Orchestrating Investment in an Evolving Power Sector: An Analysis of Capacity Markets

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Abstract

T here is increasing concern that energy-only markets are inadequate when it comes to ensuring generation adequacy in the power sector over the long term. This is reflected in the fact that several Independent System Operators have commissioned studies about security of supply over the last few years; OFGEM and CEER (Council of European Energy Regulators) are some of them. There is some empirical evidence and substantial theory as to why incentives for investments are insufficient in such markets. Capacity mechanisms are policy tools that aim at providing incentive to this investment into reliability both over the long-term and short-term. Compounding this inadequacy of energy-only markets is the expected change in the composition of the generating portfolio over the coming decades. It is expected that the European electricity industry is almost entirely carbon free by 2050. In addition, implementation of a capacity market in a country in hugely interconnected Europe might show cross border effects that need further insight and understanding.

The purpose of this work is to evaluate the effectiveness of capacity markets, a type of capacity mechanism, in its ability to ensure long term generation adequacy, and more generally, improve the performance of the electricity sector and increase consumer and producer welfare. The effectiveness of capacity markets are assessed primarily on the following indicators: performance of the electricity market (adequacy of supply, stable energy prices), consumer welfare and producer welfare. This work is part of a larger project at the Energy and Industry section of TPM, EMLab Generation, which is focused on studying the electricity market in transition towards a low-carbon regime. The methodology applied to carry out this research is agent based modelling. A model of the capacity market has been built and analysed.

In order to conceptualize a capacity market model, a thorough literature review and empirical study was carried out on the existing variations of capacity markets that are implemented across the world. While there are slight variations between them, the overarching principle beind them remains the same - to administratively place an obligation on the load to buy supply to meet a certain reserve margin of generation. The New York ISO Installed Capacity (NYISO ICAP) market was used as the primary basis to conceptualize the capacity market. The NYISO ICAP was chosen due to its relatively simple design (there are no forward capacity requirements), and well-established nature. The conceptualization was then adapted to the existing EMLab model. From this conceptual model a pseudo code for the formal model was created, and then implemented in the software.

After a lengthy process of verification, the experimental set-up was designed to reflect

- a sensitivity analysis to capacity market design parameters such as price cap and slope.
- the effect of a capacity market in a single country, with and without target investment in renewable energy
- the effect of a capacity market in a two country scenario, with one of the countries having an energy-only market, also with and without target investment in renewable energy.

The insights from the model are mainly that the capacity market works as intended, improves the performance of the electricity sector in general, affects the adequacy and therefore the stability of the power system, affects the type of generation portfolio that might arise as a result. Specifically,

On Capacity Market Design The performance of the electricity market is highly sensitive to the price cap and slope of the capacity market. To ensure the desired level of adequacy in the system, the price cap in the capacity market must be sufficiently high (1.5 times CONE) to incentivize and induce investment. If a low price cap (say, CONE) is implemented, there could still be sufficient investment signal if the demand curve is relatively flat. A vertical demand curve is detrimental to the electricity market in general, because staggered revenues from the capacity market hugely increase the volatility in the system, reducing consumer benefit, leading even to negative profits (on an average) for producers.

On Cross Border Effects of Capacity Market The capacity market ensures the desired reserve margin in the country where it has been implemented. However it does so at a higher cost to the consumers of that country. The reasoning behind this is explained in the previous chapter. Interestingly, the model suggests that, without export constraints, between the two countries involved, the surplus capacity in the country with the capacity market dampens investment in the neighbouring country with an energy only market. This even leads to a marginally higher chance of outages in the neighbouring country.

On Performance of the Capacity Market with Substantial Renewable Energy Simulations suggest that reserve margins may need to be increased if the same level of reliability were to be maintained in a scenario with substantial renewable energy generation.

Although the choice of capacity mechanism is highly dependant on the context, this work does not intend to recommend capacity market as the solution for problems with the energy only market. However, this research provides valuable insight into capacity market design, on the effects if the capacity market on producers and consumers, and in other relavant scenarios as described above.

Acknowledgements

When I began this project in February 2013, I was more than confident that I would be successful. Mid way through the work however, there were times when that confidence took a serious hit. The project was indeed, given the time constraints, a lot harder than expected. EMLab was complex, challenging, fun and frustrating all at the same time.

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I thank Ruben Verweij and Jeroen Paling, who I met while working on the thesis; they became more friends than colleagues in the end! I thank them for their constant help and motivation. It was great to work on different aspects of the same project and help each other out in the project rooms at TBM. Thank you for forcing me to take breaks to watch Tour de France, even as the debugging hadn't worked for a week. It helped me see that there is a world outside the thesis! Finally I thank my parents, Vidya and Satish - your unconditional love, and faith in my abilities has been the greatest source of strength in my life.

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Part I

Thesis Definition

Chapter 1

Thesis Definition

1.1 Introduction

It is widely debated whether the standard liberalisation prescription for the electricity sector, the textbook model [1], provides adequate price signals to ensure long-term generation adequacy and system reliability. Empirically, incidents such as the California electricity market crisis of 2000 and 2001, and shortages in New Zealand, Scandinavia and Italy lend credence to the statement [2]. Theoretically, the missing money problem, and the fact that generation adequacy and reliability have public good characteristics, have been established [3–5]. There is a need for market designs to reflect the need for the implementation of reliability in the market structure. Policy instruments commonly referred to as capacity mechanisms, that make several adjustments to market designs to solve the issue, have been proposed [2]. Yet, scientific opinion on the effectiveness of these mechanisms, in terms of achieving their many intended objectives remains equivocal. Capacity mechanisms are of several types. While some are price-based instruments, such as capacity payments and operating reserves pricing, others are quantity-based instruments, such as capacity markets and reliability contracts [6]. Price-based instruments, as the name suggests, regulate reliability based on price, while quantity based instruments regulate based on volume. Their performance objectives are manifold. The primary objective is to provide incentives for generating companies to ensure long term reliability, i.e., sufficient investment in generating capacity . Secondary objectives include disincentivising the exercising of market power, attenuation of investment cycles, and stimulation of demand price-elasticity among others [2]. The scope of this work is limited to quantity based mechanisms such as capacity markets.

This work is aimed primarily at studying the dynamic performance of capacity markets as a policy tool to ensure generation adequacy. This is done by simulating a capacity market using agent-based modelling, in a larger model of a (trans-boundary) electricity market called EMLab. The performance indicators for the capacity market are performance of the electricity market in terms of generation adequacy and volatility of prices, consumer welfare and producer welfare. The performance indicators will then be tested in the context of a transition of the power sector to a low-carbon regime, and in an open market, such as commonly found in Europe. This research is being performed as part of a larger research initiative at the faculty of Technology, Policy and Management at Delft University of Technology, called Next Generation Infrastructures (NGI). Specifically, this work is part of a project that deals with understanding complex market behaviour in the transition of the power sector to a low carbon regime [7]. The study is carried out based on a simulation using the relatively new technique of agent based modelling.

This chapter primarily defines the problem to be tackled in this research. The first section describes the problem at hand and the plausible alternative that is the capacity market. Specifically, it entails a brief description of the shortcomings of energy-only markets, and the possible need for additional policy mechanisms to ensure reliability of power supply. It then contains a brief description of capacity markets, and their performance criteria. This is followed by the state-of-the-art in the modelling of capacity markets, which is a brief literature survey of the relevant work done so far in the field. Finally, the section culminates with the main problem statement that this research aims to tackle. The second chapter deals with the research itself what this work aims to accomplish and how. It details the methodology used to tackle the research questions.

1.2 Problem Definition

This section provides the background, and context of the policy issue at hand, ultimately culminating with the problem statement.

1.2.1 Problems with Energy-only Markets

Energy-only markets are so termed to indicate that the price of electric energy is the only determinant of capacity investment. This section outlines the main issues with energy markets as is, and then outlines how the problems are compounded by the transition of the power sector towards a low-carbon regime. From literature [2, 6, 8], the following ideas comprise of the main inadequacies of energy-only markets.

- High price volatility
- Insufficient demand response.
- Reliability and stability are public goods that will not be provided by market, and hence has to be administratively ensured.
- Actions taken by system operators, specifically non-price rationing of demand, impose social costs that are not reflected in the market prices, such as reducing system voltage by 5% to reduce demand
- Reliance on bilateral out-of-market contracts to avoid rolling blackouts or network collapse.
- Another aspect of social costs incurred on the consumer is the asymmetry between costs of over-capacity versus the cost of under-capacity. A blackout or network collapse costs the society a lot more than the cost of having over-capacity. This is referred to as the asymmetric loss of welfare function.
- Opportunities to exercise market power.

Problems with energy only markets have been popularly characterised as the missing money problem, first termed so by Cramton and Stoft (2006). The idea is that the last increment in generating capacity, which is standing in reserve to meet low probability, high demand contingencies, must earn all their revenues during a few critical hours, with price spikes. Therefore the prices of ancillary services must be quite high in an energy only market. If the prices are too low, there will be underinvestment in generating capacity. Another aspect of the aforementioned problems alludes to the possibility of investment cycles. High price volatility combined with regulatory uncertainty leads to imperfect foresight and the creation of investment cycles.

Leakage in an Open Market   In an open electricity market, such as in Europe, each country has varying policy instruments. In the context of generation adequacy, it is interesting to study the effects of a capacity mechanism being implemented in one country, but not in its neighbour.

It is expected that the neigbouring country could free-ride, from the former country. However, as is evident from the literature review in 1.4 on page 5, this hypothesis may well be false.

Decarbonisation Targets There is a growing consensus that the electricity sector needs to be decarbonised, and that renewable energy generation needs to be promoted. This is reflected prominently in the policies of the European Union as a whole, as is evident in their Emission Trading Scheme, and renewable energy generation targets. Even among the member countries, regulatory support for diverse RE technologies exist. However, this has significantly increased regulatory intervention, intensifying uncertainty for investors. Further, it is unclear how structural changes to the composition of the electricity sector will impact market prices, further increasing investment uncertainty for the industry [9]. One certain consequence of substantial increase in intermittent RES is that the width of the load duration curve for thermal generators significantly reduces, possible making them financially unviable. The gravity of the problem is reflected in the UK Electricity Market Reform Bill, passed in Nov 2012, which makes provisions for addressing the dual goals of decarbonisation and security of supply.

1.3 Capacity Mechanisms: Performance Criteria

Capacity mechanisms are policy instruments designed to incentivise investment into reliability, both long-term and operational reliability, of the power sector. Capacity markets in particular, directly regulate the volume of generating capacity, rather than influencing the price. This is done by creating an additional demand for capacity, or the option of using capacity (reliability options) for the energy producers. This additional demand is the reserve margin, determined by the regulator. A comprehensive outline of performance indicators for capacity mechanisms in general, presented by [2], is mentioned below. They should ideally meet the following criteria.

- Incentives to generating companies to provide an adequate volume of generating capacity, attenuation of investment cycles
- Incentives to generating companies to maximize output during a shortage
- No new opportunities to exercise market power
- Stabilization of prices
- Effectiveness in an open market
- Robustness against a regional shortage
- Stimulation of demand price-elasticity
- Supply-side efficiency
- Physical and institutional feasibility

For capacity markets in particular, Joskow [8,10] provides further insights. Capacity markets typically incorporate an administratively determined reserve margin, R, which is defined as R= (G-D)/D, where G is the peak generating capability and D is the expected system peak demand. The value of the reserve margin criterion, R, must theoretically reflect considerations of demand uncertainty, supply uncertainty, the value of lost load from rolling blackouts and network collapses. The primary idea is that operational reliability of the system, reflecting low probability of network collapses, and stable operation of the network, also must serve as a performance criterion for capacity

1.4 State of the Art: Analysis of Capacity Markets

Among the earliest scholars who analysed the issue of resource adequacy in energy only markets are [11]. Using system dynamics, they analysed the effect of changes in parameters like

volatility in the reserve margin, variations in the loss of load probability, and different market share scenarios, on investment into future capacity. Their findings were that while the capacity planning was highly sensitive to the factor loss of load probability, the system still provided adequate signals to ensure sufficient long term investment into generation. De Vries [12] studied the effectiveness of capacity mechanisms under demand uncertainty also using system dynamics. They tested for instance, whether the market is prone to investment cycles, with capacity mechanisms. They found that all capacity mechanisms helped attenuate investment cycles, but to different degrees. Reliability contract, a type of capacity market, was found to be the most effective mechanism. In a more recent work by [13], the performance of capacity markets in an open market, i.e., between two independent markets: an energy-only market but price capped (market A), and price capped markets with forward capacity contracts obligation (market B) is analysed. Interestingly, they find that, although there are short term free-rider effects, there are actually negative externalities imposed on market A by market B in the long run.

1.5   Problem Statement

From the above discussion, the following problem statement has been formulated. It provides a brief sketch of the overarching policy issue that is being addressed in this work. For the purposes of this research, the policy makersṕerspective is considered.

   Primary Issue: How to ensure reliability of supply, without having to endure negative externalities?

   The term reliability herewith refers to long-term reliability or generation adequacy. Negative externalities refer to possible negative effects of the energy only market, such as price spikes, high probablity of blackouts due to shortages, increased market power among others, as mentioned above. As elucidated in the previous sections, the hypothesis is that capacity markets are a plausible alternative to the primary issue. Thus the secondary issues follow.

   Secondary Issues: How to ensure reliability with capacity markets

- whilst moving towards decarbonisation?(in the presence of substantial amounts of RES sources)
- in an open market?

Chapter 2

Research Overview

This section, as the title implies, is an overview of the research to be undertaken in this project. The section details the research objective, research questions and choice of methodology employed.

2.1 Research Objective and Scope

The objectives of this research involve two components, mentioned below. The primary component is the evaluation of the capacity markets themselves, while the secondary component is to study the indicators under certain specific scenarios. The objectives then are,
To evaluate the long-term, dynamic performance of capacity markets by the following indicators:

- performance of the electricity market: adequacy, price volatility
- consumer welfare
- producer welfare

The effects of capacity markets on the above indicators may then be tested in the presence of

- a neighbouring country with an energy-only market
- substantial intermittent renewable energy generation

This is to be done by simulating a capacity market using agent-based modelling, in a larger model of a (trans-boundary) electricity market. The choice of methodology is substantiated in section 2.3.2.

The scope of the research will be limited to an analysis of the centralized capacity market.

2.2 Research Questions

To meet the research objective, the following research questions have been formulated. They provide a logical sequence and structure to the research, lending an indication of the type of knowledge required, as well as the approaches that are involved iobtaining that knowledge.

Main Research Question Is a capacity market a good policy instrument to ensure generation adequacy in a western European country, given renewable energy investment targets and cross border effects?

Sub Research Questions

1. How can a capacity market be conceptualized in terms of a model?
2. Under which conditions does a capacity market perform well in terms of the following broad indicators?

   - performance of the electricity market: adequacy, price volatility
   - consumer welfare
   - producer welfare

3. How well does a capacity market, in a western European country, perform in the presence of

   - substantial intermittent renewable energy generation
   - a neighbouring country with an energy-only market

The first research question deals with characterising capacity markets and then designing a model of a capacity market. The second research question deals with analysing the performance of the capacity market based on the results of the simulation. The final research question deals with analysis of the capacity market in two specific scenarios.

2.3   Research Method and Data

This section is a description of the design of this research. It includes the research framework, it briefly introduces and compares the commonly used methods of modelling electricity markets, and explains the reason behind the choice of agent based modelling for this assignment.

2.3.1   Research Framework

The research framework indicates that the theoretical framework that this research is based on, is primarily neoclassical microeconomics. Further, theory on liberalisation of electricity markets, based also on neoclassical paradigm, but applied specifically to the electricity industry will be used. These theories serve to formulate the assessment criteria. The agent based modelling paradigm will be used to simulate the capacity market. The simulation will then be tested vis-vis the assessment criteria to arrive at conditions for good performance. Using these conditions, the simulation will be tested in the backdrop of the two scenarios mentioned in the research objective, namely, high intermittent RES and in the presence of a neighbouring country with an energy-only market. The results will then be used to arrive at recommendations for improvement of the design of capacity markets.

2.3.2   Simulation and Choice of Simulation Paradigm

A model is a way of representing and understanding the working of a system; it is a way of solving problems that are faced in the real world. It is typically used when prototyping with the real system is expensive or impossible. A simulation is then the set of rules that specify how the system being modelled will change in the future, given a certain present state. In general, simulation is a good solution when complex systems are being modelled, with time dynamics playing a prominent role [14].

A variety of techniques have been used to model electricity markets. Some of them include computational general equilibrium (CGE) models, system dynamics, game theory, and agent based modelling. The choice of modelling technique must depend on the purpose of the model. In this case, from the previous section, and from the research objective, the following is evident.

Figure 2.1: Research Framework
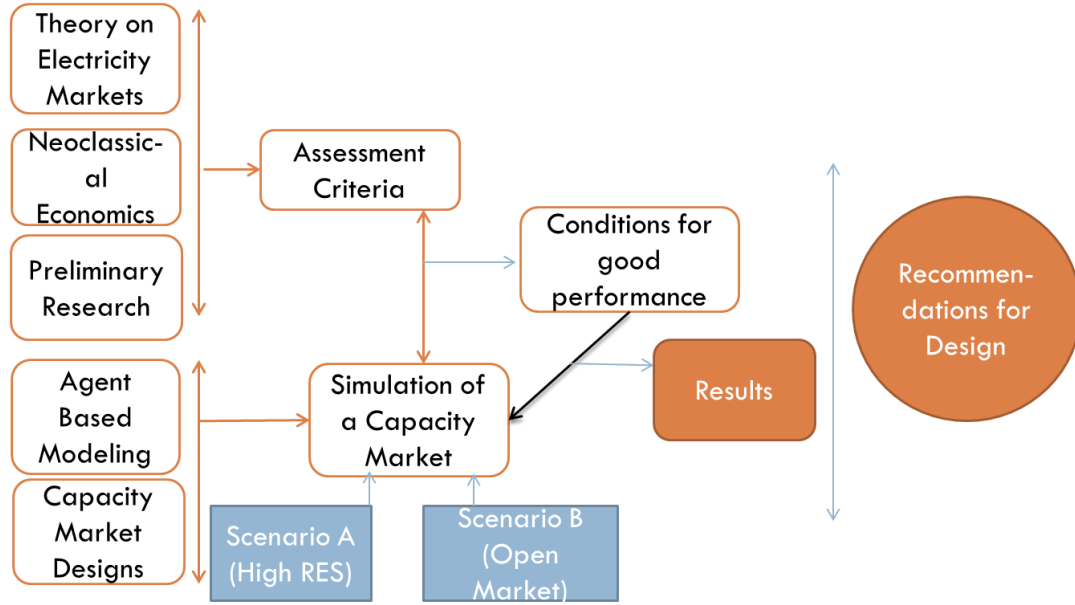
I wish to model a complex system embedded in an electricity market, to study its dynamic, long-term (30-40 years) performance. Since this is primarily a long-term model of a market, there is an emphasis on rigorous economic foundations as well as the dynamic nature of the system.

In view of these requirements I have chosen to elaborate on three of these techniques CGE, System Dynamics, and Agent Based Modelling. CGE was chosen because of its strong foundation in micro economic theory, and common application to economic markets, System Dynamics, due to its common application in modelling dynamic behaviour, and finally agent-based modelling, which is increasingly popular in simulating the electricity market. The table below describes the advantages and disadvantages of the three chosen modelling paradigms.

Table 2.1: Comparison of Modelling Techniques

Modelling Technique	Advantages	Disadvantages
System Dynamics	- Dynamic nature of the problem captured. - Easy to model nonlinearity	The system structure has to be specified, and the dynamics are dependent on the specified structure
Computational Equilibrium	- Useful for ex post analysis. - Based on strong foundations of widely-accepted micro economic theory - Easy to validate	- Poor description/representation of institutions. - Bad numerical tractability for representing complexity
Agent Based Modelling	- Models can be closely tailored to each situation. - ABM handles complexity well, and electricity markets are among the most complex systems - Behaviour is generative or emergent	- Difficult to interpret and draw generic conclusions - Lack of consensus on techniques suitable for a given situation - Difficult to validate

Given that the research objective is the study of the long term dynamics of capacity markets, embedded in electricity markets, the most appropriate choices seem to be SD and ABM. Although CGE has its advantages, its biggest drawback for this research is that it is not well-equipped to model dynamic behaviour as much as ABM is.

Apart from the ease of modelling dynamic behaviour and the existence of path dependence, which captures intertemporal relations, agent based modelling handles complexity well. This model incorporates multiple policy instruments, and multiple, connected markets; this multiplicity and diversity can be simulated with relative ease using agent based modelling. A major advantage of ABM as opposed to system dynamics is that it is not necessary to make apriori assumptions about how the system reacts to policy changes [7]. Agent behaviour is determined by decision rules and results are emergent. For these reasons, agent based modelling is the chosen modelling paradigm. To further investigate this choice, an ex ante analysis of applying agent based modelling to the research question at hand is performed below.

2.3.3 Ex Ante Analysis of ABM for Capacity Market Modelling

In this section, some of the key aspects and features of agent based models are discussed with respect to modelling electricity markets, along with their implications for modeling the capacity market.

A certain system is suitable for modelling using ABM if the following conditions are satisfied [15].

- The problem is of a distributed nature; each actor is autonomus to some extent.

- The agents (subsystems) operate in a highly dynamic environment.

- The interaction in the subsystem is characterised by flexibility: it can result from a reactive or pro-active attitude, from a propensity to co-operate or to compete.

Each of the above conditions are satisfied for the modelling of an electicity market - the agents, ie., energy producers are autonomous decision makers. The energy producers do operate in a highly dynamic environment, where past decisions affect actions in the present. And the interaction arises from a propensity to compete.

A comprehensive review by Weidlich and Veit [16] of agent based modeling applied to electricity market models reveals issues, knowledge gaps, and methodological drawbacks commonly noticed in such literature. This provides a good indicator of the pitfalls one might face while applying ABM to capacity markets.

Market Dynamics and Complexity Although agent based modelling is well poised to handle complexity, a lot of research is done by simplification of the real world significantly. For instance, in EMLab generation, the consumers are only modeled as one aggregate entity having a demand. In the capacity market model, therefore the demand side would be similarly simplified. Most studies do not consider out of equilibrium dynamics, or the circumstances under which agents reach an equilibrium. This could be a feature for consideration in the capacity market model analysis.

Validation This remains a major point of concern in agent based models, and there is little guidance to go by. Validation of agent behaviour in general is a challenging task, and even with standard verification and validation techniques, it is difficult to establish credibility for agent behavior. One major advantage of EMLab in that respect, is that there is no strategic bidding employed, or any such behaviour which might require the use of learning algorithms. Agent bidding, market outcomes and investment behaviours of the agents in EMLab are modelled based on expected behaviour in perfect competition under the assumption of perfect information in the model. This reduces the issue to a great extent, as outcomes should be interpreted as expected trends in ideal market conditions, and then they could be qualitatively analyzed for adjustments to market imperfections.

2.4 Conclusion

This section details the research objective, operationalization of the objective into research questions and finally, the research method chosen. The next two chapters set the stage for conceptualizing the capacity market with a detailed background of the electricity market, and the need for capacity mechanisms. The subsequent chapter provides a description of the electricity market model, EMLab.

Chapter 3

The Invisible Hand and Electricity

3.1 Introduction

The need for a mechanism to ensure reliable supply of electricity indicates that there are short-comings with the current system. This chapter provides a comprehensive background for the issue of generation adequacy. It describes the existing system of energy-only markets, their main characteristics, both positive and negative. It further describes capacity mechanisms and their types. It delves into capacity markets in particular, with examples of their implementation in various countries across the world.

Adam Smith's *Wealth of Nations* is widely regarded as the founding thought behind neo-classical economics today. The main idea behind the invisible hand is that public interest is best served when individuals pursue their own private interests. This free market ideology, following Reagan and Thatcher in the 80s, quickly spread across governments and various sectors. Institutions such as the World Bank promoted liberalisation and privatisation among the developing countries. Several network industries, including the railways, telecommunication and electricity began to be liberalised, privatised and regulated.

In the electricity sector specifically, liberalisation took the following form. The various segments of the electricity industry, generation, transmission and distribution, were unbundled, i.e., vertically separated. The segments that were potentially competitive were privatized. The segments that were natural monopolies were regulated and run by an Independent System Operator, new market and trading arrangements were made, and the retail tariffs were unbundled across the segments. This process constituted what is now commonly known as the standard prescription for liberalisation, or as the *textbook model* for restructuring and competition in electricity [18]. The focus, during this restructuring, lay primarily in driving monopoly to a minimum, and in regulating the natural monopolies.

3.1.1 Energy-Only Markets

Such markets, where the price indicates merely the price of energy, not reliability, are known as energy-only markets. That is, the capital costs of a generating unit must be recovered exclusively through the energy market prices. For an in-depth discussion on the theoretical basis for such markets refer Joskow and Tirole at [10] and Hogan at [19].

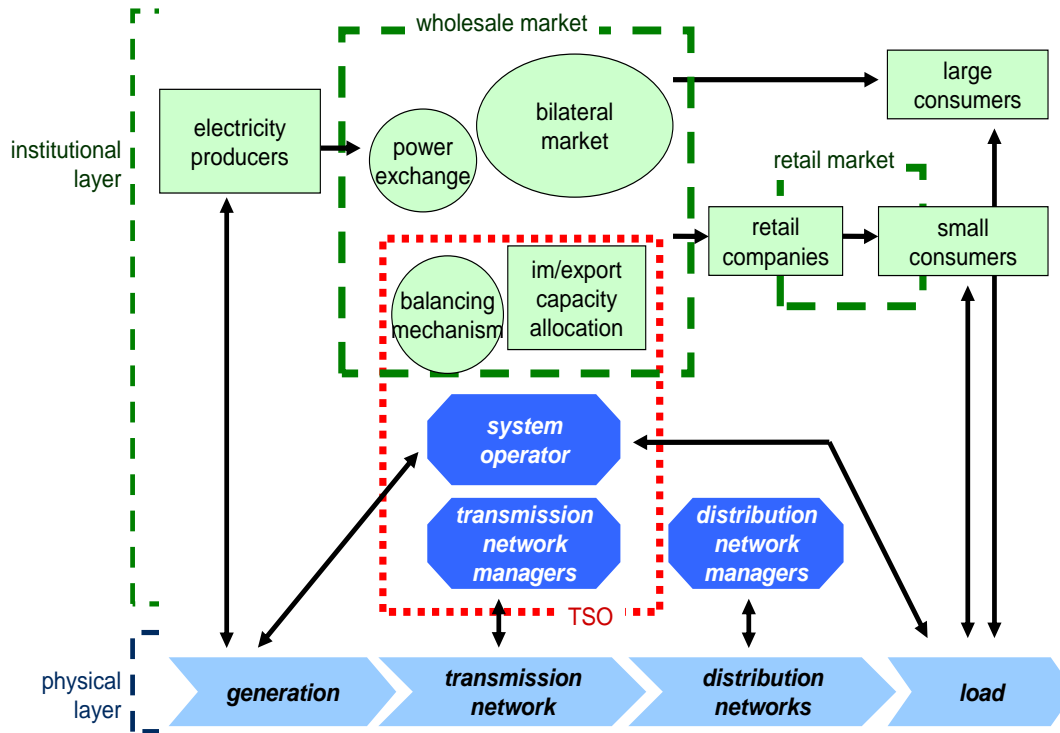Key issues with such markets are highlighted below.

Figure 3.1: Diagram of the Electricity System, from de Vries 2012 [17]

Missing Money   The missing money concept refers to the theory that in an energy only market investors are not be assured of returns that are sufficient to allow them to invest in new capacity. Thus, there is insufficient money for new investment. One of the primary reasons for this revenue deficiency is the enforcement of price caps, meant to control market power, by the regulator [4]. According to a report by the Brattle Group, which comprises of a geographically comprehensive study of electricity markets, the missing money problem is present in all active energy-only markets [20]. It is also present in markets such as the Australian NEM, where the price cap is set at VOLL. Another market which did not impose a price cap was the British NETA, yet resource adequacy problems in the UK are stark [21].

Demand Response   By design energy-only markets have moderate energy prices, with occasional severe scarcity price spikes. In other words, scarcity prices are an intentional feature, meant to attract and recover investment in capacity. For any other good an increase in prices would induce a reduction in demand, or increase in supply. Yet, typical power systems today do not have significant demand response capabilities, which implies that load reductions are not possible even if prices rise to exorbitant levels. Based on experience in California, the reason for the failure of an energy only market has been described Borenstein in [22] Stoft [23] shows that for energy markets to attract sufficient capacity, in principle, prices must be allowed to reach the Value of Lost Load (VOLL). The VOLL reflects the value of loss of electricity to consumers and at this price consumers, on average, are expected to be indifferent to whether they get

electricity or not. [1]

Price Volatility and its Implications Scarcity prices may be an intentional feature, yet high and volatile prices have their drawbacks. A major drawback is that it causes increased uncertainty in market revenues. It affects the cost of capital used by investors to evaluate projects, making the project more expensive due to an increased risk premium [10]. In addition, uncertainty in return on investment creates a preference for projects that have lower investment costs, but higher overall costs. Another important consideration is the "option value of waiting" - there is an incentive to delay investments as there is a possibility that some uncertainty may be resolved in the future. This implies that there is value in delaying investments [24]. Finally, high prices for a necessary good such as electricity is a politically sensitive issue the world over. Policy makers and regulators are unwilling to accept potentially exorbitant price levels, and therefore demand that power may be rationed instead, or impose out-of market solutions such as modest price caps below VOLL.[2]

Public Good Reliability, of which resource adequacy is a major aspect, is a public good. It is non-excludable and non-rivalrous. That is, no individual can claim ownership to its use, and it cannot be divided. This characteristic of reliability makes it susceptible to "free-ridership" by consumers who want to benefit from the high reliability without incurring any payments themselves, resulting in a "Tragedy of the Commons" effect. This is another reason why resource adequacy is not an outcome of an energy-only market.

Discerning Market Power from Scarcity Energy-only markets, as discussed earlier, rely on price spikes to signal scarcity, and the need for capacity. In many such markets, regulators implicitly leave scarcity pricing to the suppliers, i.e., they expect suppliers to accurately predict system shortages and make scarcity priced offers. However, inaccurate predictions may either lead to artificial price spikes, or result in bidding too low even during a real shortage. Moreover, it is impossible to distinguish whether price spikes are the result of exercising of market power, or because of actual scarcity. This is because suppliers can exercise market power only during shortage events. For instance, during the 2001 California crisis, proving that market power had been exercised was very problematic [25]

From the above discussion the following points may be distilled. There is insufficient investment incentive for the marginal power plant in an energy-only market, and this has been empirically observed. In addition, price spikes are (should be) an inherent feature of such markets. However, price volatility leads to uncertainty for investors, leading to a higher risk premium. And scarcity prices create an opportunity for exercising market power. A resulting characteristic of the market then is that investments become cyclical. The following section describes the policy mechanisms - price and quantity based - that have been introduced to address some of these issues.

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[1]VOLL is very difficult to estimate as it varies widely between different consumer groups (Ajodhia et. al, 2002). Yet various studies have shown that it can range between $5000/MWh to $78,000/MWh. See MISO (2006)

[2]Rationing may involve *brownouts* where power is supplied at a reduced voltage, or scheduled *blackouts*.

3.2 Ensuring Capacity

3.2.1 Introduction

As a consequence of generation adequacy problems of energy-only markets, several solutions, referred to as 'capacity mechanisms', have been implemented across the world. Most of them involve an attempt at some form of regulation of 'reliability' as a good. This regulation can be broadly characterised as either price based or quantity based. Why such a distinction is relevant is a fundamental issue that has been addressed by Weitzman [26]. The following sections describe the main approaches to regulation of capacity. The discussion of price based incentives is kept brief, as it is beyond the scope of this work. The discussion of quantity based incentives is rather broad, to provide the reader with a relevant understanding of the theory behind quantity based incentives, specifically capacity markets, and the various ways in which they have been implemented the world over.

3.2.2 Price Based Incentives

Price based incentives, as the name indicates, regulates the reserve capacity through an administratively determined price. Capacity payments are one of the oldest solutions that were used. Strategic reserves and operating reserves are other such mechanisms that have been implemented.

Capacity Payments By this mechanism the power producers receive a subsidy per unit of available generating capacity. Such payments are meant to compensate for electricity price caps in the hope that the long run market equilibrium will shift to a larger volume of generating capacity. Capacity payments have been used in Argentina, Chile, Colombia, Peru among other countries [20]. The main drawbacks of this method were that firstly there were no obligations for the generating companies to provide capacity in exchange for the payment. And secondly, as de Vries [2] noted, they reduce investment risk, but do not provide signals regarding the capacity requirements any better than an energy only market.

Strategic Reserves According to this alternative, the regulator acquires, either by purchase or contracting, a certain reserve capacity called a strategic reserve or a mothball reserve for use in the event of a shortage. This amounts to taking a certain volume of capacity out of the market. Since the investment signal depends on scarcity prices that result from this removal, this measure is considered a price based mechanism [2].

Operating Reserves Pricing In this mechanism, the system operator contracts a volume of reserve capacity through daily auctions. The system operator exhibits a limited willingness to pay and this effectively caps the market price. This is different from strategic reserves in that the system operator does not dispatch the contracted reserves, but lets market parties decide between selling their reserves to him or the spot market.

3.2.3 Quantity Based Incentives

By such policy instruments the quantity of the resource is administratively set, and the price is left to the market participants. An advantage of this method, in the context of generation adequacy is that a robust reserve margin of capacity is maintained. Several forms of quantity based incentives have been implemented by independent system operators (ISO) in several regions in the USA, Latin America, and Australia. In Europe, the implementation of a capacity

certificate system is under way in France while the UK is in an advanced stage of policy design of a forward capacity market.

While the fundamental principle remains the same, implementation has been significantly different across ISOs. While some regulators mandate consumer's participation in centralized capacity markets to meet capacity obligations, others allow simply for reliance on bilateral contracts or even self supply. Some markets offer capacity credits, while others organize a 'reliability options' system.

The following descriptions of several capacity market designs implemented across the world helps obtain an overview of the state of the art in capacity markets today. This is important to understand, as it would help in making a very informed decision while conceptualizing a market for the model. The differences or similarities between each type become evident in the following descriptions.

Centralized Capacity Market

As mentioned above, reserve requirements may be set even without organising centralised capacity markets. However, exclusive reliance on self provision or bilateral arrangements could result in limited liquidity and transparency of the market. Further, smaller LSEs face higher transaction costs. Centralized capacity markets facilitate efficient bilateral transactions by providing a transparent price and standardized capacity product. It also allows for market monitoring, by creating information necessary to mitigate market power.

NYISO: ICAP The New York Independent System Operator (NYISO) organises the installed capacity(ICAP) market, where an obligation on placed on load serving entities to procure ICAP to meet minimum reserve requirements in a certain region (refer NYISO website). Auctions are locational, which means that transmission congestion is accounted for. It incorporates the following main features:

- The Installed Reserve Margin (IRM) is established annually by an independent council, NYSRC, which requires that the loss of load expectancy (LOLE) [3] must on average be no more than once in 10 years. The minimum installed capacity requirement is calculated in megawatts as a product of the forecast peak load and the quantity one plus the IRM [27].
- Three types of ICAP auctions are carried out: Capability period (Strip) auctions [4], monthly auctions, and spot market auctions. The first two kinds of auctions are two sided, they include bids to purchase from LSEs and offers to sell from qualified capacity providers. The spot auctions comprise of supplier bids being cleared against predetermined, sloping demand curves.
- The slope of the demand curve is determined by two points: a) the cost of new entry (in $kW-month) and b)the point where price of additional capacity is zero.

Forward Capacity Market

A forward capacity market enforces reserve requirements into the future, normally between one to five years ahead, and facilitates commitments during the planning period. It increases the ability of producers to bring new units online, and it encourages new entrants thereby increasing competition and reducing market power. More importantly, capacity inadequacies are detected

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[3]The LOLE, i.e., the probability of disconnecting firm load due to a resource deficiency. This is after allowance for scheduled and forced outages and forced deratings or brownouts [27].

[4]Capability periods recognize seasonal variations, one for the summer (May 1 to October 31) and one for the winter (Nov 1 to April 30). One capability year then comprises of two capability periods.

sufficiently in time.

PJM Reliability Pricing Model PJM's Reliability Pricing Model(RPM)is a forward capacity market, which enforces commitments three years ahead. It is designed to stimulate investment both in maintaining existing generation and investing in new capacity. The LSEs may meet their obligations either by self supply or by bilateral contracts, and the capacity auctions help them procure the remaining capacity that is needed after capacity has been secured by contracts. The resources that can be offered at the auctions also include demand response and transmission facilities. It incorporates the following main features:

- Annually a Base Residual Auction (BRA) and a series of Incremental Auctions (IA) are organised, during which LSEs may buy capacity, subject to their location. This is in addition to self supply and bilateral contracts that LSEs may also use to meet their capacity obligations. The RPM comprises of several 'zones' of transmission constrained, called locational deliverability areas (LDAs) so as to represent the locational value of capacity. Each resource is associated with an LDA.
- The model implements a sloping demand curve, called the Variable Resource Requirement, against which the capacity supplies are cleared in the auctions. By the VRR required reserve margins are determined as a function of capacity prices [20].
- Apart from capacity markets, to ensure reliability PJM operates two markets for ancillary services. These include *synchronised reserves* and *regulation*. *Synchronised reserves* supply unexpected demand on short notice, while *regulation* matches generation and load on short notice to maintain desired frequency.

Brazil: Energy Auctions Brazil is a hydro dominated region, where prices vary widely depending on water availability. Their system, although based on forward capacity markets, is significantly different from those at NYISO or PJM. Distribution companies declare their own demand and conduct a joint auction for capacity procurement [20]. Following the auction, the distribution companies individually engage in long term (5-30 years) bilateral contracts with the winning generation companies. Different types of auctions are held for existing energy, and for new energy or capacity. As part of these types of auctions, different auctions are held based on the generation technology. Rego [28] provides an interesting discussion on the necessity for two types of auctions.

- Auctions for existing energy are held annually, and 5 to 15 year PPAs may be signed. DISCOs can pass their contract costs to the customers upto a reference price.
- New Capacity Auctions offer long term bilateral contracts, which kick into operation a few years ahead of the date of the auction. The contract durations range from 15 to 30 years, beginning five years prior to the delivery date. There also exist shorter contracts with a forward duration of one year, and a contract duration of 5 years.

France: Certificate Market The FCM in France is based on a capacity certificate system. The Regulator publishes a capacity adequacy criteria, based on which, obligations are set for the LSEs (refer FSR). The LSEs may meet their obligations by procurement of capacity certificates either through The TSO performs the certification of all existing and planned capacity. One generic capacity certificate is given out, depending on a certain plants contribution to reducing the black out risk.

- bilateral contracts with capacity owners
- self supply
- organized sessions of the capacity market

The delivery period of the capacity is four years ahead of the date of the auctions. Periodic market sessions during the capacity procurement period allow for LSEs to improve their load forecast. Finally, the regulator imposes sanctions at the end of the delivery period, if an imbalance is found between the availability of capacity and the certification sanctioned.

Reliability Options

The system of Reliability Options creates a product, 'reliability' that generation companies can offer as an option which can be called when the electricity spot price exceeds a certain predetermined strike price. An independent operator (like the TSO) purchases the call options from power companies on behalf of consumers. The options may simply be financial contracts or be backed by physical resources as in the case of Colombia.

Colombia: Reliability Charge A descending clock auction is held annually. The producer that wins the obligation is entitled to a stable, transparent compensation from the regulator. In exchange, they commit to deliver a predetermined quantity of energy, called the Firm Energy Obligation, OEF as its acronym in Spanish when spot prices increase beyond a certain scarcity price. The scarcity price is determined by the regulator. There is a 3 year forward planning period once the auction has been conducted, after which the commitment periods of the OEF (1,10,20 years) begin.

3.3 Conclusion

The objective behind this chapter was to provide a rationale behind the necessity for capacity mechanisms, and also to provide an overview of the various capacity mechanisms, specifically the state of the art in capacity markets around the world. Table 3.1 provides a comparison between the advantages and disadvantages of differences in major types of capacity markets, classified here based on whether the market implements a forward requirement or not.

This chapter also provides a transition to the next chapter where a capacity market is conceptualized based primarily on the NYISO ICAP market presented here. This choice was made because this market is relatively well established, and has shown to be successful. Also if does not implement a forward requirement which makes market design simpler.

Table 3.1: Advantages and Disadvantages of Different Market Design

Market Design	Advantages	Disadvantages
Centralized Capacity Markets	• They provide a transparent price and a standardized product, and help facilitate bilateral transactions. • They promote retail competition by supporting small LSEs with lower transaction costs. • Capacity market prices are determined solely through market prices rather than administrative judgement.	• There are chances of a political backlash due to greater visibility, (and consequently doubts regarding) of high costs of ensuring reliable supply. • It is unclear whether the costs for the consumer, in ensuring reliable supply are greater than in an energy-only market • Lack of forward resource requirement leave no time to respond to capacity inadequacies, and may create room for price spikes. • When participation of suppliers is not mandatory, the market is vulnerable to strategic withholding
Forward Capacity Markets	• Inadequacy of capacity is signalled early, and met. • Increases competition by encouraging entry of new resources for the future, thereby also mitigating market power.	• Long forward commitments may increase risk for some resources, in particular, resources with short lead time, such as demand-response. • Complex market design imposes high implementation costs

Chapter 4

The Electricity Market Model

The capacity market model is implemented as part of a larger electricity market model at TU Delft, called the EMLab Generation model. The main purpose of the EMLab Generation model is to explore long term effects of interacting energy and climate policies on an electricity market. The strength of the model lies in the fact that different policy instruments, can be tested on an electricity market in isolation and in combination with neighbouring electricity market with different policies. The capacity market, here, is one such policy. The simulation model comprises of various power companies as its main agents, with the producers investing in generation capacity based on inputs from the environment. EMLab Generation Model in turn is a part of a larger project, called the Energy Modelling Laboratory (EMLab) at TU Delft. A description of the project and links to its various sub-projects may be found at www.emlab.tudelft.nl. The purpose of this chapter is to provide a brief and relevant description of the EMLab Generation Model. The significance of this step, and consequently the chapter, lies in the fact that it provides a foundation, a starting point, for all work related to the capacity market model. This chapter describes the main elements of the model - the implementation framework, the existing agents, the main algorithms, and the main policies that it currently implements. Those that are relevant to the capacity market, such as the target renewable energy policies and the ETS, are described in greater detail.

Implementation Framework The model is implemented on AgentSpring, an agent based modelling and simulation framework based on Spring and Neo4j, a powerful graph database. The Spring framework is an object-oriented software pattern that calls for the demarcation of data, logic and user interfaces. An important advantage of AgentSpring is that it allows for a high degree of maintainability and expansion at later stages. The model is open source, and is synchronised with Github, an online project hosting platform. The source code can be accessed at `https://github.com/emlab/emlab-generation`.

4.1   The Basic Model

The EMLab Generation Model is essentially designed to study the effects of investment behaviour of its main agent, the Energy Producer (EP) on the electricity sector. The EPs operate in an environment of one or more energy and/or climate policies, in either one or two nodes. Nodes here may refer to regions, places or countries[1]. The EPs make decisions about purchasing

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[1]In principle, this can be extended to as many nodes as the research question requires. However in this work, the number of nodes are limited to a maximum of two.

fuel, the price at which they sell their electricity, investments in new technologies, dismantling plants when they cease to be profitable among others. Investment decisions are made based on estimates of future prices, cost of technologies, price uncertainty and other factors in the 'environment' such as policies favouring a certain technology etc. Figure 4.1 shows a flowhart of the main processes involved in the model. For detailed information on each individual process, refer the EMLab-Generation Report [7].
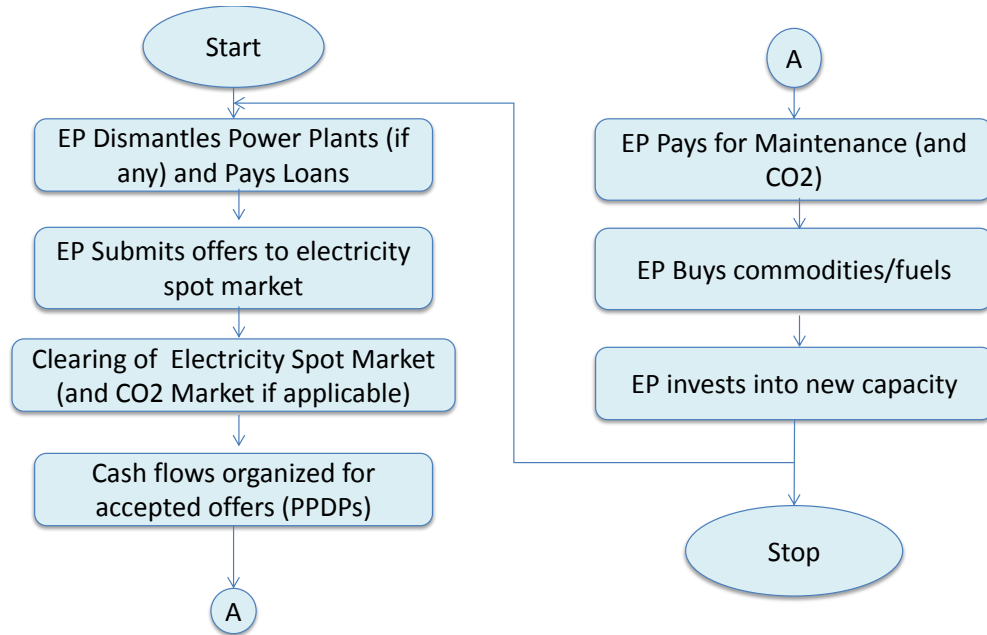
Figure 4.1: Emlab Generation Main Algorithm

4.1.1 Agents

Energy Producers The main agents in the model are the electricity producing companies. The number of energy producers is left to the choice of the modeler. The size and consistency of their power plant portfolios can also be specified. It is important to note that no strategic behaviour such as capacity withholding, or bidding strategically at higher mark-ups, have been modelled.

The electricity producers make the following strategic decisions:

- Investment - The agents decide whether investing in a new power plant is sufficiently attractive to them
- Technology type - If they decide to invest they need to make a choice about the type of generating technology. Currently the model implements the following technologies - Coal (Pulverised or IGCC), biomass, gas (Open cycle gas turbine, and combined cycle gas turbine), nuclear power, wind (off shore and onshore) and solar photovoltaic.

Apart from strategic management decisions, they also make the following operational decisions

- Sell Electricity - They make decisions regarding the price and quantity of their offers.

- Purchase Fuel - They also bid into commodity markets to purchase fuel
- Acquire CO_2 emission rights

Energy Consumers The energy consumer simply represents the aggregate demand of all domestic consumers. The demand depends on the pre-specified scenario.

