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Electricity Distribution Networks Post-Liberalisation: Essays on Economic Regulation, Investment, Efficiency, and Business Model

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Abstract

This thesis investigates some of the key current economic and regulatory challenges pertaining to grid development. These issues include: investment drivers, the relationship between investment and static/dynamic efficiency, and integration of distributed energy resources as alternatives to traditional network reinforcement. The thesis comprises four essays and uses a range of techniques including theoretical and empirical analysis in Chapters 2, 3, and 4; as well as conceptual modelling in Chapter 5. A common feature of the first three chapters is the usage of a dataset composed of 129 Norwegian distribution companies, observed between 2004 and 2010.

The issue of investment determinants and the responsiveness of companies to the regulators' incentives for investment have been investigated in Chapter 2. This chapter uses a Bayesian Model Averaging technique (BMA) to identify the investment drivers in regulated firms. The results of the chapter provide an insight into investment behaviour of network companies under incentive regulation. The identified investment determinants shed light on the effectiveness of investment incentives and can be used to improve the process of capital cost treatment under incentive regulation.

A theoretical framework for the relationship between investment and efficiency, including the concept of "no impact efficiency", which is defined as the revenue-neutral efficiency effect of investment under total cost benchmarking, is introduced in Chapter 3. The observed efficiency effect of investment and no impact efficiency are estimated using a Stochastic Frontier Analysis (SFA) technique. The concept of no impact efficiency is important because it describes the process under which incentive

regulation, with ex-post regulatory treatment of investment, achieves investment optimality. It also provides a useful benchmark for the sector regulators to examine the investment efficiency of regulated firms.

Chapter 4 explores the concept of dynamic efficiency under incentive regulation. In this respect, the notion of "inefficiency persistence" due to presence of quasi-fixed inputs, under total cost benchmarking, is introduced. The theoretical framework shows that inefficiency of regulated companies is a combination of period-specific effects (shocks) and a carry-over component from previous periods due to sluggish adjustment of capital stocks and/or production capacity. The two components of inefficiency and the rate of inefficiency transmission between periods are estimated using a dynamic stochastic frontier model in a Bayesian framework. The results show that the persistence of inefficiency can seriously affect the companies' short run productivity and, consequently, regulated revenues. This can lead to disincentives for investment and innovation.

An innovative solution to the traditional demand-driven network investment is investigated in Chapter 5. The feasibility and advantages of adopting a portfolio of distributed energy resources including distributed generation, storage, demand response and energy efficiency as alternatives to grid capacity enhancement, have been discussed. Also, a market-oriented approach termed "contract for deferral scheme" (CDS) is introduced in order to integrate these resources under an extended business model of distribution companies. The CDS contract protects the developers of distributed resources from market risks, decreases the financing costs and improves commercial bankability of investments. Additionally, CDS acts as a proxy for vertical integration and helps distribution companies to improve the efficiency of their asset utilisation.

List of Publications

Chapter 2:

Poudineh, R. and Jamasb, T. (2014), "Determinants of Investments under Incentive Regulation: The Case of the Norwegian Electricity Distribution Networks", *Energy Economics* (forthcoming).

Chapter 3:

Poudineh, R. and Jamasb, T. (2015), "A New Perspective: Investment and Efficiency under Incentive Regulation", *Energy Journal* (forthcoming).

Chapter 4:

Poudineh, R., Emvalomatis, G., and Jamasb, T. (2014), "Dynamic Efficiency and Incentive Regulation: An Application to Electricity Distribution Networks", EPRG Working Paper No.1402, University of Cambridge.

Chapter 5:

Poudineh, R. and Jamasb, T. (2014), "Distributed Generation, Storage, Demand Response and Energy Efficiency as Alternatives to Grid Capacity Enhancement", *Energy Policy*, 67: 222-231.

Overall theme of the thesis:

Poudineh, R. and Jamasb, T. (2012), "Smart Grids and Energy Trilemma of Affordability, Reliability and Sustainability: The Inevitable Paradigm Shift in Power Sector", US Association for Energy Economics, USAEE Working Paper 2111643, July.

