. A. Johnson, *Probability and Statistics for Engineers*, Miller & Freund, seventh ed., 2005.

[26] T. Kristoffersen, P. Meibom, and Risø DTU, *WP3: Prototype development for operational planning tool*, (2008).

[27] MathPages, *Introduction to Markov Modeling for Reliability.* http://www.mathpages.com/home/kmath232/kmath232.htm, 2010.

[28] National Renewable Energy Laboratory. www.nrel.gov/analysis/reeds/pdfs/reeds_chap_2.pdf.

[29] PSR Homepage. www.psr-inc.com.br/portal/psr/servicos/modelos_de_apoio_a_decisao/studio_plan/optgen/.

[30] K. D. R. Ruwanthi and W.N.Wickremasinghe, *Modelling sector-wise demand for electricity in sri lanka using a multivariate regression approach*, Journal of the National Science Foundation of Sri Lanka, vol. 27, no.1 (1999).

[31] STREAM Homepage, *An energy scenario modelling tool.* www.streammodel.org/.

[32] J. W. Taylor, L. M. de Menezes, and P. E. McSharry, *A comparison of univariate methods for forecasting electricity demand up to a day ahead*, International Journal of Forecasting, vol. 22 (2006), pp. 1–16.

[33] The Balmorel Homepage. www.balmorel.com.

[34] T. Vrana and E.Johansson, *Overview of power system reliability assessment techniques*, Norwegian University of Science and Technology, (2011).

[35] WILMAR Homepage, *Wind power integration in liberalised electricity markets.* www.wilmar.risoe.dk/.