4.1.2 Market Clearing Algorithm

The market clearing algorithm works similar to a real power exchange. The load duration curve is divided into segments, and for every segment, the price and volume are determined by the intersection of supply and demand. The generator's bid pairs are sorted from a low to high price, and the intersection of the resulting supply function with the (inelastic) demand curve determines the price and volume of electricity sold.
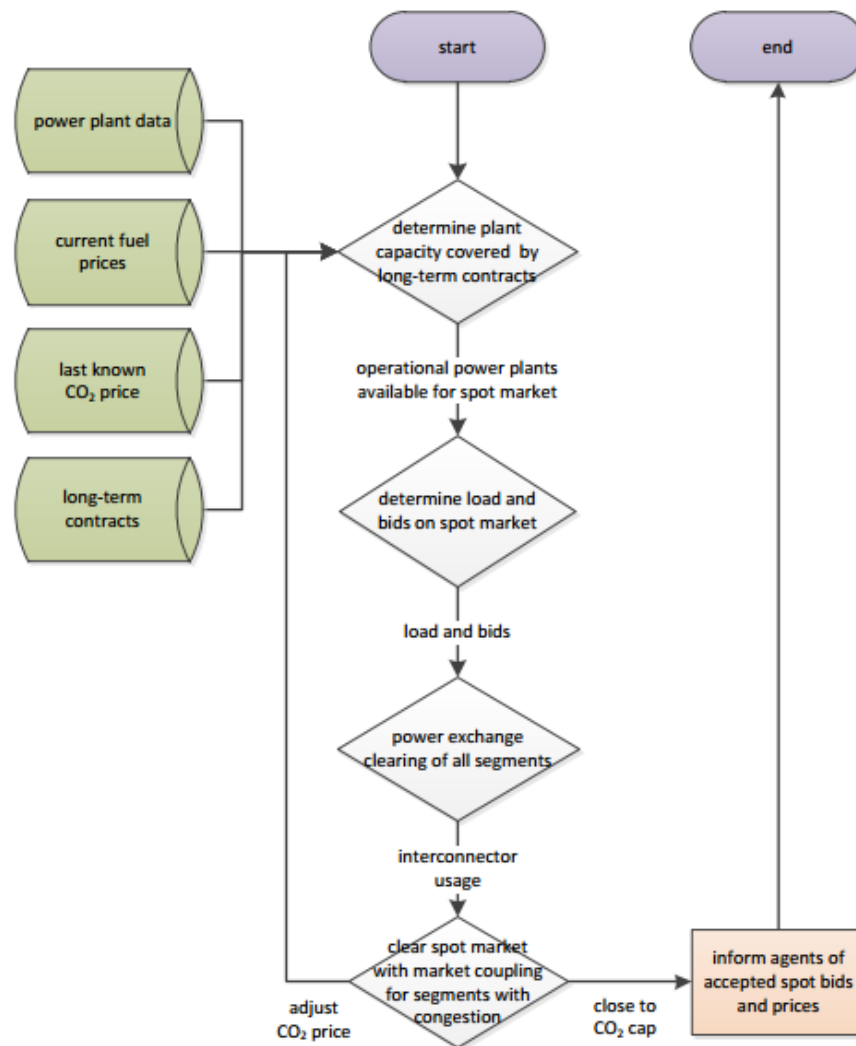
EU Emission Trading Scheme The European Union's Emission Trading Scheme (ETS), essentially a cap and trade system has also been implemented in the model. Under the ETS, a cap is set on the total amount of CO_2 that can be emitted by all participating installations. 'Allowances' are either auctioned off or allocated for free. The allowances can subsequently be traded [29]. Its implementation in the model entails the assumptions that a) there is perfect CO_2 trade between all markets, and b)the consumption of CO_2 credits can be arbitraged perfectly between the different hours in a year.

An iterative process involving both electricity and CO_2 markets is employed. Given a CO_2 price, the electricity market is cleared. If the emissions exceed the cap, then the price is increased (or vice versa) and the electricity market is cleared again. This process continues iteratively untill the cap is just met.

Modelling Congestion The two zones in the model are connected using an interconnector, using which, congestion between zones is simulated. Initially, the market clearing algorithm runs for all zones in the model, as if it were simply one market. If the resulting flows over the inter-connector exceed available capacity, market splitting (functionally equivalent to market coupling here) is employed. According to the market splitting algorithm, the two nodes are first cleared independently of each other. The demand in the low price zone is increased upto the point where the interconnector capacity is fully utilized. This additional demand is subtracted from the high-prize zone. The price in the exporting (low-prize) zone increases due to the slightly higher demand, while the price in the importing region reduces - thus reducing average cost of generation. In practice, this mimics market splitting, where the TSO buys energy upto the level of the interconnector capacity, from the low-price region and sells it in the high price region [17].

4.1.3   Investment Algorithm

The flowchart below represents the investment algorithm. The main processes involved are gathering alternatives for investment, calculating NPVs, and finally selecting the power plants with the highest return on investment: refer flow chart in figure **??**.
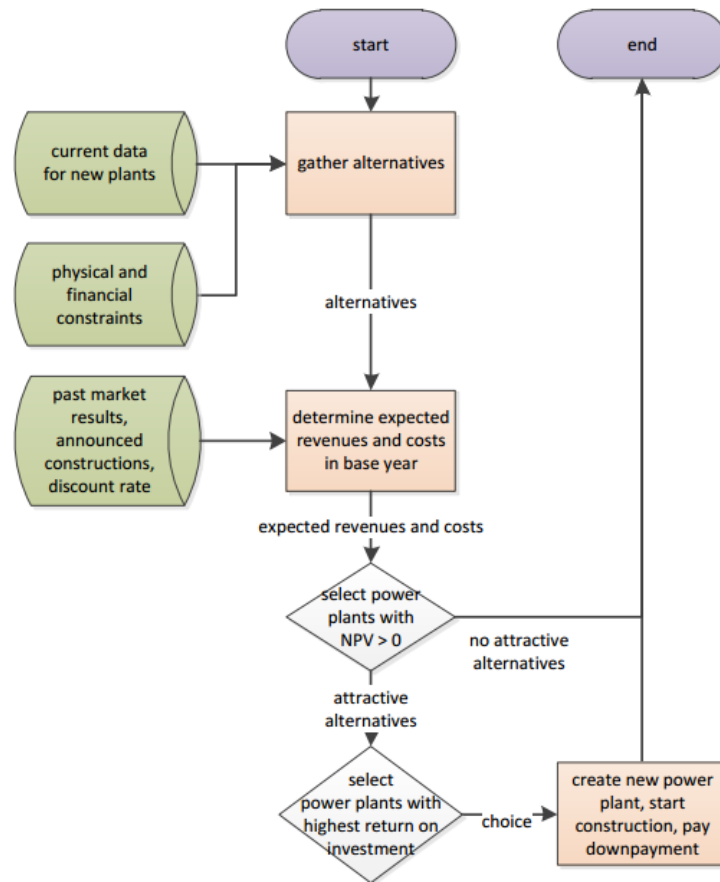
Targeted Investment into Renewable Energy There is an optional section in the investment algorithm which allows for targeted investment into renewable energy. An agent, the renewable energy agent, has been created, who carries out the following function. If private investors do not meet the national (government-specified) target for a specific year the renewable target investor simply invests exactly the missing capacity (MW) regardless of any budget constraints.

This has been created to simulate a scenario where excess renewable energy forms part of the energy mix. This enables the analysis of market prices, investments in other technologies etc in the presence of substantial amounts of RE capacity.

4.2 Relevance to Capacity Markets

The capacity market model shall be implemented in the following manner within the main algorithm. The design of the capacity market is closely dealt with in the following chapter.
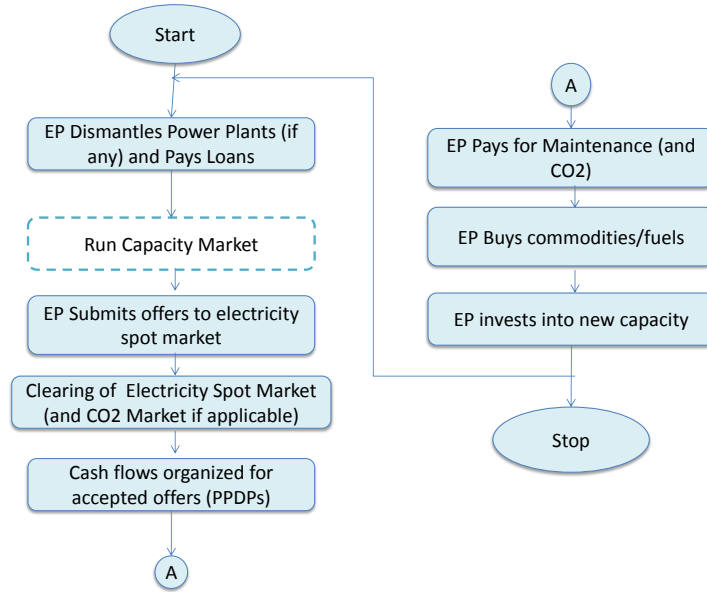
Figure 4.2: Emlab Generation Main Algorithm - with capacity market

Given the EMLab-Generation description thus far, I seek to draw the reader's attention aspects of the model that make way for the implementation and analysis of the capacity market. The capacity market shall be implemented as an optional module that may be turned on or off as required. The existing framework allows for the capacity market to be implemented a rather independent module, in that it does not need to interface with the existing processes at too many junctures. One very obvious juncture of interface is that in the investment algorithm, the revenues from the capacity market need to be considered. Another juncture of interface is in the dismantling algorithm, where existing plants whose costs are covered, given the presence of a capacity market and revenues from it, should not be dismantled.

The optional implementation of the policies of CO_2 ETS and targeted RE generation makes way for a rich analysis of the performance of capacity markets; this relates back to the original research question.

4.3 Conclusion

With this chapter, it is hoped that the reader has a basic understanding of the conceptualization behind the existing EMLab-Generation model. The model in a sense both limits and enables new the manner in which a capacity market may be designed, implemented and analyzed.

At the outset, given the variety of existing policy options in the model, even an abstract implementation of a capacity market will suffice to yield a rich analysis. The following chapter delves into the elements that contribute to the design of a simple capacity market.

Part II

Conceptualization

Chapter 5

Centralized Capacity Market

In the previous chapters the problem statement has been outlined, and the background of the electricity sector, and the issue of security of suppply has been discussed. The objective of this chapter is to understand and decide on the composition and boundaries of the system. The need for this step in agent based modelling is explained by [15]: it seeks to "identify the internal structure of the system under analysis to permit a generativist description."

Although several ISOs have implemented capacity markets, the design choices here have been made primarily based on the NYISO ICAP Market. The NYISO market design implements a capacity market with no forward capacity obligations, and thus is a relatively simple design, in reality and in terms of model implementation. It is also an example of a capacity market that is arguably well established and successful; it was one of the first capacity markets to be established in the USA (in 2000), and it is working well, as it is projected that no new resource requirements are necessary till 2018 [30, p.11]. For a brief description of the NYISO ICAP market refer section 3.2.3.

This chapter is structured as follows - the capacity market system is decomposed into three parts, the supply side, the demand side and finally the market clearing by auctions. For each part the 'ideal' capacity market design, loosely based on NYISO, is first described. This is then followed by sections, 'Translation to Model' which describe how the ideal capacity market design may be delineated and modified, so that it may be adapted to the existing EMLab model.

5.1   Basic Design

This design mainly mandates a reserve requirement, determined by the system operator, together with a centralized capacity market, also administered by the system operator. Such an arrangement does not preclude the possibility that market participants meet their obligations by self supply or bilateral contracts. The capacity market becomes a sort of residual market for settling uncommitted resources and unsatisfied obligations.

An independent regulator determines the capacity needed to satisfy resource requirements that include an independently set reserve margin. They further check the amount of capacity available from each energy producer and the load requirement for every LSE. Sales and purchases of capacity is conducted through transparent auctions. Auction formats may be different. A committed power plant that is not available for production results in the energy producer being penalized. Also, the LSEs that do not meet their obligations may be penalized.
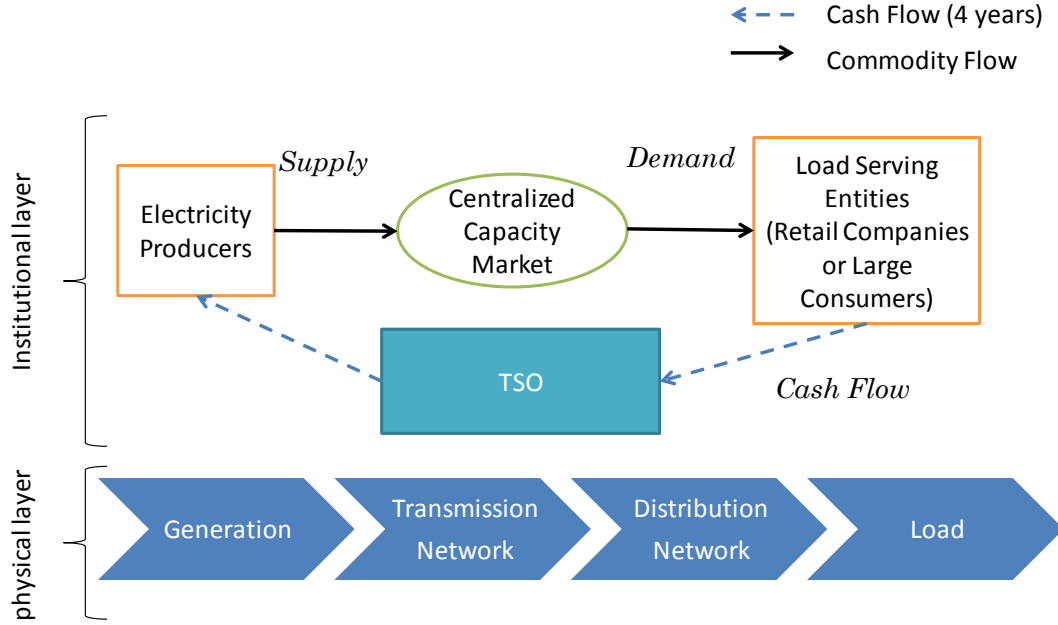
Figure 5.1: Centralized capacity Market

This arrangement, in principle, must ensure a robustly maintained reserve volume of capacity while esuring that productive efficiency is achieved in maintaining that level of reserve. The reserve margin makes sure that signals for investment appear much before shortages do. They consequently ensure that there is always sufficient capacity in the system, and that there no forced outages. This then means that the prices in the energy market are expected to be more stable.

The following sections outline in detail aspects of the market design such as supply, demand and the auctions.

5.2 The Demand Side

The ISO calculates the minimum installed capacity requirement (D) in megawatts as a product of the forecast peak load (V_{peak}), and the quantity one plus the 'reserve margin' (r). The reserve margin is determined by an independent agency. In the case of the NYISO, the reserve margin, called the Installed Reserve Margin (IRM) is established annually by the New York State Reliability Council (NYSRC) [31, p.2-3]. The total minimum installed capacity requirement for the whole jurisdiction of the ISO is given by the following equation.

$$D = V_{peak} \times (1 + r) \tag{5.1}$$

While the minimum installed capacity requirement is calculated for the entire region, the commodity that is traded in the market is 'Unforced Capacity', which is different from 'installed capacity'. This is the measure of capacity used to determine the amount of capacity that each resource is qualified to supply, and the LSEs qualified to procure. It is determined by the NYISO is based on the Unforced Capacity Methodology [31, p.2-2]. According to this

method, unforced capacity requirement is estimated *after recognizing forced outages*, i.e, with the following considerations using the equation below.

- the Equivalent Demand Forced Outage Rate (EFORd) is the probability that a generating unit will not be available due to forced outages or deratings when there is demand on the unit to operate.
- the location of the unit
- limitations on unforced capacity from external areas.

UCAP is calculated as,

$$UCAP = ICAP * (1 - EFORd) \tag{5.2}$$

The minimum UCAP requirement, after considering locational constraints, are calculated and assigned for each LSE on a transmission district basis. Standards as regarding the product are established collaboratively with all market participants. Based on the standards established, the ISO determines the amount of unforced capacity that each installed capacity supplier is allowed to supply. The exact computation of Unforced Capacity is described in detail in appendix A.1.

5.2.1 *Forecast Demand: Translation to Model*

In the current version of the EMLab model, power plants and energy producers are not identified by a 'location' attribute, rather only by a 'zone' atrribute. That is to say, that the model does not account for locational and transmission constraints within a single zone. Further, the time step of the model is too large to accommodate blackouts/brownouts or forced or unforced outages, thus making the computation of 'unforced capacity' irrelevant. Further, since EMLab has one consumer agent per zone, who represents the aggregate demand, the computation of installed capacity requirements is simply done once, for the aggregate demand. Modifications will need to be made to the code to accommodate locational constraints and multiple consumers at a later stage, when required. The process of imposing a demand requirement in the model follows thus.

- *an independent regulator is assigned per zone.*
- *the reserve margin (r) is a property of the regulator.*
- *the peak demand for the current year is forecast, by extrapolation of past values of demand, by geometric trend regression.*
- *the minimum installed capacity requirement, referred to hereafter as 'demand target' (D_t) is computed as*

$$D_t = V_{peak} \times (1 + r) \tag{5.3}$$

Involvement of the LSEs

LSEs may satisfy their obligations to procure capacity either by engaging in bilateral contracts with suppliers or by participating in the auctions for capacity. In the NYISO ICAP market, three types of auctions are organized. Strip auctions, for every *capability period*[1], monthly auctions, and spot auctions [27]. The first two types are two-sided which means that both suppliers and the LSEs bid into them. For the spot auctions, a demand curve is published prior to the auction, and the NYISO procures capacity on behalf of the LSEs.

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[1]Capability periods recognize seasonal variations, one for the summer (May 1 to October 31) and one for the winter (Nov 1 to April 30). One capability year then comprises of two capability periods.
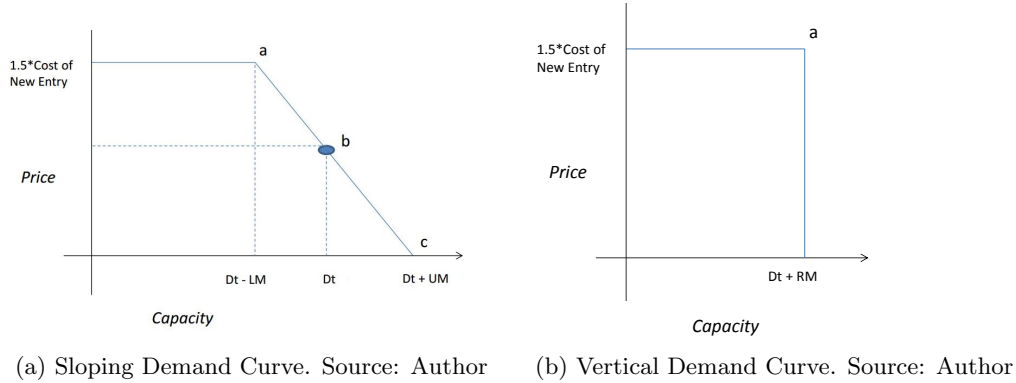
(a) Sloping Demand Curve. Source: Author   (b) Vertical Demand Curve. Source: Author

Figure 5.2: Demand Curves

Sloping Demand Curve

A vertical demand curve makes the capacity market susceptible to high price volatility, even leading to bipolar prices. The prices are at the price cap when there is insufficient capacity and close to zero when there is sufficient capacity. This is due to the fact that shortages in supply even by small margins leads to very high prices for capacity. Further, it creates incentives for abuse of market power. The sellers may manipulate prices by withholding very small amounts of capacity, while buyers may bring prices close to zero by adding small amounts of capacity with self-supply.

These issues are addressed by the introduction of a downward sloping demand curve, as is included in the NYISO unforced capacity market and the PJM forward capacity market[2]. The sloping demand curve stabilizes market prices because any movement along the demand curve results in relatively small price changes, consequently allowing for fewer opportunities for market manipulation [20]. The figure 5.2 illustrates this.

The figure 5.2a shows a sloping line segment comprising of three points a, b, and c. The price cap is set at 1.5 times the cost of new entry (explain CONE further in a foot note). The slope is essentially determined by a bandwidth, comprised of a lower margin(LM) and an upper margin (UM), so to say around the Demand Target (D_t) to be achieved.

Determination of Slope At **NYISO**, the determination of the slope of the demand curve is based the slope of a line passing through the following two points:

- a point at which ICAP supplied is equal to the NYCA minimum installed capacity requirement, and the price of ICAP is equal to the monthly reference point price [3].
- a point at which the amount of ICAP supplied is set at the smallest quantity of installed capacity counting toward the NYCA minimum installed capacity requirement, for which the price of ICAP is zero.

The above two points while specific, are computationally tricky for the determination of a slope.

On the other hand, the determination of slope at **PJM Interconnection**, for their sloping demand curves, known as Variable Resource Requirements, is done in a conceptually similar

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[2]However, there are markets that do not employ a sloping demand curve, such as the Midwest ISO. This is probably to limit complexity in market design.

[3]The monthly reference point price is calculated as the cost of a peaking unit less an estimate of annual net revenue offsets from the sale of energy and ancillary services.

manner, and yet is easy to implement and conceptually simpler to understand. It is composed of three reference points. For each reference point, the price is a muliple or fraction of the quantity Cost of New Energy (CONE) minus the net revenues expected from energy and ancillary services (Net E & AS), and the quantity (MW) is determined as the demand target (D_t), but offset by certain percentage points from the predetermined IRM (installed reserve margin).

An illustrative example of the curve is shown in figure 5.3. It is based on the three reference points described in the following table (figure 5.4).
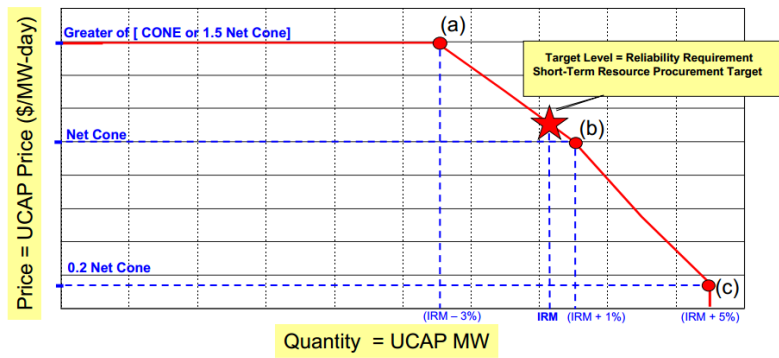
Figure 5.3: Illustrative Example VRR Curve. Source: [32, p.19]

Point	Price (UCAP Price)	Quantity (UCAP MW)
a	$\dfrac{Greater\,of\,[CONE\,or\,1.5(CONE-NetE\,\&\,AS)]}{1-Pool\,Wide\,EFORd}$	$\left[Rel\,Req\dfrac{(100\%+IRM-3\%)}{(100\%+IRM)}\right]-\dfrac{STRP}{Target}$
b	$\dfrac{[1.0(CONE-NetE\,\&\,AS)]}{1-Pool\,Wide\,EFORd}$	$\left[Rel\,Req\dfrac{(100\%+IRM+1\%)}{(100\%+IRM)}\right]-\dfrac{STRP}{Target}$
c	$\dfrac{[0.2(CONE-NetE\,\&\,AS)]}{1-Pool\,Wide\,EFORd}$	$\left[Rel\,Req\dfrac{(100\%+IRM+5\%)}{(100\%+IRM)}\right]-\dfrac{STRP}{Target}$

Where:	Rel Req =	STRP Target =
RTO VRR Curve	PJM Region Reliability Requirement	RTO Short Term Resource Procurement (STRP)Target
LDA VRR Curve	LDA Reliability Requirement	LDA Short Term Resource Procurement (STRP) Target

Figure 5.4: Reference Points VRR Curve. Adapted from [32, p.18]

In figure 5.4, the prices are divided by the quantity (1-Pool Wide EFORd) so as to convert the price to UCAP terms. For further explanation, refer the PJM Capacity Market Manual [32, p.17].

Implementation The implementation of the sloping demand curve is done such that the independent regulator bids regularly into the auction on behalf of all the LSEs as per the sloping demand curve. If the prices are higher than the price at reference point b in figure 5.2a, then the the market clears at a quantity less than the demand target, else if the prices are lower than that at reference point b, the market clears at a quantity higher than the demand target. The LSEs are then all required to pay the market clearing price to the suppliers, for the quantity they need.

At NYISO, the sloping demand curve is implemented by way of the third type of auction, i.e., the spot auction. All LSEs are required to participate in the spot auctions. The demand curves, at a predetermined slope, are published before the auction date[4]. The NYISO submits monthly bids on behalf of all LSEs at a level determined by the applicable ICAP demand curve.

At PJM Interconnection too, the sloping demand curve is enforced by way of a system called the Reliability Pricing Model (RPM), where again, the ISO bids on behalf of the LSEs at a level determined by the VRR curve. The Suppliers (EPs) submit their offers into the auction, and the auction clearing price is the price that the LSEs pay to secure capacity.

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[4]The demand curve is determined in accordance with the NYISO Section Tariff, and is described in the ICAP Manual [31, p.5-5]

5.2.2 Demand Curve: Translation to Model

In the capacity market model, an abstract version of the demand curve employed in PJM and NYISO is implemented. The abstraction has been made to support the generality of the concept.

The demand curve in the model is as shown in figure 5.2a, and is made up of two line segments:

1. a horizontal line segment at the price cap (P_c), upto point a. The price cap is set as in NYISO, equal to 1.5 times the estimated cost per (MW-year) of a new peaking unit.

2. a sloping line segment passing through end points points a and c:

    at point a, price is set at the price cap, while the demand is set at $D_t \times (1 - LM)$, where LM is a fraction of D_t.

    point c is at the intersection the demand target at its upper margin (UM) at $D_t \times (1 + UM)$, and the price at 0.

The equation for the sloping demand curve is

$$\text{demand} = \text{D˙t} \times (1 - rLM) + (CP_c - price) \times (rUM + rLM) \times D_t/CP_c \quad (5.4)$$

5.3 The Supply Side

Ideally, under conditions of perfect competition, it is expected that the energy producers bid at marginal cost into a market. The marginal cost in the case of 'capacity' is given by the fixed cost of operation and maintenance of a generation plant minus an estimate of the net revenue offsets from the sale of energy and ancillary services, referred to hereafter as the Net CONE. The equilibrium value of the capacity product in a well designed capacity market must equal the size of the 'missing money', commensurate to the desired reserve margin. Net CONE, therefore represents the lonbg run marginal cost of supplying capacity at the reserve margin [33]. It is assumed that there is no strategic behaviour.

Submitting of a capacity bid does not imply that only generation capacity must be submitted. On the contrary, many capacity market designs do not percieve a difference between actual generation capacity on the one hand, and demand response measures on the other. This means that demand response measures such as interruptible loads or local generators can account as 'capacity' in terms of MWs, in the capacity market. In the NYISO system, such resources are referred to as 'Special Case Resources'; refer [31, p.4-53] for a detailed explanation.

5.3.1 *Supply Side: Translation to Model*

Since modelling of actual bidding conditions needs a thorough empirical analysis, the ideal case (of perfect competition) in the capacity market, with no strategic behaviour, is assumed here. Secondly, the demand side in EMlab Generation is rather simple, and cannot, at the moment characterise individual consumer loads. This makes it difficult to incorporate demand response measures in the bidding, because of which, market participants can only bid actual generation capacity into the capacity market. The following steps briefly outline how submitting of bids may be modelled in EMLab.

Submitting Bids

- *The energy producers bid into the capacity market by submitting bid prices and quantities for each of his power plants that are located in the zone with the capacity market.*

- *The bid price is the fixed operation and maintenance of a power plant, offset by net revenues from the electricity spot market.*

- *If the net electricty spot market (ESM) revenues are greater than the fixed operation and maintenance cost of the power plant, the energy producer bids at zero price. However, if the net ESM revenues are less than the fixed operation and maintenance cost of the power plant, the difference amounts to the bid price.*

- *The quantity component in the bid is determined based on the availability of the plant only in the peak segment, and not the nominal capacity of the power plant. This means that plants with intermittent generation (renewable energy) submit only partial capacities into the market.*

5.4 The Auctions and Market Clearing

At the outset, it must be noted that only a part of the total capacity requirements are traded via the capacity auctions, the rest are through bilateral transactions, which may be influenced by the auctions. Under the NYISO jurisdiction, about 45% of the capacity transactions are traded through the NYISO's capacity auctions [34, p.2-1].

Most capacity markets (forward or centralized) have one main auction, followed by a few intermediate auctions, for the transaction of a capacity commitment of a certain period. This is evident in the brief overview of capacity market designs presented in section 3.2.3. At the NYISO in particular, three types of auctions are held as part of the NYISO Capacity Market Operations. The strip auctions, the monthly auctions and the spot auctions. The strip and monthly auctions are two-sided, while the spot auctions are one-sided where participants can only sell capacity. Each auction is essentially a uniform price auction, but organized at different intervals for different periods (lengths) of time. Each is described below:

Strip Auctions The strip auctions are organized every capability period[5] (six months), where unforced capacity can be bought for that capabity period. They are organized atleast one month before the start of the capability period for which the unforced capacity is being traded. Participants that want to either purchase capacity, or sell it - both the LSEs and the energy producers are allowed to participate. The results of the auctions are published prior to the monthly auctions.

Monthly Auctions These auctions, as the name suggests, are held at monthly intervals, during which capacity may be bought or sold for the forthcoming [31, p.5-3] Obligation Period, or any of the remaining months in the capability period. They are held approximately 15 days before the start of the next obligation period.

Spot Auctions Spot auctions are organized immediately (a few days) preceding the start of each obligation procurement period. It is mandatory that all LSEs participate in this auction i.e., the NYISO participates on behalf of the LSEs in terms of the predetermined demand curve.

This market design with one main auction and a few intermediate ones offers a chance for the market participants to both plan ahead, and curtail risk to some extent. In some cases it

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[5]Capability periods recognize seasonal variations, one for the summer (May 1 to October 31) and one for the winter (Nov 1 to April 30). One capability year then comprises of two capability periods.

may even be used for arbitrage. For instance, a monthly auction may be used as a cover in the following way: A supplier may sell 300MW of capacity committment in the strip auction at 90 Euros/MW, however he soon discovers that his CCGT plant needs repair and cannot meet the demand, he can then sell his capacity committment in the following monthly auction. If the capacity clearing price at the monthly auction is less than that at the initial strip auction, he stands to gain. That is, if the capacity clearng price at the mothly auction is 80 Euros/MW, the supplier stands to gain 10 Euros/MW. Another instance could be that an LSE owns more capacity credits than it needs as per its minimum installed capacity requirements for an certain obligation period, in which case it can sell its capacity commitments at the spot auction or the monthly auctions. By the end of the third round of auctions - the spot market, all requirements must be met by the LSEs for the forthcoming monthly obligation procurement period.

5.4.1 *Market Clearing: Translation to Model*

While translating into the model, the capacity market design has been abstracted to simply simulating the third type of auction - the spot auction. This abstraction does not have 'functional' implications to the working of the capacity market itself; it merely cuts-to-the-chase, so to say, in the auction process. Furthermore, modelling the first two variations of the auction would require bidding from the consumer side as well; the consumer side, as is already known, is under-developed in the model.

- *The market clearing is designed simply based on uniform price clearing.*

- *The bids are sorted by order of increasing price.*

- *The sorted bids are accepted in ascending order of price until the point at which demand is satisfied with the cumulatively accepted bid quantities.*

- *The clearing point price (in EUR/MW-year) is therefore determined as the price of the last bid accepted, and volume (in MW) of course, is the cumulatively accepted bid quantities.*

Financial Transactions   The load serving entities transfer the cost of the capacity onto the consumers. *This is simulated as a transfer of cash from the aggregated consumer of a certain 'zone' or country in the model to the energy producers. On clearing of the capacity market, all the generating units, whose bids were accepted, are paid the clearing price for the capacity made available by them. While making investment decisions, the energy producers must take into account the possible revenues from the capacity market, by forecasting values based on previous years' capacity market prices.*

5.5   Fines and Non Compliance

If an LSE has not satisfied its minimum installed capacity requirements after the Spot Market Auction preceding a certain obligation procurement period, the ISO charges *supplemental fee.* This supplemental fee is equal to the ICAP Spot Market Auction clearing price multipled by the number of MWs the LSE needs to meet its share of the minimum installed capacity requirements, or minimum locational installed capacity requirements as applicable. The ISO uses this supplemental fee to purchase capacity from eligible suppliers at a price no more than the ICAP Spot Market Auction clearing price.

If a supplier is deemed to have a capacity shortfall, due to derating or any other reason, and is unable to cover that shortfall in a timely manner, the ISO will purchase sufficient unforced capacity at the relevant ICAP Spot Market on behalf of the supplier to meet the shortfall.

Curtailment of Export Capacity Both NYISO and PJM curtail exports and allow only imports. This has not been implemented in the model so far.

5.5.1   *Fines in the Model*

Fines are not implemented in the model as the model does not incorporate unscheduled maintenance for generation plants or other such random events. Also, on the demand side, since the aggregate load is represented by a single consumer, there is little scope for shortfall, unless there is actual capacity shortfall itself. Hence fines are not incorporated in the model.

5.6   Conclusion

This chapter sums up the conceptualisation of the capacity market. The main agents are the regulator, energy producer and consumer. Their roles and interactions, as applicable has been delineated in this chapter. The following chapter formalizes the concepts into a pseudo code.

Part III

Formalization

Chapter 6

The Formal Model

In the previous chapter the structure of the system was identified and boundaries were drawn. The objective of this chapter is to formalize the system identified. The concepts themselves may be formalized in terms of classes and objects; the relations between classes and objects, interactions between them and the processes are formalized in terms of a narrative or a pseudocode. Since the existing model has been built on the platform AgentSpring, the first section describes the basic elements of coding, such as types of classes, and their classification on AgentSpring. The following section formalizes the concept, and the subsequent section provides the pseudocode.

6.1 Modeling on AgentSpring

The existing EMLab-Generation model identifies different types of Java classes and other files, described below. For a more detailed description refer, the decarbonisation report [7].

6.1.1 Types of classes and other files

Classes are grouped into packages in the following manner.

Domain classes are the definitions of things and their properties. Classes such as *EnergyProducer* and *EnergyConsumer* under package *Agent*, and classes such as *Bid* and *ClearingPoint* under package *Market* are examples.

Role classes capture behaviour, executed by specific classes from the *domain* packages. For instance, the agent *EnergyProducer* acts the *SubmitOffersToElectricityMarketRole*.

Repository classes contain functions that deal with interaction of model code and the database. They also assist in updating current information and storing new information.

Scenario xml files consist of all the data required to define and initialize a simulation run. It contains data as well as relations between objects.

6.2 Concept Formalisation

This section elucidates, based on the concepts and interactions identified in the previous chapter, the states, properties and actions associated with every agent class. Figure 6.1 is a representation of all agents that comprise of the capacity market model. Every agent is characterised by its properties, the 'type' of a property (object, primitive data type etc). For agents that enact roles, the roles have been mentioned as well.
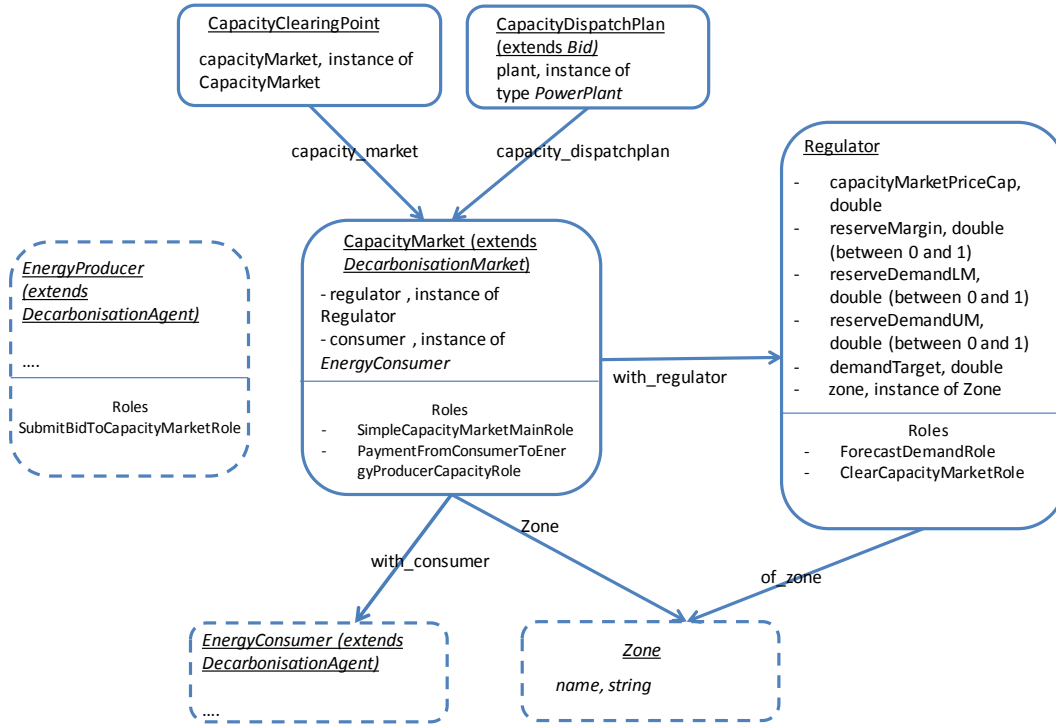
Figure 6.1: Concept Formalisation

As is observed in the figure above, essentially four classes have been introduced into the EMLab model:

- Regulator
- CapacityMarket
- CapacityClearingPoint
- CapacityDispatchPlan

Since it is a model that builds on the existing EMLab-Generation model, it makes use of existing data structures. These existing classes in the figure are distinguished by a slanting font, and are not described in full detail.

- The one major existing class that is vital to the fuctioning of the capacity market is the *EnergyProducer* class. The EnergyProducer agent bids into the capacity market via the *SubmitBidToCapacityMarketRole*, makes investment decisions taking into account revenue from the capacity market in the *InvestInPowerGenetationTechnologiesRole*, and finally recieves payment for their available capacity as per the capacity market clearing.
- Another example is the class *CapacityMarket* extends the existing *DecarbonisationMarket* class, and the class *CapacityDispatchPlan* extends the existing class *Bid*.
- Similarly, classes such as the CapacityMarket relate to existing classes such as *Zone* and *EnergyConsumer*.

The figure, in addition, is a representation of agents as nodes in the graph database, neo4J; the arrows represent relationships between the agents and the direction attribute of the rela-

tionship. The graph database is used to access data from the repository, as required by the roles.

6.3   Model Formalisation and Narrative

While the previous section described the what and the who, i.e., things, objects and agents, this section is a description of the model narrative. The model narrative is a story that relates the behaviours of the agents with time, i.e., it explains which agent does what with whom and when [15].

The section begins with a description of the initial set-up and parameter settings that are necessary for the execution of the model. The pseudocode is then presented per role. A role, as mentioned in section 6.1, is a class that captures behaviour of an agent. It is logical therefore, that the narrative is a series of roles. Every role is preseneted either as an alogorithm or as a flowchart, depending on whichever is the more befitting one. Every role is accompanied with explanations that follow directly from the 'Translation to Model' subsections (see 5.2.2) in chapter 5.

6.3.1   Initial Conditions

To set up a capacity market for a certain region in the model, one object of class *Regulator*, and another object of class *CapacityMarket* must be defined for that region. Furthermore, properties of the regulator such as the reserveMargin, the priceCap etc, as listed below must be set. These settings comprise of the design parameters of the capacity market.

Thus the following initial conditions must be set:

- **Regulator** is introduced with the following properties

  - reserveMargin (double, $0 \leq reserveMargin \leq 1$) a percentage, initially set to 0.156
  - capacityMarketPriceCap (double): in euro/MW-day, set to a multiple of CONE [1] ($2 \times CONE$)
  - reserveDemandLowerMargin (double, $0 \leq x \leq 1$)
  - reserveDemandUpperMargin (double, $0 \leq x \leq 1$)
  - zone(string), set to CountryName
  - noOfYearsLookingBackToForecastDemand (double)

- **Capacity Market** is introduced with the following properties

  - regulator(of type Regulator), set to regulator of corresponding Zone
  - zone(string), set to CountryName

6.3.2   The Narrative

This section presents the pseudocode: an explanation leading to the pseudocode is first presented, followed by the pseudocode itself. To keep the presentation uncluttered for the reader, a more transparent version here in this chapter. For a detailed version of the pseudocode, refer appendix C.1.

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[1]Cost of New Energy

The table 6.1 below lists the notations employed in the capacity market code. For a list of notations from the existing EMLab code, refer appendix B.1.1, on page 99.

Table 6.1: Notations employed in the algorithm

Variable	Unit	Description
$PL_{c,t}$	MW	Peak load across all segments of a load duration curve for a country
$\hat{f}_t$		Expected demand growth for time t
$PL_{c,t}$	MW	Expected peak demand
rm		Reserve Margin of Capacity Market, set by Regulator
$CDP_{p,t}$		Instance of Capacity Dispatch Plan of power plant p at time t
$CDP.price_{p,t}$	euro/MW-Year	price of capacity dispatch plan of power plant p at time t
$CDP.volume_{p,t}$	MW	volume of capacity dispatch plan of power plant p at time t
$F_{O\&M,p}$	euro/MW-Year	fixed operating and maintenance cost of power plant per year
$ESMRevenue$	euro	Revenue from the energy market
CP_{cap}	euro	Capacity market price cap

Forecast-Demand Role

The process of imposing a demand requirement in the model follows thus. The peak demand for the current year is forecast at the beginning of the year, by extrapolation of past values of demand, by geometric trend regression. The minimum installed capacity requirement, the 'demand target' (D_t) is computed as

$$D_t = V_{peak} \times (1 + r) \tag{6.1}$$

The algorithm for the forecast-demand role is as follows.
ForecastDemandRole, acted by Regulator
1: get peak load $PL_{c,t}$ across $LDC_{c,t}$ from repository
2: get demand growth trend $\hat{f}_t$ for current year t
3: $PD_{c,t} \leftarrow PL\dot{\,}c,t \times \hat{f}_t$
4: $D_t \leftarrow PD_{c,t} \times (1 + rm)$
5: set Regulator's demandTarget as D_t

Submit Bid to Capacity Market

The energy producers bid into the capacity market by submitting bid prices and quantities for each of his power plants that are located in the zone with the capacity market. The following steps briefly outline how submitting of bids may be modelled in EMLab.

- The bid price is the fixed operation and maintenance of a power plant, offset by net revenues from the electricity spot market. If the power plant was out of the merit order in the energy market, then it would earn no revenues from the energy market, then simply keeping the power plant online would be a cost to the energy producer.

  Check if the power plant was in the merit order in the previous year. If yes, proceed to compute electricty spot market (ESM) revenues. Else, assign electricty spot market (ESM) revenues as zero.

  If the electricty spot market (ESM) revenues are greater than the fixed operation and maintenance cost of the power plant, the energy producer bids at zero price. However, if the net ESM revenues are less than the fixed operation and maintenance cost of the power plant, the difference amounts to the bid price.
- The quantity component in the bid is determined based on the availability of the plant only in the peak segment, and not the nominal capacity of the power plant. This means that plants with intermittent generation (renewable energy) submit only partial capacities into the market.

Clear Capacity Market Role

The capacity market design has been abstracted to simply simulating the spot auction, as a uniform price auction. The capacity bids are sorted by price in ascending order, and are iterated through until the desired demand is met. While iterating through the bids, the demand target corresponding to the bid price is computed according to the sloping demand curve. If there is a shortage, higher prices (price cap) are correspondingly reflected. See figure 6.3 for the algorithm employed.