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List of Abbreviations

BMA	Bayesian Model Averaging
CDS	Contract for Defferal Scheme
CENS	Cost of Energy Not Supplied
CHP	Combined Heat and Power
COLS	Corrected Ordinary Least Square
DEA	Data Envelopment Analysis
DG	Distributed Generation
DNO	Distribution Network Operator
DSO	Distribution System Operator
EU	European Union
ECF	European Climate Foundation
EV	Electric Vehicles
GHG	Green House Gas
ISO	Independent System Operator
ISO NE	ISO New England
MCMC	Markov Chain Monte Carlo
NVE	Norwegian Water Resource and Energy Directorate
OFTO	Offshore Transmission Owner
PHEV	Plug In Hybrid Electric Vehicles
PIP	Posterior Inclusion Probability
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PMP	Posterior Model Probability
RAB	Regulatory Asset Base
RODG	Reliability Options for Distributed Generation
SFA	Stochastic Frontier Analysis
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
TSO	Tranmission System Operator

Declaration

I hereby confirm that the thesis submitted is based on my own research. The thesis also includes the results of joint publications in Chapter 2, 3, 4 and 5. In all these cases, the key ideas, primary contributions, modeling, empirical analysis and interpretation were performed by the author and the contribution of co-authors was primarily through the provision of the dataset, comments and feedback on the works. No part of this thesis has been submitted for a degree or any other qualification to any other university. Appropriate credit has been given within the thesis where reference has been made to the work of others.

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Dedicated to

the memory of my father

Chapter 1

Introduction

Access to a reliable electricity supply is an indispensable part of modern life. Traditionally, electricity services were provided by public utilities that owned the entire supply chain from generation to retail (Joskow, 2008). This arrangement of the power industry, although it might improve reliability as one organisation is responsible for management of the entire sector, suffers from deficiencies owing to lack of incentives for cost-reducing measures. The monopolistic nature of the industry and the lack of private ownership caused the cost of services to be higher than optimum.

The inefficiencies in the operation of utilities and the significant scope for cost-reducing measures were the driving force behind liberalisation of electricity markets at the end of 1980s (Newbery, 1997). This led to unbundling different elements of the publicly owned vertically integrated monopolies. In this way, generation and retail supply, which are potentially competitive, were separated from distribution and transmission which are proved to be natural monopolies. Thus, the power sector reform has been accompanied with the introduction of two markets and regulation of the network segment. The wholesale market was created to allow generators to compete in order to sell their produced energy. On the retail side, a market was formed to promote competition for end-user supply.

The liberalisation and privatisation brought along new challenges and opportunities to the power industry[1]. Form an economic perspective, the introduction of

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[1] The wave of power sector reform was not limited to developed countries as many of developing

competition in generation and retail supply would reduce the cost in these elements of the supply chain. The competitive pressure in a market with surplus of generation capacity can reduce electricity prices. There is evidence suggesting that market liberalisation has generally promoted cost efficiency of the sector (Newbery, 1997). At the grid level, however, the dynamics are different as the networks are natural monopolies and, therefore, subject to economic regulation (Jamasb and Pollitt, 2001). The regulation of network companies has always been a challenging task. The regulators around the world have adopted different incentive mechanisms to induce cost efficiency and mimic the outcome of a competitive market in this segment of the supply chain.

Reform and regulation of the electricity system is an on-going process, which aim at its transformation. This involves promotion of a sustainable power system through large scale integration of renewable resources, deployment of smart technologies, penetration of electric vehicles and enabling demand side participation. These, on the other hand, require ample amounts of investment and innovation in grid infrastructure as the networks need renewal, reinforcement and reconfiguration to support the transition toward a sustainable power system and, in consequence, a low carbon economy. The evolution of the operating paradigm in the power industry makes the distribution networks a crucial element of low carbon economies, which have a critical role to play in the smart and sustainable electricity sectors of the future. Therefore, a major current issue is the development of a modern, efficient and reliable grid that can pave the way towards achieving a sustainable economy.

Overview of the networks in the power sector

Power networks are the crucial component of power systems that transport elec-

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and transitional economies also started to implement these reforms. Although, in developing countries privatisation was received most attention, these countries also aimed at wider reforms such as market liberalisation and structural changes in terms of unbundling and introduction of new laws and regulation. However, issues such as lack of relevant institutions, independent regulator, expertise and quality data impede these countries to fully utilise the benefits of power sector reform.

tricity from resource-concentrated regions to load centres. Therefore, efficient, safe and reliable operation of the grid is critical. The grid includes two different networks for transmission and distribution that are separated based upon their voltage level. The transmission grid comprises high voltage circuits designed to transfer bulk power from major power plants to demand areas. The higher the voltage, the larger is the amount of power transferred though the lines. Hence, the step-up transformers are used to raise the voltage to the required level. The organisational arrangement of the transmission system in terms of ownership and control can be different across the countries. However, in many countries there is often one national company that owns the physical infrastructure. At the same time, transmission systems are operated by a Transmission System Operator (TSO) or Independent System Operator (ISO) (Pollitt, 2012). The management of the transmission grid is done through control centres known as “dispatch centre”, which balance the supply and demand and reconfigure the network to tackle planned and unplanned outages for every hour during the day. In addition to system operation, the ISO usually does the task of (wholesale) market operation as well.

The distribution grid, on the other hand, transfers power from the transmission grid to the end user and, ergo, works in low voltage. The step-down transformers are located at substations to reduce the voltage to a level suitable for distribution. Unlike the transmission function, the number of distribution companies in a given country can be high such that each one serves a specific region within the country. In each area, the distribution network is owned and managed by the regional Distribution Network Operator (DNO). The DNO is responsible for the efficient operation, reliability and safety of the network in accordance with the national regulation and other relevant standards practiced by the industry (Shaw et al., 2010). Distribution companies are also responsible for quality of electricity supply, based on the terms and conditions specified in their licence. Almost all the residential and commercial customers and many of the industrial consumers are connected to the distribution grid.

Although grid development involves all the elements from transmission to distribution, the main focus of this research is on the distribution network companies.

This is mainly because these networks have been experiencing a rapid change in recent years, as a result of sustainability policies. Distribution grids are originally designed as passive transporters of electrical energy. However, their operational philosophy is evolving to manage bi-directional power flows and the use of information and communication technologies in grid operation. Moreover, the penetration of distributed generation, electrical vehicles and storage facilities create techno-economic challenges which require grid reinforcement, technological improvement and the introduction of new business models for distribution utilities. Furthermore, distribution networks are the main points of interaction between the end user and the grid where many of the new concepts such as demand response, smart metering and consumer empowerment can be implemented. This involves changes in planning and operation at the distribution level.

The next section discusses the importance of grid and post-liberalisation challenges of the power sector. These challenges and the need for grid development are the main motivation of this research. Section 1.2 provides a brief review of the economic environment of network utilities as regulated natural monopolies. The objective of the thesis has been stated, in Section 1.3, with a view to the necessity for grid modernisation in the presence of a regulated environment, which influences the behaviour of network utilities. The thesis objective, then, has been narrowed down into four fundamental questions, which are addressed in Chapters 2, 3, 4 and 5 using appropriate methodologies and techniques, as outlined in Section 1.3.

1.1 Thesis motivation

Power sector reform, in the first place, was motivated by efficiency improvements in electricity supply. However, in the years following privatisation and market liberalisation, a new dimension of energy policy objectives, related to the concept of sustainability, emerged. This, along with previous policy objectives has originated an energy trilemma of affordability, reliability and sustainability. The support for sustainability was motivated by environmental concerns regarding the amount of fossil fuels consumption and their possible impact on the climate at regional and global levels. Therefore, the international community has endeavoured to reach an agreement which mandates effective measures, in relation to climate change mitigation, from all major economies.

These efforts led to the Kyoto protocol in 1997, which sets binding targets for 37 industrialised countries as well as the European Community to reduce greenhouse gas (GHG) emissions. The specified targets require these countries to reduce GHG emissions by an average of 5% with respect to the 1990 level (8% for EU15 countries) over the period of 2008-2012 (Capros et al., 2011).