Payment From Consumer to Producer Role

This is simulated as a transfer of cash from the aggregated consumer of a certain 'zone' or country in the model to the energy producers. On clearing of the capacity market, all the generating units, whose bids were accepted, are paid the clearing price for the capacity made available by them. While making investment decisions, the energy producers must take into account the possible revenues from the capacity market, by forecasting values based on previous years' capacity market prices.
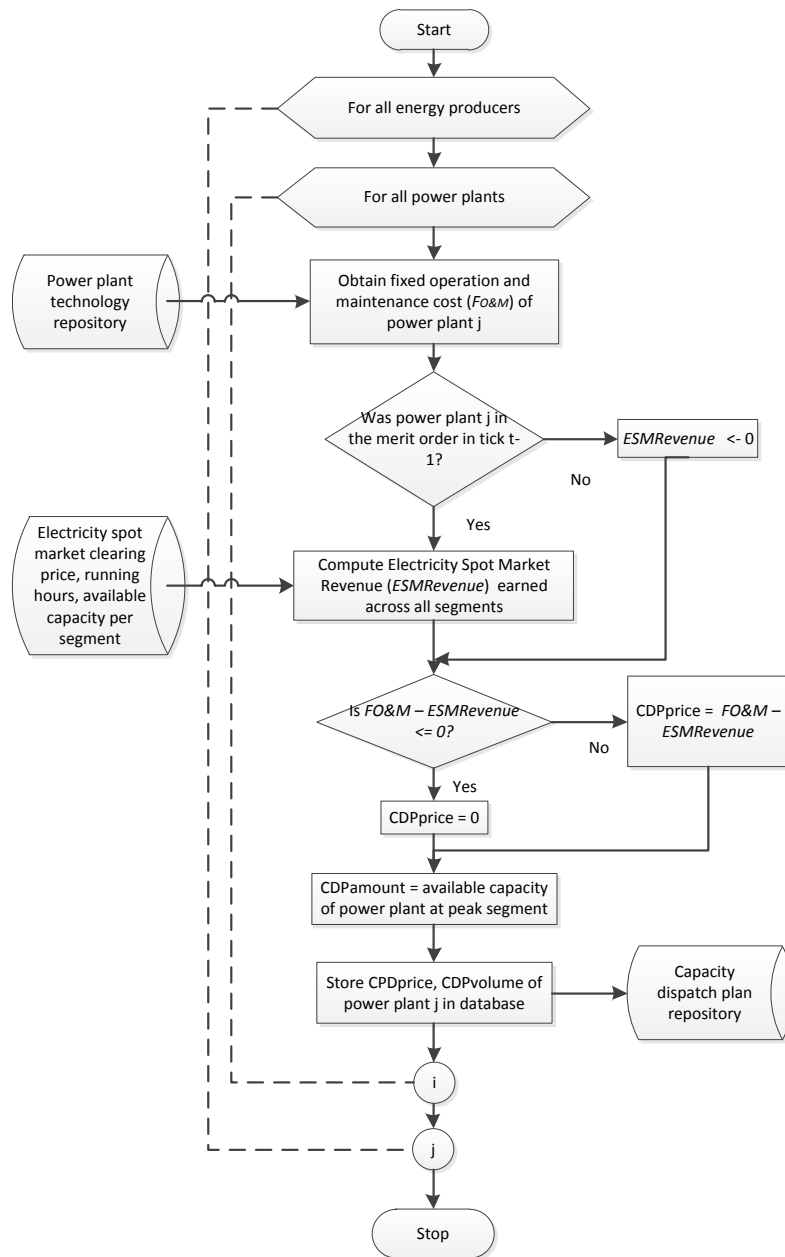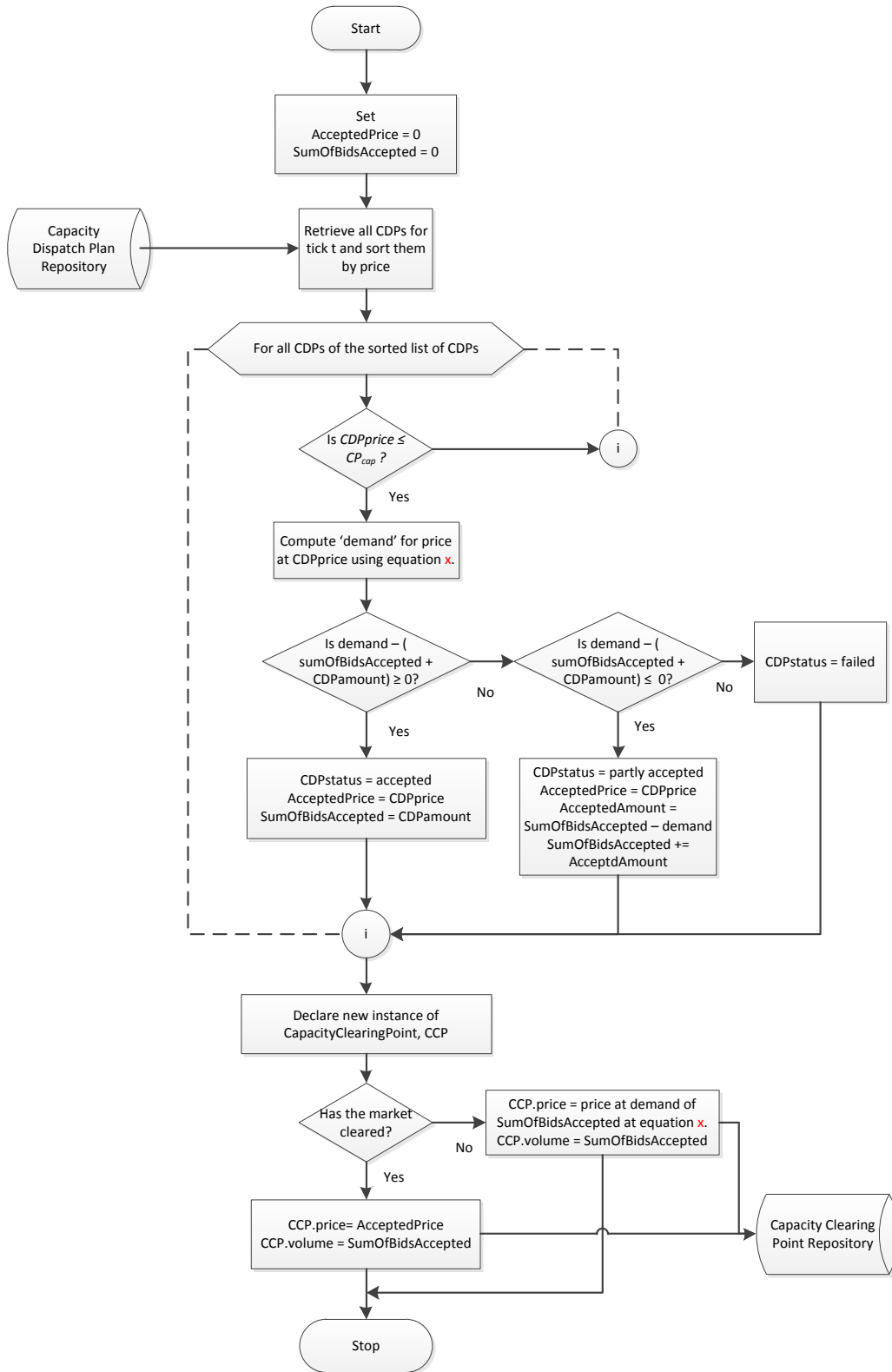
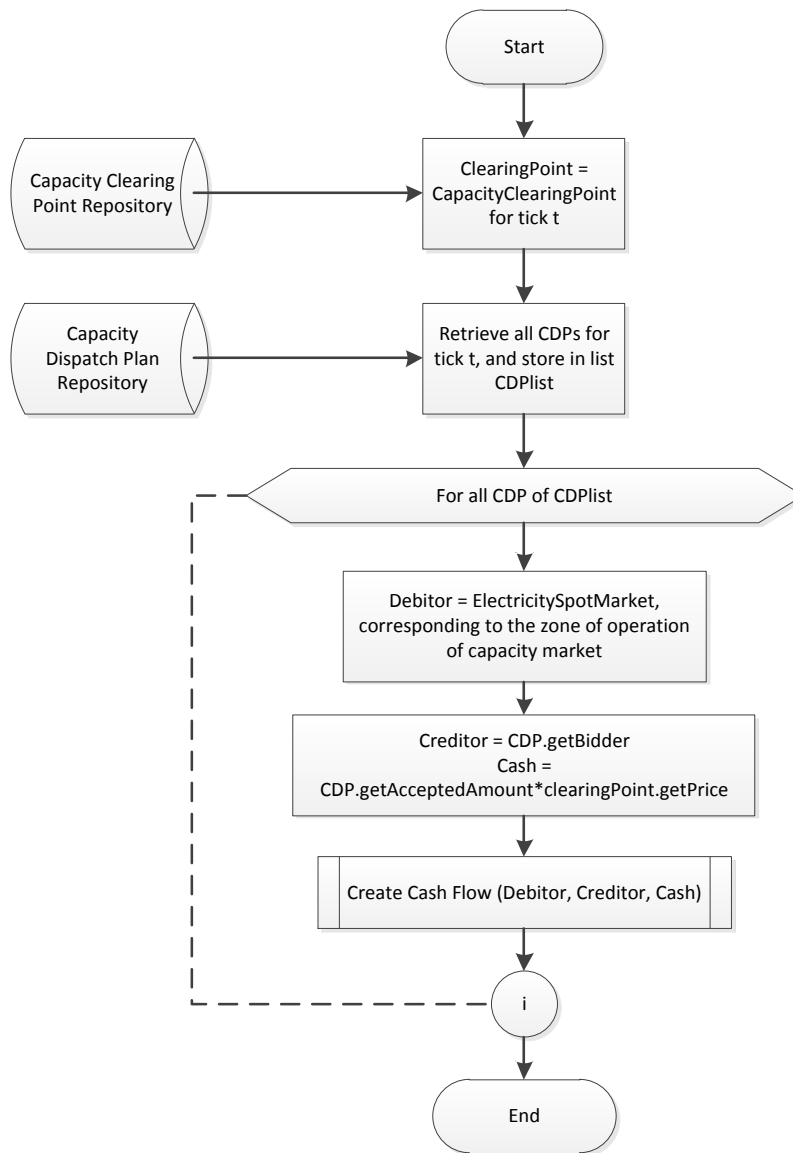Figure 6.2: Submit Bid into Capacity Market Flowchart

Figure 6.3: Clear Capacity Market Role Flowchart

Figure 6.4: Payment Role Flowchart

Update Revenue in Investment Algorithm

Parts of the following role, that are not relevant to the capacity market, have been described only broadly. The part describing the updating of revenue from the capacity market is described in detail, see pseudo code below.
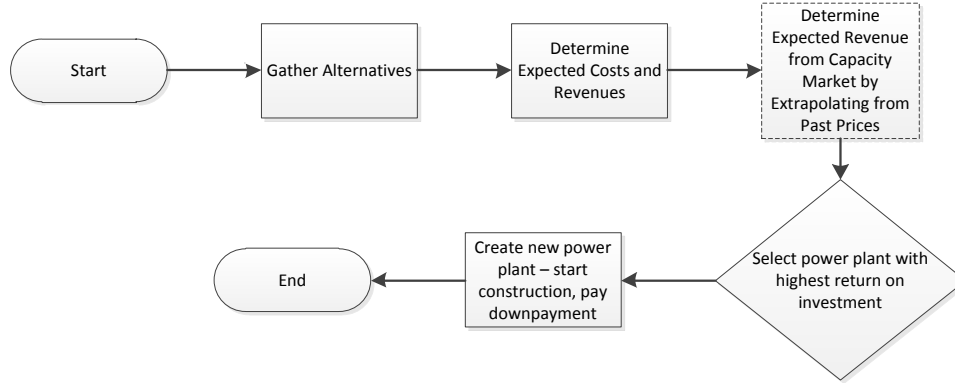

Figure 6.5: Update Revenue in Investment Algorithm Flowchart

Essentially, the energy producers calculate an average of the capacity clearing prices of the past 4 years, and factor that into the NPV calculations.

InvestInPowerGenerationTechnologies, acted by EnergyProducer

1: Obtain market information about investors market for futureTimePoint ▷ expectedFuelPrices, expectedCO2Price, expectedDemand
2: **for all** $technology$: findAllTechnologiesFromRepository **do**
3:     Create a new power plant, $plant$ of type $technology$
4:     Check whether physical and financial constraints are met
5:     Determine expected revenues and costs, $operatingProfit$
6:     Regulator $regulator \leftarrow$ findRegulatorGivenZoneOfEnergyProducer ▷ the regulator of energy producer's zone is retrieved from the repository
7:     double $capacityRevenue \leftarrow 0$ ▷ Initialize capacity revenue to 0
8:     **if** $regulator \neq null$ **then** ▷ Checks if there is a regulator for the relevant zone. The presence of a regulator indicates the presence of a capacity market in the zone.
9:         $x \leftarrow energyProducer.noOfYearsOfLookingBackForForecasting$
10:         $sumCapRev \leftarrow 0$
11:         **for** $time \leftarrow getCurrentTick; time \geq (getCurrentTick - x); time- = 1$ **do** State double $capRevTemp \leftarrow clearingPointPrice$ ▷ Find one capacity clearing point price for current tick
12:             $sumCapRev+ = capRevTemp$
13:         **end for**
14:         $capacity \leftarrow plant.getExpectedAvailablePeakCapacity$ ▷ Retrieve expected available capacity for peak segment at the future time point

15:          $capacityRevenue \leftarrow capacity \times sumCapRev \div (getCurrentTick - time)$

16:     **end if**

17:     $OperatingProfit+ = capacityRevenue$

18:     Compute NPV

19: **end for**

20: Select power plants with highest NPV, ≥ 0

21: Create new power plant, start construction, pay downpayment

Integration of Roles   The following role integrates all the above methods into one single role that can be called from the main EMLab 'DecarbonisationModel' role.

    SimpleCapacityMarketMainRole*, acted by *CapacityMarket

1: Regulator $regulator \leftarrow$ CapacityMarket.getRegulator

2: $forecastDemandRole.act(regulator)$

3: **for all** $producer \leftarrow findAllEnergyProducers$ **do** $submitCapacityBidToMarketRole.act(producer)$

4: **end for'**

5: $clearCapacityMarketRole.act(Regulator)$

6: $paymentFromConsumerToProducerforCapacityRole.act(market)$

6.4   Conclusion

This chapter provides a synopsis of the code itself, and its implementation within EMLab. The classes, agents introduced for the capacity market model have been described, followed by the pseudocode of the model, while clarifying how it integrates with the EMlab code. The next chapter verifies whether the model indeed works as per the pseudocode.

Chapter 7

Validation

It is widely acknowledged that validation constitues of one the central epistemological problems of computer simulations. This holds especially true for agent based simulations, that do not always build on well established theoretical models [16,35]. Certifying whether such models and their simulations can be reliably used is therefore an integral part of answering the research questions. I shall use the evaluation process presented by Balci [36], which discerns between verification, validation and certification.

Verification is the assessment of transformational accuracy, validation is the assessment of behavioral or representational accuracy, and certification is independently assuring sufficient credibility of complex models and simulations. [36]

7.1   Verification

Verification confirms whether the conceptual model has been correctly translated to the computational model. Verification for the capacity market model was done primarily in the following ways:

- Recording and tracking of agent behaviour
- Role testing, using J-Unit tests

The first method, recording and tracking agent behaviour, was used by implementing loggers in the Java code; it is useful for making sure that the model is operating as expected. This method is used quite often to track behaviours of the agent, in the intial stages of code. While loggers are simple, they may not always be convenient when one wants to test a small part of the code, instead of running the whole code.

J Unit is a unit testing framework for Java. It allows the verification of a single role, when all inputs required for the role are specified. The role being tested is like a black box to the J Unit test, and the output(s) from the role may be compared against a predetermined value to check whether the test is working or not. It is also useful to track agent behaviour role by role, if specifying the inputs for the role is not a humungous task. An example of a J Unit test is presented in appendix D. It was written for the *forecastDemandRole*.

Verification in EMLab   At this juncture it is important to mention that verification in EMLab was a very challenging, if not the most challenging and time consuming part of the process. The reasons for the difficulty are the following -

- The sheer size and complexity of EMLab makes it challenging. A substantial part of the code was out of the scope of my work; parts which I had little familiarity with, but could still affect my work.

- The modular nature of EMLab is both a blessing and a curse - verifiying that a module works does not guarantee that it will work as part of the full model exectution. At times it is not even possible to fully verify a part of the code by J Unit testing simply because specifying all the inputs required for the J unit test might take a lot longer than running the code several times. When a module does indeed work individually, problems could still arise during the full execution due to the various interdependent aspects such as the repositories, the queries and other aspects which require specification and setting-up.

- Checking whether the code worked as a whole required executing the model several times. The long run time was a huge disadvantage. Every time a small parameter was changed, the code would have to be run again. Running the code the full length would take about 30 minutes for a single country scenario and about 45-60 minutes or more for a two country scenario.

- Even if you were to run the code the whole length, depending on what aspect you were testing for, you still couldn't trust the results of a single run, as in an agent based model, given its random and chaotic nature, every single run could be an outlier. And to compare or percieve real differences in a reliable manner one must run simulations several times.

- Another area of caution is that different scenarios (RES/EU ETS) might introduce different errors, and verification needs to be done for every scenario.

Table ?? outlines some of the main tests carried out, errors corrected and aspects verified in the model, role by role. Some of the errors took days, if not weeks, and generous help from PhD students to resolve.

7.2 Validation

Validation is the assessment of behavioural or representational accuracy of the model [36]. It should ideally answer the question, 'Are we creating the right thing?' In order to address this question sufficiently, it is important to define what the model is meant for, to define the purpose of the model. A model may be valid for one set of experiments and invalid for another. It is important therefore that the purpose of the model is clearly specified first, and that the validity of the model is determined with respect to that purpose [37].

Validation is not a one-stage process, but spans the entire life-cycle of model development. The process of validation employed here again is loosely based on the life cycle evaluation process presented in [36]. The main steps are

1. Conceptual Model Evaluation Process
2. Requirements Evaluation Process
3. Design Evaluation Process
4. Executable Modules Evaluation Process
5. Results Evaluation Process

Conceptual Model Evaluation   The conceptual model, thoroughly described in chapter 5, has been developed either from well-established systems and practices in current use, such as the NYISO and the PJM, or from theoretical foundations. Also, at the end of the each process, including the making of the conceptual model the outcomes were assessed by supervisors.

Table 7.1: Verification of Capacity Market Model

Role	Test	Error	Outcome
Forecast Demand	• Regulator's *demandTarget* must correspond to expected value	Query for *peakLoad* not working	Corrected. Verified.
Submit Bid to Capacity Market	• *ESMRevenue* must be computed and accessed correctly, across all segments • *bidPrice* and *bidVolume* must correspond to expected values	Error in scope of variables in loops leading to only revenue from the last segment being computed, adder (+=) does not work. Query to access status of *PPDP*s not working	Corrected. Verified with loggers more than J unit test.
Clear Capacity Market	• Check if the sloping demand curve works accurately • Check if bids are accepted upto required quantity under different conditions • Check if the clearing point is correctly determined and stored		Verified.
Payment Role	Check whether consumers' and producers' cash balances have changed appropriately		Verified
Update Revenue in Investment Algorithm	Verify whether the average across the capacity clearing point prices are computed accurately	Capacity clearing prices were not multiplied by the capacity of the plant.	Corrected, verified.
Full Model Execution	Capacity adequacy, capacity market prices	Capacity prices reflected the shortages and excesses in capacity, but insufficient investment, due to price cap being set very low.	Corrected, verified.

Requirements and Design Evaluation   Specifying requirements is the part where the purpose of the model is defined. This is critically important as the specification of requirements forms a pint of reference for the remainder of the work. The requirements were specified in discussion with my supervisors. They held me back when I became too ambitious and encouraged me to pursue relevant research questions and directions.

Once the design was specified in algorithm form, it was thoroughly assessed by my PhD student-supervisor and other PhD students involved in the EMLab project, and modified to adapt to EMLab. Errors, accidental omissions were identified with a critical eye before the actual implementation began.

Executable Modules Evaluation   This step concurs with the verification phase, and was implemented by J-unit testing.

Results Evaluation   This phase is addressed in chapter 9 Results and Validation.

7.3   Conclusion

Validation is an important but costly and time consuming process. It therefore cannot be performed over the entire domain of the models' applicability. It is performed to an extent with which sufficient confidence is obtained in the model. The validation of the process upto the design of the model has been a rigouros process. The validation of the results and possible errors in the existing code will be discussed in chapter 9

Part IV

Analysis and Conclusions

Chapter 8

Experiment Design

8.1 Introduction

The design of the experiments takes us back to the main research objectives of this work. As mentioned in section 2.1, the research objectives comprise of studying the performance of a capacity market

- in the presence of substantial renewable energy generation.
- in the presence of a neighbouring country, with cross-border effects.

In this chapter, all elements of the experimental design that address the aforementioned research objectives are described. This involves establishing hypotheses, determining scenarios necessary to reflect on a hypothesis, determining the parameter space over which the hypothesis is tested, and describing and justifying the key performance indicators.

The experiments are designed to essentially test four hypotheses, and additionally perform a sensitivity analysis. The four hypotheses are each tested in an experiment comprising of a comparison between two scenarios - the 'Base Case' scenario' and the 'Capacity Market' scenario. The two scenarios only differ by the implementation of the capacity market - the 'Base Case' scenario does not implement the capacity market, while the 'Capacity Market' scenario does, all other factors remaining equal. The following table presents a brief snapshot of the experiment design.

8.2 Experiment Design

This section describes all aspects of the experimental set-up. The hypotheses, the data employed for the scenarios and the execution of the experiments. At the outset, it must be noted that all

Table 8.1: Experiment Design

	No. of Countries	RE Target
Experiment 1	1	No
Experiment 2	1	Yes
Experiment 3	2	No
Experiment 4	2	Yes

experiments are designed to run for fifty ticks, with each tick representing a year. Preliminary runs on EMLab show that the model reaches stability or equilibrium, and is independent of instabilities (oscillations) caused by initial conditions, after the first 15-20 ticks. The hypotheses being tested study the long term effects of the capacity market. The one-country experiments are performed on Country A, loosely based on the Netherlands, while the two country experiments are performed on Country A and Country B; Country B being modelled based on Germany.

8.2.1   Hypotheses and Sensitivity Analysis

Sensitivity Analysis   This analysis employs the simple, plain, Capacity Market scenario from experiment 1, without the RES target policy, to test the sensitivity of the performance of the capacity market to two design parameters, namely a. Price Cap of the capacity market and b. Slope of the demand curve. The idea behind the sensitivity analysis follows from the research methodology described in section 2.3, where the capacity market is first evaluated by the 'assessment criteria', operationalized into Key Performance Indicators explained in section 8.3. The choice of the design parameters used in each of the scenarios in experiments 1 to 4 build on the results from the sensitivity analysis.

The elements of the demand curve- the price cap and the slope continue to remain subjects of scrutiny and contention for stakeholders. For instance, PJM was recently involoved in a lengthy settlement process regarding the setting of the administratively determined Cost of New Energy (CONE) values with the Maryland Public Service Commission [38] and the NYISO is currently introducing its triennial demand curve review process [33]. The sensitivity analysis is therefore an important component of the analysis. It is performed for 3 values of the price cap, and 3 values of the slope of the demand curve, giving a total of 9 unique scenarios, as shown in the following table.

Table 8.2: Scenarios for Sensitivity Analysis

	Price Cap	Slope
Scenario 1	CONE	(0,0)
Scenario 2	1.5*CONE	(0,0)
Scenario 3	2*CONE	(0,0)
Scenario 4	CONE	(0.025, 0.025)
Scenario 5	1.5*CONE	(0.025, 0.025)
Scenario 6	2*CONE	(0.025, 0.025)
Scenario 7	CONE	(0.05, 0.05)
Scenario 8	1.5*CONE	(0.05, 0.05)
Scenario 9	2*CONE	(0.05, 0.05)

The values for capacity market design parameters are set as follows:

- Slope (Upper margin = 0.025, Lower Margin =0.025)
- ReserveMargin = 0.156
- PriceCap= 2*CONE = 2*Fixed Cost Of a CCGT plant = 2*29470

Hypothesis 1   A capacity market, as a standalone policy instrument, ensures generation adequacy in one, isolated country. It has been more than a decade since the first capacity markets were implemented. From the decade of experience, it is apparent that capacity markets have achieved their fundamental design objective of maintaining resource adequacy in

deregulated markets [33]. This hypothesis therefore does not as much aim to present or discover a novel effect, so much as it validates the model itself. This hypothesis will study the effect of a capacity market in one country, considered in isolation by comparing a Base Case scenario versus a Capacity Market scenario. This country is modeled based on the Netherlands in terms of its capacity, number of energy producers, power generation technology mix, load etc. Additionally, the Capacity Market scenario designed for this experiment is used to perform a sensitivity analysis.

Hypothesis 2   A capacity market, as a policy instrument in combination with targeted investment in renewable energy, ensures generation adequacy in one, isolated country. This hypothesis tests the effects of two policies: the capacity market, as well as targeted investment in renewable energy on a region modeled over the Benelux area. The targeted investment in renewable energy is based on the National Renweable Energy Action Plan until the year 2020 for the Netherlands [39]. The first ten years of the simulation use the NREAP data until 2020. It then extrapolates that data for the next forty years. With this experiment, I seek insight into how the design of a capacity market might have to adapt in the presence of substantial intermittent energy generation. Insight may also be gained into how risk may be allocated differently between stakeholders, changes in the generation portfolio etcetera. A sub-hypothesis examines a case where the performance of the capacity market is tested in the presence of the NREAP targets as well as the EU ETS; the cap on the emissions is based on the cap for the phase II of the ETS (2008-2012) [40].

Hypothesis 3   A capacity market, as a policy instrument in country B, ensures generation adequacy in country B while it is interconnected with country A. This hypothesis explores the cross border effects of a capacity market across two interconnected, neighbouring countries with deregulated electricity markets, where one country, say Country B implements the capacity market, and Country A does not. Here Country B is modelled based on Germany, and Country A on the Netherlands. An interconnector capacity of 4441MW is employed between the two countries, and no export curtailment policy is modelled in either country. The export capacity is a static value of 4441 MW across the whole simulation. The interconnector capacity is based on data from Tennet, the TSO of the Netherlands [41]. This experiment is designed to explore free rider behaviour - whether investment in Country B driven by the capacity market leaks into country A, given that consumers in the country B are explicitly paying for generation adequacy and counsumers in country A are only paying for energy.

Hypothesis 4   A capacity market in country B, as a policy instrument in combination with targeted investment in renewable energy, ensures generation adequacy in country B while it is interconnected with country A. Hypothesis 4 explores the cross border effects of a capacity market in a scenario where both countries invest in renewable energy generation as per the NREAP plans for the next fifty years. The generation portfolio here is markedly different from that of hypothesis 3, and it is interesting to observe how aspects such as intermittency, risk allocation, price levels, and possibly free-rider behaviour play out in such a scenario. A sub-hypothesis is a scenario where the EU ETS is implemented along with the RES targets.

8.2.2   Scenario Specification

This section consists of a description of the assumptions as regards demand growth, fuel prices for the next fifty years. In addition, the initial electricity supply portfolio for each country is

also described.

Demand Growth and Fuel Prices

The demand and fuel price growth trends are exogenously simulated using monte carlo experiments that follow a triangular distribution. For each trend, the top, minimum and maximum values are specified, along with the start value. The top refers to the top of the triangle, while the minimum and maximum values are the lower and upper limits respectively.

The top, min, and max values for the demand growth are based on demand data (from 1990 to 2010) from the Union of the Electricity Industry in Europe [42]. The following table indicates the growth rates used in the scenarios.

Table 8.3: Growth Trends

	Top	Min	Max
Demand Growth NL	1.0194	0.9516	1.0435
Demand Growth DE	1.0082	0.9422	1.0549
Coal Price	1.0107	0.9707	1.0507
Gas Price	1.0146	0.9446	1.0846
Biomass Price	1.0100	0.9700	1.0500
Uranium Price	1.0100	1.0000	1.0200

Country A: Energy Mix

As mentioned earlier, country A is modelled based on the Netherlands. There are four Energy Producers based in Country A in the model, each representing a major power generation company in the Netherlands. The various generation technologies, their capacities, i.e., the generation portfolio is specified based on data from the Union of the Electricity Industry in Europe [42] and data from the European Network of Transmission System Operators for Electricity (ENTSOE) [43]. Similarly, data on peak loads has also been obtained from [43]. The initial allocation of power plants to the generation companies or Energy Producers is performed randomly by uniform distribution, such that overall generation mix corresponds to the following proportions, shown in the table below.

Table 8.4: Power Portfolio for Country A

Technology	Percentage
Coal Pulverized Super Critical	0.33
CCGT	0.40
OCGT	0.16
Biomass PGT	0.01
Nuclear PGT	0.03
Wind PGT	0.07

Country B: Energy Mix

Country B, is based on Germany, and has five Energy Producers. Again, the data for the generation portfolio is based on data from Union of the Electricity Industry in Europe [42] and

from ENTSO-E [43]. The intial generation capacities are randomly assigned across the energy producers based on the following portfolio.

Table 8.5: Power Portfolio for Country B

Technology	Percentage
Lignite PGT	0.1436
Coal Pulverized Super Critical	0.1931
CCGT	0.1071
OCGT	0.0851
Biomass PGT	0.0302
Nuclear PGT	0.0724
Wind PGT	0.1725
Photovoltaic PGT	0.1453

8.2.3   Experiment Set-up

The experimental set-up for an agent based model is a vital part of the analysis - the scenario space over which the experiment is run, the number of experiments to be run - determine to a large extent the limitations of one's analysis, and hence has to be done with care.

A golden rule with agent based modelling is to never trust the outcome of one single run, for every single run could be an unrepresentative outlier [15]. This section explains in brief why agent based modelling in general, and this model in particular, needs multiple runs to arrive at statistically significant conclusions. All the same, the richness of the analysis that one may obtain with a wide scenario space must be traded off against the resources (time and computing) that is required to perform the runs.

The following paragraphs outline the scenario space chosen for this model, and how those choices may either enable or limit further analysis. They also discuss the aforementioned trade-offs between scenario space and time requirement in greater detail.

Randomness

The randomness between two runs of the same scenario arises from the following factors.

- Randomised agent iteration in order to prevent first-mover artifacts - this is an intrinsic feature of the model.
- Stochastic demand growth trends, as specified in section
- Stochastic fuel price trends
- Randomness in age of power plants - the age is drawn from a uniform distribution between 0 and the technical lifetime of a power plant.
- Randomness in power plant ownership - based on the generation portfolio described in sections 8.2.2 and 8.2.2

Experiment Execution

Given the randomness and chaotic nature of every unique scenario, it has been found that the results are statistically significant and stable only with a minimum of 120 runs.

Depending on the nature of a scenario, exectution may take more or less time per run. A one country run would take roughly 30 minutes on a personal computer; running one scenario 120 times would translate to 2 days per scenario on the personal computer. Using a cluster therefore

became a necessity - executing the same one country run 120 times on a high performance cluster (HPC) would take a few hours. A two country run, however has twice as many energy producers, with each producer having to make more complex investment decisions, and therefore takes much longer even on the HPC - executing one scenario would take about a full day.

Since the scenarios amounted to 14 one country scenarios and 6 two country scenarios, giving a total of 2400 (120* 20) single runs, the execution required approximately 6 days on the high performance cluster. The following paragraph is a discussion on the scenario space employed in the context of the aforementioned time constraints.

Scenario Space

Every scenario by itself as mentioned earlier incorporates substantial randomness in its demand growth trends, fuel price trends, power plant age and their ownerships. This randomness in the model, which ultimately necessitated a minimum of 120 runs per scenario, is vital in ensuring that specific, predetermined trends do not cause artifacts in the results. This is especially important while performing a simulation of a fifty year period, wherein speculation is rife, while predicting growth trends.

Each of the four main hypotheses (H1, H2, H3 and H4) outlined earlier in the chapter are designed to test whether, under the specified conditions, a macroscopic regularity of interest emerges from the model. Such experiments employ only individual scenarios. The experiments performed under the sensitivity analysis (Hypothesis S1 and S2), on the other hand are more explorative in terms of the design parameters and behaviour of a capacity market as an isolated policy instrument. The nine scenarios designed for the sensitivity analysis comprise of a scenario space built to explore the behaviour of the capacity market design.

It could be argued that a full factorial analysis could have been empoyled for the design parameters of the capacity market - the price cap, slope and the reserve margin. However, realizing randomness in predicting fuel price, demand trends and agent iteration took implicit priority in the face of time and resource constraints. This arrangement however greatly improves the robustness of the results of every hypothesis, at the same time enabling analysis of salient aspects of the capacity market design.

8.3 Description of Indicators

The Key Performance Indicators with which the effects of a capacity market may be evaluated are distilled by the following themes: electricity market performance, consumer welfare and producer welfare, and importantly, the capacity market performance. The relevance behind the themes, and their operationalisation into indicators (graphs and data) is described below.

Graphs and numerical data from Experiment 1 have been used as sample graphs to explain the indicators. This explanation also serves as a guide to reading the results fromt he results chapter. The run -length for all experiments, i.e., for every scenario as mentioned earlier is 50 ticks, with each tick representing a year. In addition, every scenario is run 120 times. The graphs show mainly the median value (blue line), and confidence intervals.

8.3.1 Electricity Market Performance

Indicators for the performance of the energy market takes us back to concepts introduced in chapter 3. Some of the primary arguments in favour of the capacity market are that an energy-only market might not sufficiently incentivize *adequate* investment in (*the right type of*) capacity. I allude specifically to the word 'adequate' and 'the right kind of' as they describe the very

characteristics that make for relevant indicators. In conditions where the energy market is strong enough to ensure adequacy, there is the risk of high electricity price volatility (due to scarcity pricing), and excercising of market power. In the following paragraphs the indicators for adequacy, generation portfolio, and the electricity price are described.

Adequacy   Adequacy refers to whether sufficient operational capacity exists to meet demand. An indicator therefore, would be the the ratio of operational capacity to the peak demand, namely the **Supply Ratio**, defined below. Another indicator, one that is an industry standard for measurement of reliability, is the Loss of Load Expection (LOLE), also defined below.

Supply Ratio: This indicator is measured as the ratio of *Total Operational Capacity Per Zone(in MW)* to *Peak Demand Per Zone (in MW)*. A value of supply ratio below 1 would clearly indicate a shortage. A sample graph measuring supply ratio for both the 'base case' and the 'capacity market' scenario is shown in figure E.11. The blue line indicates the median value, and the red or blue shaded areas indicate the 50 percent confidence interval. The grey shaded area indicates the 95% confidence interval.
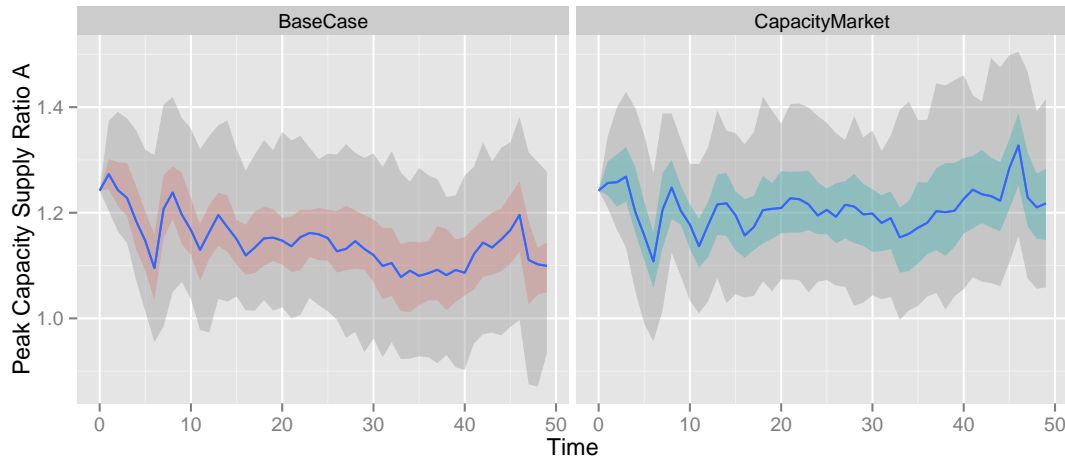
Figure 8.1: Exp 1: Supply Ratio

Loss of Load Expectation (LOLE) is a generation adequacy indicator wich measures how long on average the generation capacity is likely to fall short of the demand. It is measured in hours per year. In this simulation, the average LOLE is calculated across 120 runs per tick, yielding the following graph. The mean of the 50 values then obtained is the numerical indicator for LOLE per scenario.

Base Case
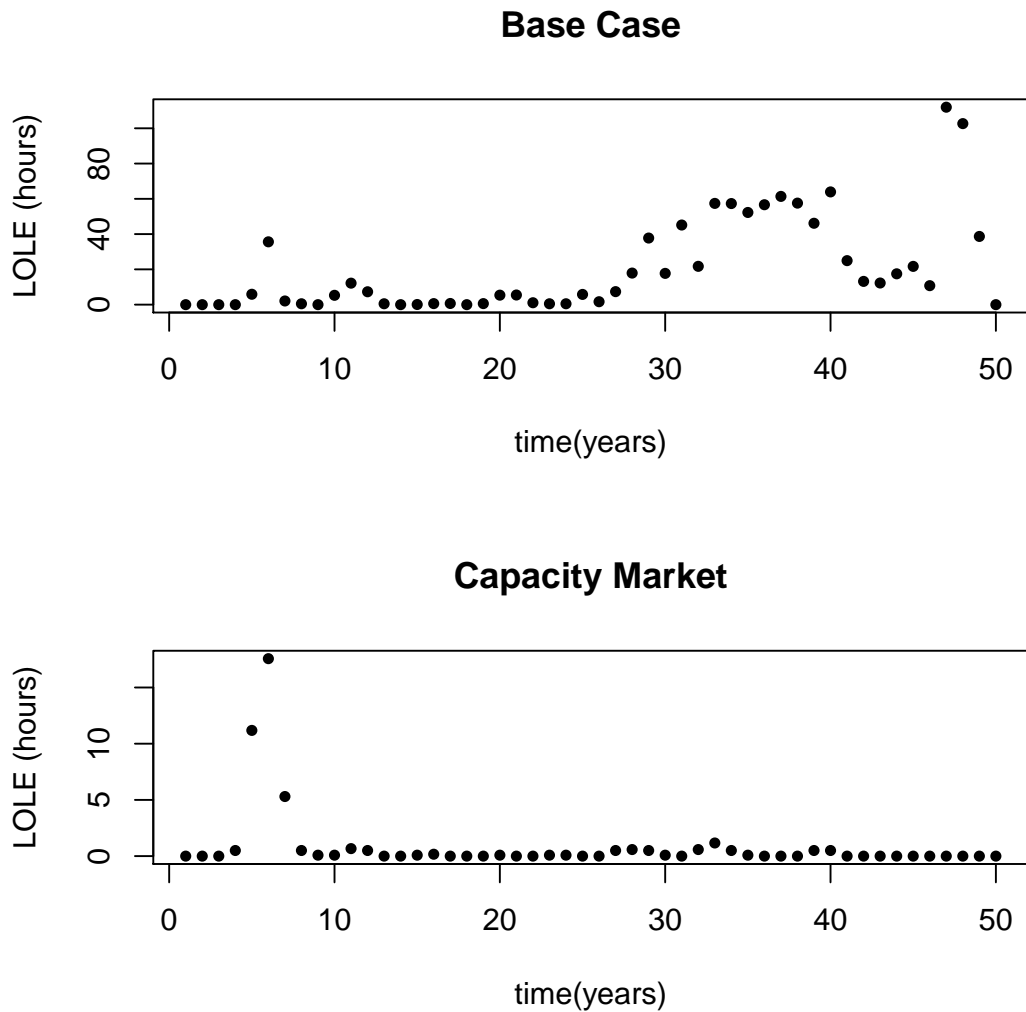
Capacity Market

Figure 8.2: Exp 1: Average Loss of Load Expectation

Average Electricity Price : This indicator, as the name suggests, is an average of electricity prices across all segments of the electricity market in a given tick (year). The figure E.12 shows the average spot market price for experiment 1. Again, the blue line indicates the median value, and the red or blue shaded areas indicate the 50 percent confidence interval. The grey shaded area indicates the 95% confidence interval.
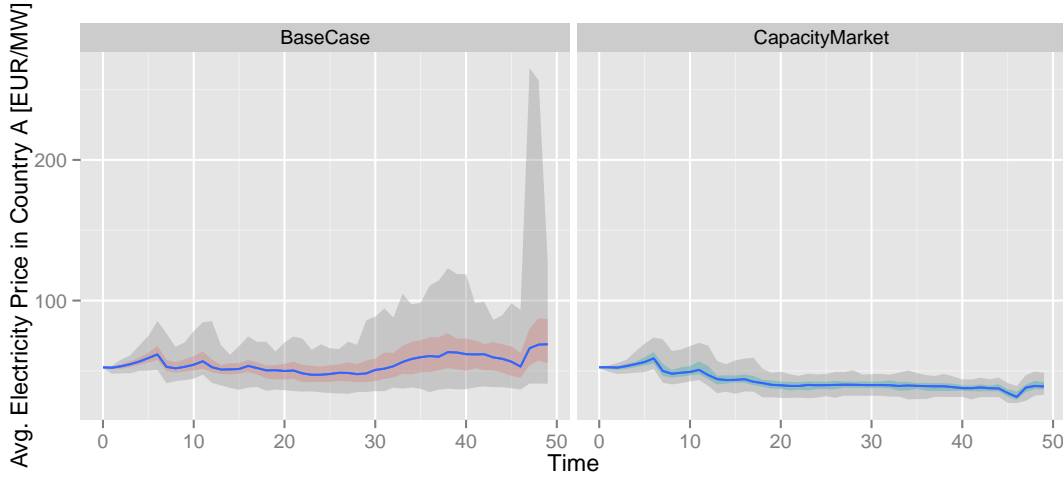
Figure 8.3: Exp 1: Average Electricity Price

Electricity Price Volatility is measured as the standard deviation of Average Electricity Spot Market (ESM) Price [1]. This indicator is vital as it has implications for energy producers trying to forecast revenues, as well as political implications where stable prices, i.e., lower volatilities, are favoured.

Generation Portfolio : This graph provides an overview of the types and quantities of generation capacities installed in each country. This graph shows how the generation portfolio might develop differently with time as an effect of a certain policy. A sample graph is shown in figure E.19.

8.3.2 Consumer Welfare

To determine the absolute value that the consumer places on reliability is an onerous task. Value of Lost Load (VoLL) is the amount that cosumers would pay to avoid having supply interrupted during a blackout. Estimations of VoLL vary widely across consumer groups (industrial, commercial or domestic), across time of day, among other factors.

A solution therefore is to measure the change in consumer surplus due to a certain policy, rather than the surplus itself. This is done by using the indicator, Consumer Expenditure.

Consumer Expenditure encompasses expenses of the consumer in the energy market as well as the capacity market, when present. The mean value of consumer expenditure is measured for base case and capacity market scenarios, and the difference between the two yields the change in consumer expenditure.

$$ChangeinCE = CE_{CapacityMarket} - CE_{BaseCase} \tag{8.1}$$

8.3.3 Producer Welfare

Producer surplus is slightly easier to measure as compared to consumer surplus, as it is the difference between the cost to the producer minus the revenues, which amounts to the aggregate profit.

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[1]Standard deviation is commonly used in finance as an indicator for price volatility [44]
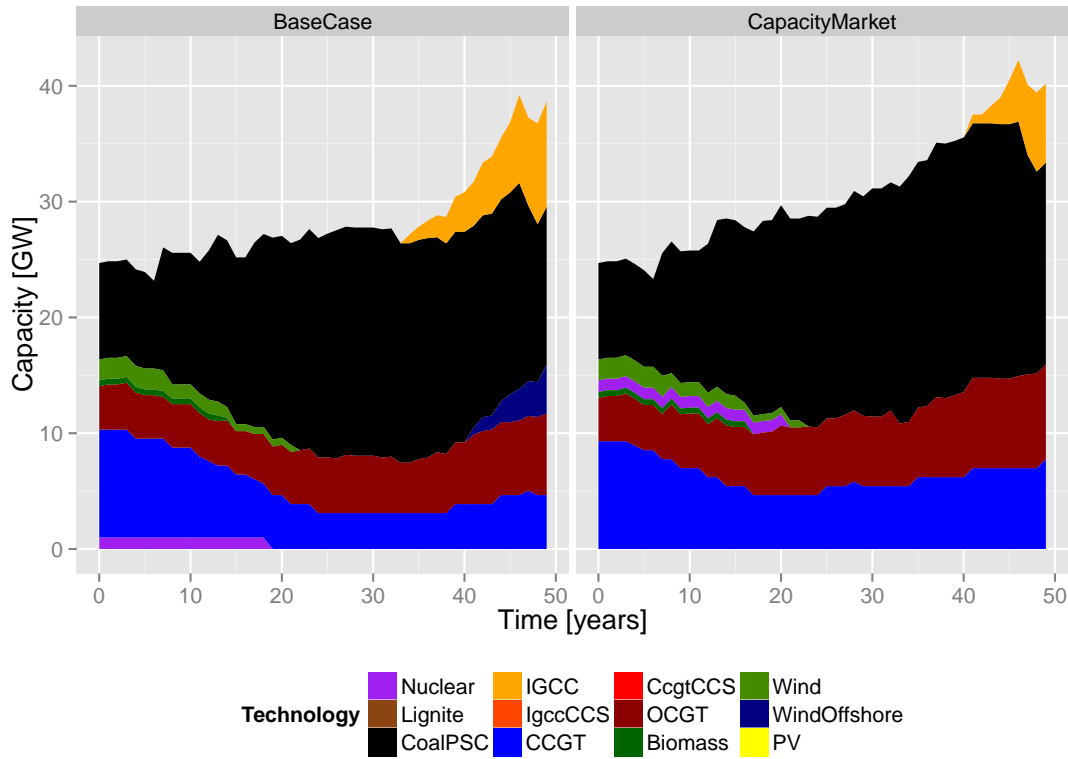
Figure 8.4: Exp 1: Stacked Capacity Diagram

Producer Cash: simply measures the cash balance of a producer at each tick. A sample figure is shown in figure 8.5. The whiskers indicate the 50% confidence interval. A standard deviation of the producer cash is an indicator for producer risk.

Aggregate Profit: measures the sum of the profit, that is total revenues minus total cost, earned by each producer in a given zone. Here, total revenues entail revenues from the capacity market and the energy market. The total costs include the fixed O&M costs, commodity costs (such as fuel), CO_2 tax if applicable, loans and downpayment. A sample figure is shown in figure 8.6. The whiskers indicate the 50% confidence interval.

Risk: Another factor vital to a producer's financial well being is the risk they are exposed to while making investment decisions. Uncertainty in return on investment makes projects more expensive due to an increased risk premium. Therefore, a simple indicator to provide insight into the risk a producer faces is useful. Here, the standard deviation of producer cash has been used as proxy to measure such risk.
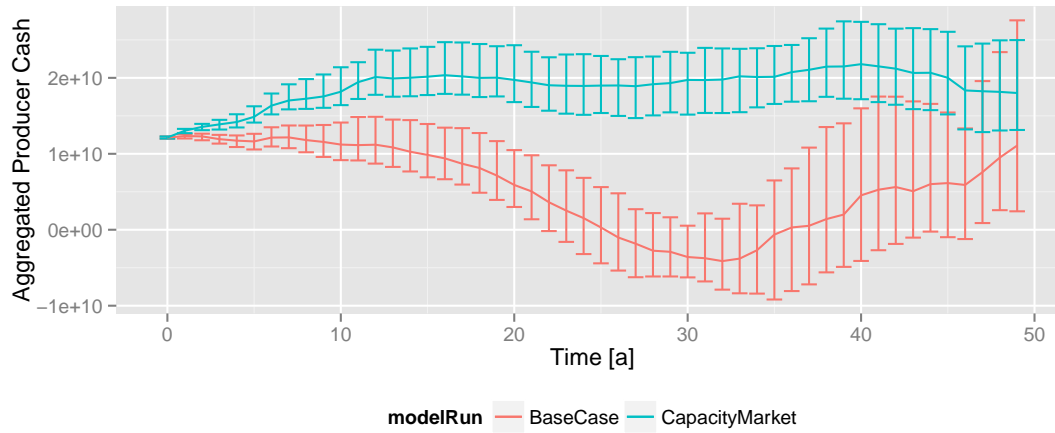
Figure 8.5: Exp 1: Aggregate Producer Cash
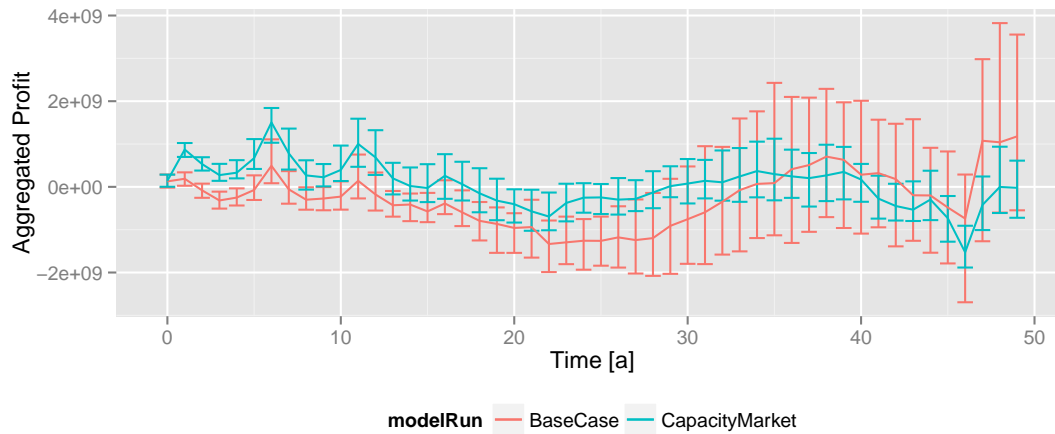
Figure 8.6: Exp 1: Aggregate Producer Profit

8.4   Conclusion

This chapter provided an explanation of the experimental design and set up, and the reasons behind them. It also described indicators that are to be used to assess the results. The next chapter shall present the results of the simulation.

Chapter 9

Results and Validation

9.1 Introduction

Having described how the experiments have been designed, set-up, and why they have been set up that way, this chapter presents the results of the simulation. The results are presented per experiment as observations and then interpreted. They are presented first for the sensitivity analysis, and then for each of the experiments outlined earlier.

Reading guide   For every scenario, key numerical indicators are either the mean or the standard deviation (SD) of the variable. Each scenario has 6000 observations (120*50). For every indicator, the mean is first computed across one run of 50 ticks, yielding a vector of 120 fields. The final mean or SD of the variable is calculated using this vector of means.

9.2 Sensitivity Analysis

The sensitivity analysis tests the sensitivity of an isolated country A, modelled based on the Netherlands, to varying values of capacity market price cap and slope of the demand curve in the capacity market. The reserve margin remanins constant across all scenarios. The capacity market design, as mentioned earlier, is tested for 3 values of price cap and three values of the slope, yielding nine scenarios, shown in the table below. The table forms a reference for the series of graphs presented.

The results of the sensitivity analysis are analysed, by the themes following from section 8.3: Electricity Market Performance, Consumer Welfare, Producer Welfare and performance of capacity market.

The value of a CONE is taken to be the fixed operation and maintenance cost of one Combined Cycle Gas Turbine (CCGT) plant in the simulation, 29470 Eur per MW-Year.