Around 10 years later, in March 2007, in a landmark decision, EU leaders committed to make Europe a highly energy efficient and low carbon economy by setting ambitious targets (EC, 2008). These targets, which are known as 20-20-20, aim at: a) 20% reduction of greenhouse gases with respect to 1990 level, b) increasing the share of renewable consumption to 20% of the overall EU energy mix and c) improving EU energy efficiency by 20% (EC, 2007). The 20-20-20 target was later followed up with longer term commitments at the European level to address the issue of climate change. At the G8 summit in July 2009, European leaders announced another even more ambitious objective to reduce the greenhouse gases by at least 80% with respect to 1990 level by 2050 (ECF, 2010a).

Although the objective of a low carbon economy embraces all sectors in modern economies, the electricity sector is at the focal point of any strategy aiming at mitigating climate change. A significant portion of current CO_2 emissions is related to fossil fuels consumed in power generation. The European Climate Foundation (ECF) initiated a study to investigate the implications of the 2050 target for European industries and in particular the power sector. The result of this study showed that transition to a fully reliable and decarbonised electricity sector is a precondition to achieve 80% economy-wide emission reductions (ECF, 2010b).

Therefore, decarbonising the electricity sector plays a pivotal role in the path towards a sustainable economy. Achieving this goal entails promotion of large scale renewable energy resources, including onshore and offshore wind and photovoltaic cells, enabling effective demand side participation, deployment of smart technologies and empowering consumers to have more control over their energy consumption.

A green power sector, also makes electrifying the transport industry worthwhile. These, however, require an efficient and modern power grid which is able to support integration of renewable resources and also provides sufficient level of flexibility, reliability and resiliency.

The design and technology of the current electricity networks in many countries, and especially at the European level, date back to around half a century ago. Accordingly, these networks lack the required capacity, flexibility and resiliency to address the current and future challenges of the power sector. This problem, if unaddressed, will result in bottlenecks for renewable integration, congestion in the distribution networks, higher risks of power outages, loss of quality of supply and finally emission target failure. In what follows, we briefly review some of the most significant post-liberalisation challenges in the power sector, which affect the future development of the grid. These challenges include integration of renewable resources, smart grid deployment, market issues, network security and quality of supply. Some of these issues such as smart grid deployment, market issues and network security are not directly addressed in the thesis but they are still relevant to the overall discussion on grid development and rationalising the thesis objective.

1.1.1 Integration of renewables

A shift to renewable resources has been viewed as an effective measure of energy conservation and climate change deceleration, which can contribute significantly to CO_2 reduction by 2050 (IEA, 2011). At the European level, many countries have started to increase the share of renewables in their current energy mix. The European electricity generation from renewable resources has been doubled from 100 GW in 1995 to 200 GW in 2008 (Ruska and Kiviluoma, 2011). Although around half of the renewable generation capacity in 2008 was related to hydropower resources, wind power 25-folded over the aforementioned period and dominated the non-hydro renewable capacity (Ruska and Kiviluoma, 2011). Furthermore, in 2009, wind power reached 39% of newly installed generation capacity in the EU (EWEA, 2010). This made the year 2009 the second year in which wind power installation surpassed any other generation technology (EWEA, 2010). The fast penetration of renewable resources in the EU energy mix necessitates investment both in non-intermittent generation and grid modernisation.

The required average investment in order to meet 20-20-20 target, with respect to renewable resources is estimated to be between 61 to 70 billion Euro annually over the period 2011 to 2020 (Klessmann et al., 2013). The current level of expenditures and renewable development is different across the member states and therefore requires different levels of effort to achieve the renewable target. For example, in 2005, the share of renewable resources in gross final energy consumption ranged from 1% in Luxemburg to 42% in Sweden (Capros et al., 2011).

The rapid growth of renewable energy in recent years has driven the European network capacity to its limit and consequently has created several technical challenges which can hinder further penetration of these resources. Also, promising renewable resources, such as offshore wind, are located far from load centres and require grid expansion and reinforcement to transfer energy. Perhaps the lack of a sufficiently modern and developed grid to support renewable integration is among the most serious obstacles facing penetration of these resources. In practice, the European renewable targets, geographical restructuring of conventional power plants and projection of demand rise have already created bottlenecks in some regions as the network does not meet the $N-1$ reliability criteria due to 100-180% overload condition at times of high wind power (Battaglini et al., 2009).