Table 9.1: Scenarios for Sensitivity Analysis

	Price Cap	Slope
Scenario 1	CONE	(0,0)
Scenario 2	1.5*CONE	(0,0)
Scenario 3	2*CONE	(0,0)
Scenario 4	CONE	(0.025, 0.025)
Scenario 5	1.5*CONE	(0.025, 0.025)
Scenario 6	2*CONE	(0.025, 0.025)
Scenario 7	CONE	(0.05, 0.05)
Scenario 8	1.5*CONE	(0.05, 0.05)
Scenario 9	2*CONE	(0.05, 0.05)

9.2.1 Performance of Electricity Market

The first series of graphs show the *Supply Ratio, Average Electricity Price* and *Average Loss of Load Expectation* graphs in figures 9.1, 9.2 and 9.3 respectively. Each figure shows all nine scenarios, facetted with each other.
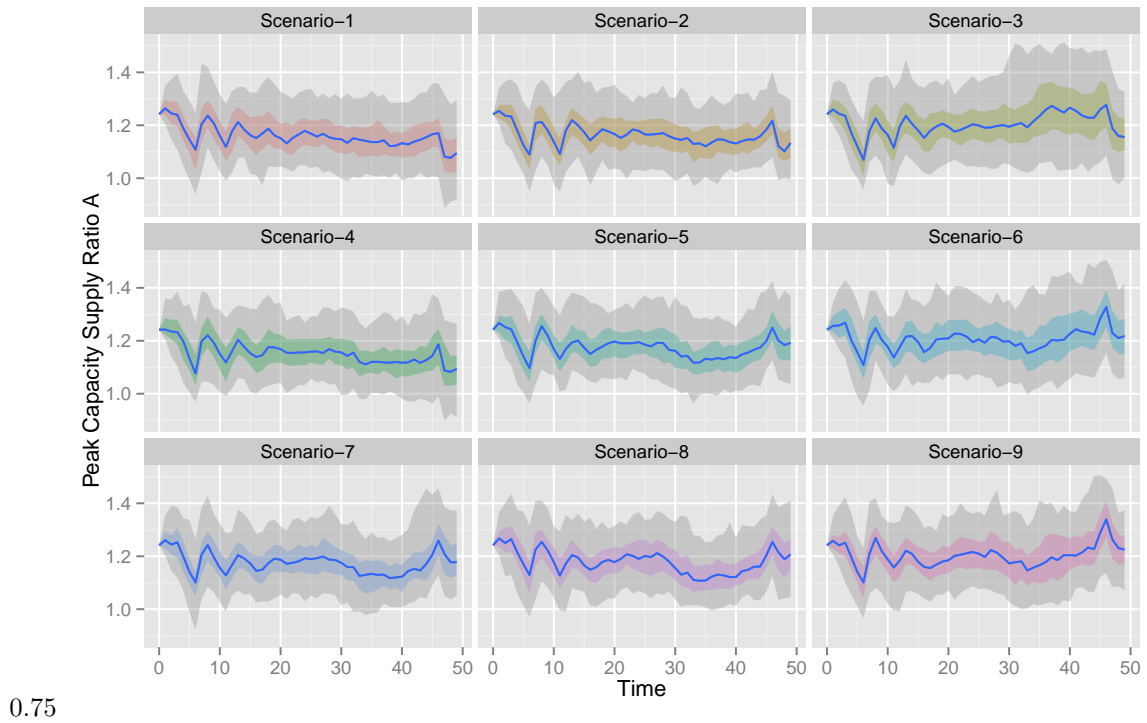
Figure 9.1: Supply Ratio

0.75
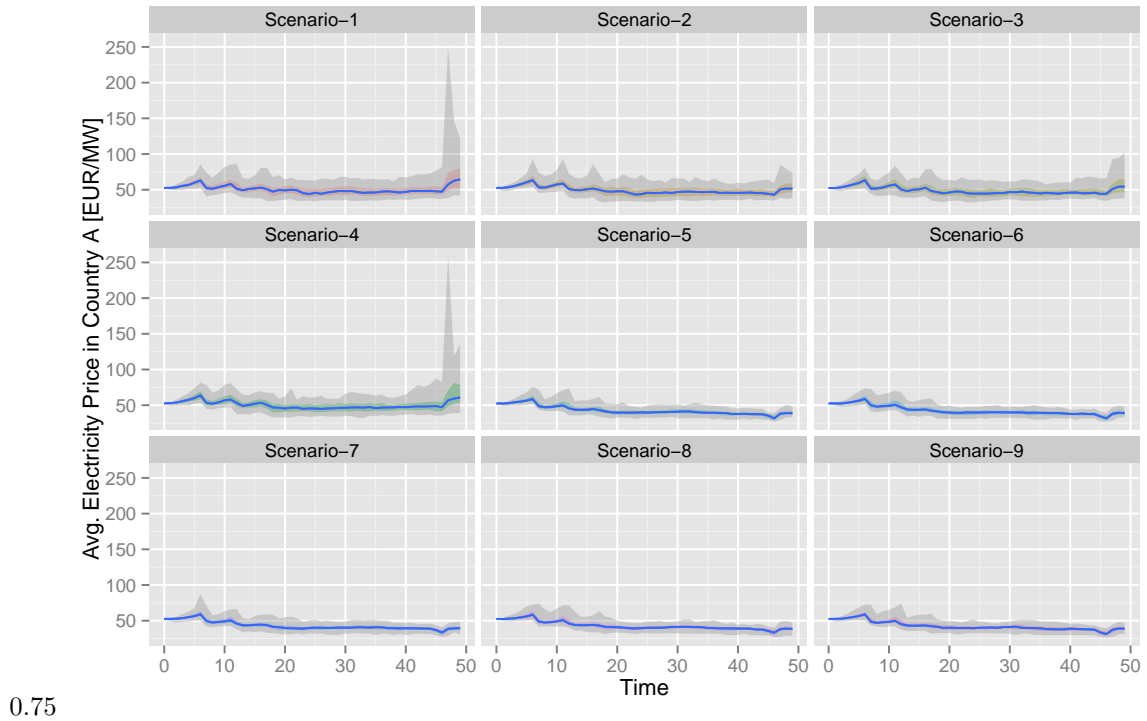
Figure 9.2: Average Electricity Price

Observations

- The first 15 to 20 years show very similar *Supply Ratio* trends in each of the 9 scenarios in figure 9.1. The Supply Ratios seem to oscillate in the same fashion for those initial years.

- Further, all scenarios show a median value of atleast around 1.16 i.e., a 16% reserve margin in figure E.1.

- Scenarios 3, 6 and 9, having a price cap of 2*CONE, i.e., 58940 Eur/MWh, show a markedly higher Supply Ratio after year 30.

- In scenarios 1 and 4, from figure 9.2, there is a high probability of outages around tick 48. This is also evident from figure 9.3, with Average LOLEs as high as 80 hours/year in those scenarios.

- Scenarios 1, 2, and 3 and 4 have very high standard deviations of Average Electicity Price, with values of 3.15, 3.34, 2.71 and 3.20 Eur/MWh respectively. The remaining scenarios 5,6,7,8 an 9 have standard deviations that are are almost half as much, with values of 1.75, 1.51,1.46, 1.60 and 1.46 Eur/MWh respectively.

Interpretation

- **Equilibrium** The similar initial oscillations across the 9 scenarios, suggest that the initial conditions of the model cause them, and that the simulation attains equilibrium only after the first 15 to 20 years. The oscillations themselves could be explained by the fact

that, since every scenario begins with the same generation portfolio, power plants of the same technology type have a high probability of being dismantled simultaneously, causing simultaneous investment by the producers, leading to similar cycles initially. Depending on the financial environments per scenario, the probability of investments in a certain technology may increase or decrease, leading to differences further (after the first 15-20 years) in every scenario. This is corroborated by the Stacked Capacity graph in figure E.9 from the appendix.

- **Effect of price cap and slope on *Adequacy*** The mean supply ratio seems to increase with an increase in the capacity market price cap, refer 9.2. Although theoretically, the price cap should not have an effect on the amount of investment, too low a price cap (in this case, at the CONE value) seems to limit investment when the demand curve is vertical. This suggests simply that the capacity market does not provide sufficient signal for capacity addition at such low price caps, leading to a higher probability of shortages in the long run as is seen in scenario 1 and 4 in figure 9.3. Interestingly, the price cap seems to have a greater effect on the LOLE than the slope. However, at low values of price cap, the LOLE seems to be highly sensitive to the slope, i.e., in scenarios 1, 4 and 7, when the price cap = CONE, the LOLE is reduced and the adequacy improves when the slope of the demand curve reduces to a value corresponding to demand curve margins of (0.05, 0.05). This effect is easily explained - the flatter the demand curve, the greater the capacity market price, and consequently revenue, beyond the exact demand target. At high price caps, this might inefficiently lead to unnecessarily high investment, as is observed in sceario 6 and 9 where the mean supply ratio reaches 1.21! At lower price caps, however, this same effect is positive as it reinforces whatever little investment the price cap can incentivise.

- Finally, the slope of the demand curve seems to be correlated with the volatility of prices in the energy market; i.e., the more vertical a demand curve, the greater the volatility in energy prices.

Table 9.2: Sensitivity Analysis - Data Table

	Scenario-1	Scenario-2	Scenario-3
5[0]*SupplyRatio	1.16	1.17	1.21
	Scenario-4	Scenario-5	Scenario-6
	1.16	1.18	1.21
	Scenario-7	Scenario-8	Scenario-9
	1.18	1.18	1.21
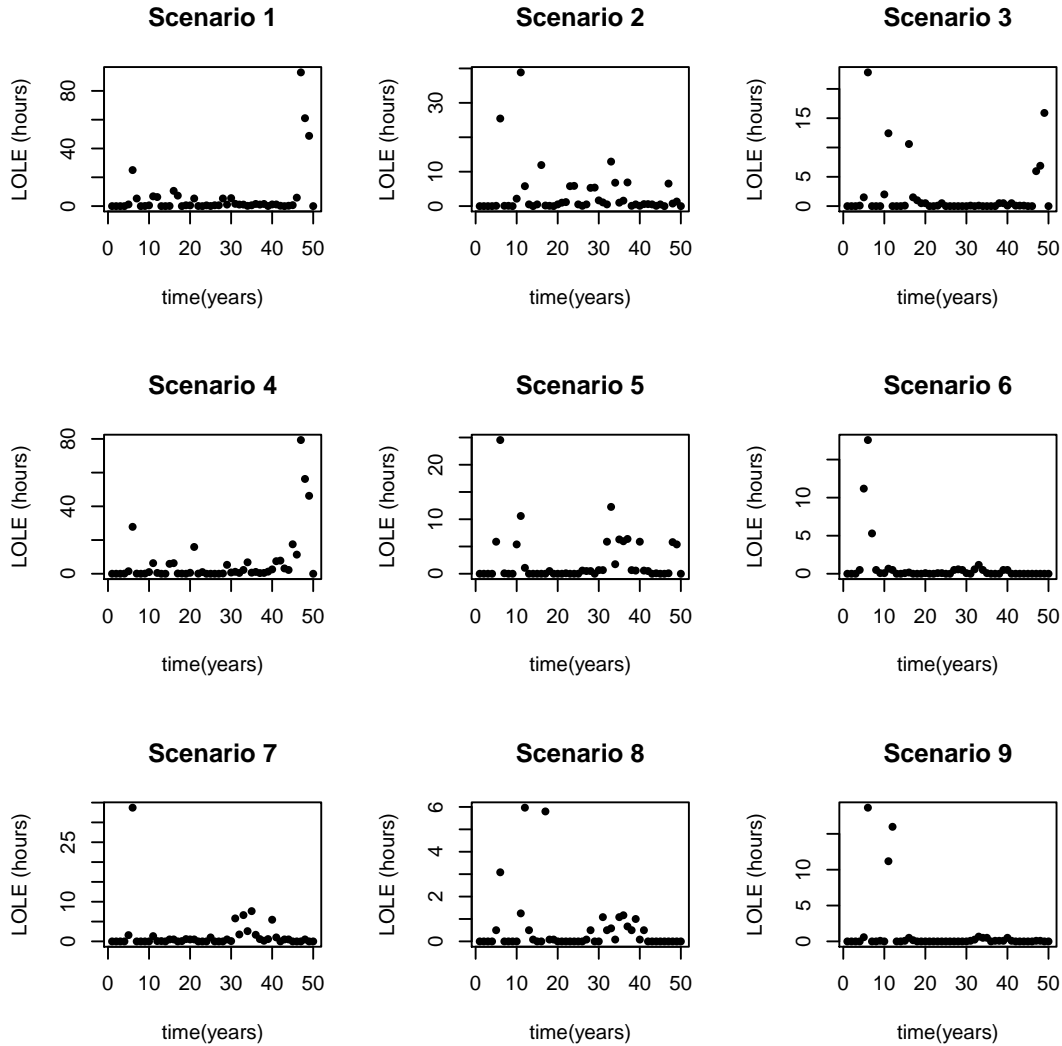
Figure 9.3: Average Loss of Load Expectation

9.2.2 Consumer Welfare

Observation

The mean consumer expenditure, is on an average 9% higher in scenarios 1, 2 3 and 4 as compared to the rest, see table **??**. Interestingly, the price cap seems to have a lesser effect on consumer expenditure, as compared to the slope. Higher price caps do not necessarily cause consumers to spend more.

Interpretation

One possible interpretation is that the this effect is due to the fact that vertical demand curves yield very staggered signals for investment, causing the market in general to be volatile. This is

seen in the higher standard deviations of *Average Electricity Prices*, *Capacity Market Clearing Prices*, and *Aggregate Producer Cash* among other indicators. This volatility may be causing prices on an average to be higher. This is definitely reflected in the high average capacity clearing prices observed in figure fig:S˙CapacityPrice1 for the same scenarios, and the data table in appendix E.

Table 9.3: Consumer Expenditure Data

	Scenario-1	Scenario-2	Scenario-3
ConsumerExpenditure-Mean (Eur)	1.93E+11	1.99E+11	1.97E+11
	Scenario-4	Scenario-5	Scenario-6
ConsumerExpenditure-Mean (Eur)	1.93E+11	1.77E+11	1.78E+11
	Scenario-7	Scenario-8	Scenario-9
ConsumerExpenditure-Mean (Eur)	1.71E+11	1.74E+11	1.76E+11

9.2.3 Producer Welfare

In the current investment algorithm employed in EMLab, there is a hard constraint of 30% downpayment for any new investment. Therefore the indicator *Producer Cash* has a direct influence on the investment, while *Aggregate Profit* is simply an indicator of overall performance. Refer to table E.3 in the appendix E for the data.

Observations

- The price cap seems to have a direct influence on the mean Producer Cash. The greater the price cap, the higher the producer cash under the observations presented.

- However, the slope has a greater influence on the volatility of producer cash: the more vertical the demand curve, the higher the volatility in revenue and therefore, higher the risk faced by the producer while making investment decisions.

- Aggregate producer profit is negative for scenarios 1,2,3 and 4. It is the minumum for scenario 7, and maximum for scenario 5.

Interpretation

- A high price cap in general allows the market prices to reflect commodity shortages better, therefore one could argue that a higher price cap leads the market closer to ideal conditions. This then would suggest that the reliability margin may indeed be too high. A highly plausible explanation for this high supply ratio is a quirk of the model in the investment algorithm, due to which energy producers do not take into account whether their planned plant could be outside the merit order of the capacity market while making a decision to invest. This means that they simply expect revenues from the capacity market irrespective of whether there is insufficient supply or not. In cases with a low price cap, the earnings from the capacity market are never enough to let the supply ratio increase beyond a certain level. Due to this deficiency in the model, it may show a supply ratio that's higher than what the capacity market signals.

- As argued under consumer welfare, higher volatility in the capacity market increases overall market volatility.

- The high volatility and low price cap conditions of the 1, 2 ,3 and 4 scenarios result in insufficient revenue for the energy producers, leading to negative profits.

0.75
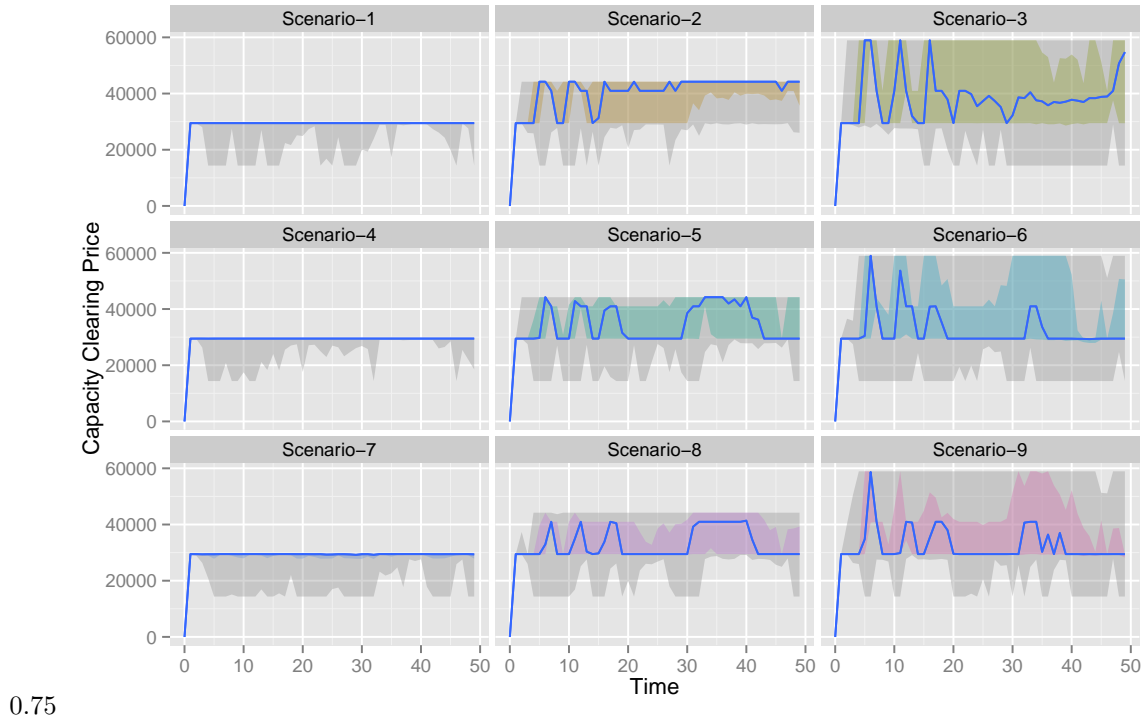
Figure 9.4: Capacity Market Clearing Price

9.2.4   Conclusion

This sensitivity analysis has brought about several interesting insights. I shall recapitulate the insights starting from the most intuitive/bland ones to the interesting, unexpected ones. Too low a price cap is insufficient incentive for investment, unless the slope of the demand curve is sufficiently flat. A low price cap with a relatively flat demand curve, say with upper and lower margins of (0.05, 0.05), is sufficient for attracting the required investment. A high price cap ensures the required adequacy, slightly overstated here due to a deficiency in the model explained in the previous subsection. Interestingly, the demand curve being relatively flat at high price caps does not cause a significantly higher supply ratio, or lead to a higher cash balance for producers. This is a slightly unintuitive result and is in contrast to current scientific knowledge. A vertical demand curve has an overall negative effect on the system - the producers make lesser profits, the consumers spend more, the investment into capacity is generally more volatile. Between a slope of (0.025, 0.025) and (0.05, 0.05) there does not seem to too much difference in the overall performance.

On the whole, scenario 7 seems to perform especially efficiently on all indicators. A low price cap with a relatively flat slope seems to encourage enough investment, while keeping volatility low, consumer expenditure low, and producer profits also just enough, and keeping producer cash sufficiently high.

9.3 Experiment 1

Hypothesis 1 A capacity market, as a standalone policy instrument, ensures generation adequacy in one, isolated country.

This experiment is perfomed on Country A, based on the Netherlands. It compares the Base Case Scenario, without the capacity market, against the Capacity Market scenario. The series of figures below 9.5, 9.6 and 9.7 show *Supply Ratio, Average Electricity Price* and *Capacity Market Clearing Price* respectively.

The capacity market scenario has a price cap of 2*cone, a reserve margin of 15.6% and the sloping demand curve has lower and upper margins of 0.025.
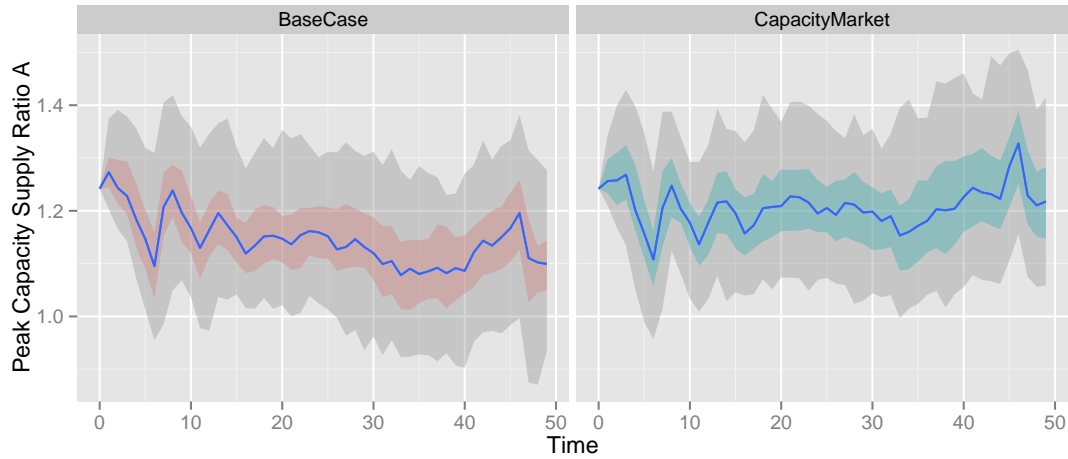
Figure 9.5: Exp 1: Supply Ratio
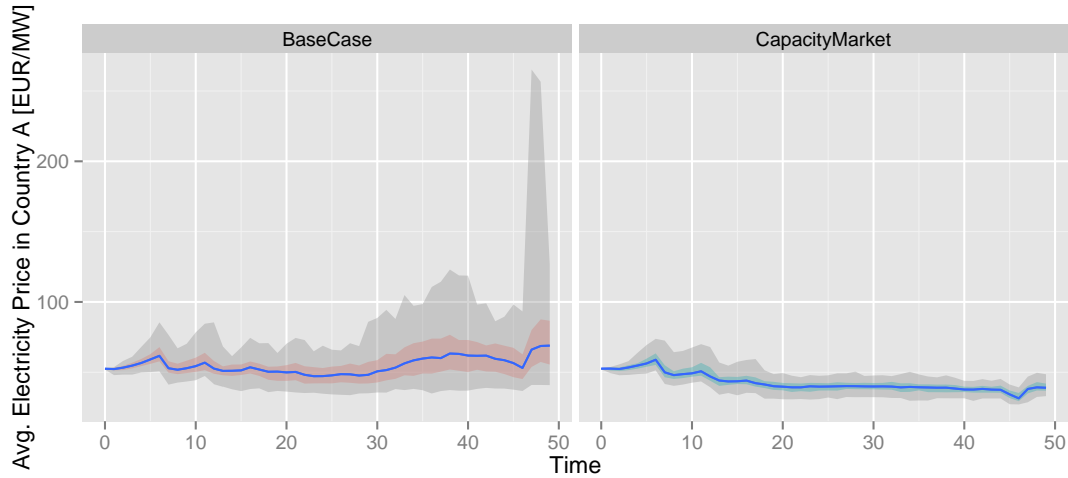
Figure 9.6: Exp 1: Average Electricity Price
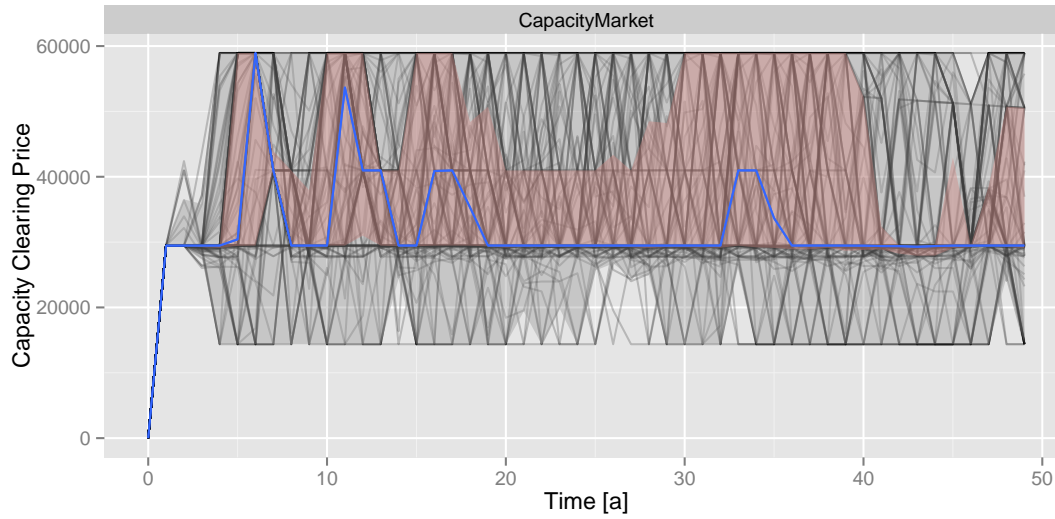
Figure 9.7: Exp 1: Capacity Market Clearing Price

Table 9.4: Experiment 1: Data Table 1

	BC (Mean)	BC (SD)	CM (Mean)	CM (SD)
AvgElectricityPrice (Eur/MWh)	57.73	3.91	43.09	1.50
SupplyRatio	1.15	0.03	1.21	0.02
ConsumerExpenditure (Eur/Year)	1.87E+11	1.94E+10	1.78E+11	1.52E+10
ProducerCashSum(Eur/year)	8.16E+09	7.82E+09	1.98E+10	5.38E+09
AggregateProducerProfit (Eur/year)	1.63E+08	6.12E+08	1.49E+08	1.81E+08

Table 9.5: Experiment 1: Data Table 2

	Base Case	Capacity Market
LOLEinHours	20.91	0.84
PercentageChangeProducerCash	64.10	49.14
	Mean	SD
CapacityPrice(Eur/MW-year)	36311.86	2847.24
CapacityVolume(MW)	27881.35	2384.82
ProbabilityOfShortageInCM		0.19

9.3.1 Observations

Performance of Electricity Market

- The mean supply ratio in the capacity market scenario is 5% higher than the base case scenario, see table 9.4.
- The average electricity price is 32% lower in a capacity market scenario, as compared to the base case, see table 9.4. From figure 9.6, it is evident that while the trends follwow similar

paths upto year 20, there is a marked decrease in median average electricity prices, and a continuous, slow declining trend, beyond year 20. Refer figure E.16 for a segment-wise price plot.

- The average LOLE decreased to less than an hour in the capacity market scenario from about 21 hours in the base case scenario, see table 9.5 and figure E.20

Consumer Welfare

Consumers on average pay lesser with the capacity market present. The change in consumer surplus, computed from data in table 9.5, in percentage is approximately a 5% increase.

Producer Welfare

- The Producer Cash is consistently higher, and has a lower spread in the case of a capacity market scenario. See figure E.13.
- On the other hand, the mean aggregate profit is lower in a capacity market scenario, see E.14

Performance of Capacity Market

From figure 9.7 we observe that the capacity prices vary, as expected, to reflect the supply ratio. In the initial years, during periods of a low supply ratio, the capacity price increases to reflect the shortage. Conversely, during periods of sufficient capacity, the capacity prices indicate a much lower value.

9.3.2 Interpretation

The electricity market performance sees a marked improvement in adequacy. The capacity market seems to perfom as expected, responding to shortages, and incentivizing investment. As is observed in figure E.20, there is a high LOLE value around tick 6, but this is during the initial stages of the model run, while the model is still trying to attain equiblibrium, and therefore can be ignored.

The investment is into Open Cycle Gas Turbine (OCGT) and (Closed Cycle Gas Turbine) CCGT technologies, as is evident from figure E.19, where we see a considerable increase in the share of OCGT and CCGT plants in the generation mix. This conforms with the theortical expectation, whereby the capacity market incentivizes investment into peaking units, such as gas turbines which have the lowest marginal cost in the capacity market. The declining trend of the average electricity prices beyond year 20 correspond with the increasing trend of the supply ratio, indicating lesser scarcity pricing in the energy market.

The improvement in producer welfare, both in terms of risk, and cash levels is also theoretically expected from a well designed capacity market. A pleasantly surprising outcome is that mean consumer expenditure is lesser with the capacity market. This can be attributed to the lack of scarcity rents in the energy market, while the expenditure into the capacity market seems to be lesser than the savings from the lack of scarcity rents.

One point to be noted is that the supply ratio in the stable region of the runs (beyond tick 20) increases to 1.21, far beyond the reserve margin of 1.15. This could be attributed to the way the expected revenue from the capacity market is accounted for in the investment algorithm of EMLab. Currently, any plant that is located in a country with a capacity market, expects to earn revenue from the capacity market based on past capacity clearing point prices, irrespective of the expected demand target, and expected supply at that future point. If supply is expected

to be greater than the demand, the plant should not expect to earn any revenue, and this does not happen with the current model. This is a major failing of the model, and is one possible reason for the over investment.

9.3.3   Conclusion

Experiment 1 demonstrates the working of the simplest version of a capacity market. The results fit in well with what is expected of the capacity market in theory. This experiment therefore serves well to validate the model. One interesting insight is that the consumers pay lesser on average despite spending on the capacity market. This means that the reduction in scarcity prices in the energy market more than compensates for the expenditure in the capacity market. This is an interesting insight mainly since there is no empirical evidence that consumers pay lesser with a capacity market, and expert opinions are divided on the issue. One aspect that is ignored in the model is the transaction costs.

Producers too have healthier cash balances and earn a lesser profit on average. This indicates an increase in economic efficiency in the system.

9.4   Experiment 2

Hypothesis 2   A capacity market, as a policy instrument in combination with targeted investment in renewable energy, ensures generation adequacy in one, isolated country.

This experiment employs country A again, to analyse the performace of the capacity market in the presence of target renewable energy generation.
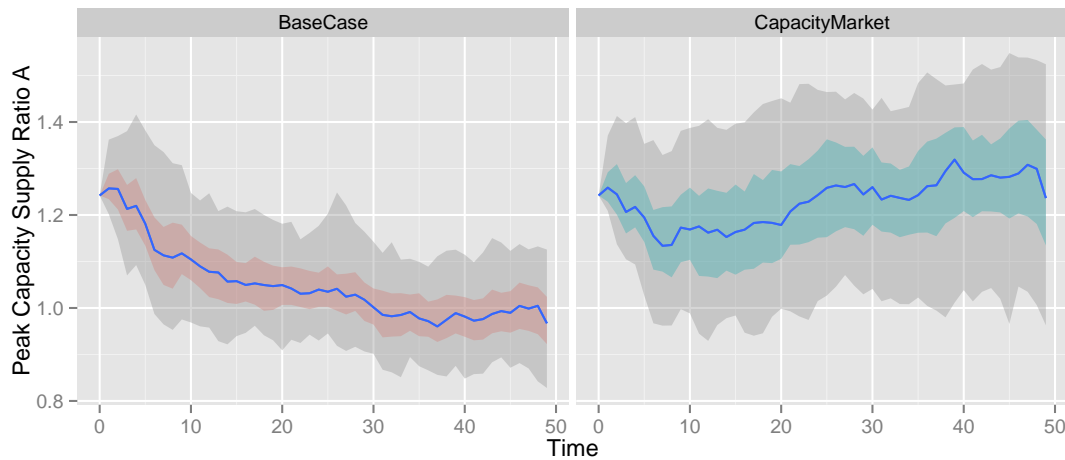
Figure 9.8: Exp 2: Supply Ratio
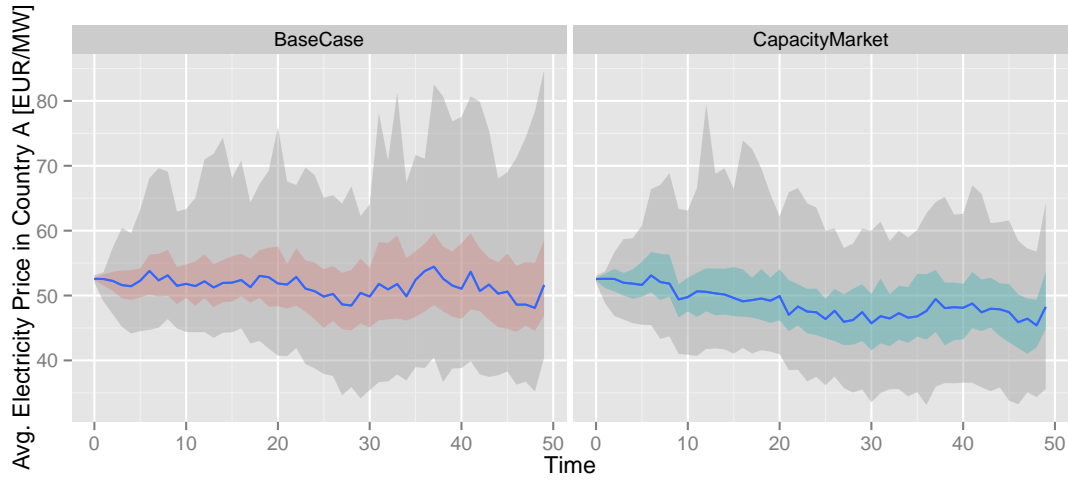
Figure 9.9: Exp 2: Average Electricity Price
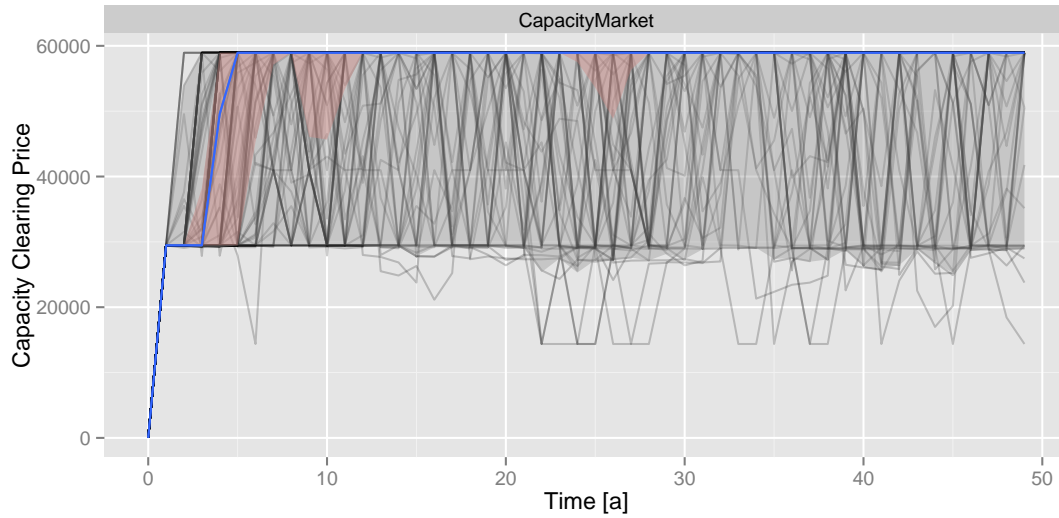
Figure 9.10: Exp 2: Capacity Market Clearing Price

Table 9.6: Experiment 2: Data Table 2

	BC (Mean)	BC (SD)	CM (Mean)	CM (SD)
AvgElectricityPrice (Eur/MWh)	5.24E+01	3.17E+00	4.93E+01	3.10E+00
SupplyRatio	1.06E+00	2.65E-02	1.23E+00	4.26E-02
ConsumerExpenditure (Eur/year)	1.80E+11	1.84E+10	1.99E+11	2.02E+10
ProducerCashSum (Eur/year)	-2.43E+10	6.99E+09	-6.90E+09	8.44E+09
AggregateProducerProfit (Eur/year)	-3.12E+07	2.14E+08	7.62E+08	1.89E+08

Table 9.7: Experiment 2: Data Table 2

	Base Case	Capacity Market
LOLEinHours	27.75166667	2.360333333
PercentageChangeProducerCash	-550.9598229	-295.8357198
	Mean	SD
CapacityPrice(Eur/MW-year)	51443.08111	2183.691731
CapacityVolume(MW)	24908.22288	2652.583406
ProbabilityOfShortageInCM		0.730333333

9.4.1 Observations

Performance of Electricity Market

- The supply ratio in the base case begins with sufficient over a capacity, but quickly falls to around 1, see figure 9.8.

- The capacity market (CM) scenario, on the other hand shows a quick progression to a supply ratio of roughly 1.25 towards the latter half of the simulation.

- Average electricity prices in the CM scenario see a declining trend, and is 6% lower than average electricity prices in the base case scenario.

- The generation portfolio, in figure E.29 sees a substantial increase in OCGT as compared to the base case. The CCGT levels remain similar.

Consumer Welfare

The mean consumer expenditure has increased from 180 trillion in the base case to 199 trillion in the CM scenario.

Producer Welfare

Mean Producer Cash shows a negative value for both scenarios, although the CM scenario shows a less negative value. Interestingly, the SD of Producer Cash in the CM scenario is higher than the Base Case. A look at figure E.23 tells us that producer cash is more volatile in the initial 20 ticks, but reduces beyond 30 ticks, as compared to the base case.

Performance of Capacity Market

The capacity market seems to be under stress for the most part. Median capacity clearing price coincides with the price cap 70% of the time. This is also indicated in the P*robability of Shortage in CM* indicator, in table 9.7

9.4.2 Interpretation

In a market with a high share of intermittent generation from renewable energy, the intermittency of the renewable energy generators, combined with their extremely low marginal costs results in a situation where the conventional plants get a lesser share of the load duration curve. That is, the conventional generators, having higher variable costs, now face a higher risk of insufficient return on investment, making such plants less attractive. When the share of conventional power plants reduces in the generation mix, the capacity of the overall generation mix

to provide power at peak demand reduces, which is exactly what is reflected in the base case supply ratio graph in figure 9.8. The capacity market supply ratio graph shows an extremely 'healthy' curve, partly I suspect, due to the modelling error in accounting for expected revenues from the capacity market in the investment algorithm. It is no surprise that the average electricity prices decline in a market where there is more than sufficient supply of capacity. The producer cash is negative as it includes cash balances of the target renewable energy investors. The higher consumer expenditure must be attributed to the consistently high capacity prices in the capacity market.

Model Error The shortage in the capacity market, as indicated by the prices is surprising considering the high supply ratio. In principle, the capacity prices should mirror the supply ratio - when the reserve margin increases beyond the target level, the capacity prices are expected to decline. In this experiment, the supply ratio seems to have little effect on the capacity price. Investigation revealed yet another error in the model that causes this over supply, and unresponsive capacity market - in the current version of the model, the *Target Renewable Energy Investors* are not allowed to participate in the capacity market. Considering their huge share in the generation portfolio, this omission results in substantial shortage in the capacity market, which then is reflected in the consistently high capacity prices, which further incentivizes more generation capacity. Unfortunately, there was not sufficient time to do a full re-run on the HPC and demonstrate a correct version of the results. However, a single run of the corrected version was performed, and the results are briefly presented in E.6. The corrected version shows, as opposed to the results presented here, that the capacity prices promtly reflect shortages in the supply and do not incentivize over capacity beyond the administrative reserve margin.

Implications of the Error The error has major implications on the results. Apart from the fact that the supply ratio is highly over-stated, I believe it also explains the higher costs that are incurred by the consumers as compared to the base case. I suspect that consumer expenditure would decrease in experiment 2 as well in the capacity market scenario, as in experiment 1, due to the reduction in scarcity prices. The indicator *Producer Cash* is also overstated due to scarcity rents from the capacity market, and the producers earn more profit than they should. However, one result that remains valid despite the error is the change in the average generation portfolio towards a more reliable mix with OCGT and CCGT, and the necessity for that change.

9.4.3   Conclusion

The capacity market does improve generation adequacy in experiment 2, it also induces the right *type* of generation technology in a scenario with a substantial share of renewable energy generation. The error does have a big effect on the results. All the same, the experiment suggests that the capacity market can induce the right mix of generation technology, which is necessary in a scenario with a substantial share of renewable energy generation. The differences between the base cases of experiment 1 and experiment 2 indicate that there is a higher porobaility of outages in the case with renewable energy - the LOLE increases from 21 hours to 28 hours with the introduction of renewable energy. This shows that, to attain the same level of reliability as in the base case, the reserve margin in a capacity market would have to be correspondingly higher in the capacity market with renewable energy target policy.

However, whether that level of reliability is worth the cost is a question left to posterity (or further research).

9.5 Experiment 3

Hypothesis 3 A capacity market, as a policy instrument in country B, ensures generation adequacy in country B while it is interconnected with country A.

This experiment employs two country scenarios. The Base Case scenario with Country B modelled after Germany, and Country A modelled after the Netherlands. The electicity markets of the two counties are interconnected with an interconnector capacity of 4441 MW [41] and there is market coupling between the two countries.

Tha capacity market scenario implements the capacity market policy in Country A, while Country B remains an energy-only market.

The main results of the simulation are presented in the following figures and tables.
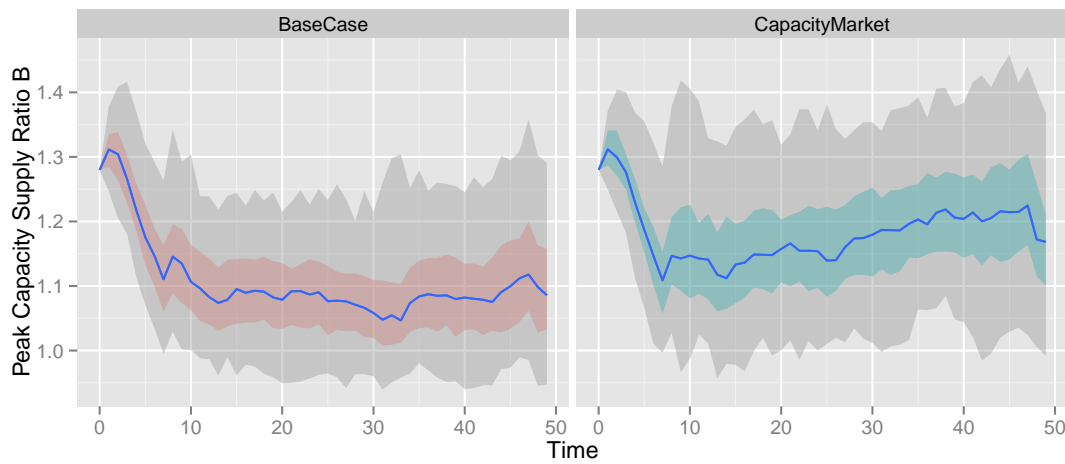
Figure 9.11: Exp 3: Supply Ratio, Country B
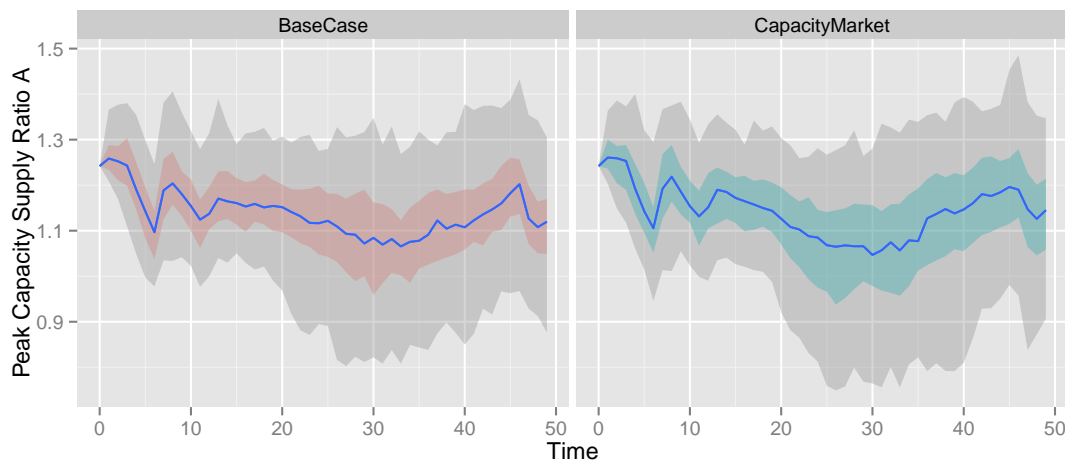
Figure 9.12: Exp 3: Supply Ratio, Country A
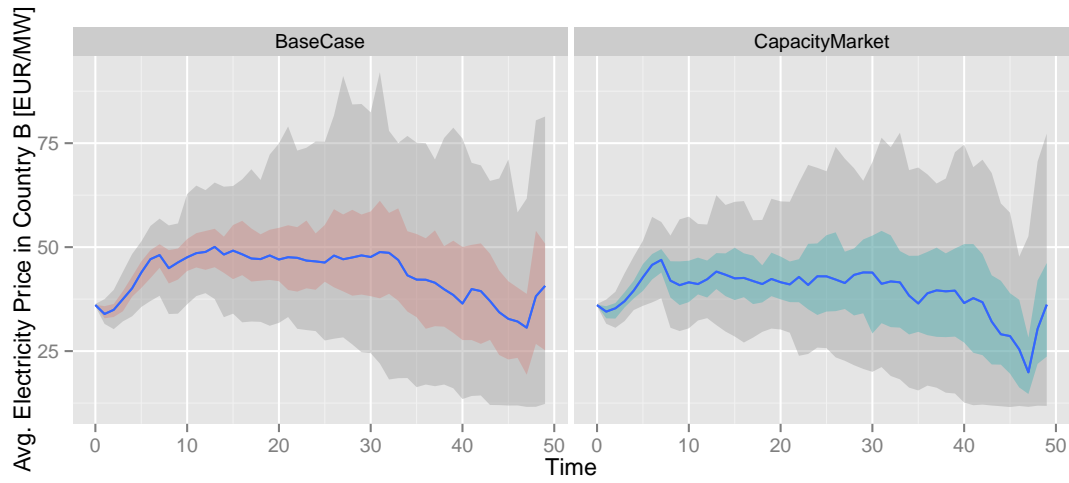
Figure 9.13: Exp 3: Average Electricity Price, Country B
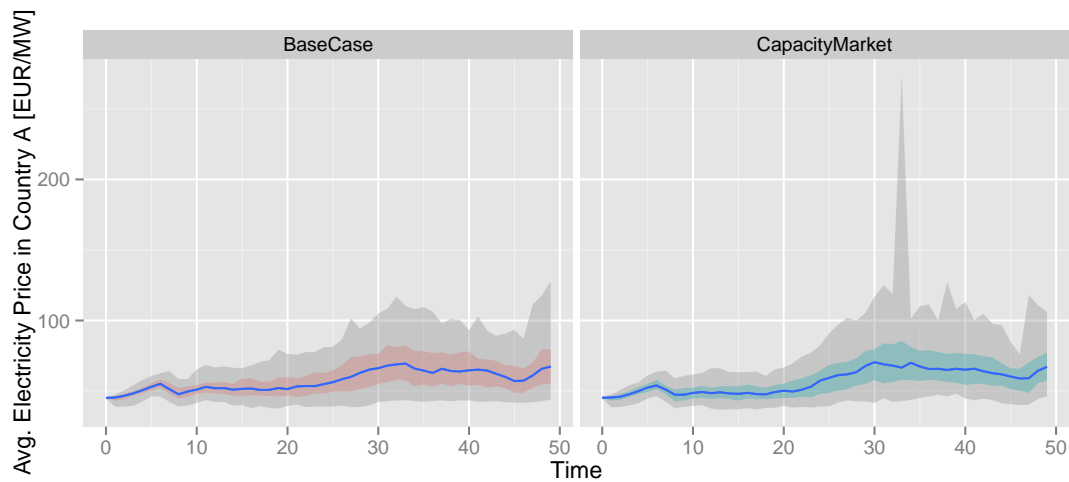
Figure 9.14: Exp 3: Average Electricity Price, Country A
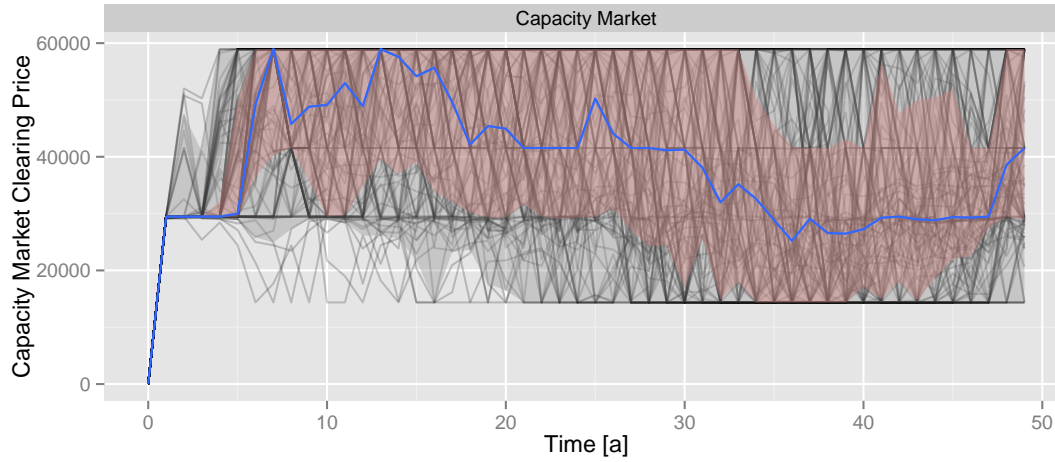
Figure 9.15: Exp 3: Capacity Market Clearing Price

Table 9.8: Exp 3: Data Table 1

	BC (Mean)	BC(SD)	CM(Mean)	CM(SD)
AvgElectricityPriceCountryA	5.88E+01	3.65E+00	5.89E+01	3.90E+00
AvgElectricityPriceCountryB	4.43E+01	3.51E+00	4.01E+01	2.77E+00
SupplyRatioCountryA	1.14E+00	4.37E-02	1.14E+00	4.70E-02
SupplyRatioCountryB	1.11E+00	2.83E-02	1.19E+00	2.43E-02
ConsumerExpenditureCountryA	1.54E+11	1.80E+10	1.46E+11	1.68E+10
ConsumerExpenditureCountryB	6.50E+11	5.98E+10	6.94E+11	6.08E+10
ProducerCashSumMean	1.21E+11	3.43E+10	1.71E+11	3.27E+10
AggregateProducerProfit	5.20E+09	1.86E+09	7.01E+09	1.65E+09

Table 9.9: Exp 3: Data Table 2

	BaseCase	CapacityMarket
LOLEinHoursCountryA	7.28	10.26
LOLEinHoursCountryB	3.90	0.56
	Mean	SD
CapacityPrice	38814.35	3284.67
CapacityVolume	100823.34	9345.10
ShortageCM		0.30

9.5.1 Observations

Performance of Electricity Market

- The average supply ratio in Country B shows an increase in the capacity market scenario from a mean value of 1.11 to 1.19 , while it remains very similar (between base case and capacity market scenarios) in Country A.