1.1.2 Smart grid deployment

The increasing concerns with the capability of the current electricity grids to support a sustainable power system (through integration of renewable resources and the use of electric vehicles (EVs) as a clean replacement for conventional cars with combustion engine) heightens the interest in the notion of smart power grids. The basic concept of smart grid is to add monitoring, analysis, control, and digital communication capabilities to the electrical delivery systems to maximize the throughput of the system, technically and economically (Poudineh, 2012). The intelligent grid management, together with effective regulations, reduces the technical challenges of renewable energy integration and electric vehicles uptake. Overall, the areas of smart grid function include grid operation and utilisation optimisation, grid infrastructure optimisation, distributed resource integration, new market and end user services, ICT services on the grid, and active distribution network (Agrell et al., 2013).

The ability to match changing electricity demand and supply in real-time is vital for reliable operation of the power system, revenues of utilities, and security of supply. An increase in the share of intermittent renewables sources, in the generation mix, raises the stochastic characteristic of power supply. At the same time, the output of intermittent resources does not necessarily coincide with the demand. The development of a smart grid environment helps to absorb part of the supply variation (Clastres, 2011). This will be done through the adoption of smart technologies that facilitate access to dispatchable demand and supply resources for the purpose of system balancing.

Likewise, a shift to electrical vehicles (EVs) will increase demand for electricity which varies with respect to time and location. On the other hand, many of the existing electricity networks are not designed for the extra load from electric vehicles. This is because EVs will be a new load on distribution feeders while many of these circuits are already being operated at their maximum capacity. Thus, parts of the network on the medium and low voltage levels might be unable to deliver the demand and this can potentially disrupt grid stability and significantly affect power system dynamics (Webster, 1999).

It is expected that deployment of a smart grid environment will facilitate penetration of intermittent renewable resources and electric vehicles. Load control in a smart grid environment is done using demand response, local energy storage, consumption scheduling, real time pricing signals and local demand signals (Agrell et al., 2013). This means that by consolidating data from different sources (e.g., conventional generators, renewable resources, consumers and network operators and EVs) demand and supply are matched favourably for network security and sustainability (Webster, 1999).

1.1.3 Market issues

Technical challenges are not the only factors that require investment in power networks. There are also economic issues related to the electricity markets which call for grid development. An important precondition, among all other factors, for the well-functioning of an electricity market is the access of suppliers to the power network (Newbery, 2002). Presence of sufficient number of competing generation units to supply power requires an adequate transmission grid. Any network constraint fragments the electricity market and reduces the number of generators which compete to sell their energy in the submarkets (Newbery, 2002). In summary, the power transmission grid plays the role of facilitator in the electricity market. The configuration of the transmission network specifies the degree to which suppliers face competition for a given geographic distribution of demand. The expansion of transmission lines will increase the number of hours in a year that a supplier faces sufficient competition, which can place a downward pressure on market clearing price (Wolak, 2012).

Previous studies show that network capacity constraints increase the incentives for strategic behaviour in pursuit of increasing profit. For example, Borenstein et al.(2000) studied a two-node model of quantity-setting imperfect competition between two suppliers which are separated through finite transmission capacity and serve price-responsive demand at both nodes. They showed that, under the condition of limited transmission capacity between nodes, each firm has an incentive to restrict its output in order to create congestion in the transmission line into its local market in anticipation of a price increase. Moreover, they demonstrated that a moderate investment in transmission lines will raise the competitiveness of the market significantly.

The issues of network access and capacity constraints are crucial for integration of renewable resources as well. Promotion of competition among renewable technologies requires access to the distribution grid as they are often connected to low voltage networks. Along with traditional technical problems related to integration of these resources, the presence of sufficient network capacity is a necessity for the successful operation of the market. This is where the concept of smart grid and active network management can come to play an important role. Under the current planning and operation of distribution networks, the capacity to integrate renewable generation is limited, because this excess capacity often reserved for the purpose of addressing outages. Consequently, there is not enough capacity available to support a competitive market for renewable resources. All in all, network adequacy is an important part of promoting a competitive electricity market.