- Average electricity prices in Country B see a decrease, while those in Country A remain the same and see a marginal increase in volatility. A look at individial segment prices in figure E.55, shows that the capacity market in Country B does have a positive effect on prices in country A in segments 1 and 2. Segments 3 and 4 of country A however show an *increase* in the probability of shortages in the presence of a capacity market in the neighbouring country.
- LOLE in Country B decreases from 3.9 hours to 0.56 hours, LOLE in Country A increases from 7.28 hours in the BC scenario to 10.26 hours in the CM scenario.

Consumer Welfare

Consumer expenditure for country A increases by 6.7% when a capacity market is introduced, and it decreases by 5.4% for Country B in the capacity market scenario.

Producer Welfare

Producer's financial well being has increased in both countries. There is an increase in overall Producer Cash as well as the Aggregate Producer Profit.

Performance of Capacity Market

The capacity market, similar to experiment 1, responds well to changes in the supply ratio, with prices reflecting scarcity or over-capacity, as appropriate.

9.5.2 Interpretation

The capacity market in Country B creates both a positive and negative effect on Country A. The positive effect is that there is a lesser probability of outages in Country A in segment 1, due to additional, cheaper supply of peak segment resources from country B. But this effect is only limited to segment one. Segment 3 and 4 actually show an increase in the probability of outages. Unfortunately for country A, it sees an overall increase in the LOLE by 3 hours per year! This effect can be explained as follows.

Increased LOLE in Country A The market splitting algorithm employed to resolve the congestion between the two countries, results in exporting of energy from the low price zone to the high price zone to the extent that the interconnector allows it. The demand for Country B is increased by the extent of the interconnector capacity, and the demand in Country A decreased by the same level. This then causes a subsequent increase of average electricity prices in Country B and reduction of average electricity prices in Country A, bringing the prices closer together. The lowering in demand of Country A is reflected in the investment decisions, resulting in a lower investment in plants that supply energy to the peak segments (such as CCGT), causing increased shortages in segments 2 and 3. Segment 1 can boast of lesser shortages as the interconnector capacity (4441MW) allows for sufficient energy transfer to help partially reduce the shortages in that segment (appr. 8000MW) only.

Increased consumer expenditure in country B Due to country B being a consistently low price region compared to country A, there is constant export of energy from Country B to country A. This increase in demand causes more probability of shortages in the capacity market (30%) than in an isolated single country scenario, which has a probability of 19% shortage in

the capacity market. The higher expenditure of consumers therefore can be attributed to the overall increase in capacity prices in the country B.

9.5.3 Conclusion

The major insight from this experiment is that in a two country scenario, there are leakage effects if one of those countries has an energy only market, while the other has a capacity market. This means that consumers in the country with the energy only market free ride on the reliability that the consumers in Country B pay for, in segment 1 - the peak segment. However there are other interesting effects that ultimately overshadow the benefits of having a neighbouring country with a capacity market. The reduced demand in Country A results in a slightly lower investment, leading to an overall increase in the LOLE for Country A. Despite this effect, there is a decrease in overall consumer expenditure for country A as compared to the base case, which can be attributed to lower average elctricity prices in country A, relative to the base case, due to increased trade (import) into country A.

Crossborder effects seem to make the capacity market more expensive than the base case in a two country scenario. The neighbouring country sees an increase in LOLE, but decrease in consumer expenditure.

9.6 Experiment 4

Hypothesis 4 A capacity market in country B, as a policy instrument in combination with targeted investment in renewable energy, ensures generation adequacy in country B while it is interconnected with country A.

This experiment employs two country scenarios. The Base Case scenario with Country B modelled after Germany, and Country A modelled after the Netherlands. The electicity markets of the two counties are interconnected with an interconnector capacity of 4441 MW and there is market coupling between the two countries.

Tha capacity market scenario implements the capacity market policy in Country A, while Country B remains an energy-only market. Both countries implement renewable energy targets according to their individual National Renewable Energy Action Plans.

The main results of the simulation are presented in the following figures and tables.
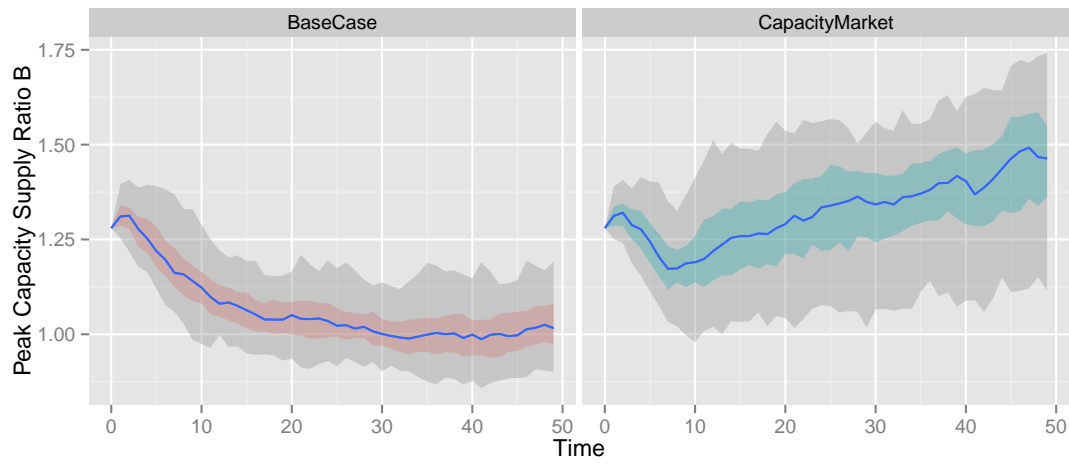
Figure 9.16: Exp 4: Supply Ratio, Country B
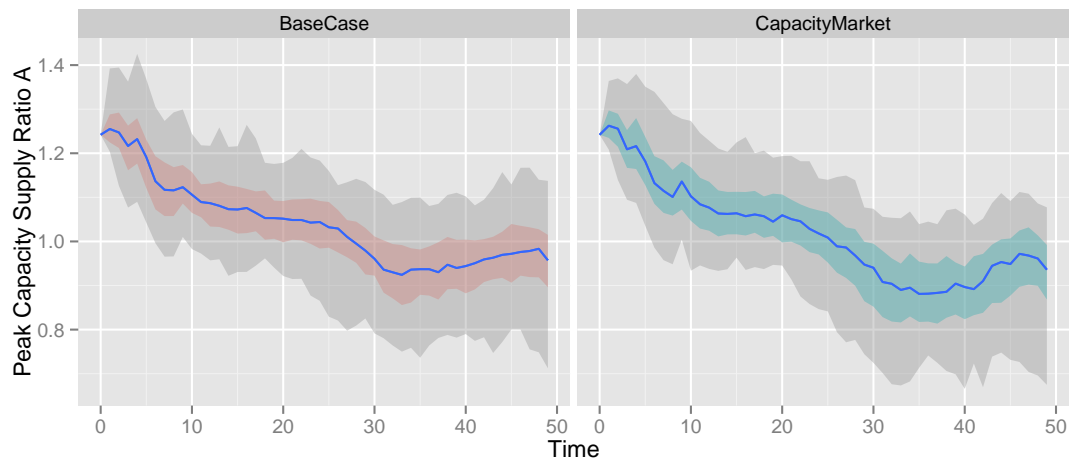
Figure 9.17: Exp 4: Supply Ratio, Country A
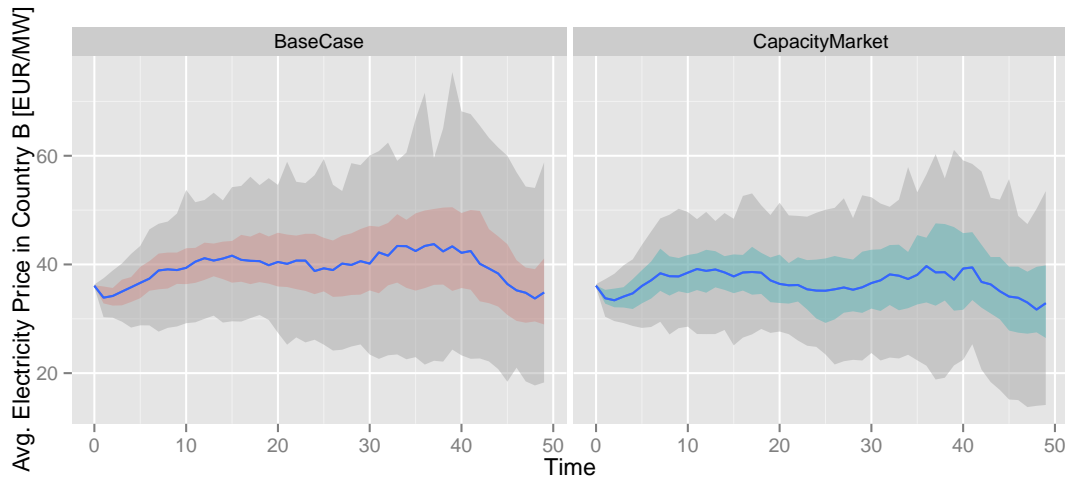
Figure 9.18: Exp 4: Average Electricity Price, Country B
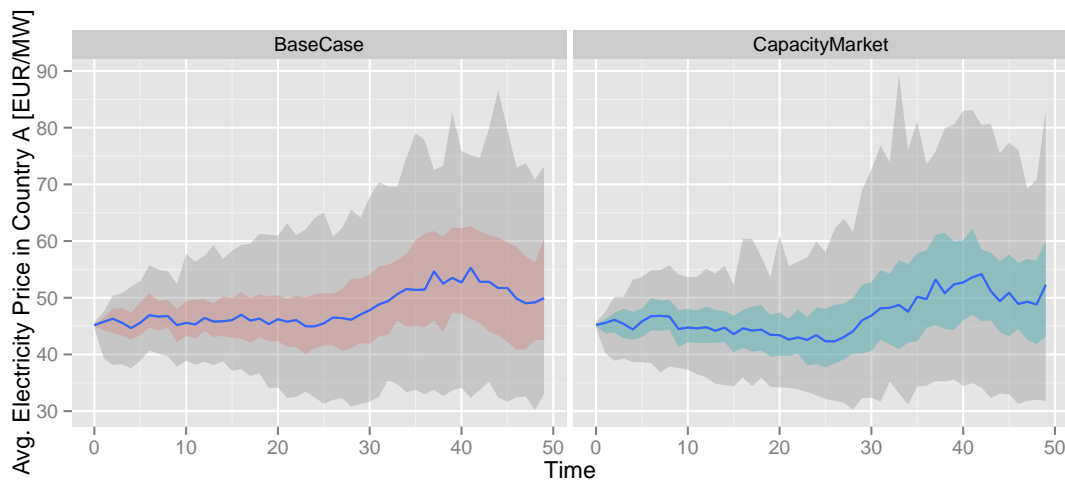
Figure 9.19: Exp 4: Average Electricity Price, Country A

9.6.1   Observations

Performance of Electricity Market

The performance the electricity market of country B is quite similar to that of country A in experiment 2.

- Country B shows a marked increase in Supply Ratio from 1.07 to 1.32, while that of country A remains very close.
- Country B shows a decrease in average electricity prices. Although Country A does see fewer outages in terms of prices in the peak segments under the capacity market scenario,

Table 9.10: Experiment 4: Data Table 1

	BC(Mean)	BC(SD)	CM(Mean)	CM(SD)
AvgElectricityPriceCountryA	4.87E+01	3.74E+00	4.78E+01	3.86E+00
AvgElectricityPriceCountryB	3.98E+01	2.60E+00	3.69E+01	2.40E+00
SupplyRatioCountryA	1.04E+00	3.34E-02	1.02E+00	3.38E-02
SupplyRatioCountryB	1.07E+00	2.47E-02	1.32E+00	4.45E-02
ConsumerExpenditureCountryA	1.31E+11	1.64E+10	1.24E+11	1.49E+10
ConsumerExpenditureCountryB	5.60E+11	5.12E+10	6.33E+11	6.22E+10
ProducerCashSumMean	-2.64E+11	2.67E+10	-2.10E+11	3.08E+10
AggregateProducerProfit	1.50E+09	7.13E+08	4.13E+09	9.67E+08

Table 9.11: Experiment 4: Data Table 2

	Base Case	Capacity Market
LOLEinHoursCountryA	17.55	17.81
LOLEinHoursCountryB	13.05	0.11
	Mean	SD
CapacityPrice	45739.02	2499.395
CapacityVolume	95026.88	9543.073
ShortageCM		0.53

the reduction does not seem to be large enough to have a significant effect on the average prices across all segments.

- In terms of the generation mix, Country A does not see much of a difference between the base case and capacity market scenarios. Country B, on the other hand, has a significant increase in OCGT in its share.

Consumer Welfare

Like in experiment 3, consumer expenditure is higher in the capacity market scenario for country B as compared to the base case, and is lower in Country B as compared to the base case.

Producer Welfare

Overall producer welfare has increased. An analysis of individual producer welfares would have been very valuable, however time and computaional constraints did not permit it. However, the aggregate producer profit has decreased in both countries.

Performance of Capacity Market

The performance of the capacity market again, shows an extremely high likelihood of shortages (in the capacity market) even when the supply ratio very healthy. The capacity market prices seem to react to the over capacity, only when the supply ratio hits a value close to 1.5. This again reflects the error mentioned in Experiment 2.

9.6.2 Interpretation

The interpretation of the effects observed here again, is very close to those of experiments 2 and 3. The error due to the renewable enery target investors not being able to participate in the

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capacity market causes undue shortage in the capacity market, increases capacity prices to a level greater than required, incentivizing more generation than necessary. This error skews the results, but in a direction that enhances cross border effects observed in experiment 3.

For the neighbouring country, country A, although there is a reduction in probability of shortages in the first two segments, there is an increase in the probability of shortages in segment 3 and 4, due to the same reasons observed in experiment 3. This is corroborated by the fact that the supply ratio is much lower during those years than in the base case. Even so, the overall effect of the average electricity price decrease due to increased import from country B causes the consumer expenditure to reduce in country A. There is an increase in consumer expenditure in country A, as observed in experiment 3, again due to the presence of a capacity market with higher prices.

9.6.3 Conclusion

Although the results are skewed due to the aforementioned error in the model, the insights observed from this experiment corroborate the conclusions of experiment 3, in terms of the over active capacity market. Unfortunately no new insights can be reliably gleamed from this experiment, due to the error. However, it is still possible to make an educated guess, so to say, as regards the effect of renewables. The LOLE in the base case has increased between experiment 3 and experiment 4 from 7 and 3 hours in experiment 3 to 17 and 13 hours in experiment 4! The increased LOLE would imply that the relaibility margin in the capacity market needs to be increased to arrive at the same level of reliability as in experiment 3. The slope of the demand curve could also be decreased, to reduce volatility.

9.7 Validation of Results

Traditionally, model validation is the process of checking whether the model corresponds to reality. For an electricity market model designed to simulate effects over several decades, checking whether the model corresponds to reality is infeasible. However, it is possible to demonstrate that the insights from the model are useful and convincing, and therefore that the model is fit for its purpose. A large part of the validation has been performed in the interpretation of the results itself, which largely conform with what was expected. At the same time, there are some new insights into aspects that are still widely debated over in scientific literature.

The validation may be divided into validation based on literature review, and comparison with empirical studies and key model outcomes which conform with expected behaviour in theory. Validation by key model outcomes shall not be dealt with here, as it has been sufficiently covered in the former sections on interpretation.

Empirical Evidence Spees et al., in [33], provide an empirical analysis of how well capacity markets have performed in their first decade of operation. They find that capacity markets have fulfilled their primary design objective of maintaining desired planning reserve margins. This success though has been observed in the context of capacity surplus, and must not be overstated, they observe. They also conclude that market efficiency has substantially improved by allowing all types of capacity to compete on an equal footing. There are cases still of substantial inefficiencies in capacity market design caused by price floors and other administrative pricing mechanisms that prevent capacity prices from reflecting market fundamentals such as in ISO NE. This corroborates well with the general finding of this research. They state however, that capacity price uncertainty and price volatility remain major concerns, and have been expressed as so by a variety of stakeholders. This research sheds light on that front.

Josesph Bowring performs a study on the evolution of the PJM capacity market [45]. Comparing the annual net revenues from the capacity market at PJM with those obtained from the model is a good indication of the representational value of the model. The PJM net revenues from the capacity market show values of $47,469, $54,670 and $44,282 in dollars per MW-year for a peaking unit for the years 2009, 2010, 2011. Converting them to Euros [1], and averaging them, we obtain a value of 36,605 Eur/MW-year. The mean capacity annual revenue from the model in experiment 1 and experiment 3 are 36311.86 and 38814.35 Eur per MWyear respectively. A direct comparison is not a fair one, as PJM implements locational pricing, and limits exports. Nevertheless, these values roughly correspond with each other, and this does serve to increase the researcher's confidence in the model.

As regards cross border effects, one particularly interesting work employs system dynamics to model cross border effects between a country with an energy only market and another with a capacity mechanism, for a period of 30 years [13]. They find very similar results. The short term effects on the country with the energy only market show some degree of free rider behaviour. However, like this model shows, there are substantial negative externalities to the country without the capacity mechanism. Therefore they recommend that the capacicity mechanisms are harmonized between neighbouring countries.

9.8 Conclusion

This chapter presents the results of the sensitivity analyses and the four experiments. At the outset, it must be mentioned that there are two quirks in the model that distort results. The first one, is that the investors, while computing expected revenue to determine investments, do not account for the possibility that their plant may be out of the merit order in the capacity market. This causes investment decisions to be made based on overstated revenues for some energy producers, leading to a greater investment than is desired or administratively required. This flaw however, does not distort the result by too much, as the capacity market signals the overcapacity and reduces incentive for investment over a certain period. The second flaw is the more serious one; it makes the results of the experiments with target investment in renewable energy highly suspect. It is caused by the fact that renewable energy target investors in the model are not allowed to invest in the capacity market, causing undue shortages in the capacity market, further resulting in a much higher investment than desired. Despite these flaws in the results, the model does provide some very useful insights, the salient ones of which are recapitulated below.

The Sensitivity Analysis shows that a vertical demand curve is detrimental to the entire system. Staggered revenues from the capacity market hugely increase the volatility in the system, reducing consumer benefit, leading even to negative profits for producers. The price cap should be high enough to signal investment. Interestingly, a combination of a low price cap (the minimum price cap must be CONE) and a relatively flat slope in the demand curve works very efficiently. Although it may not be too effective if there is a sudden need for a huge amount of capacity. At high price caps, the performance indicators are less affected by the slope.

Experiment 1 shows that a capacity market works well to achieve its desired objective, validates the model and interestingly shows that in the long run consumers do spend lesser with the capacity market present in an isolated market. This is an interesting insight mainly since there is no empirical evidence that consumers pay lesser with a capacity market, and expert opinions are divided on the issue. Producers too have healthier cash balances and earn a lesser profit on average. This indicates an increase in economic efficiency in the system. One aspect

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[1]Conversion rate of 1 dollar equals 0.75 euro

that is ignored in the model is the transaction costs. Implementing a capacity market, of a good design, is not a trivial aspect, and entails significant administrative effort. Such transaction costs have not been incorporated in the model and is out of the scope of this research, but is an important consideration for policy.

Experiment 3 shows interesting cross border effects between a country having an energy only market (Country A) and a neighbouring, interconnected country with a capacity market (Country B). The model suggests that without export constraints country B's surplus capacity, the capacity market dampens investment in country A, leading to marginally higher LOLE in country A. The capacity market ensures the desired reserve margin in Country B, however at a higher cost to the consumer in country B, but at a lower cost to the consumer in country A.

Experiments 2 and 4 suggest that reserve margins may need to be increased if the same level of reliability were to be maintained in a scenario with substantial renewable energy generation.

On a deeper level it is worthwhile to ask whether this level of reliability is indeed necessary. Some consumers may be satisfied with a lower level of reliabilty while others are willing to pay more for the reliability, and this difference cannot be reconciled in the market unless demand response technologies imrove enough to let prices have an effect on the demand.

Chapter 10

Conclusion

The main research question in this work was: *Is a capacity market a good policy instrument to ensure generation adequacy in a western European country, given renewable energy investment targets and cross border effects?*

This research concludes that, a capacity market, when designed well is a likely a good policy instrument to ensure generation adequacy in a western European country. This is not to say that the capacity market is the the best instrument to accomplish the same goal, but it is a very good market-based approach for inducing the *right type* and the *right amount* of investment in generation capacity, when designed appropriately. The answers and intricacies to the sub-research questions are addressed in the following section.

10.1 Insights from the Model

On Capacity Market Design   The performance of the electricity market is highly sensitive to the price cap and slope of the capacity market. To ensure the desired level of adequacy in the system, the price cap in the capacity market must be sufficiently high (1.5 times CONE) to incentivize and induce investment. If a low price cap (say, CONE) is implemented, there could still be sufficient investment signal if the demand curve is relatively flat[1]. A vertical demand curve is detrimental to the electricity market in general, because Staggered revenues from the capacity market hugely increase the volatility in the system, reducing consumer benefit, leading even to negative profits (on an average) for producers.

On Cross Border Effects of Capacity Market   The capacity market ensures the desired reserve margin in the country where it has been implemented. However it does so at a higher cost to the consumers of that country. The reasoning behind this is explained in the previous chapter. Interestingly, the model suggests that, without export constraints, between the two countries involved, the surplus capacity in the country with the capacity market dampens investment in the neighbouring country with an energy only market. This even leads to a marginally higher chance of outages in the neighbouring country.

On Performance of the Capacity Market with Substantial Renewable Energy   Experiments 2 and 4 suggest that reserve margins may need to be increased if the same level of reliability were to be maintained in a scenario with substantial renewable energy generation.

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[1]Slope of a demand curve where the upper and lower margins from the demand target are 0.05, 0.05

10.2   Relevance to the Real World

This section addresses issues that the model does not incorporate or has simplified.

Locational Pricing   Locational pricing is the pricing of capacity based on its location. It is implemented in both PJM and NYISO markets by way of publishing a different demand curve for each of the locations that their regions are divided into. A review of the evolution of PJM by [45] expresses how valuable an addition locational pricing was to the design of the capacity market, it ensured investment in desired locations. Implementing locational pricing in EMlab would enable a richer analysis of its benefits.

Export Curtailment   Given the two country cross border effects observed in the results of experiment three, implementing export curtailment would seem to be a solution to reduced investment in the neighbouring energy only market, and to some extent, free rider behaviour by the neighbouring country. However, it is worthwhile questioning whether export curtailment would be an efficient solution in the economically highly interconnected European Union. If a capacity market were to be implemeted it would make more sense to implement it overall across both the countries, rather than in one individual country, to optimize reliabilty.

Improvement in demand response   The theory behind capacity markets rests strongly on the fact that demand response capabilities of the electricity sector are currently not sufficient to induce a change in demand based on price. Some ISO's, for instance, the ERCOT ISO may not inclined to introduce capacity markets, partly because it is expected that demand response advancements that have been made are sufficient to reduce the need for capacity mechanisms in general. In the lng run this may be a very important point for consideration. If demand respsone capabilites reach a level where demand reacts to price, there may not be a need for capacity mechanisms any longer. On a different note it is interesting to observe that capacity markets in the USA have attracted a huge amount of supply in terms of demand response, thus deferring the need for new investment by about ten years [33]. This has been the been the biggest surprise of the capacity market performance so far.

Transaction Costs   One of the drawbacks of neoclassical economics is that transaction costs are largely ignored, but in reality they could lead to hugely different outcomes. In the world of capacity markets, setting up a well designed market in itself is complex and cost intensive compared to some non-market based alternatives to ensuring security of supply. The complexity of organizing a well designed capacity market results in some ISOs making highly simplifying decisions. An example is the case of MISO, which implements a vertical demand curve even while a sloping curve would be the more optimal choice.

10.3   Insights for Science

The model finds new insights for effects of the capacity market on consumer welfare, the effect of volatility on the electricity market and for cross border effects between two neighbouring interconnected countries.

One major source of debate and conflict of opinion is on the shapes and parameters defining the demand curve. PJM, ISO NE and the NYISO all have either been involved in settlement processes, or regulatory proceedings, or organize periodical demand curve review processes.

My research contributes significantly on that front, with a thorough sensitivity analysis of the electricity sector to those design parameters.

Empirical studies on the performance of capacity markets over the last ten years show that the greatest concern expressed by a wide variety of stakeholders is that capacity prices tend to be volatile and difficult to predict [33]. The results of the simulation show that volatile capacity market prices cause staggered investment signals, increasing the volatility in *electricity* prices, and volatility in the revenues for the sector. Theoretically, a capacity market has no direct intervention in the electricity market, so this model has improved understanding the relationship between the two better.

The cross border effects shown in the model also provide significant insight into possible outcomes. It corroborates with the results from a model that used system dynamics to perform similar experiments [13].

With respect to renewable energy, there is work that does a qualitative analysis on the long term development of capacity mechanisms in combination with renewable energy policies, see [46]. They discuss how risk may be allocated differently given different combinations of policies, and raise important questions about who makes the decisions regarding prioritising a policy.

10.4 Insights for Policy Makers

- A capacity market is a very good market-based instrument for ensuring generation adequacy.
- The design of a capacity market is important. A sufficiently high price cap is necessary. A sloping demand curve adds several advantages.
- Volatility has very negative effects - regulatory uncertainty due to changing parameters of the capacity mechanism adds to such uncertainty.
- A capacity market in one country and an energy only market in another causes inefficiencies. An integrated capacity market across multiple countries is recommended. If that is too lofty a goal, it is recommended that export curtailing of energy is implemented in the country with a capacity market.
- In a scenario with substantial renewable energy, policy makers must consider increasing the reserve margin

10.5 Directions for Future Research

The following points could be interesting for further research.

- This research has not examined boundary conditions for equilibria in capacity markets. That aspect could be interesting for further research.
- Implementing option based capacity market mechanisms (such as reliability options) to quantitatively study the differences, or implemetation of forward capacity markets to observe if shortages are indeed indicated earlier, and whether that makes a considerable difference in market outcomes.
- Implementation of a system wide capacity market, i.e., across multiple countries with limited interconnector capacitiies.
- Effects of different capacity mechanisms in different neighbouring countries.

Chapter 11

Reflection

For any project, the reflection is a very valuable aspect if not the most, as it the one step that allows us and future generations to learn from mistakes, and not repeat them, hopefully. Looking back, although there are so many features of the project that still could do with improvements, or done in greater detail, or even simply more efficiently, this project has nevertheless been a personally highly fulfilling experience. The consistently steep learning curve that it entailed made it very challenging, the collaborative parts made it fun, some of the results pleased me, but the end product made it all worth the while! Here I shall reflect on the usefulness of the model, the methodology employed and finally on the process I undertook during the project.

Usefulness of Model   The capacity market model as part of EMLab is an extremely useful tool. This is more because of the modular nature of EMLab than the capacity market model alone. This is simply because of the range of analysis that EMLab allows, and the granularity of the results it produces, which allows the modeller to understand exactly *why* a certain effect or type of result arises.

Having said that, the capacity market model by itself is a valuable contribution. Although in this project time constraints resulted in the verification not being done thoroughly enough for some of the scenarios, causing small omissions which skewed part of the results, the valid results that were obtained provide new and useful insight into capacity market theory, especially with respect to capacity market design and cross border effects. The model itself commands confidence, and is quite versatile. The permutations and combinations of different scenarios that could be created are considerable. Further analysis could be performed with different export capacities, with a different capacity mechanism employed in a neighbouring country, in a scenario with three countries etc. Each of these could yied valuable scientific and policy insights.

However, it must be mentioned that the usefulness of the model is limited by its complexity and resource consuming nature. One must not underestimate (the way I did), the amount of effort that each experiment takes to create and analyze sufficiently, correctly, and simply the huge amount of resources required for one such single analysis.

Reflection on Methodology   The primary methodology used for this research was agent based modelling. A reflection therefore on the use of agent based modelling for the project is due.

Randomness and chaotic nature of a model is inherent to agent based modelling. This places the onus on creating the 'right' scenario space during experiment design.'Scenarios must be approached cautiously as they may reflect wishful thinking on the system', caution the authors

of [15]. Choosing the scenario space must be done with extreme caution and care, as that is the one part which either limits or enables further analyses and sets boundaries for your work.

My work, from this standpoint, employs a scenario space which essentially tests the 'robustness' of the model against exogenously determined factors such as demand growth, price growth trends. In hindsight, this scenario space in itself was so large that it limited the scenarios I could have explored with respect to capacity market design. The huge scenario space that every run demanded cost me that much valuable time and resources to execute and analyse each of those runs. In hindsight, I probably could have tested the resilience of the capacity market better with fixed fuel and demand trends. In that case, the results from every experiment would have been shorter, faster, yet, less robust. It was a choice that was implicitly made while choosing my scenarios, but a choice that had significant implications on the results.

Validation is another big area of concern while using agent based modelling, as models need not be based on established theories like in the physical sciences. Validating the structure of the model was not a big concern in the case of my work as it is based on established theory and current practices, however validation of the results is a different matter. It is important then to realize that the crux of using agent based modelling, lies in being able to interpret the emergent behaviour that arises from the model. A good interpretation itself validates the results to a large extent. Sufficient time must be allocated for this, given the wealth of data that EMLab produces for every run.

All in all, ABM is unique in its characteristic of emergent behaviour, and is a useful addition to traditionally applied economic models such as computation general equilibrium. ABM is also useful for explaining behaviour we see, but do not understand. While we start with a simple capacity market, which we do understand, complex scenarios involving several policies interacting - the RES, the EU ETS along with the capacity market can be understood quite easily with agent based modelling.

Reflection on Process   This project has been a consistently steep learning curve for me. The initial parts of the literature review, delving into the theory behind capacity markets was rather staightforward. But each step beyond that part involved learning a new tool, a new software, every few weeks and being able to successfully apply each of those tools. Coding has been a very big part of the project. The list begins with relatively easy Java, stubborn Gremlin, initially frustrating LaTex, learning to use Agent Spring and Github, implementing Linux, and finally using a statistical software like R to be able to analyze all the data. It is impossible to get hold of all this together, and still graduate in six months or less, without working as part of a team.

Practical issues aside, some parts of the process were easier than others. Coding into EMLab was relatively simple as compared to the phases that followed. However, the simplicity was limited to roles that were completely new and relatively independent of existing code. A particularly difficult and unexpectedly time consuming phase was trying to code the 'Update Revenue in Investment Role'. The initial plan was to simulate a capacity market in the investment algorithm so that the energy producers could estimate the expected revenue from the capacity market. This method would have been very accurate, and avoided one existing drawback in the model, where the investors do not take into account the possibility that the plant might be out of the merit order in the future capacity market. Variable scope issues specific to EMlab, extremely complex looping structures and other such issues made the task unreasonable. It took me an entire month to finally give up on the idea and use a very, very simple substitution, where they simply extrapolated expected revenues based on past prices.

Given the highly integrated nature of the capacity market model into various different roles and parts of EMLab, a lot of which was out of the scope of my work, verifying the model became a difficult task. The verification phase took impossibly long, almost two months. While

the individual roles seem to work well by themselves, the code in entirety did not give me reasonable results. J-Unit tests were only helpful upto a certain point, beyond which running the whole code to verify it was a tedious necessity. Another reason for the difficulty in the verification phase has to do with the fact that the error may lie outside the scope of your work on the EMLab model, in which case your reasoning powers with respect to the working of the full model is insufficient to enable narrowing down possible reasons for the error. Even after the final results were obtained, it turns out that there were errors in a few of the scenarios. This was partly also due to the shortage of time, and the amount of effort it takes to set up each scenario, which again I hugely underestimated intitally.

The scope of the project was rather big. Reducing the number of scenarios to analyze would help reduce the load. Especially if the scenarios span very different parts of EMLab, and are not limited to simple parameter variations only within your part of the code.

Conclusion Looking back, this project has been the classic case of biting off more than I can chew. I am definitely disappointed with the fact that the results presented in some of the scenarios consist of errors. However, executing EMLab once more with a small variation in the model should solve that issue. All in all, I am happy with the deliverable that is a working model of a capacity market in EMLab and the contribution of some interesting insights into capacity market design.

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Appendix A

Centralised Capacity Market

A.1 Calculation of Minimum Capacity Requirement

This section provides an overview of the installed capacity planning process. The following steps are taken. These steps are based on the NYISO ICAP Manual 2013 [31].

- The New York State Reliability Council, NYSRC, sets the Installed Reserve Margin, and the NYISO determines the NYCA Minimum Installed Capacity Margin Requirements as per the standards set by the NYSRC.

- The NYISO converts the Minimum Installed Capacity Requirement (ICAP), based on the rating of a unit into a Minimum Unforced Capacity Requirement (UCAP), which is the installed capacity that is not on average excperiencing a forced outage, thus:

$$UCAP = ICAP * (1 - EFORd) \qquad (A.1)$$

  The Equivalent Demand Forced Outage Rate (EFORd) is a measure of the probability of a generating unit not being available due to forced outages or forced derating when there is demand on the unit to operate.

- The minimum UCAP requirement, including locational minimum UCAPs are calculated and assigned for each LSE on a transmission district basis.

- Standards, qualifications and requirements are established in collaboration with market participants, which will apply to all participants - LSEs, suppliers, transmission owners etc involved.

- Finally the NYISO determines the amount of unforced capacity that each installed capacity supplier is authorised to supply based on the aforementioned standards and qualifications.

Appendix B

Software Implementation

B.1 Relevant Existing EMLab Code

B.1.1 Notations

Variable	Unit/Content	Description
t	a	Time step, in years
i		Generator agent index
c	{A,B}	Country index
$S_{s,c}$	(D_s, l_s)	Segment is a tuple of demand and length
$D_{s,c}$	MW	Demand in Segment S
l_s	h	Length of Segment S (identical for both countries)
s	$\{1,\dots,20\}$	Segment index
$LDC_{c,t}$	$\{S_{c,1},\dots,S_{c,20}\}$	Load Duration Curve with 20 segments
$b_{c,s,p,t}$	$(p_{c,s,p,t}, V_{c,s,p,t})$	Bid into country c, segment s, year t for power plant p, excluding CO2 cost
$p_{c,s,p,t}$	$\text{€}/MWh_{el}$	Bidded price
$V_{c,s,p,t}$	MW	Bidded capacity
$\rho_{c,s,t}$	$\text{€}/MWh_{el}$	Segment clearing price
p	$\{1,\dots,P\}$	Power plant index
e_p	t_{CO_2}/MWh	Emission intensity of power plant p
p_{CO_2}	$\text{€}/ton$	CO_2 Market Price
$F_{CO_2,c,t}$	$\text{€}/ton$	CO_2 Price Floor in country C
$T_{CO_2,c,t}$	$\text{€}/ton$	Complimentary CO_2 tax in country C
$c_{p,fuel}$	$\text{€}/MWh_{el}$	Variable fuel costs of power plant p
p_f	$\text{€}/MWh_{th}$	Price of fuel f
$s_{p,f}$	MWh_{th}	Amount of fuel in fuel mix
$\eta_{p,c}$		Efficiency of power plant p
$a_{s,p}$		Segment dependent availability of power plant p
m_g		Price mark-up of generator g
$\hat{r}_{p,s,t}$	h	Expected running hours of power plan p, in segment s, in year t
I_p	€	Investment cost of power plant p
$k_{e,i}$		Interest rate for equity
$k_{d,i}$		Interest rate for debt

Figure B.1: Notations, existing EMLab Generation Code

Appendix C

Formalisation: Pseudocode

C.1 Capacity Market Model: Roles

This algorithm consists of five main sections, which are exectued in the following manner.

ForecastDemandRole, **acted by** ***Regulator***
1: get peak load $PL_{c,t}$ across $LDC_{c,t}$ from repository
2: get demand growth trend $\hat{f}_t$ for current year t
3: $PD_{c,t} \leftarrow$ PL˙c,t$\times \hat{f}_t$
4: $D_t \leftarrow PD_{c,t} \times (1+rm)$
5: set Regulator's demandTarget as D_t

SubmitCapacityBidRole, **acted by** ***Energy Producer***
1: **for all** energyProducers **do**
2:     **for all** powerPlants of energyProducer **do**
3:         CapacityMarket $market \leftarrow$ findCapacityMarketForZone   ▷ assign to 'market' by querying for the corresponding capacity market, based on location of powerPlant from repository
4:         ElectricitySpotMarket $eMarket \leftarrow$ findElectricitySpotMarketForZone   ▷ Assign to 'eMarket' by querying for the corresponding capacity market from repository
5:         $initializeCDP.price_{p,t} \leftarrow 0$
6:         $F_{O\&M,p} \leftarrow$ fixedoperatingcostOfPowerPlantTechnolgy   ▷ Retrieves fixed operating and maintenance cost of a certain technology from repository
7:         $marginalCost \leftarrow$ calculateMarginalCostForPowerPlant
8:         **for all** segmentLoads of $eMarket$ **do**
9:             $PPDP \leftarrow$ Retreive plant's power plant dispatch plan from previous tick
10:            Initialize $ESMRevenue \leftarrow 0$
11:            **if** $PPDP.status \geq 2$ **then** ▷ PPDP.status as 2 signifies a partially accepted bid, while PPDP.status 3 signifies a fully accepted bid
12:                double $capacityAccepted \leftarrow PPDP.getAcceptedAmount$
13:                double $expectedElectricityPrice \leftarrow \rho_{c,s,t-1}$ ▷ Previous tick's segment clearing point price
14:                $ESMRevenue$
15:                **if** $marginalCost \leq expectedElectricityPrice$ **then**

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16:         $hours \leftarrow r_{p,s,t}$ ▷ running hours of segment given segmentLoad

17:         $ESMRevenue+ = (expectedElectricityPrice - marginalCost) \times hours \times$ $capacityOfPlant$

18:         **end if**

19:         **end if**

20:     **end for**

21:     double $ESMRevenuePerMW \leftarrow ESMRevenue/plant.getNominalCapacity$

22:     $marCostCapacity \leftarrow F_{O\&M,p} - ESMRevenuePerMW$

23:     **if** $marCostCapacity \leq 0$ **then** $bidPrice \leftarrow 0$

24:     **else**$bidPrice \leftarrow marCostCapacity$

25:     **end if**

26:     $bidCapacity \leftarrow CapacityOfPowerPlant$

27:     create new $CDP_{p,t}$

28:     set $CDP_{p,t}.price \leftarrow bidPrice$

29:     set $CDP_{p,t}.capacity \leftarrow bidcapacity$

30:   **end for**

31: **end for**

ClearCapacityMarketRole, acted by _Regulator_

1: boolean $isTheMarketCleared \leftarrow false$

2: double $acceptedPrice \leftarrow 0d$

3: double $sumOfBidsAcc \leftarrow 0d$

4: Retrieve all CDPs for current time t and sort them by order of increasing price

5: **for all** CDP of $SortedListOfCDP$ **do**

6:     **if** $CDP_{p,t}.price \leq priceCap$ **then**

7:         double $demand \leftarrow CDP_{p,t}.amount$

8:         double $price \leftarrow CDP_{p,t}.price$

9:

$$demand \leftarrow D_t \times (1 - rLM) + \mid (CP_c - price) \times (rUM + rLM)_t / CP_c \qquad \text{(C.1)}$$

10:         **if** $isTheMarketCleared \equiv false$ **then**

12:            **if** $demand - (sumOfBidsAcc + CDP_{p,t}.amount) \geq 0$ **then**

13:                $acceptedPrice \leftarrow CDP_{p,t}.price$

14:                $CDP_{p,t}.setStatus(ACCEPTED)$

15:                $CDP_{p,t}.setAcceptedAmount \leftarrow CDP_{p,t}.amount$

16:                $sumOfBidsAcc \leftarrow sumOfBidsAcc + CDP_{p,t}.amount$

17:            **else if** $demand - (sumOfBidsAcc + CDP_{p,t}.amount) \leq 0$ **then**

18:                $acceptedPrice \leftarrow CDP_{p,t}.price$

19:                $CDP_{p,t}.setStatus(partlyACCEPTED)$

20:                $CDP_{p,t}.setAcceptedAmount \leftarrow sumOfBidsAcc - demand$

21:                $sumOfBidsAcc \leftarrow sumOfBidsAcc + CDP_{p,t}.AcceptedAmount$

22:            **else**

23:                $CDP_{p,t}.setStatus(FAILED)$

24:                $CDP_{p,t}.setAcceptedAmount(0)$

25:            **end if**

26:         **end if**

27:     **end if**

28:     Create new CapacityClearingPoint, $clearingPoint$

29:     **if** $isTheMarketCleared \equiv true$ **then**

30:         $clearingPoint.setPrice(acceptedPrice)$

31:        $clearingPoint.setVolume(sumOfBidsAcc)$

32:        $clearingPoint.setTime(getCurrentTick)$

33:        $clearingPoint.setMarket(market)$

34:        $clearingPoint.persist$ ▷ The persist function saves the object, clearing point in the repository

35:    **else**

36:        $acceptedPrice = CP_c \times (D_t \times (1 - rLM) - sumOfBidsAcc)/((rUM + rLM) \times D_t)$

37:        $clearingPoint.setVolume(sumOfBidsAcc)$

38:        $clearingPoint.setTime(getCurrentTick)$

39:        $clearingPoint.setMarket(market)$

40:        $clearingPoint.persist$

41:

PaymentFromConsumerToProducerForCapacityRole, acted by CapacityMarket

1: CapacityClearingPoint $clearingPoint$ ← findOneCapacityClearingPointForTime(getCurrentTick) ▷ Retrieves capacity clearing point for this tick from repository

2: ElectricitySpotMarket ESM ← findElectricityMarketForZone(capacityMarket.getZone)

3: **for all** CDP : findAllCDPOfThisTick **do**

4:    $debitor \leftarrow$ esm ▷ The ElectricitySpotMarket agent, unique for every zone, serves as a good representation of the consumer for that zone.

5:    $creditor \leftarrow$ CDP.getBidder

6:    $cash \leftarrow CDP.getAcceptedAmount * clearingPoint.getPrice$

7:    $cashFlowID \leftarrow CashFlow.SIMPLE_C APACITY_M ARKET$ '

8:    $createCashFlow(debitor, creditor, cash, cashFlowID, getCurrentTick, CDP.plant$ ▷ The general CashFlow function from nonTransactionalCreateRepository is employed

9: **end for**=0

Parts of the following role, that are not relevant to the capacity market, have been described only broadly, while the updating of revenue from the capacity market is described in detail.

InvestInPowerGenerationTechnologies, acted by EnergyProducer

1: Obtain market information about investors market for futureTimePoint ▷ expectedFuelPrices, expectedCO2Price, expectedDemand

2: **for all** $technology$: findAllTechnologiesFromRepository **do**

3:    Create a new power plant, $plant$ of type $technology$

4:    Check whether physical and financial constraints are met

5:    Determine expected revenues and costs, $operatingProfit$

6:    Regulator $regulator$ ← findRegulatorGivenZoneOfEnergyProducer ▷ the regulator of energy producer's zone is retrieved from the repository

7:    double $capacityRevenue \leftarrow 0$ ▷ Initialize capacity revenue to 0

8:    **if** $regulator \neq null$ **then** ▷ Checks if there is a regulator for the relevant zone. The presence of a regulator indicates the presence of a capacity market in the zone.

9:        $x \leftarrow energyProducer.noOfYearsOfLookingBackForForecasting$

10:       $sumCapRev \leftarrow 0$

11:       **for** $time \leftarrow getCurrentTick; time \geq (getCurrentTick - x); time- = 1$ **do** State double $capRevTemp \leftarrow clearingPointPrice$ ▷ Find one capacity clearing point price for current tick

12:           $sumCapRev+ = capRevTemp$

13:       **end for**

14:   $capacity \leftarrow plant.getExpectedAvailablePeakCapacity \triangleright$ Retrieve expected available capacity for peak segment at the future time point

15:   $capacityRevenue \leftarrow capacity \times sumCapRev \div (getCurrentTick - time)$

16: **end if**

17: $OperatingProfit+ = capacityRevenue$

18: Compute NPV

19: **end for**

20: Select power plants with highest NPV, ≥ 0

21: Create new power plant, start construction, pay downpayment

The following role integrates all the above methods into one single role that can be called from the main EMLab 'DecarbonisationModel' role.