1.1.4 Network security and quality of supply

Due to the critical role of electricity supply in the well-functioning of the whole economy, uninterrupted availability of electricity is an indispensable part of energy policies. Meanwhile, more than 90% of interruption incidences are triggered in the distribution networks (Hammond and Waldron, 2008). Electricity supply can be affected by several factors, such as technical failures, accidental threats, natural disasters, manmade attacks to the network (cyber or physical) and risks related to the regulatory framework and organisation, including underinvestment and network pricing. Moreover, with the increase in intermittent renewable generation and demand, without having proportional network development, maintaining the security of the electricity network is expected to be more challenging than ever.

The issue of network security affects the consumers through quality of supply. Accordingly, regulators incentivise distribution companies to reduce power outages using, for example, quality-incorporated regulatory models or specific service quality targets (Jamasb et al., 2012). The strong interdependencies between the power industry and other critical infrastructures cause electricity supply perturbations to propagate to other sectors rapidly. This makes other sectors and consequently the whole economy dependent on the level of security measures taken in the electricity sector.

An increase in power system resiliency can potentially avoid or mitigate the adverse impact and cascading effects of electricity supply interruptions. However, resiliency enhancement requires system design, planning and adoption of smart technologies, which currently do not exist in many power grids. Furthermore, along with technical measures, network security and reliability require economic and regulatory measures (Heng et al., 2009) .

In order to withstand reasonable contingency and maintain the integrity of the system, an efficient network pricing model must be designed such that it reflects the cost imposed by new generation and load to the network. Also, timely investment and network reinforcement, along with efficient operation and utilisation of the grid are other important factors that significantly contribute towards network security. However, network companies are natural monopolies and their revenues are regulated. Therefore, in the long term, the risk of underinvestment in system resiliency and security are among the most significant threats to the operation of the grid (Nepal and Jamasb, 2013).

1.2 Economic regulation of networks

As discussed in the previous section, there is a range of factors such as renewable integration, market issues, network security, the need for a smart grid environment, and electric vehicle penetration that motivate development of a modern, reliable and resilient grid. Development of the grid comprehend various areas, such as investment in new technologies and grid expansion as well as innovative network solutions, the latter of which may require changes in the business model of distribution companies. In addition, the measures to develop the grid need to be consistent with regulatory framework as the revenues of natural monopolies are set by sector regulator.

A market with natural monopoly features makes the concentration of service provision in one single company more efficient than in two or more companies. The cost structure of these companies is such that capital cost dominates and hence, creates high economies of scale which results in barrier to new entry. The non-competitive nature of the network business creates several problems. Joskow (2005) argues that a natural monopoly suffers from various performance deficiencies such as productive inefficiency, excessive prices, poor quality of service and perhaps unwanted distributional effects.

Moreover, the lack of competition in this segment of the electricity supply chain has considerable impacts because network charges account for around one-third of the final electricity price (Jamasb and Pollitt, 2008). This highlights the need for an effective regulatory regime that prevents network utilities from monopoly pricing and discriminatory access charges and at the same time ensures an efficient production process for a given level of quantity and quality of service.

1.2.1 A brief summary of regulatory models

As mentioned previously, a characteristic of natural monopoly is that it exhibits a high economy of scale relative to the size of market. The presence of scale economies prevents the application of marginal cost pricing because the regulated company would not be able to recover its capital cost. Therefore, a great deal of discussion in the regulatory economics literature revolves around investigating the optimal pricing for regulated monopolies (Joskow, 2005).

Average pricing covers the capital costs of companies but it is not welfare maximising. Therefore, the economics literature suggests alternative second-best methods such as Ramsey pricing, in which the price is set to maximise social welfare subject to the firm's break even or balanced budget constraints (Currier, 1986; Joskow, 2005). Ramsey pricing is higher than marginal cost and it is inversely related to the product's elasticity of demand. Thus, this relationship allows the supplier for third-degree price discrimination in the sense that the same product can be sold with a higher price to those consumers with lower elasticity of demand (Shepherd, 1992; Joskow, 2005).