 SimpleCapacityMarketMainRole, acted by CapacityMarket

1: Regulator $regulator \leftarrow$ CapacityMarket.getRegulator

2: $forecastDemandRole.act(regulator)$

3: **for all** $producer \leftarrow findAllEnergyProducers$ **do** $submitCapacityBidToMarketRole.act(producer)$

4: **end for'**

5: $clearCapacityMarketRole.act(Regulator)$

6: $paymentFromConsumerToProducerforCapacityRole.act(market)$

Appendix D

Verification: J Unit Test

The following is an example of the implementation of the J Unit test for the *forecastDemandRole*. It shows how the code constructs all the inputs necssary for the execution of only the *forecastDemandRole*. Such inputs include declaring a regulator, the reserve margin, the base loads for each segment, peak load, past duration over which the future demand is calculated, etc.

```
package emlab.gen.role.capacitymarket;

import static org.junit.Assert.assertTrue;

import java.util.HashSet;
import java.util.Set;

@RunWith(SpringJUnit4ClassRunner.class)
@ContextConfiguration({ "/emlab gen test context.xml" })
@Transactional
public class ForecastDemandRoleTest {
    Logger logger = Logger.getLogger(ForecastDemandRole.class);

    @Test
    public void checkForecastDemandFunctionality() {

        Zone zone = new Zone();
        zone.persist();
        Regulator regulator = new Regulator();
        regulator.setTargetPeriod(0);
        regulator.setReserveMargin(0.15);
        regulator.setNumberOfYearsLookingBackToForecastDemand(3);
        regulator.setZone(zone);
        regulator.persist();

        Segment S1 = new Segment();
        S1.setLengthInHours(20);
        S1.persist();
```

```
        Segment S2 = new Segment ();
        S2.setLengthInHours (30);
        S2.persist ();

        SegmentLoad SG1 = new SegmentLoad ();
        SG1.setSegment (S2);
        SG1.setBaseLoad (2500);
        SG1.persist ();

        SegmentLoad SG3 = new SegmentLoad ();
        SG3.setSegment (S1);
        SG3.setBaseLoad (3700);
        SG3.persist ();

        Set<SegmentLoad> segmentLoads1 = new HashSet<SegmentLoad >();
        segmentLoads1.add(SG1);
        segmentLoads1.add(SG3);


        TriangularTrend demandGrowthTrend = new TriangularTrend ();
        demandGrowthTrend.setMax (2);
        demandGrowthTrend.setMin (1);
        demandGrowthTrend.setStart (1);
        demandGrowthTrend.setTop (1);

        demandGrowthTrend.persist ();

        ElectricitySpotMarket market1 = new ElectricitySpotMarket ();
        market1.setName("Market1");
        market1.setLoadDurationCurve(segmentLoads1);
        market1.setDemandGrowthTrend(demandGrowthTrend);
        market1.setZone(zone);
        market1.persist ();

        fDemandRole.act(regulator);

        logger.warn("Target Demand for this tick: " + regulator.getDemandTarget());
        assertTrue(regulator.getDemandTarget() == 4255);

    }
}
```

Appendix E

Results

E.1   Sensitivity Analysis

Table E.1: Scenarios for Sensitivity Analysis

	Price Cap	Slope
Scenario 1	CONE	(0,0)
Scenario 2	1.5*CONE	(0,0)
Scenario 3	2*CONE	(0,0)
Scenario 4	CONE	(0.025, 0.025)
Scenario 5	1.5*CONE	(0.025, 0.025)
Scenario 6	2*CONE	(0.025, 0.025)
Scenario 7	CONE	(0.05, 0.05)
Scenario 8	1.5*CONE	(0.05, 0.05)
Scenario 9	2*CONE	(0.05, 0.05)

Table E.2: Sensitivity Analysis Data Dable

	Scenario-1	Scenario-2	Scenario-3
AvgElectricityPrice-Mean (Eur/MWh)	5.22E+01	5.02E+01	5.00E+01
AvgElectricityPrice-SD (Eur/MWh)	3.15E+00	3.34E+00	2.71E+00
SupplyRatio-Mean	1.16E+00	1.17E+00	1.21E+00
SupplyRatio-SD	3.16E-02	2.89E-02	3.10E-02
ConsumerExpenditure-Mean (Eur)	1.93E+11	1.99E+11	1.97E+11
AggregateProducerProfit-Mean(Eur)	-8.60E+07	-9.63E+07	-7.05E+07
ProducerCashSum-Mean (Eur)	1.23E+10	1.70E+10	1.67E+10
ProducerCashSum-SD (Eur)	6.24E+09	8.58E+09	6.66E+09
CapacityPrice-Mean (Eur/MW-year)	2.84E+04	3.76E+04	3.99E+04
CapacityPrice-SD (Eur/MW-year)	9.77E+02	2.28E+03	3.18E+03
CapacityVolume-Mean (MW)	2.50E+04	2.50E+04	2.74E+04
CapacityVolume-SD (MW)	2.74E+03	2.27E+03	2.10E+03
PercentageChangeInProdCash-Mean	3.70E+01	3.00E+00	1.41E+01
LOLEMean (hours)	6.08E+00	3.12E+00	1.69E+00
Probability CM-Shortage-Mean	8.06E-01	4.93E-01	3.16E-01
	Scenarioof -4	Scenario-5	Scenario-6
AvgElectricityPrice-Mean (Eur/MWh)	5.17E+01	4.34E+01	4.31E+01
AvgElectricityPrice-SD (Eur/MWh)	3.20E+00	1.73E+00	1.51E+00
SupplyRatio-Mean	1.16E+00	1.18E+00	1.21E+00
SupplyRatio-SD	3.18E-02	2.15E-02	2.39E-02
ConsumerExpenditure-Mean (Eur)	1.93E+11	1.77E+11	1.78E+11
AggregateProducerProfit-Mean(Eur)	-5.09E+07	1.65E+08	1.49E+08
ProducerCashSum-Mean (Eur)	1.21E+10	1.93E+10	1.98E+10
ProducerCashSum-SD (Eur)	5.96E+09	6.13E+09	5.38E+09
CapacityPrice-Mean (Eur/MW-year)	2.84E+04	3.45E+04	3.63E+04
CapacityPrice-SD (Eur/MW-year)	7.80E+02	1.82E+03	2.85E+03
CapacityVolume-Mean (MW)	2.51E+04	2.75E+04	2.79E+04
CapacityVolume-SD (MW)	2.56E+03	2.30E+03	2.38E+03
PercentageChangeInProdCash-Mean	3.47E+01	-2.36E+01	-2.41E+01
LOLEMean (hours)	6.44E+00	2.18E+00	8.38E-01
Probability CM-Shortage-Mean	7.46E-01	2.97E-01	1.98E-01
	Scenario-7	Scenario-8	Scenario-9
AvgElectricityPrice-Mean (Eur/MWh)	4.35E+01	4.34E+01	4.31E+01
AvgElectricityPrice-SD (Eur/MWh)	1.46E+00	1.60E+00	1.46E+00
SupplyRatio-Mean	1.18E+00	1.18E+00	1.21E+00
SupplyRatio-SD	2.53E-02	2.75E-02	2.13E-02
ConsumerExpenditure-Mean (Eur)	1.71E+11	1.74E+11	1.76E+11
AggregateProducerProfit-Mean(Eur)	8.14E+06	1.34E+08	1.34E+08
ProducerCashSum-Mean (Eur)	1.54E+10	1.85E+10	1.95E+10
ProducerCashSum-SD (Eur)	5.23E+09	5.45E+09	5.84E+09
CapacityPrice-Mean (Eur/MW-year)	2.78E+04	3.34E+04	3.60E+04
CapacityPrice-SD (Eur/MW-year)	1.23E+03	2.11E+03	2.22E+03
CapacityVolume-Mean (MW)	2.63E+04	2.70E+04	2.74E+04
CapacityVolume-SD (MW)	2.21E+03	2.26E+03	2.04E+03
PercentageChangeInProdCash-Mean	-2.39E+01	-2.55E+01	-2.52E+01
LOLEMean (hours)	1.53E+00	5.04E-01	1.00E+00
Probability CM-Shortage-Mean	3.81E-01	1.93E-01	1.22E-01
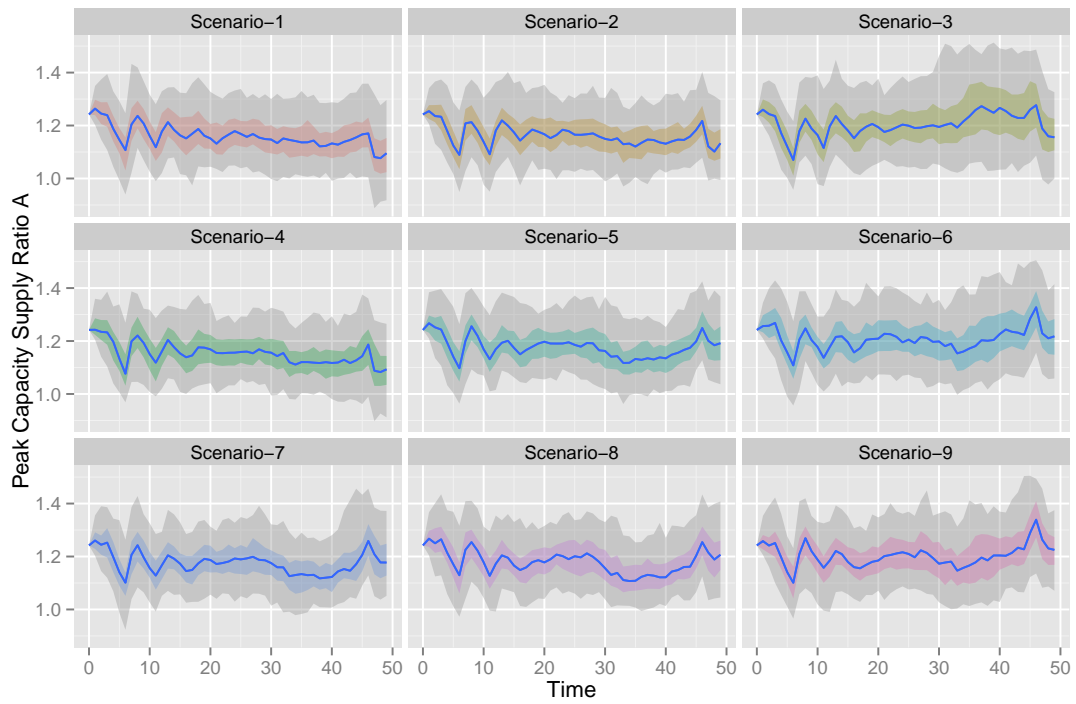
Figure E.1: Supply Ratio
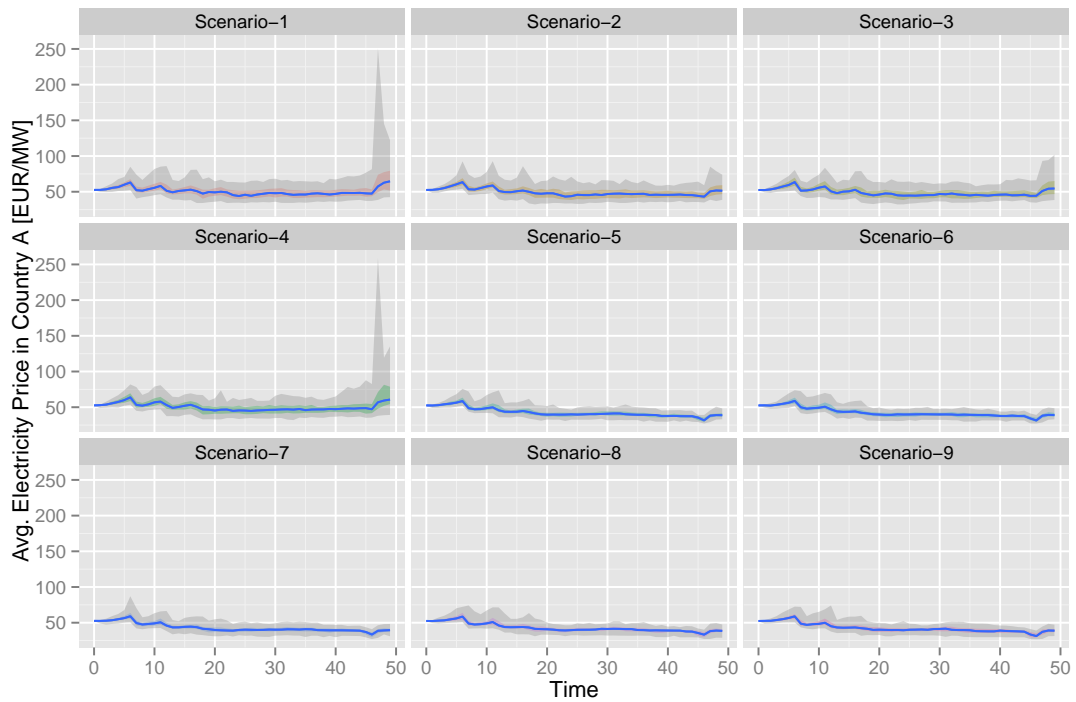
Figure E.2: Average Electricity Price
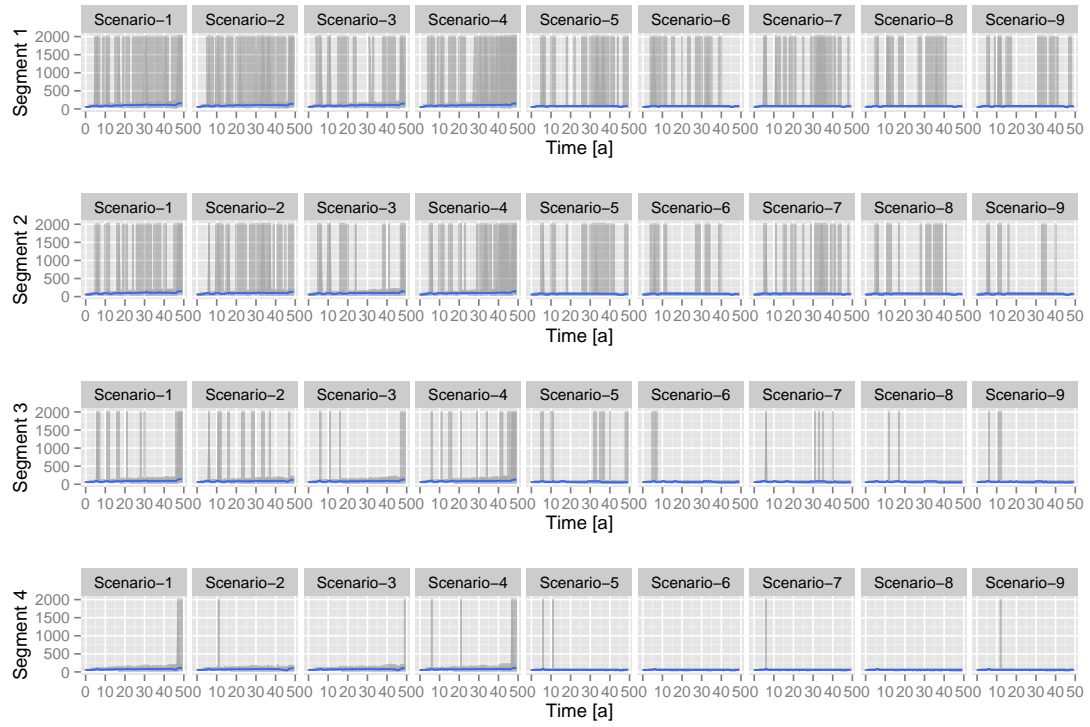
Figure E.3: Segment Prices
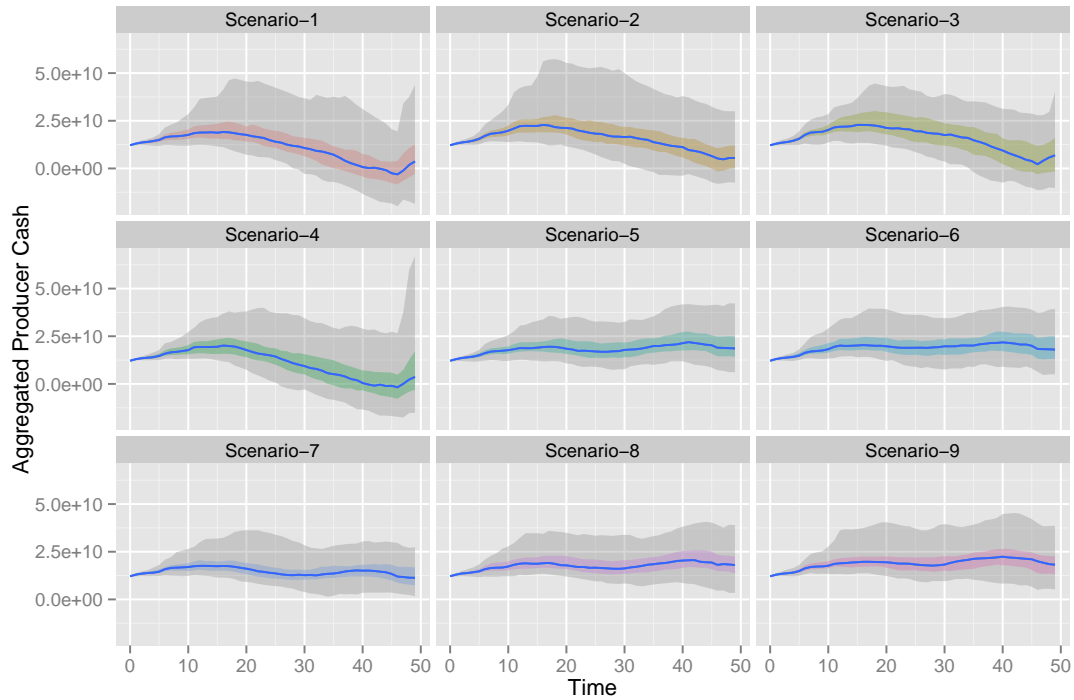
Figure E.4: Aggregate Producer Cash

Table E.3: Producer Welfare Sensitivity Table

	Scenario-1	Scenario-2	Scenario-3
AggregateProducerProfit-Mean(Eur)	-8.60E+07	-9.63E+07	-7.05E+07
ProducerCashSum-Mean (Eur)	1.23E+10	1.70E+10	1.67E+10
ProducerCashSum-SD (Eur)	6.24E+09	8.58E+09	6.66E+09
	Scenario-4	Scenario-5	Scenario-6
AggregateProducerProfit-Mean(Eur)	-5.09E+07	1.65E+08	1.49E+08
ProducerCashSum-Mean (Eur)	1.21E+10	1.93E+10	1.98E+10
ProducerCashSum-SD (Eur)	5.96E+09	6.13E+09	5.38E+09
	Scenario-7	Scenario-8	Scenario-9
AggregateProducerProfit-Mean(Eur)	8.14E+06	1.34E+08	1.34E+08
ProducerCashSum-Mean (Eur)	1.54E+10	1.85E+10	1.95E+10
ProducerCashSum-SD (Eur)	5.23E+09	5.45E+09	5.84E+09

TUDelft Delft University of Technology
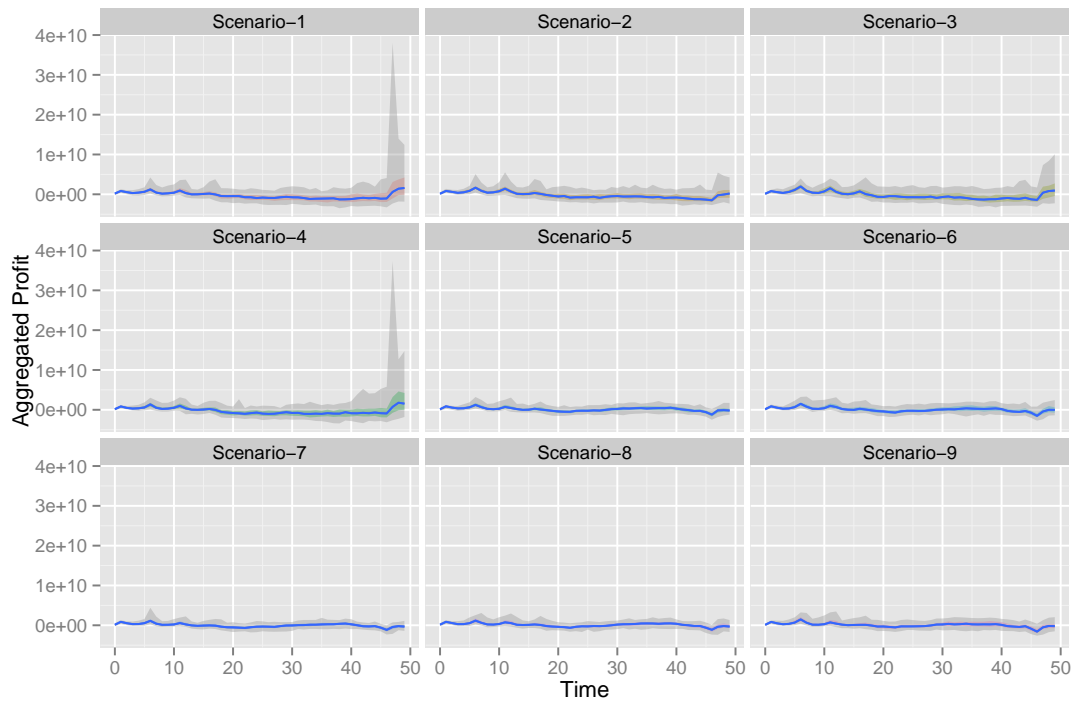
Figure E.5: Aggregate Producer Profit
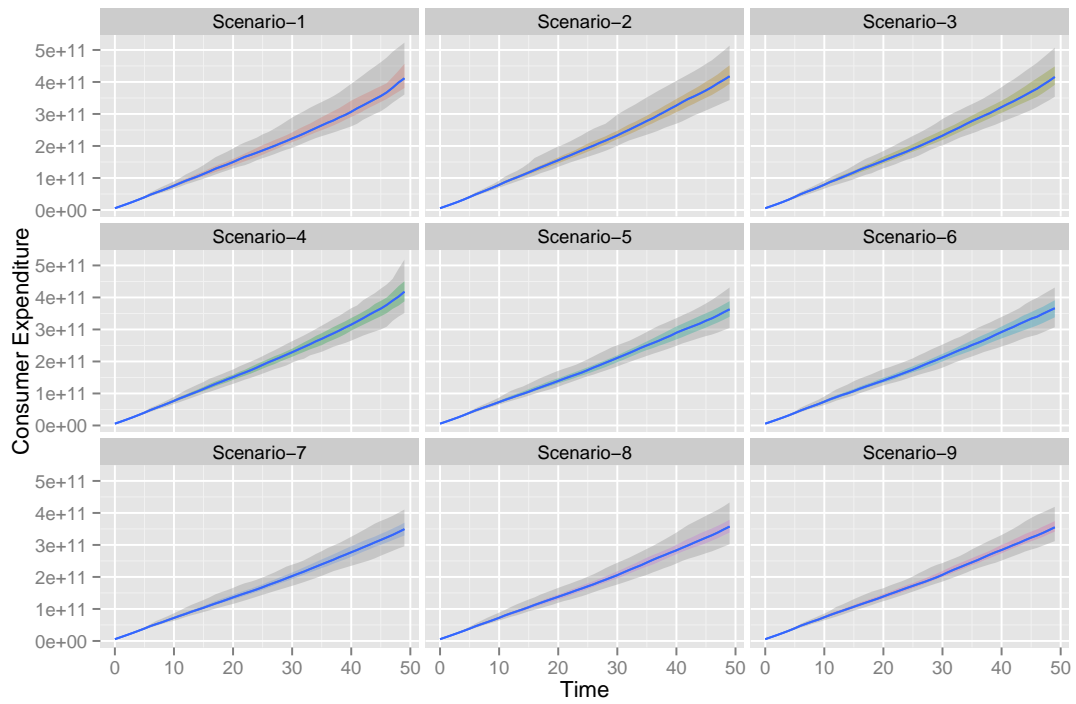
Figure E.6: Consumer Expenditure
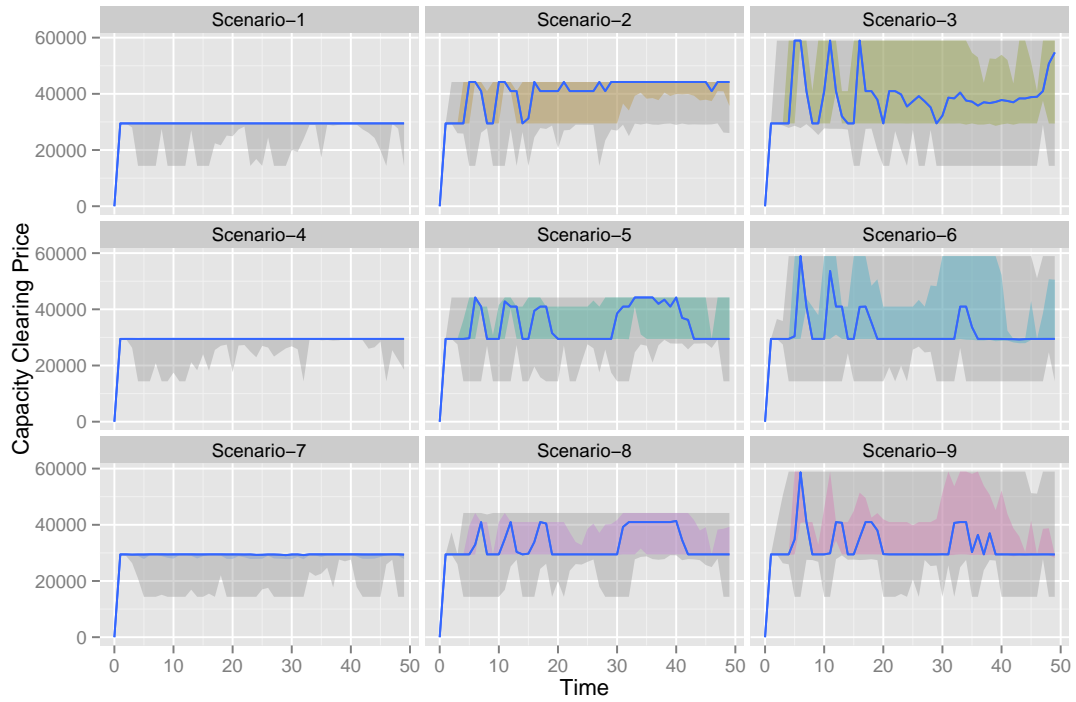
Figure E.7: Capacity Market Clearing Price
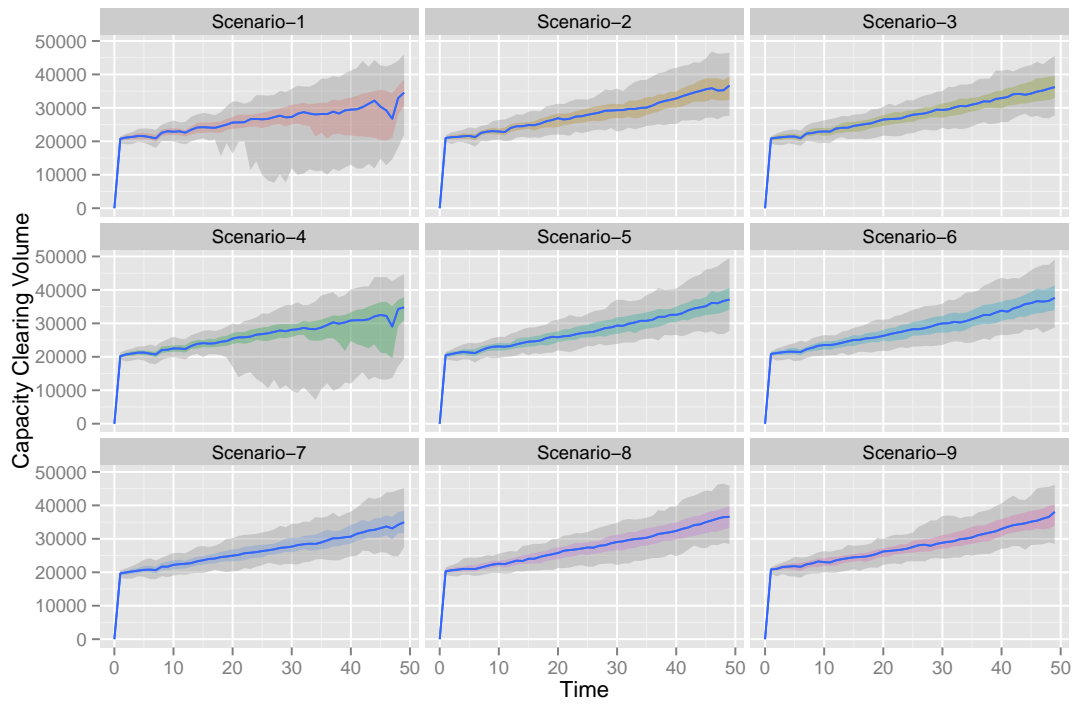
Figure E.8: Capacity Market Clearing Volume
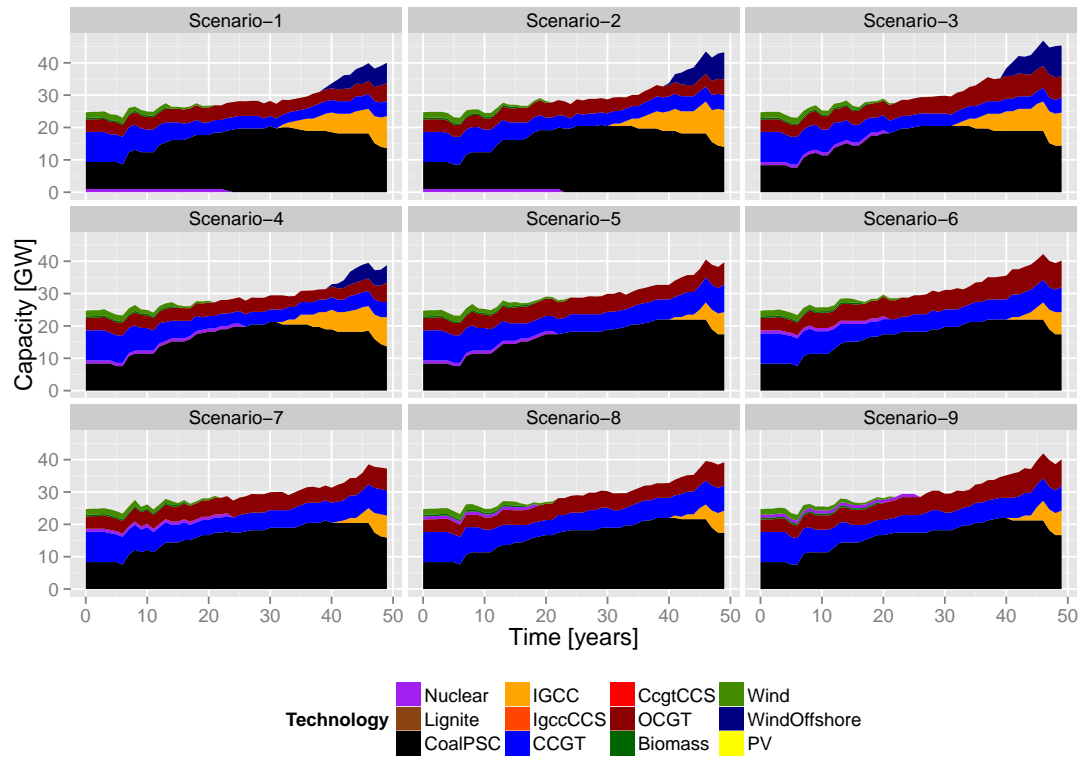
Figure E.9: Stacked Capacity Diagram
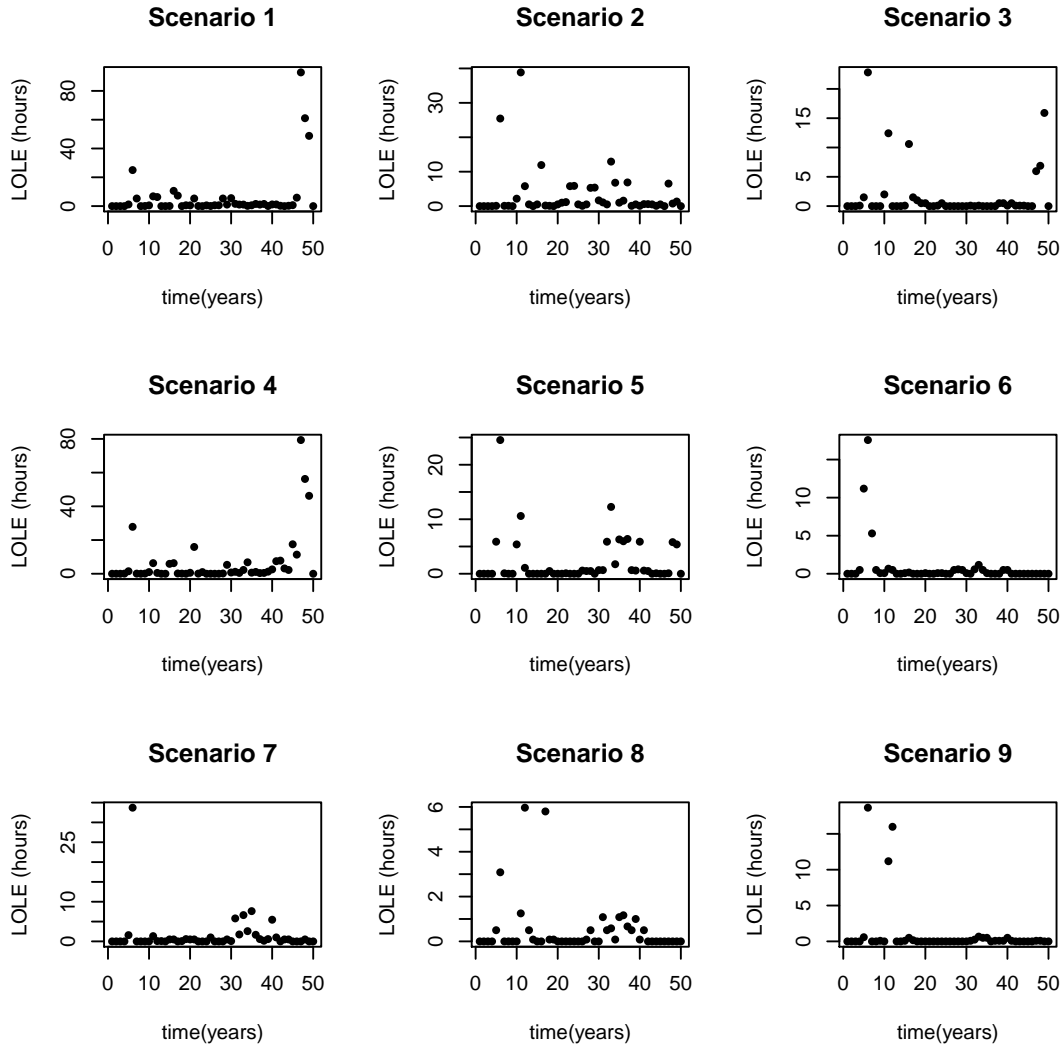
Figure E.10: Average Loss of Load Expectation

E.2 Experiment 1

A capacity market, as a standalone policy instrument, ensures generation adequacy in one, isolated country.
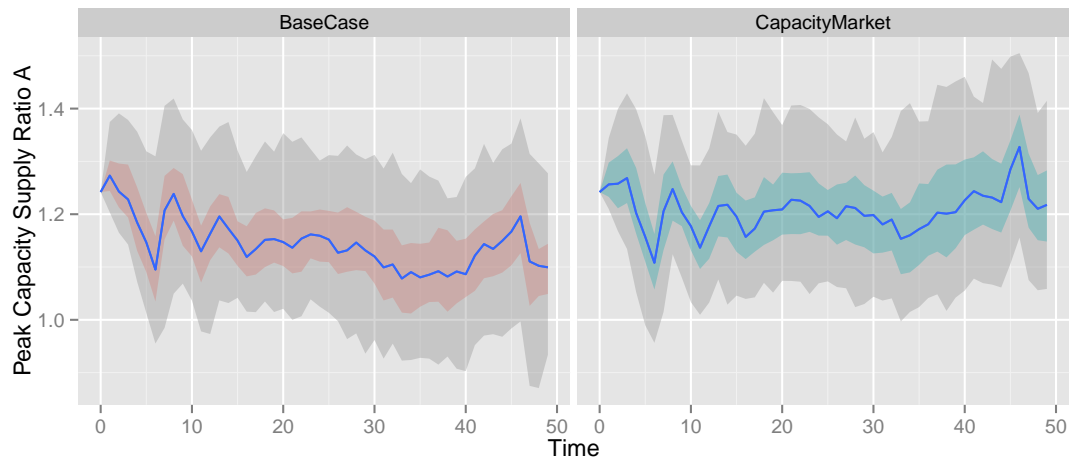
Figure E.11: Exp 1: Supply Ratio
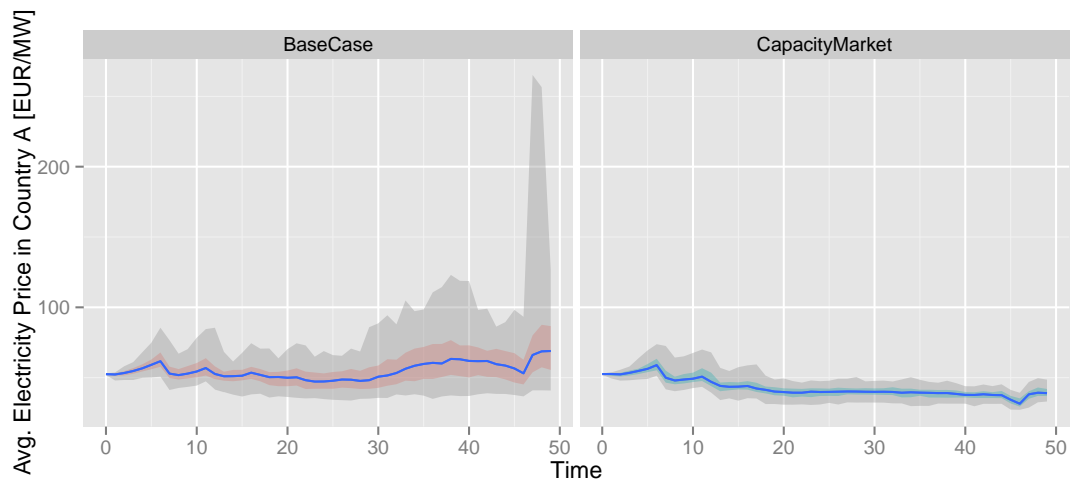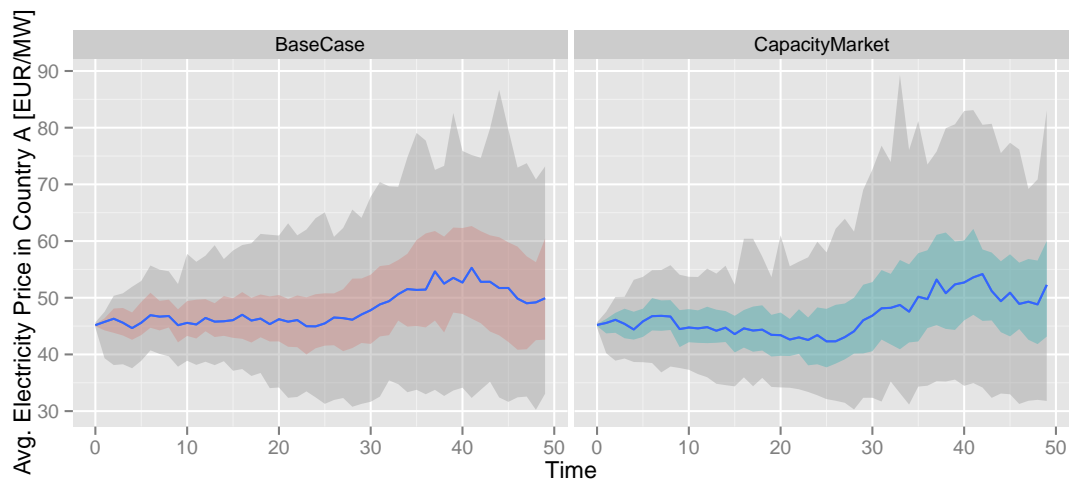

Figure E.12: Exp 1: Average Electricity Price
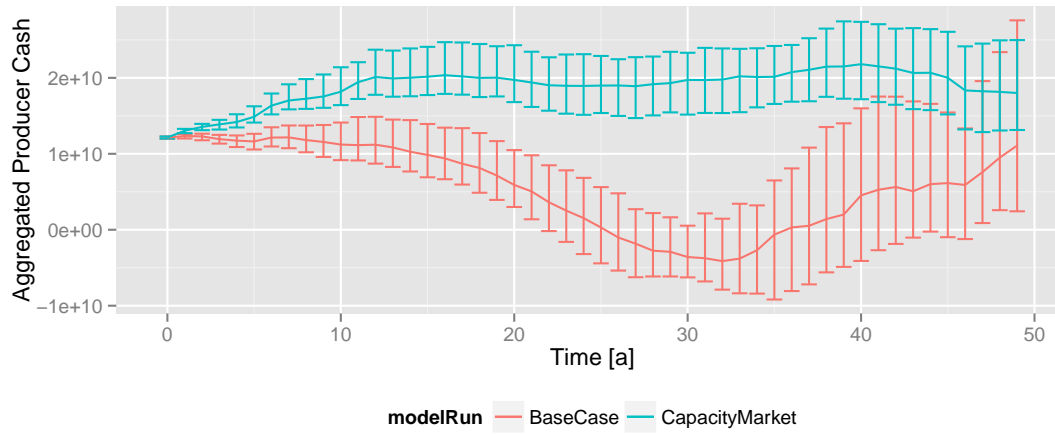
Figure E.13: Exp 1: Aggregate Producer Cash
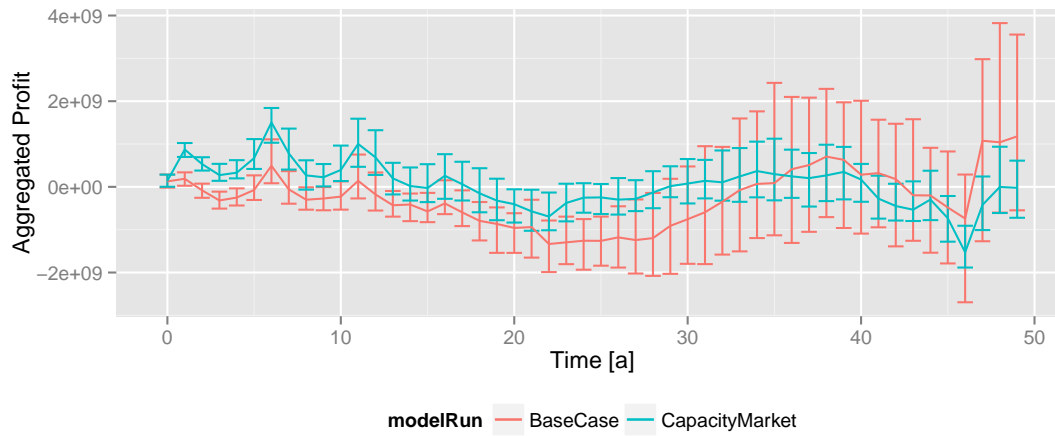
Figure E.14: Exp 1: Aggregate Producer Profit
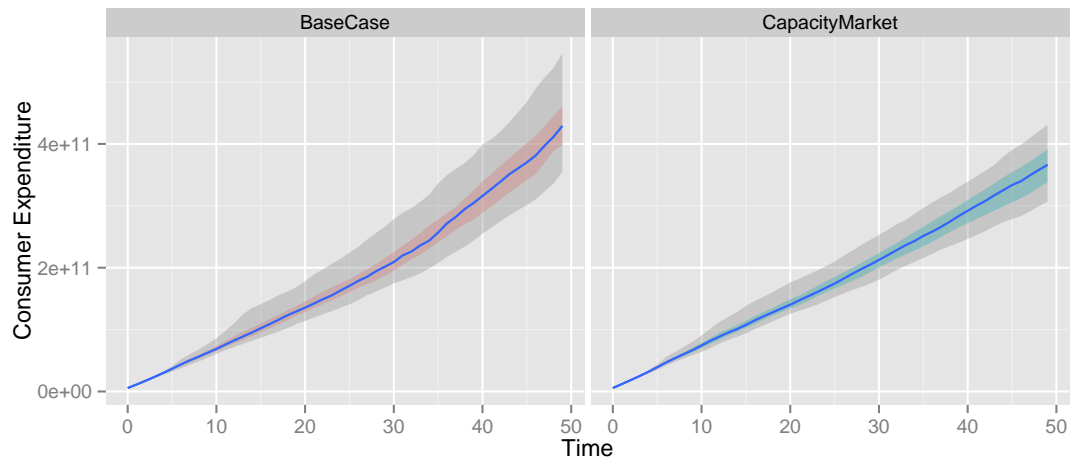
Figure E.15: Exp 1: Consumer Expenditure
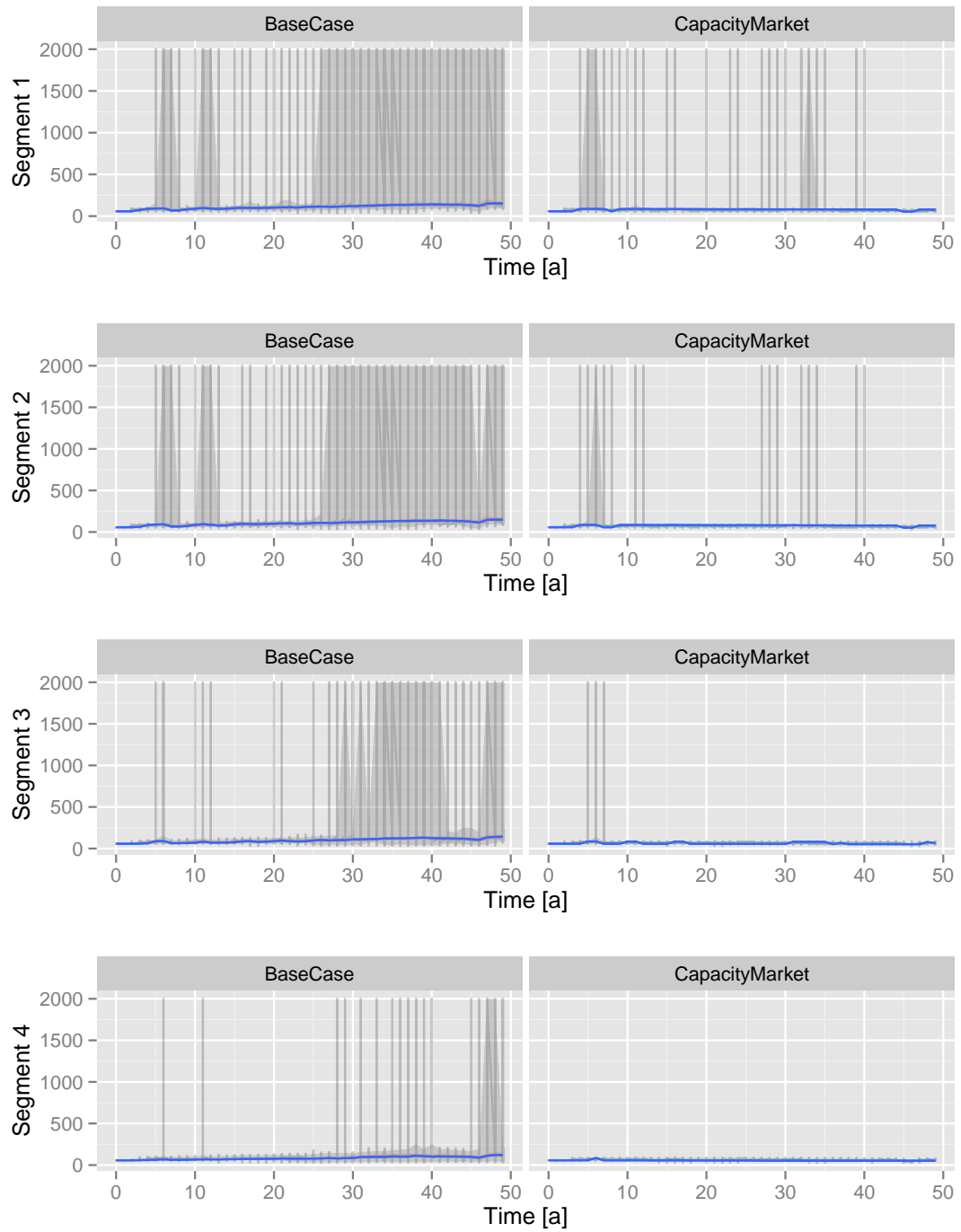
0.75

Figure E.16: Exp 1: Segment Prices
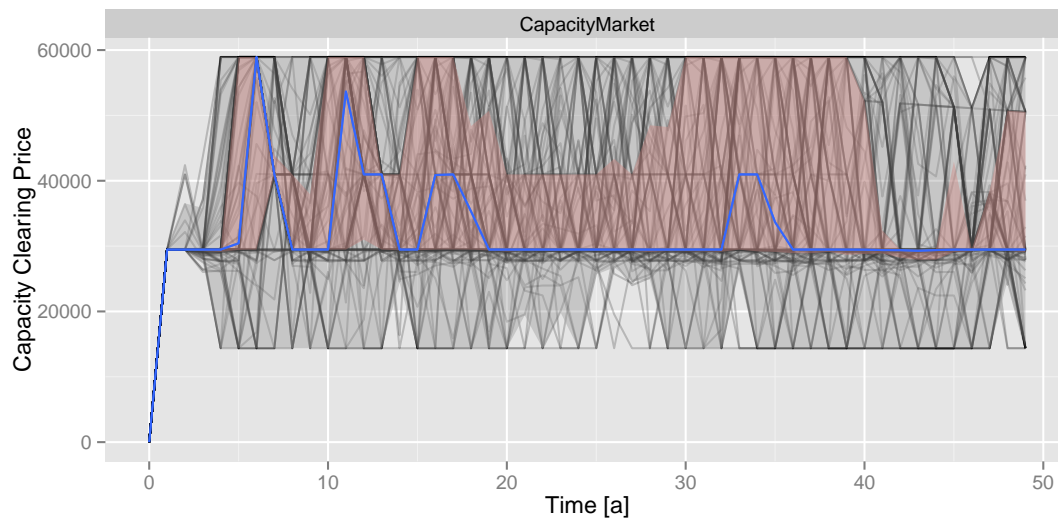
Figure E.17: Exp 1: Capacity Market Clearing Price
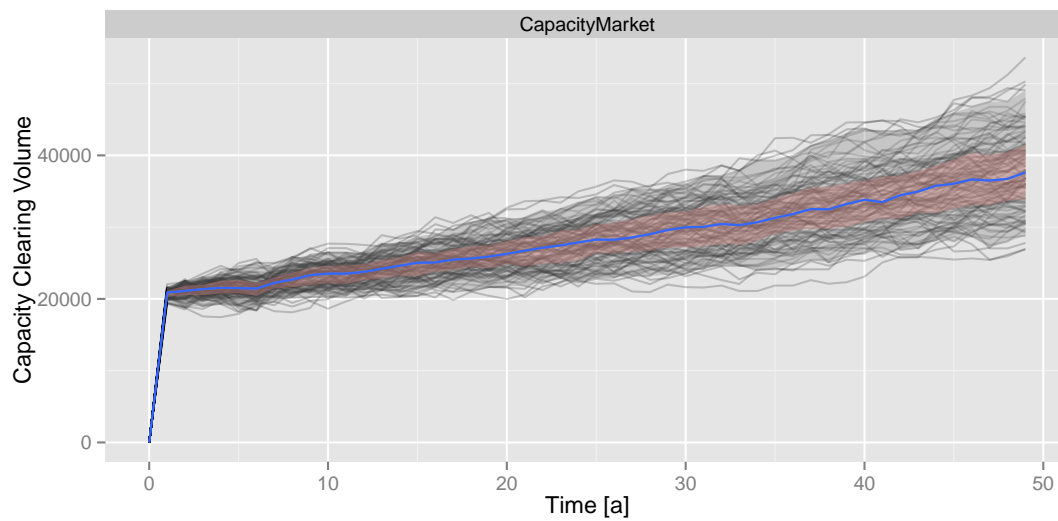
Figure E.18: Exp 1: Capacity Market Clearing Volume
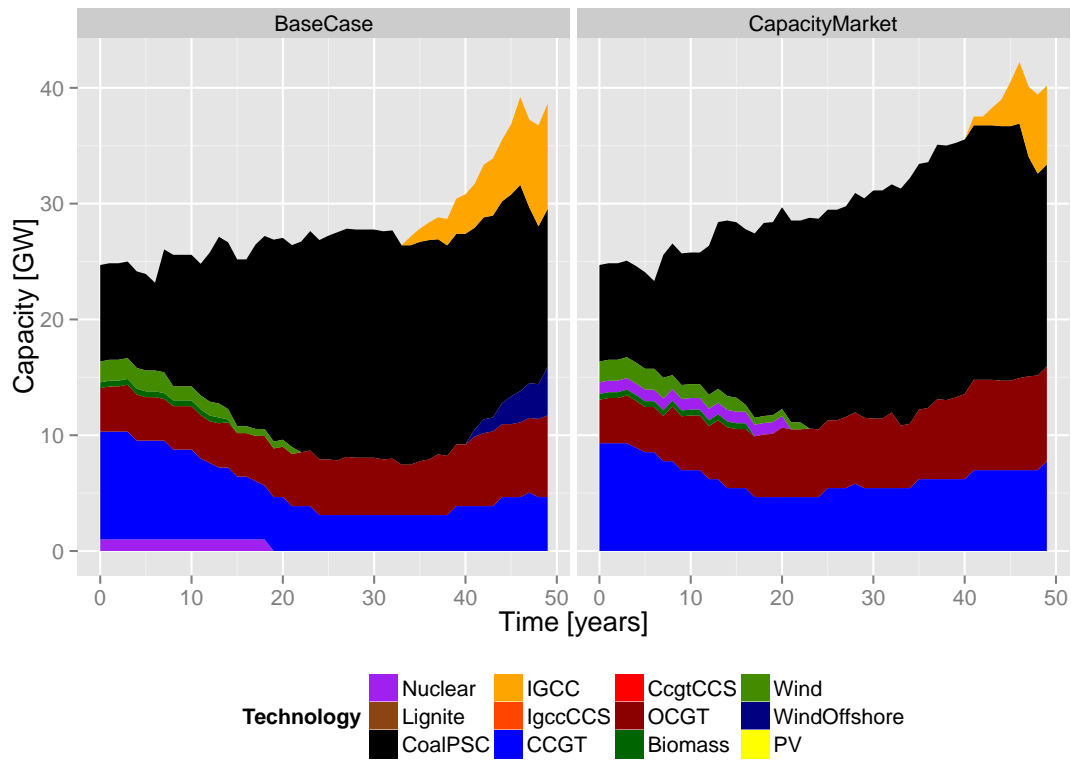
Figure E.19: Exp 1: Stacked Capacity Diagram

Base Case
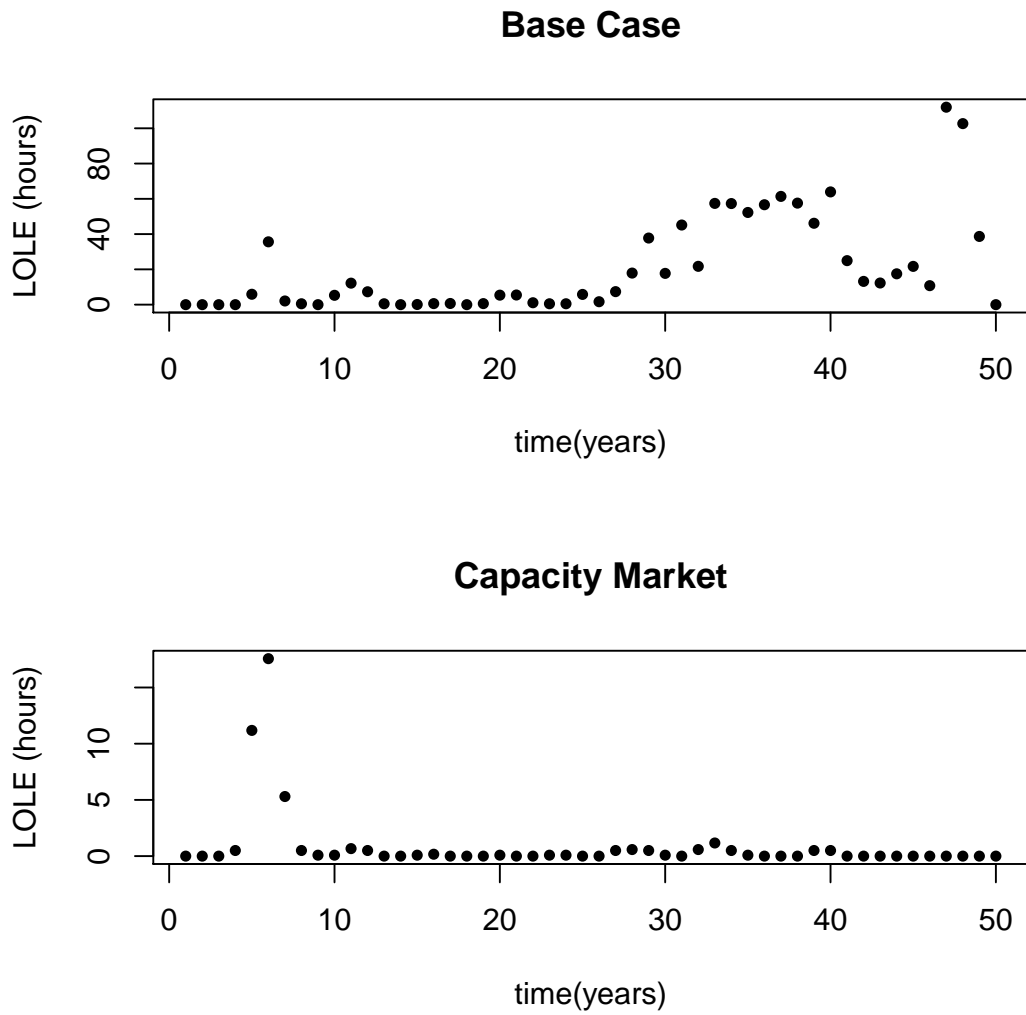
Capacity Market

Figure E.20: Exp 1: Average Loss of Load Expectation

E.3 Experiment 2

A capacity market, as a policy instrument in combination with targeted investment in renewable energy, ensures generation adequacy in one, isolated country.
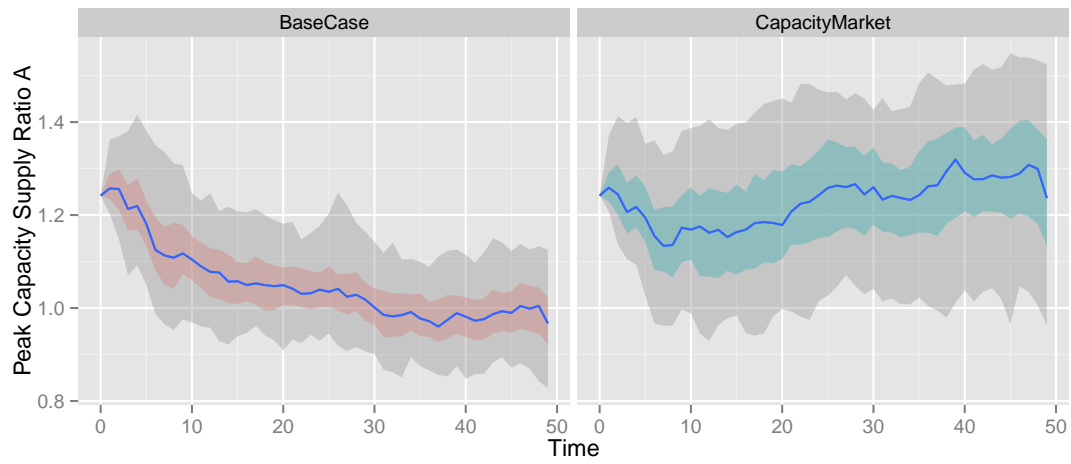
Figure E.21: Exp 2: Supply Ratio
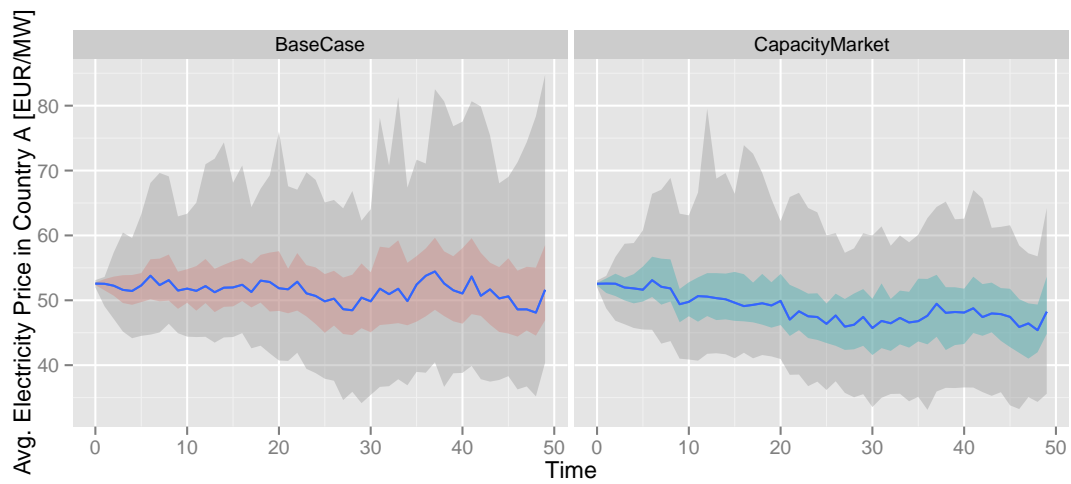

Figure E.22: Exp 2: Average Electricity Price
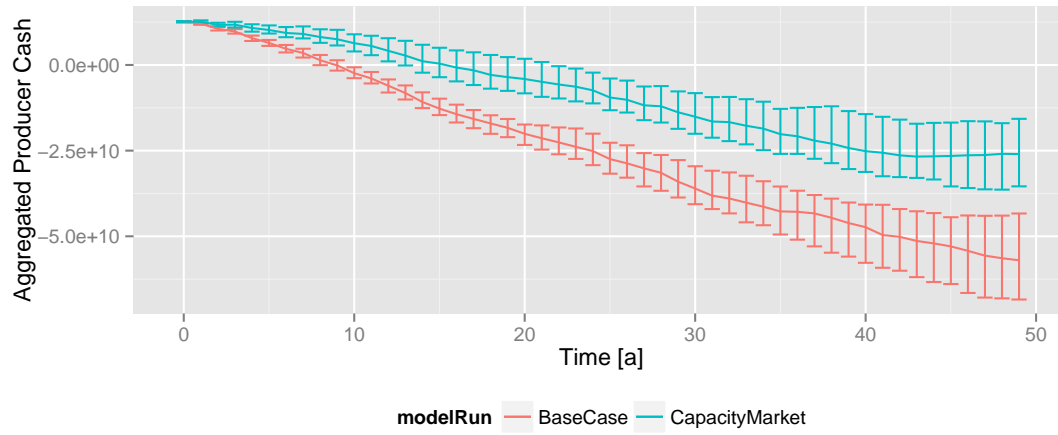
Figure E.23: Exp 2: Aggregate Producer Cash
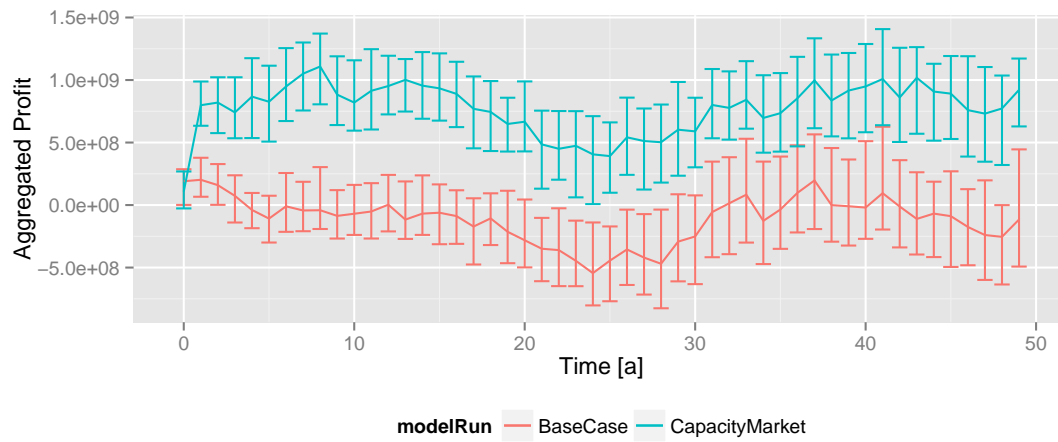

Figure E.24: Exp 2: Aggregate Producer Profit

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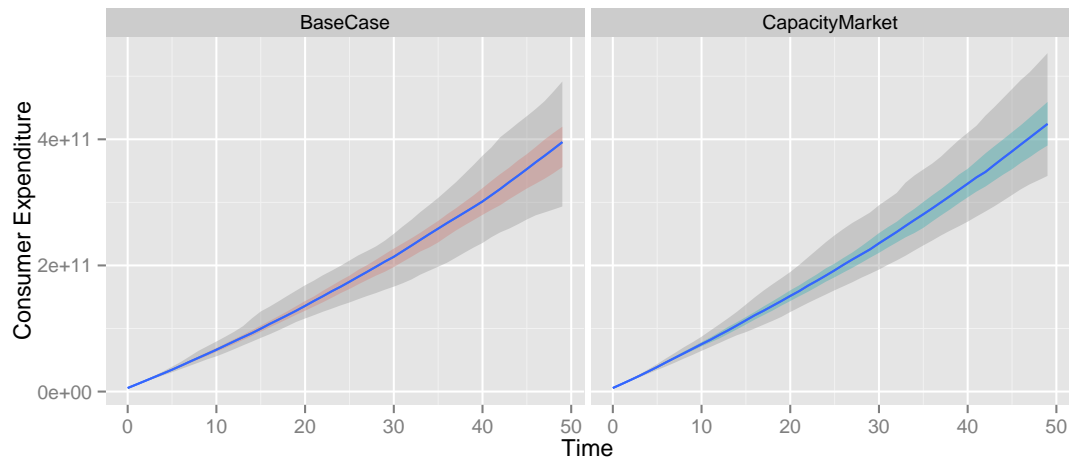
Figure E.25: Exp 2: Consumer Expenditure
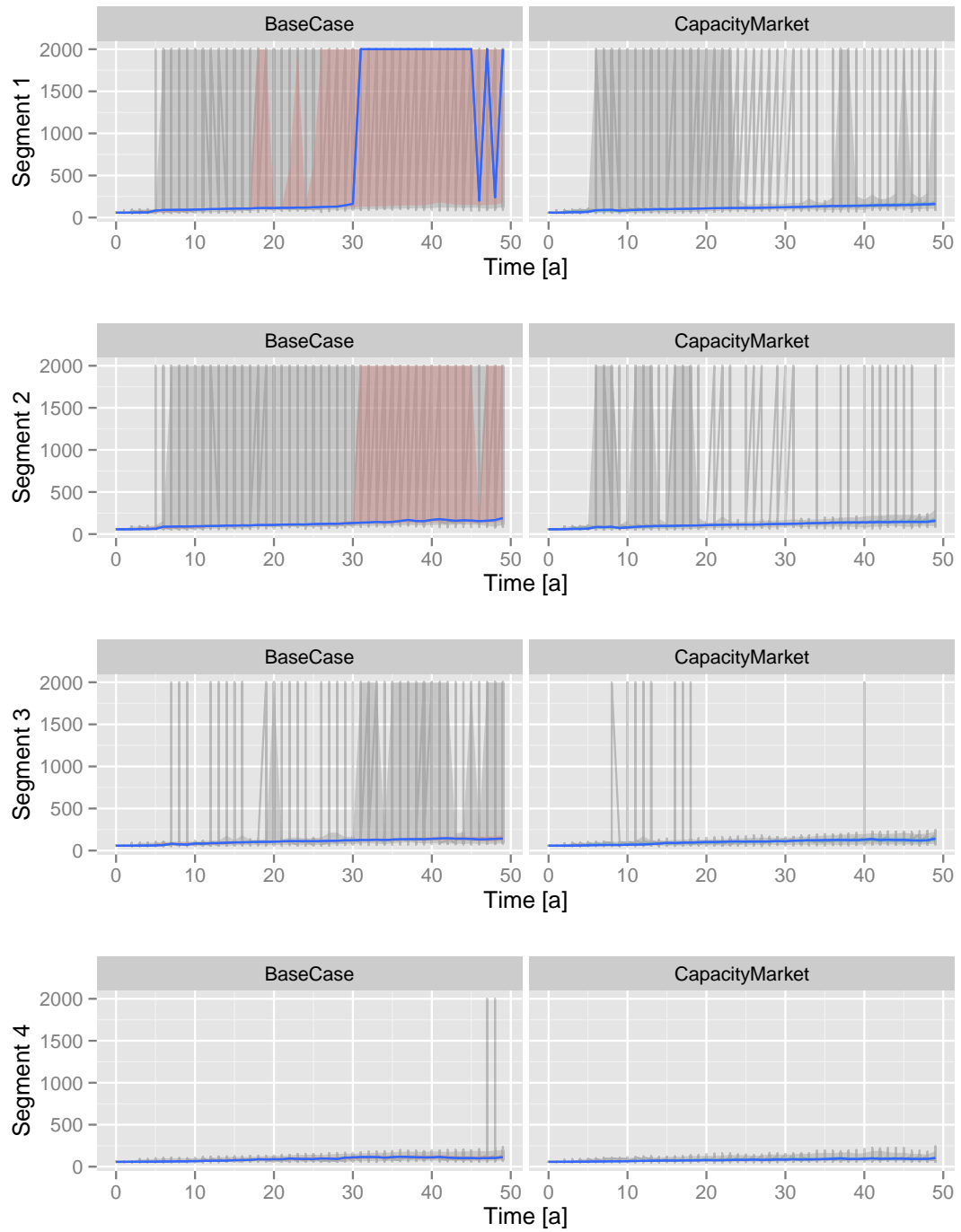
0.75

Figure E.26: Exp 2: Segment Prices
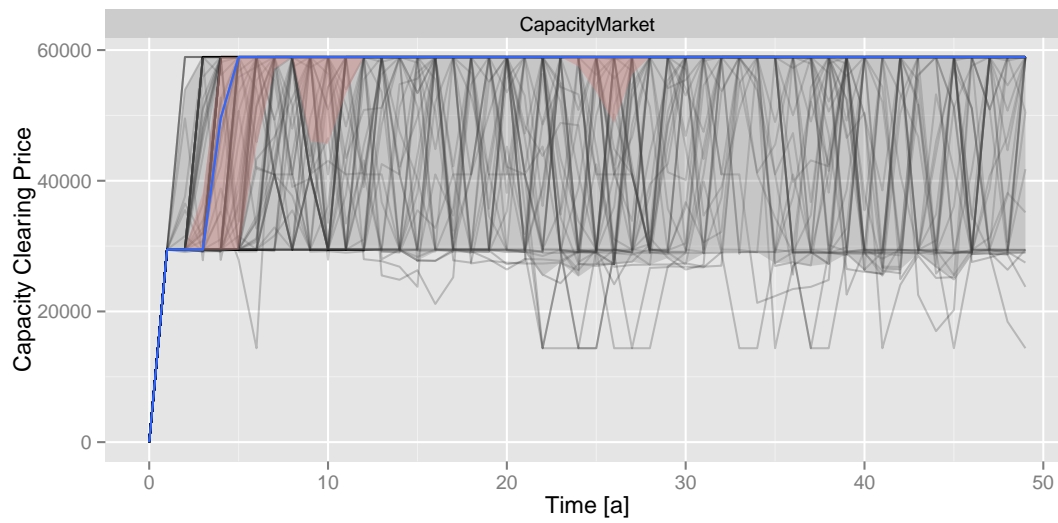
Figure E.27: Exp 2: Capacity Market Clearing Price
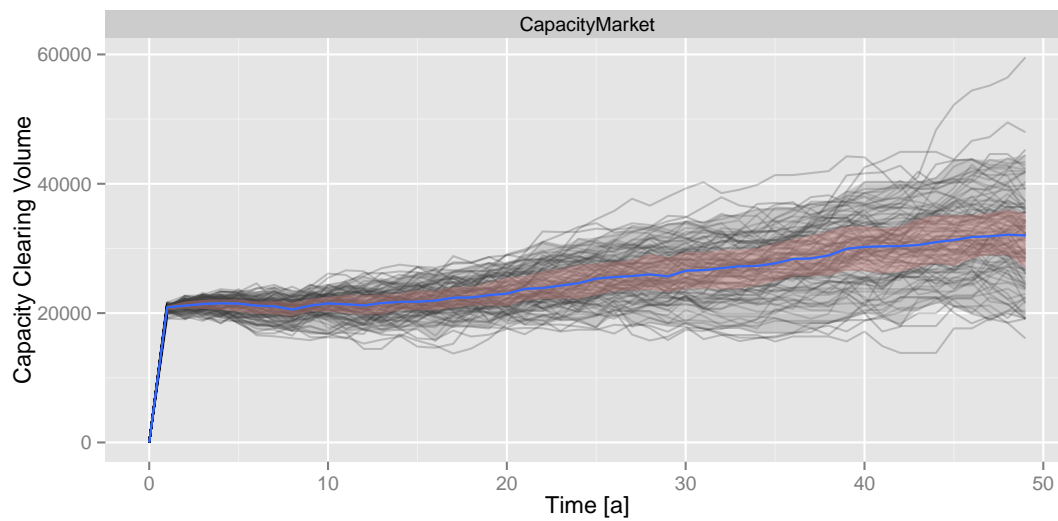
Figure E.28: Exp 2: Capacity Market Clearing Volume
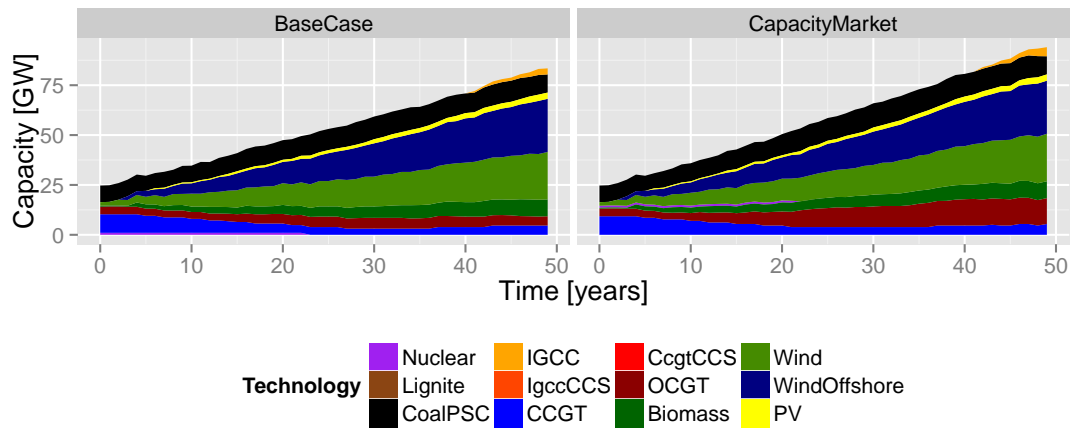
Figure E.29: Exp 2: Stacked Capacity Diagram

Base Case
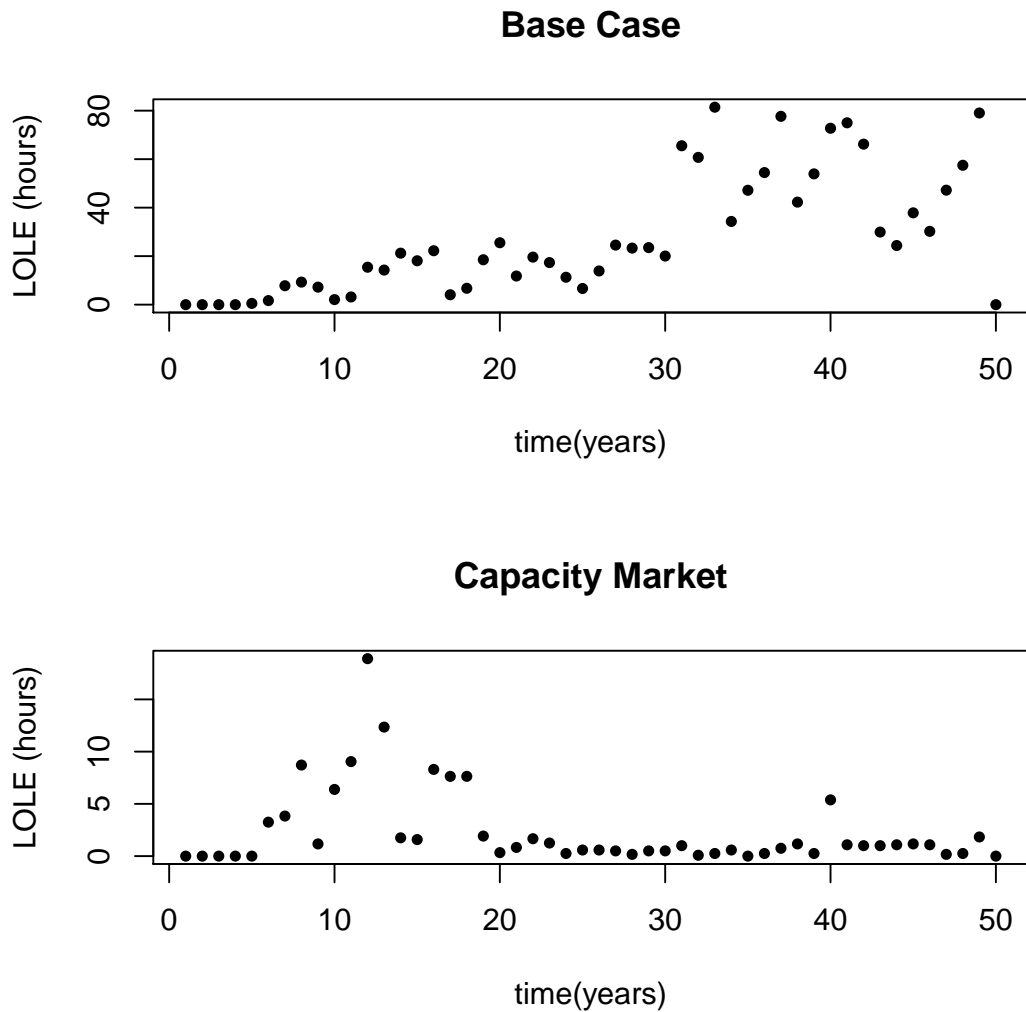
Capacity Market

Figure E.30: Exp 2: Average Loss of Load Expectation

E.4 Experiment 3

A capacity market, as a policy instrument in country B, in combination with target RES investment and the EU ETS, ensures generation adequacy in country B while it is interconnected with country A .
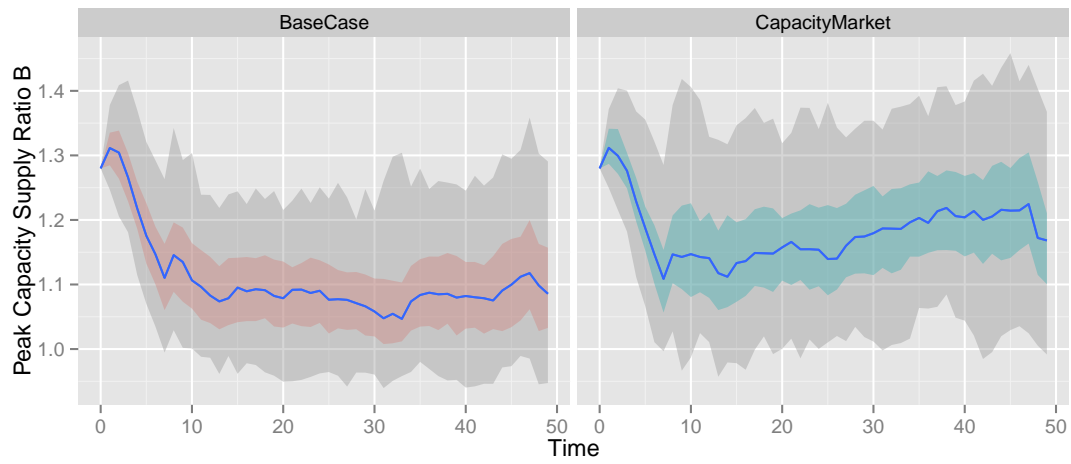
Figure E.31: Exp 3: Supply Ratio, Country B
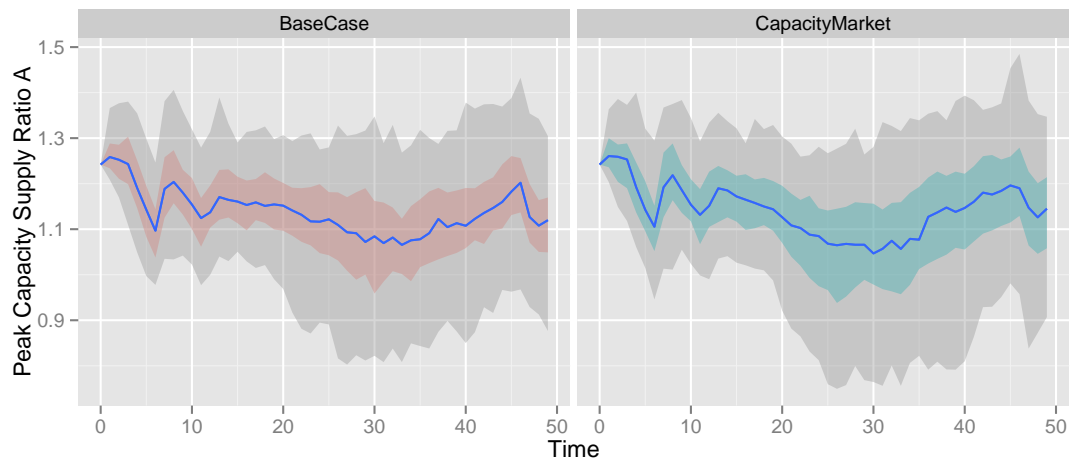
Figure E.32: Exp 3: Supply Ratio, Country A

135
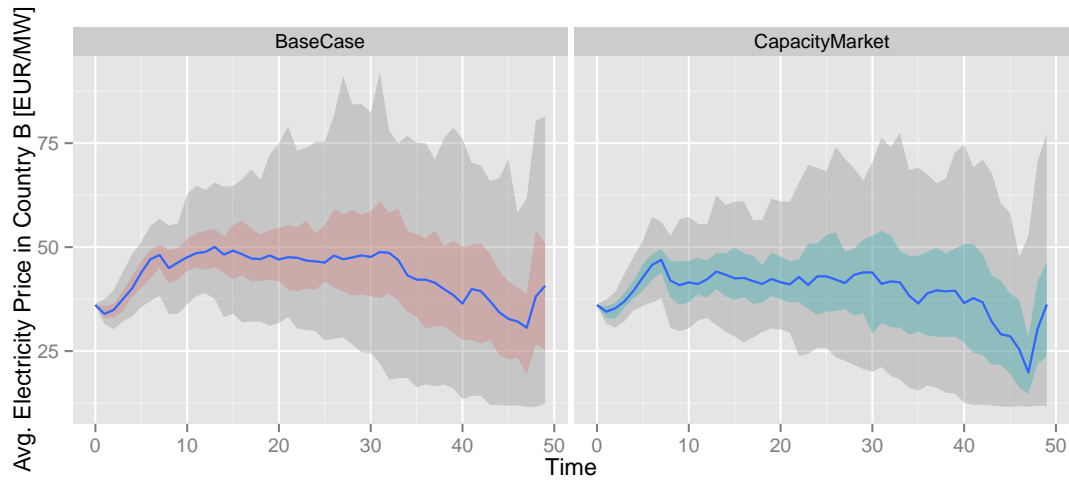
Figure E.33: Exp 3: Average Electricity Price, Country B
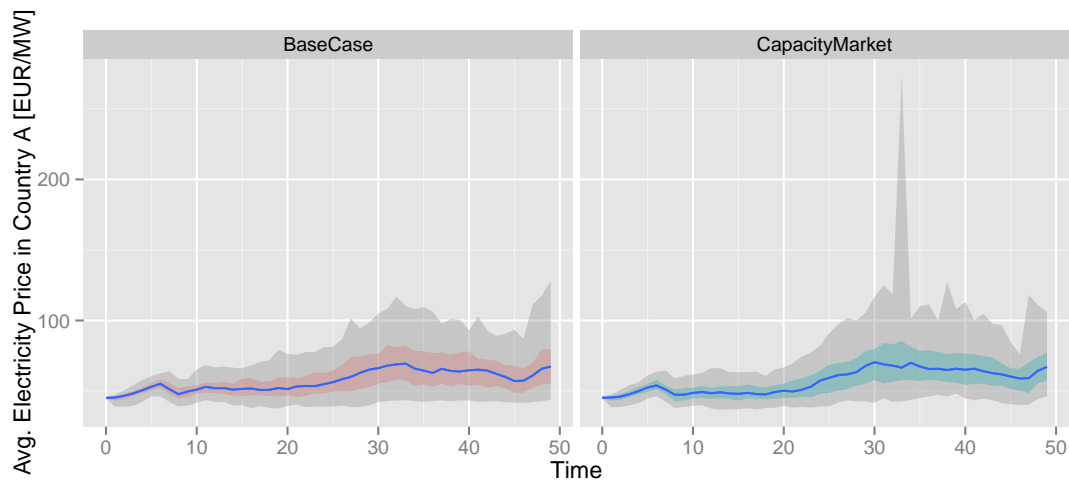
Figure E.34: Exp 3: Average Electricity Price, Country A
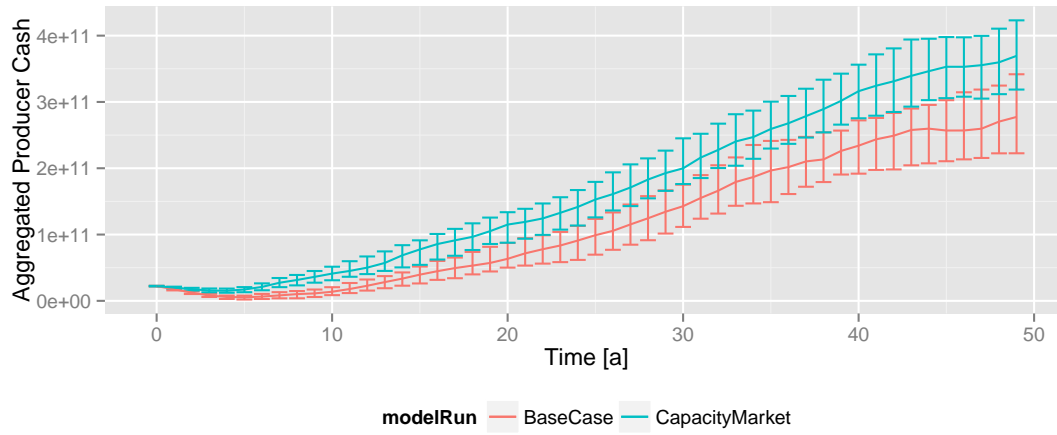
Figure E.35: Exp 3: Aggregate Producer Cash
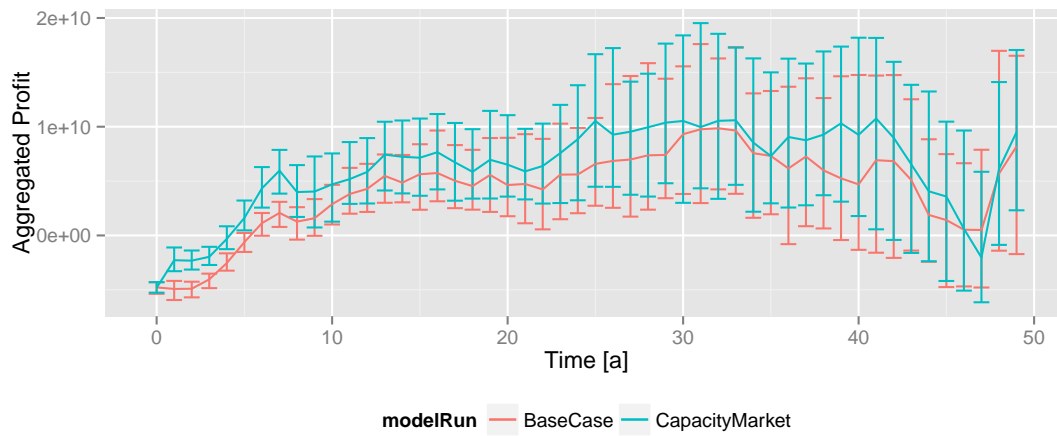
Figure E.36: Exp 3: Aggregate Producer Profit
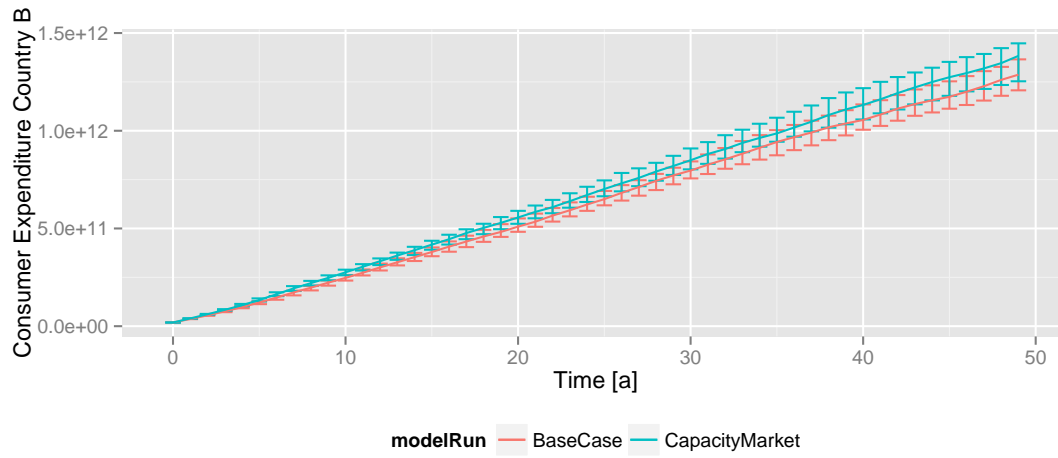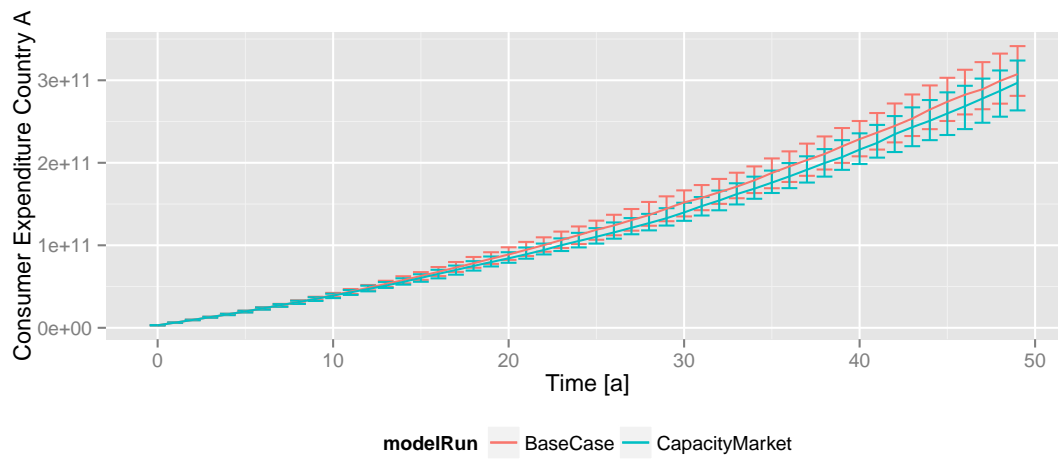
Figure E.37: Exp 3: Consumer Expenditure Country B
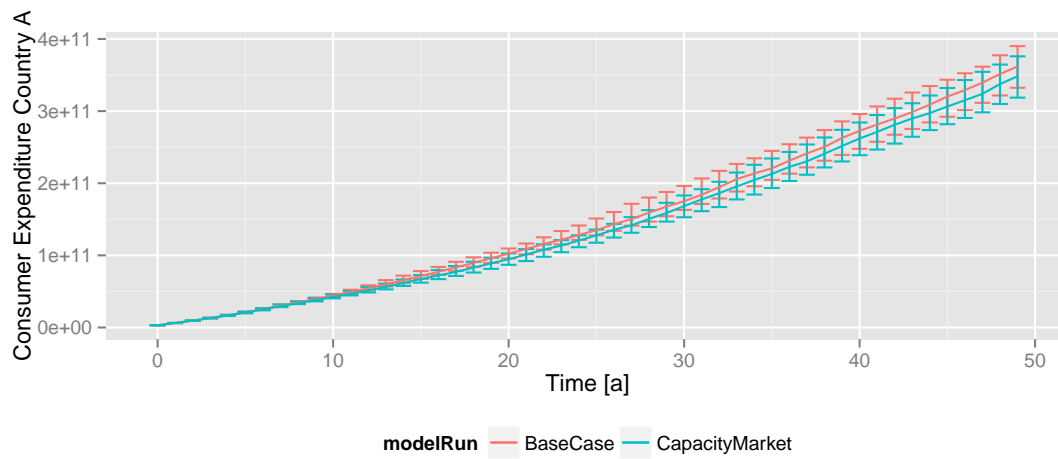
Figure E.38: Exp 3: Consumer Expenditure Country A
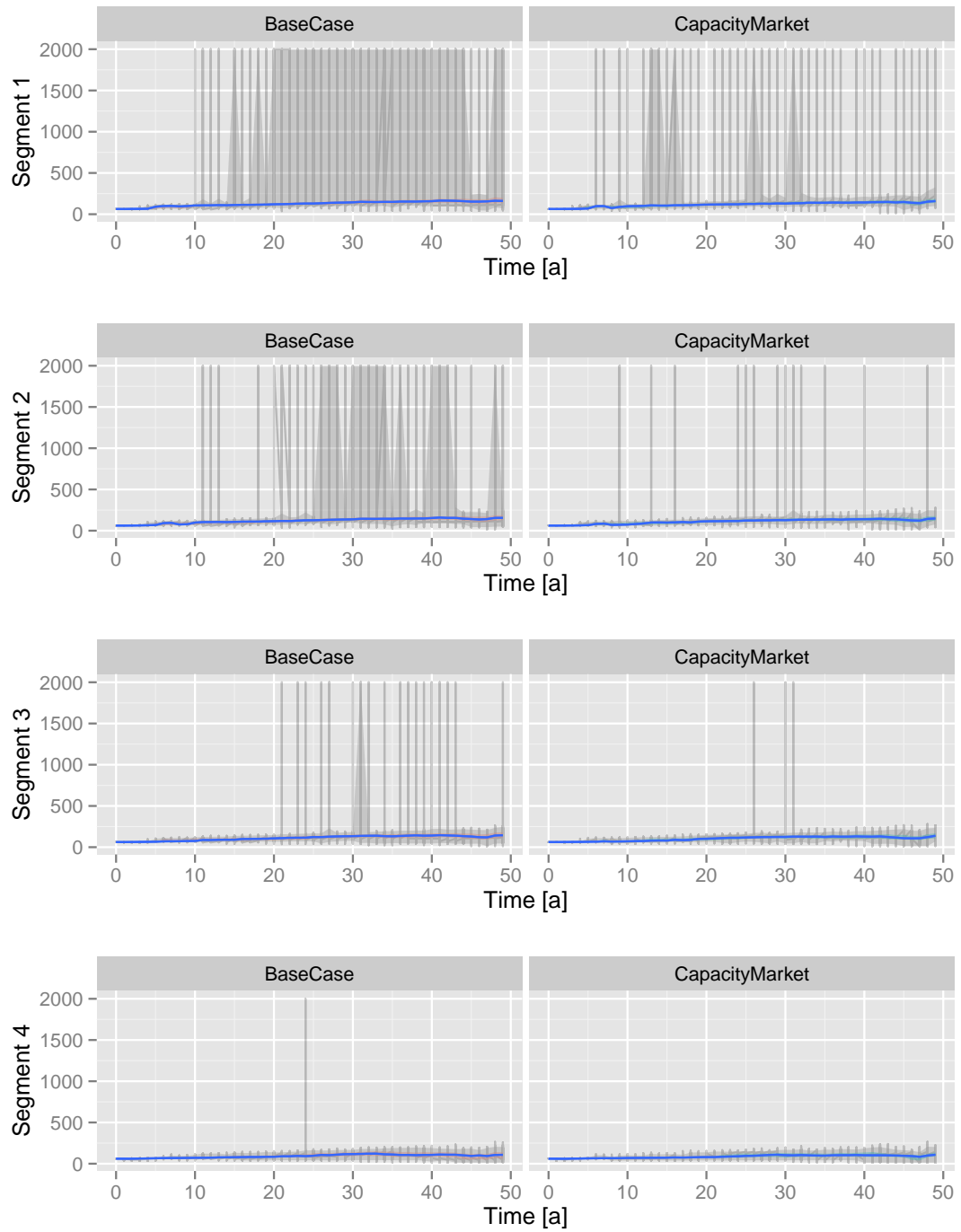
0.75