Another form of price setting for the products of a regulated firm is a two-part tariff in which consumer pays a fixed cost as well as a variable cost which depends on the units consumed. From an efficiency perspective the two-part tariff does a better job compared with second best Ramsey pricing when consumers are identical and the fixed part is small compared to the net surplus after consumer pays marginal cost (Joskow, 2005). Under the condition of diverse customers, the regulator can set a variant of two-part tariff in which consumers can choose from the menu of tariffs that are different in the fixed and variable parts (Joskow, 2005). The consumers with lower demand can choose the tariff with lower fixed cost while the high demand consumers can opt for the tariff with lower variable cost. This reduces the distortion in social welfare compared with a fixed two-part tariff.

The optimal pricing models heavily rely on the assumption of a fully informed regulator which has the same information as the firms do about their cost structure and consumers demand (Joskow, 2005). However, in reality, the presence of asymmetric information between the regulator and regulated firms makes the application of optimal pricing impracticable. Therefore, alternative regulatory models have been considered to address the problem of uninformed or imperfectly informed regulator.

The rate of return or cost of service regulation has been traditionally the main method of regulating network utilities. It is based on an approach in which the companies are reimbursed for their costs, based on a "reasonable" rate of return which is at least equal to the cost of capital (Gilbert and Newbery, 1994). At the early stage of power sector reforms this regulatory model was more appealing because of the incentives for investment. However, the main criticism of the rate of return regulation is that it reimburses the companies for their "costs" rather than "performance" and therefore it does not promote efficiency in the production process. Moreover, setting the right level of the regulatory asset base and also defining reasonable rate of return can be sources of dispute between regulator and network utilities.

The dissatisfaction with rate of return regulation led to new forms of regulatory regimes in which the emphasis was placed on the cost-reducing incentives and performance-based revenue setting. This regulatory strand is known as "incentive regulation". As noted in Jamasb and Pollitt (2001), the emergence of incentive regulation was not the result of new contributions from economic theory but rather was the result of the need for practical approaches to induce cost-reducing measures in pursuit of efficiency gains in natural monopolies.

The most employed models of incentive regulation are price cap, revenue cap, yardstick regulation, targeted-incentive models, sliding scale, menu of contracts, and partial cost adjustment (Jamasb and Pollitt, 2007). A common feature among all these forms is to achieve cost efficiency through penalty and reward schemes[2]. At

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[2] Apart from the aforementioned incentive regulation models to incentivise cost efficiency and

the same time, regulators need to ensure that consumers will benefit from efficiency gains in operating and investment expenditures of these companies.

Asymmetric information between the regulator and regulated company is a key issue in the regulation of natural monopolies (Jamasb, et al., 2004). Due to the presence of this problem, efficiency and productivity analysis, based on sector information, is an indispensable part of incentive regulation. This is to strike a balance between firms own information and sector information by comparing them against their peers. This allows the regulator to extract more information on the cost structure of network companies. Nevertheless, it complicates the process of revenue and tariff setting because the choice of a benchmarking technique, estimation procedure and interpretation of results are not straightforward.

1.3 Thesis objective

There is compelling evidence which suggests that the environmental policies for promotion of renewable share in the European energy mix will not proceed without proportional development of technically capable electricity grids. At the same time, in many countries network companies are regulated on the basis of incentive regulation aided by efficiency and productivity analysis. Thus, given the characteristics of incentive regulation, it is important to analyse the behaviour of distribution companies in order to understand and identify the possible barriers to the objective of grid development.

Additionally, the fact that environmental policies will change the configuration of power sector suggests that distribution companies need to adapt to an environment with high penetration of distributed energy resources. This requires a shift in the traditional operating paradigm and also the business model of these companies. This is because network utilities are often considered as passive transporters of electrical

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service quality in electricity networks, there are other forms of regulations in the power sector to address the issues such as environmental commitments/constraints of generation facilities. For these, regulator might use a wide range of instruments such as mandatory targets, voluntary schemes or even taxes.

energy with their revenues being based on the connection and use of system charges. However, renewable resources penetration, close to the site of demand, will reduce the volume of energy transported in the grid and hence, may adversely affect the companies' revenue.