Figure E.39: Exp 3: Segment Prices Country B
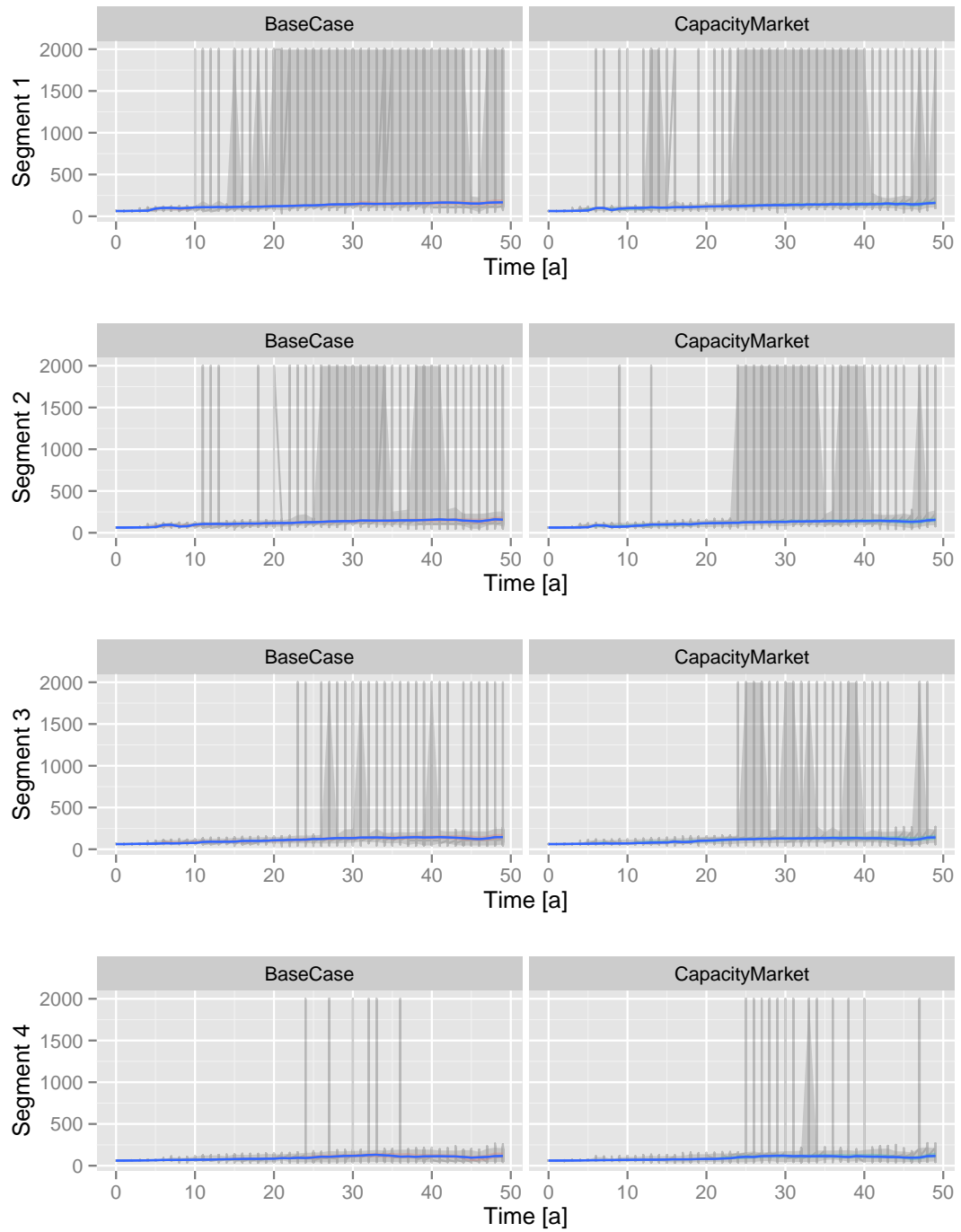
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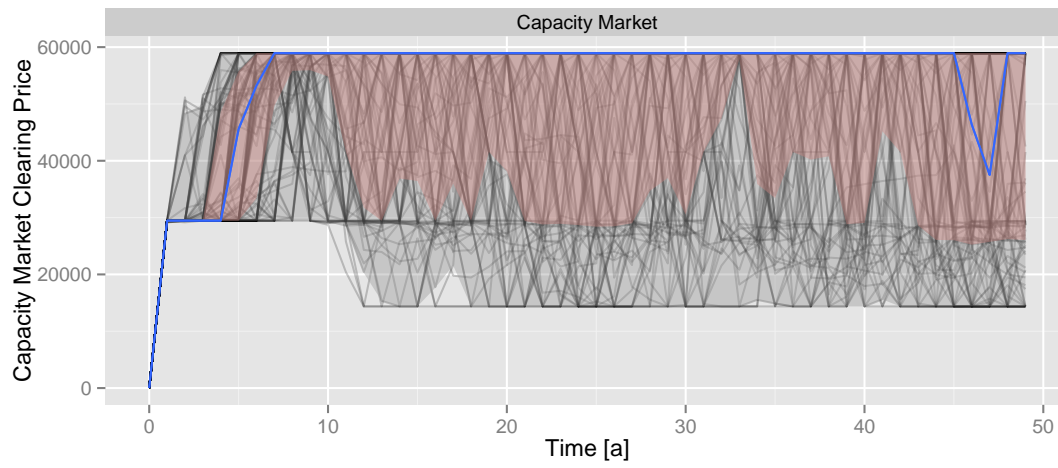Figure E.40: Exp 3: Segment Prices Country A
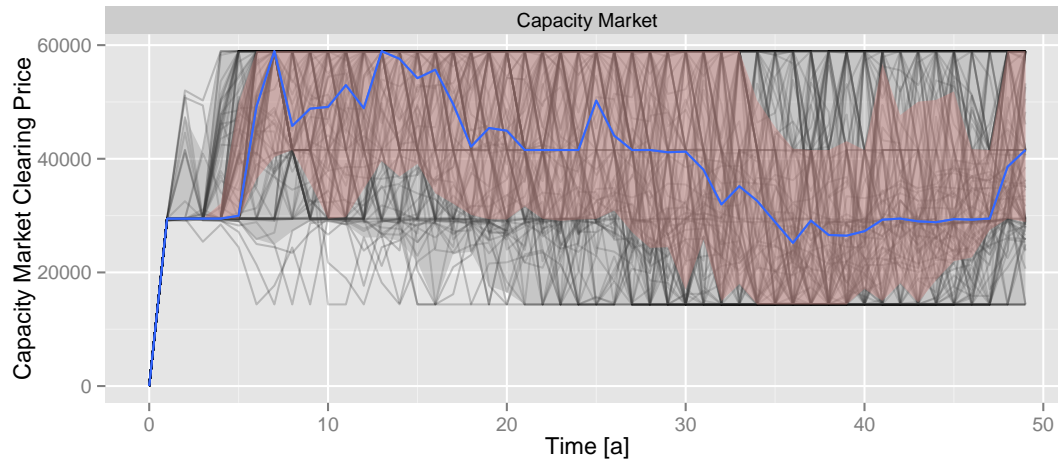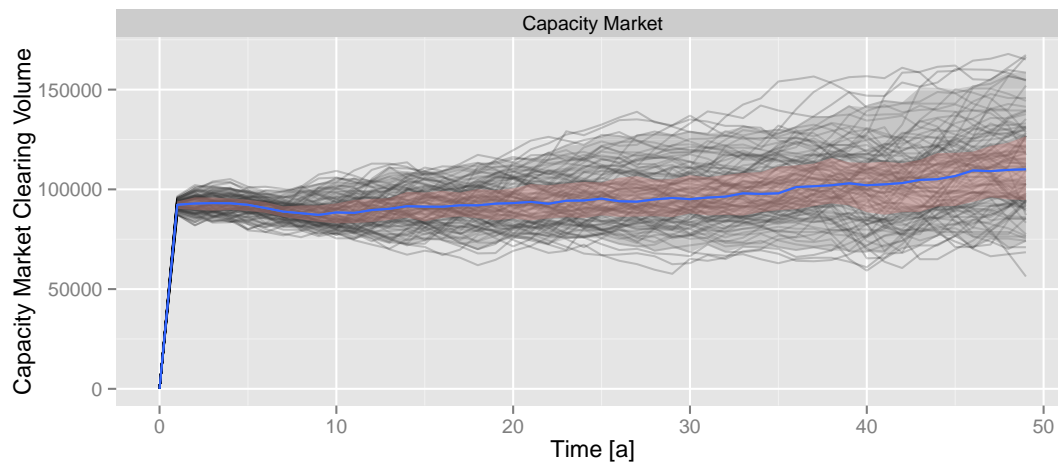
Figure E.41: Exp 3: Capacity Market Clearing Price
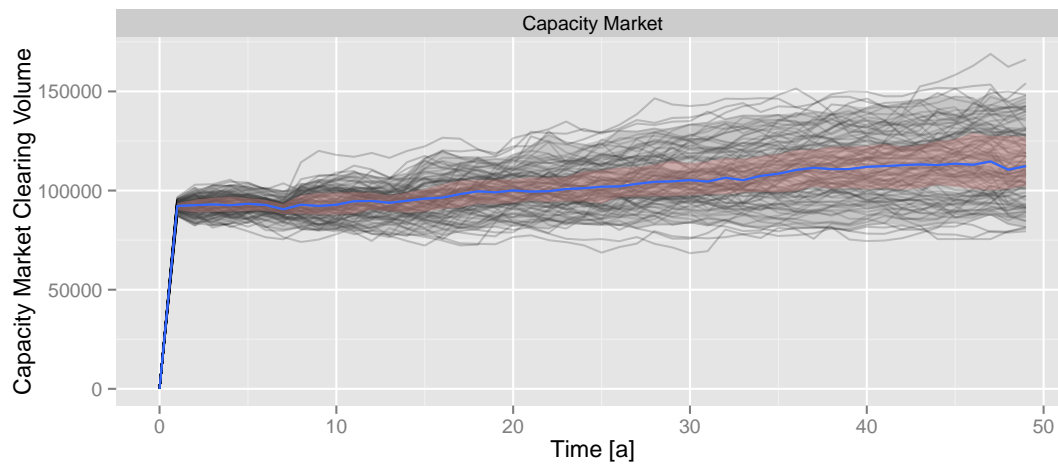
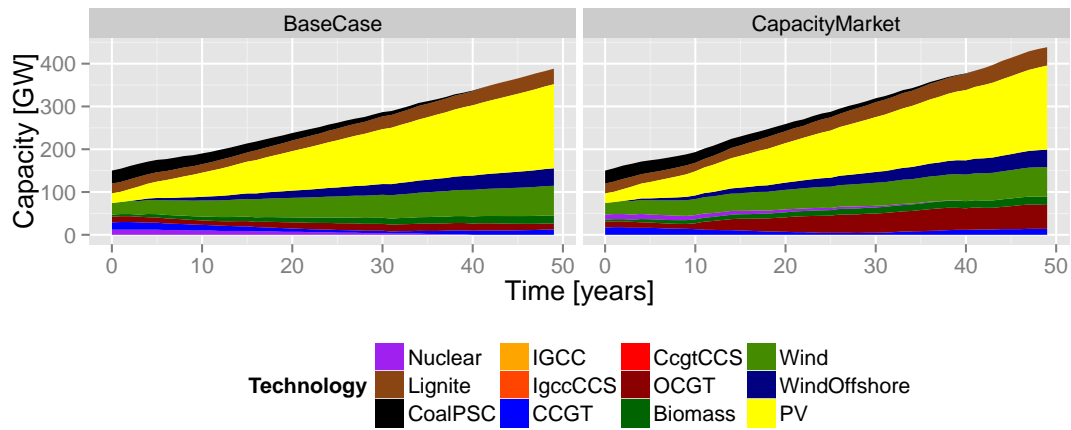Figure E.42: Exp 3: Capacity Market Clearing Volume
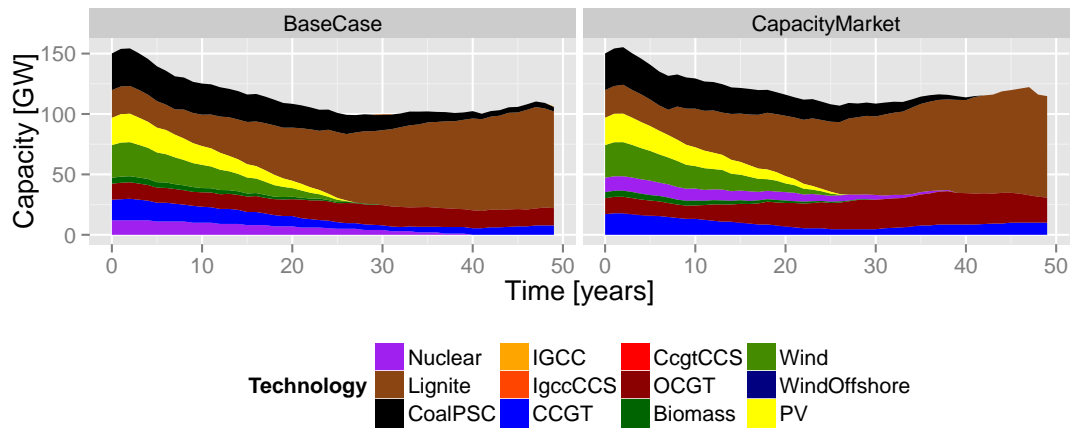
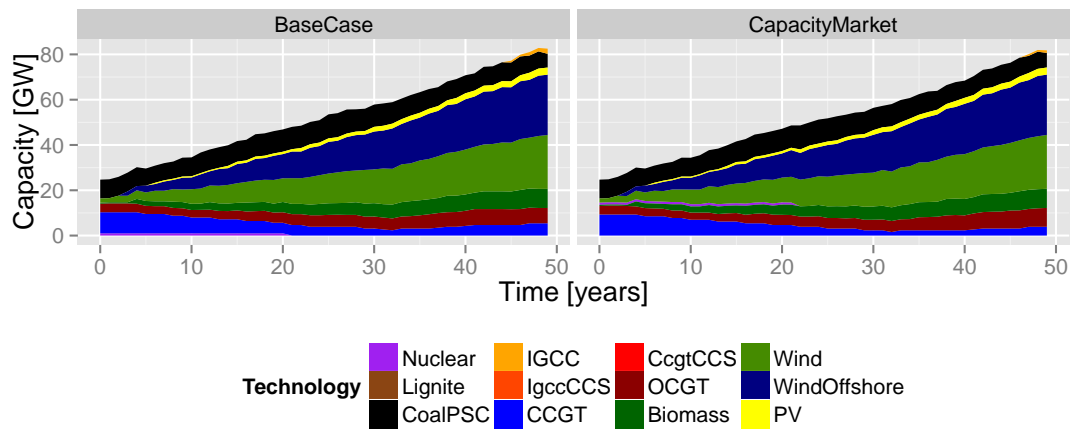Figure E.43: Exp 3: Stacked Capacity Diagram Country B
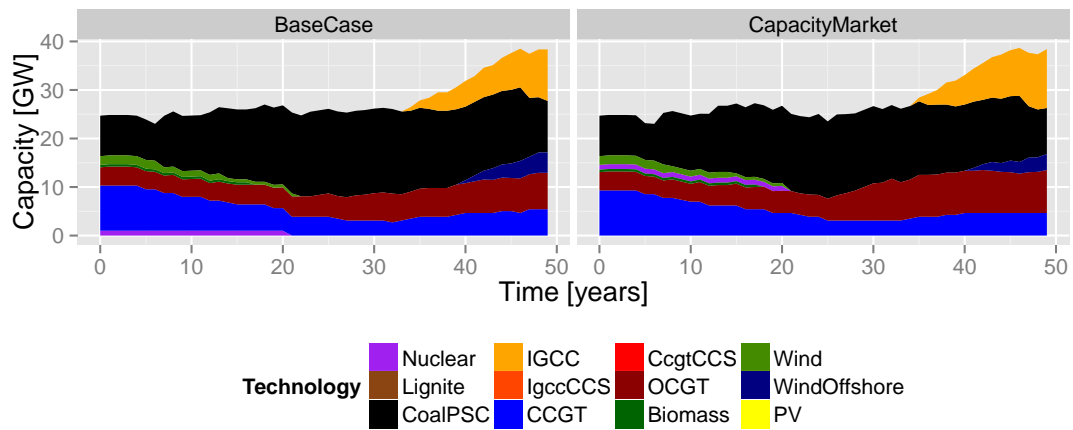
Figure E.44: Exp 3: Stacked Capacity Diagram Country A
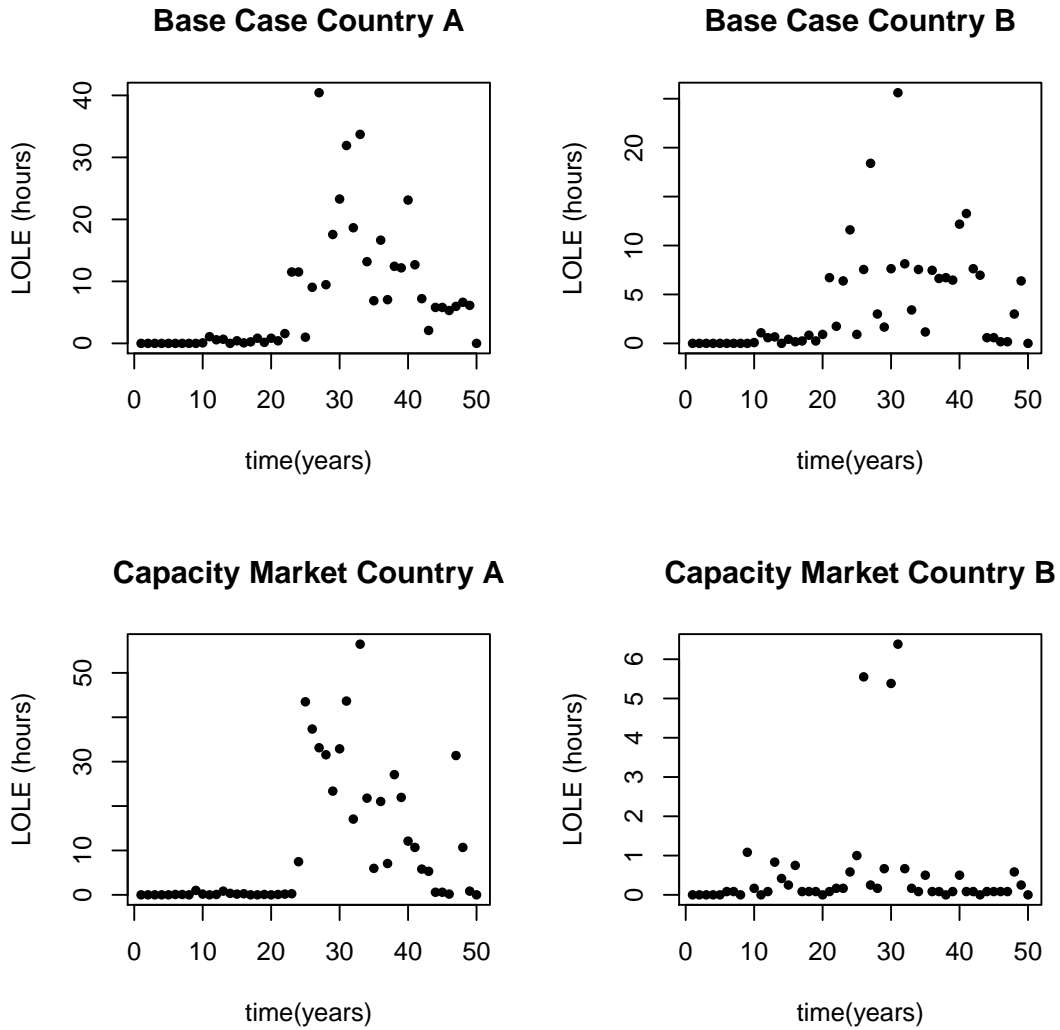
Figure E.45: Exp 4: Average Loss of Load Expectation

E.5 Experiment 4

A capacity market, as a policy instrument in country B, in combination with targeted investment in RES, ensures generation adequacy in country B while it is interconnected with country A .
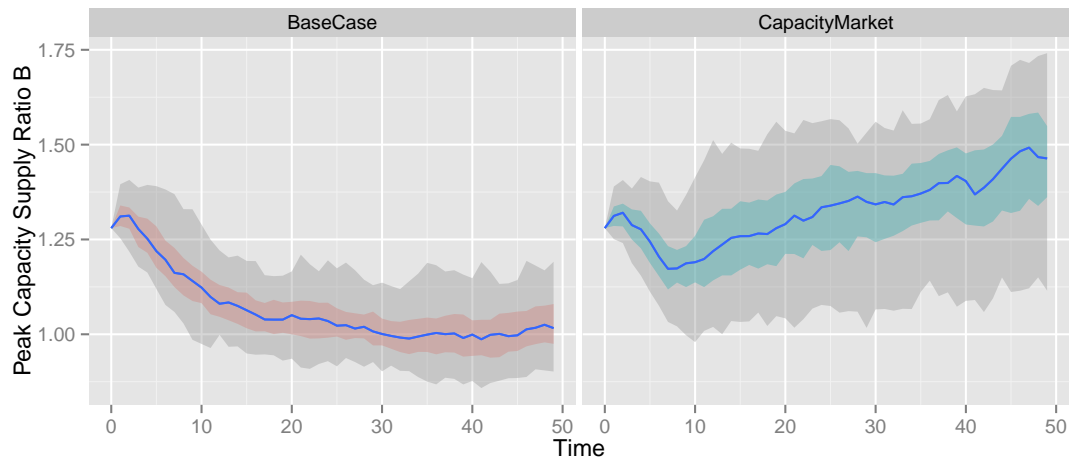
Figure E.46: Exp 4: Supply Ratio, Country B
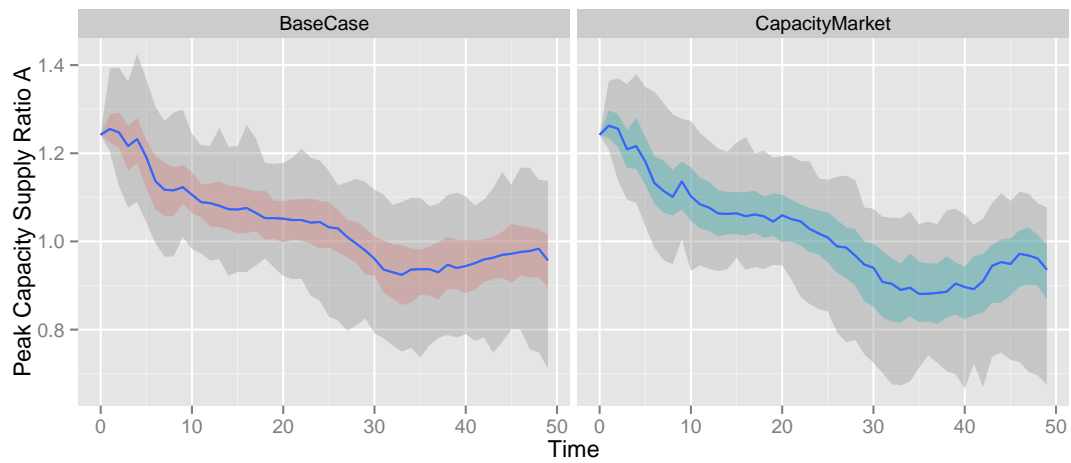
Figure E.47: Exp 4: Supply Ratio, Country A
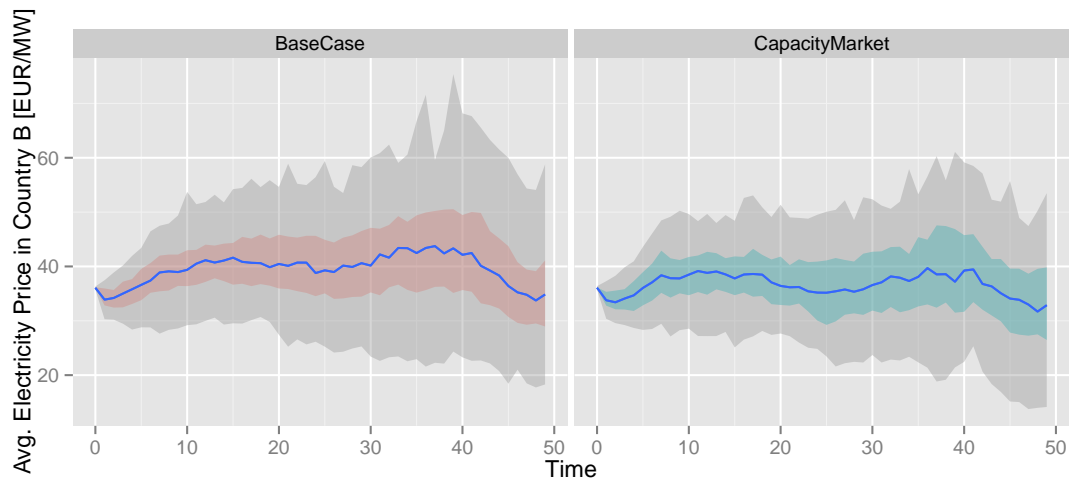
Figure E.48: Exp 4: Average Electricity Price, Country B

Figure E.49: Exp 4: Average Electricity Price, Country A
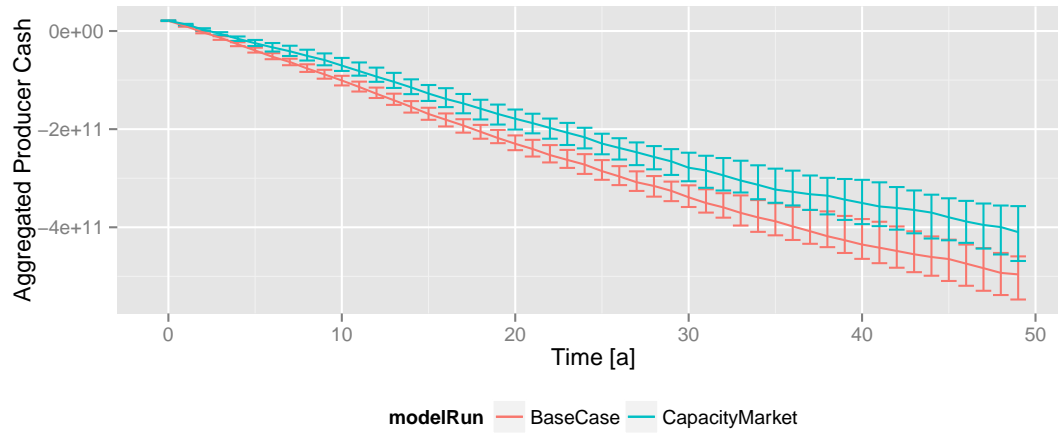
Figure E.50: Exp 4: Aggregate Producer Cash
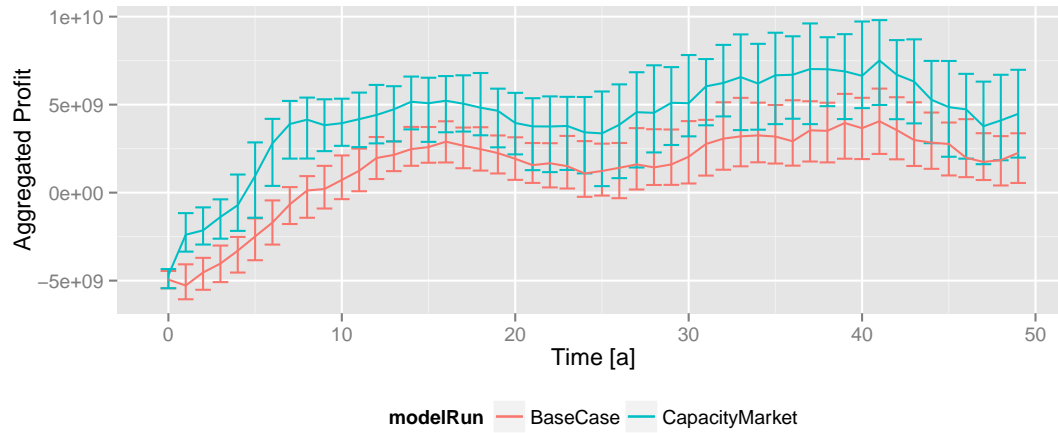
Figure E.51: Exp 4: Aggregate Producer Profit
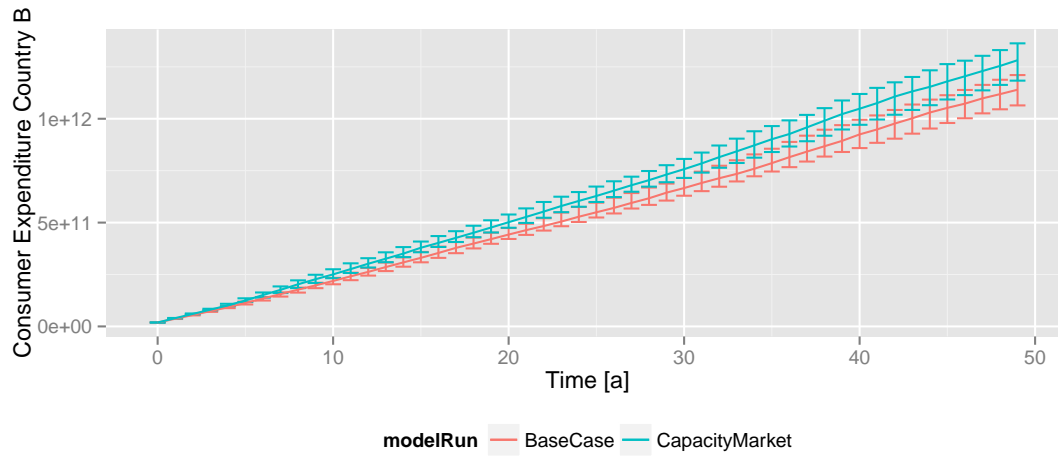
Figure E.52: Exp 4: Consumer Expenditure Country B

Figure E.53: Exp 4: Consumer Expenditure Country A
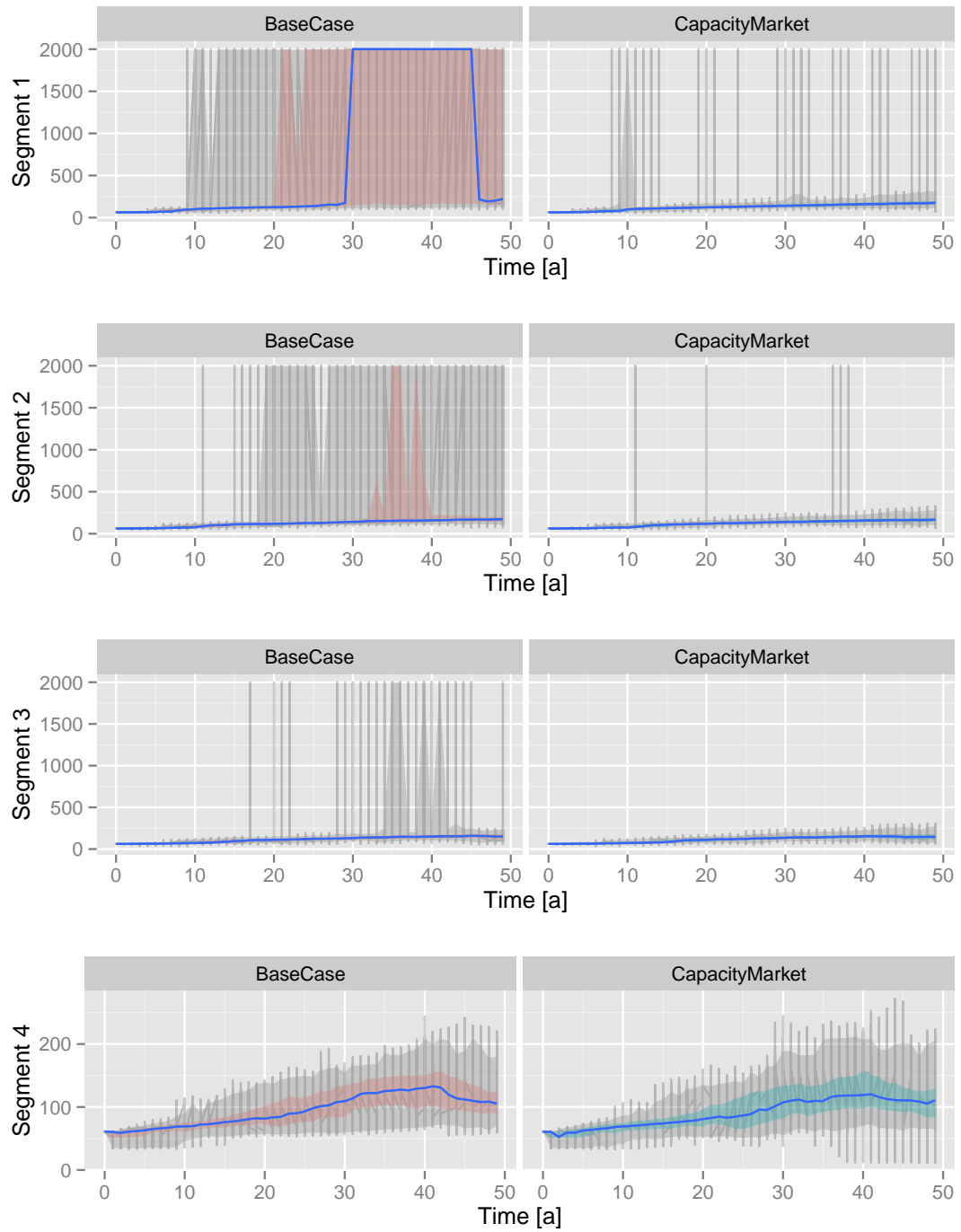
0.75

Figure E.54: Exp 4: Segment Prices Country B
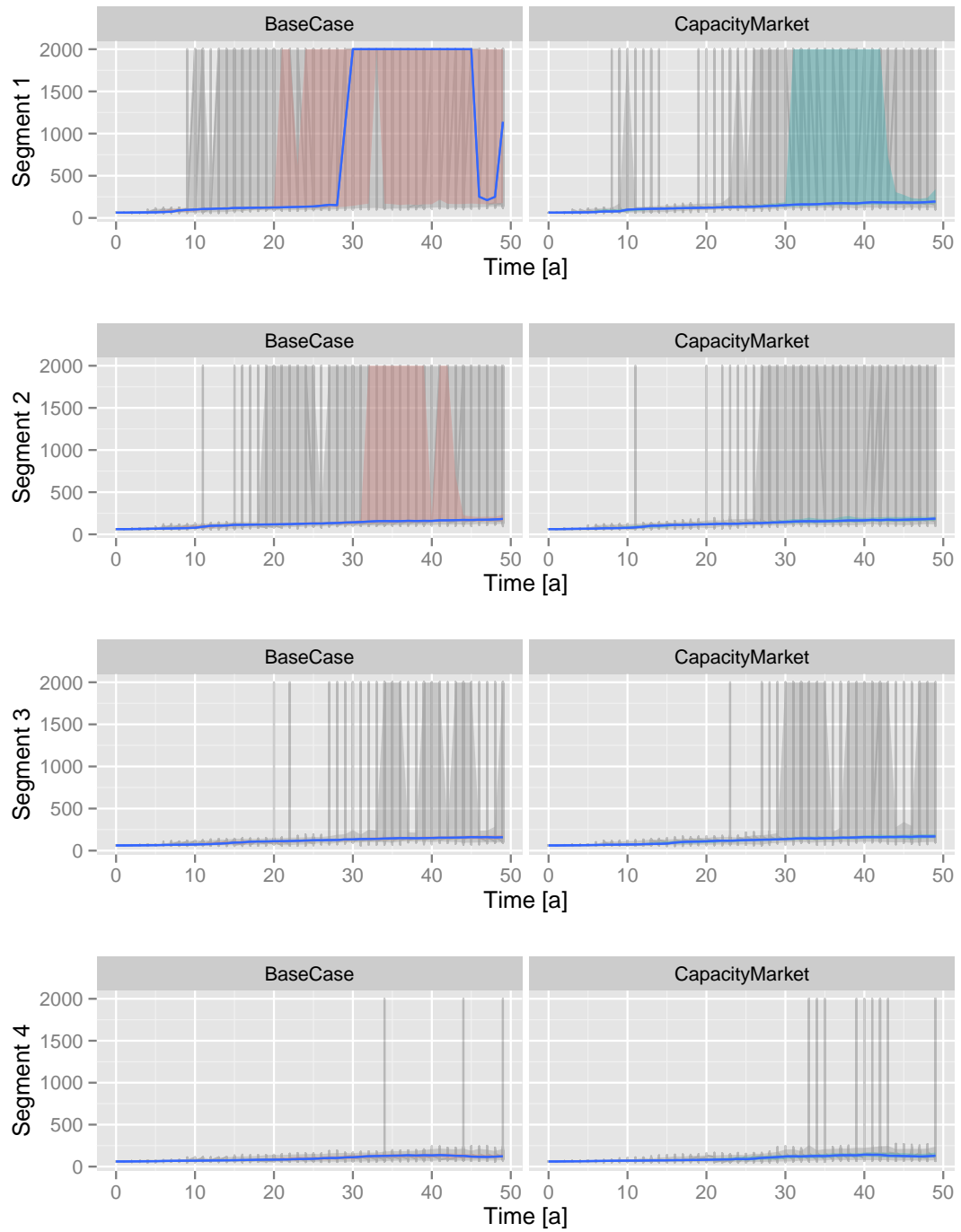
0.75

Figure E.55: Exp 4: Segment Prices Country A

Figure E.56: Exp 4: Capacity Market Clearing Price

Figure E.57: Exp 4: Capacity Market Clearing Volume

Figure E.58: Exp 4: Stacked Capacity Diagram Country B

Figure E.59: Exp 4: Stacked Capacity Diagram Country A
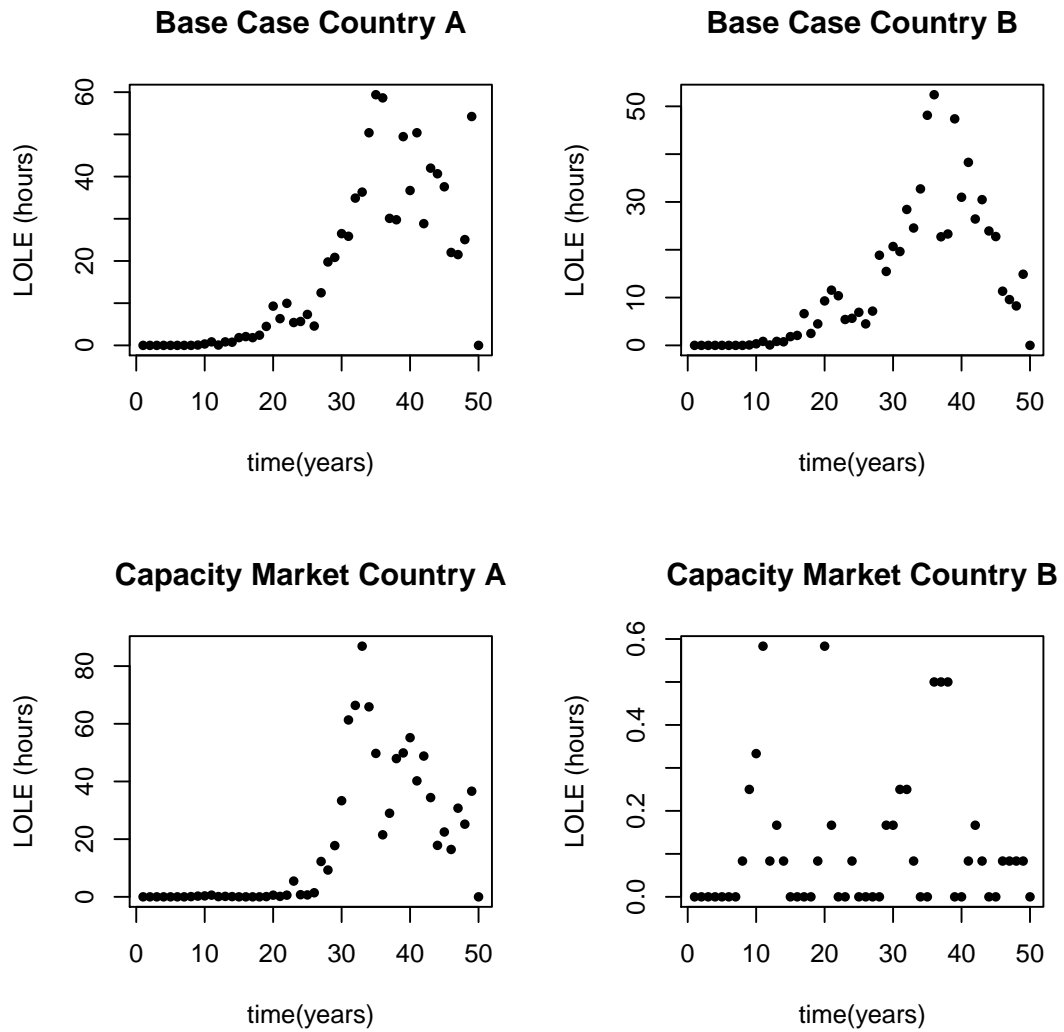
Figure E.60: Exp 5: Average Loss of Load Expectation
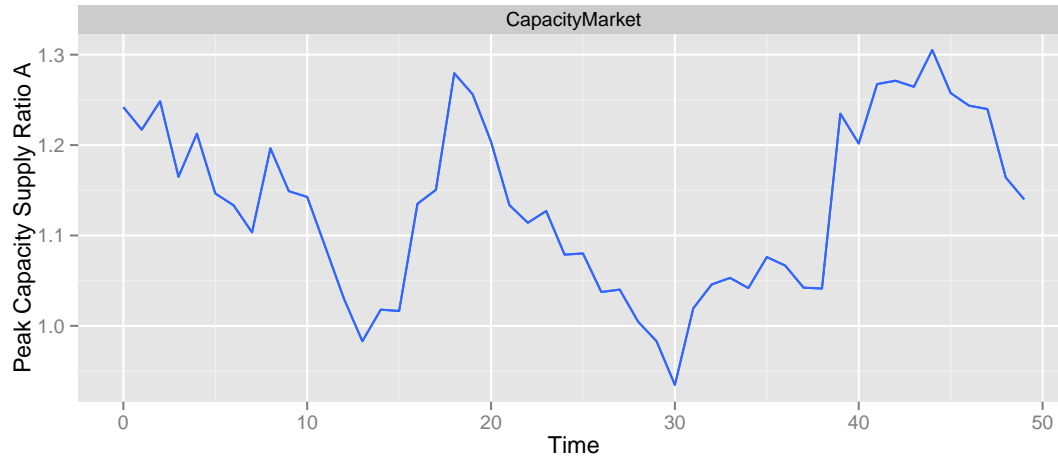
E.6 Experiment 2: with correction

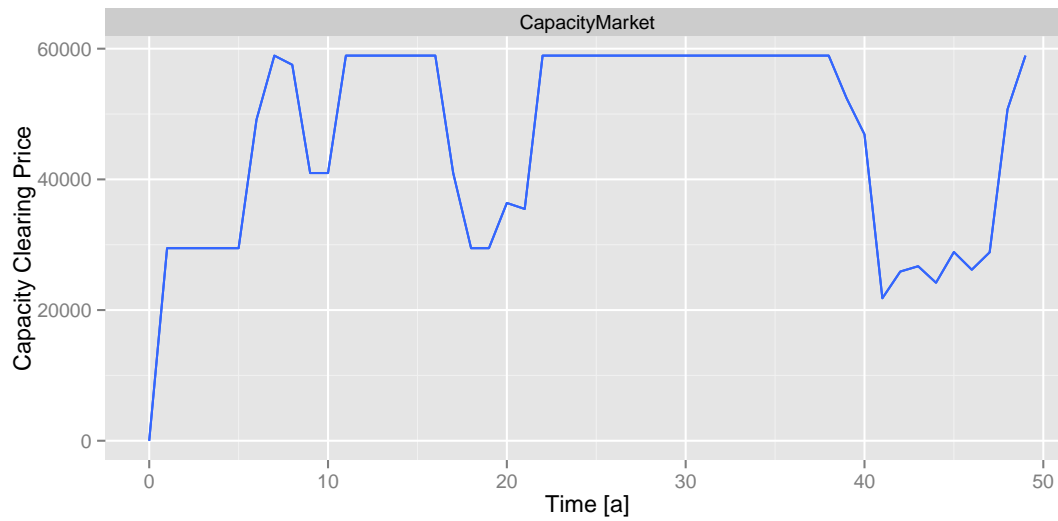Figure E.61: Exp 2a: Supply Ratio
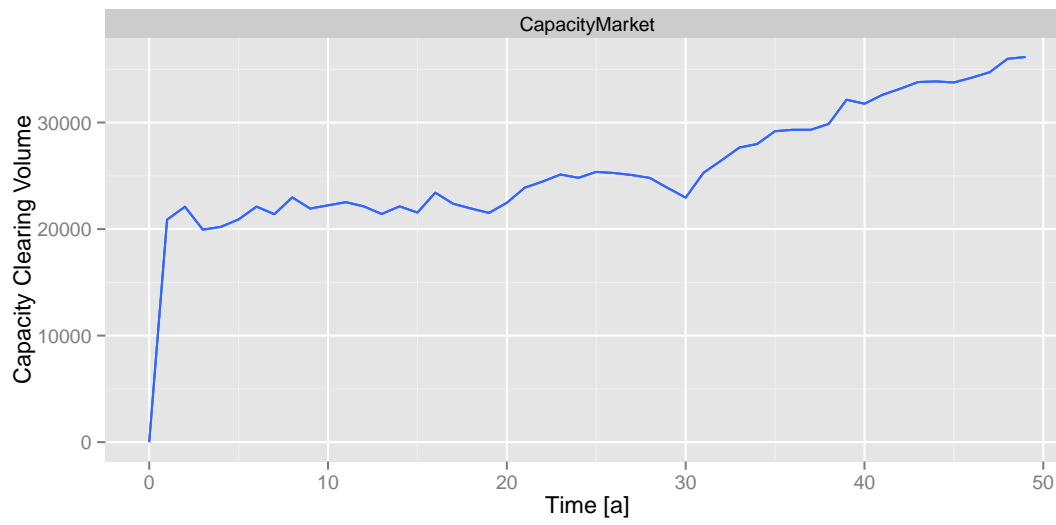

Figure E.62: Exp 2a: Capacity Market Clearing Price

Figure E.63: Exp 2a: Capacity Market Clearing Volume