Given this background, the objective of this research is to investigate the economic, regulatory and policy issues related to grid development and analyse their impact on the behaviour of distribution companies. These issues include investment, static and dynamic efficiency, and the development of an innovative business model to integrate distributed energy resources as alternatives to network reinforcement. The objective of this research can be broken down into more specific research questions, as follow:

I) How do network companies respond to the regulator's incentives to maintain and modernise the grid? What are the determinants of investments under incentive regulation?

II) Given that incentive regulation aims at improving cost efficiency whereas investment raises costs, what is the relationship between investment and cost efficiency under an incentive regulation framework?

III) How does incentive regulation address the long term nature of investment and innovation? Does incentive regulation, with the current forms of regulatory treatment of investment, lead to a dynamically efficient behaviour among the regulated firms?

IV) How can distribution companies adapt to an environment with high penetration of distributed energy resources? Is there a way to take advantage of the synergy between increasing penetration of distributed resources, on the one hand, and the need for network investment on the other hand? What is the appropriate business model to adopt this innovative solution as an alternative to traditional network reinforcement?

1.3.1 Thesis outline

This thesis comprises six chapters. Apart from the Introduction and Conclusions, the remaining four chapters address the above research questions. Chapters 2, 3 and 4 utilise a panel data set of 129 Norwegian distribution companies observed from 2004 to 2010.

The next chapter deals with the issue of investment determinants under incentive regulation. It reviews the investment and associated incentives in distribution networks. The review of state-of-the-art literature also informs the choice of the empirical model which is based on a Bayesian Model Averaging (BMA) technique. The identified investment determinants provide an understanding of investment behaviour under incentive regulation.

Chapter 3 investigates the relationship between investment and cost efficiency under incentive regulation. The issue of investment efficiency and regulatory treatment of investment are explored through a literature survey. A theoretical framework for the relationship between investment and efficiency including the concept of “no impact efficiency”, as the revenue neutral efficiency effect of investment under total cost benchmarking, is introduced. The observed efficiency effect of investment and no impact efficiency are estimated using a Stochastic Frontier Analysis (SFA) technique. This chapter also discusses the implications of cost benchmarking for the investment behaviour of distribution companies.

Chapter 4 addresses the issue of the dynamic aspects of firm behaviour and explores the concept of dynamic efficiency under incentive regulation. The chapter reviews the most recent and relevant literature on dynamic efficiency measurement and tries to bridge the gap by applying theoretical and empirical models to a regulated industry. In this respect, the notion of inefficiency persistence due to the presence of quasi-fixed inputs under total cost benchmarking is introduced. The theoretical framework shows that inefficiency of regulated companies is a combination of period specific effects (shocks) and a carry-over component which is related to the sluggish adjustment of capital stock and/or production capacity. The two components of inefficiency and the rate of inefficiency transmission between periods are estimated using a dynamic stochastic frontier model in a Bayesian framework.

An innovative solution to the traditional demand driven network investment is investigated in Chapter 5. This chapter begins with the necessity of reducing deficiency in traditional network reinforcement and reviews the previous works on the impact of distributed resources on investment deferral. The methodological approach of the chapter is qualitative and based upon critical analysis of literature and development of a conceptual model. The feasibility and regulatory challenges of adopting a portfolio of distributed resources including demand response, energy efficiency, storage and distributed generation as alternatives to grid capacity enhancement have been discussed. Also, a new method to integrate these resources under a three stage market-oriented approach termed "contract for deferral scheme" (CDS) is introduced. Moreover, as penetration of renewables might lead to the shrinkage of the revenue base in distribution companies, an extended business model for these companies has been suggested.

Finally, Chapter 6 presents the concluding remarks of the thesis. It synthesises the main findings and discussions from the previous chapters, making explicit reference to the stated research questions, and attempts to draw scientific conclusions, considering the limitations of this research.

Chapter 2

Determinants of investment under incentive regulation

Electricity networks are capital intensive and exhibit natural monopoly characteristics and are, therefore, subject to economic regulation. In recent years, the need for network expansion, integration of renewable energy resources, enabling demand side participation, and adoption of new technologies such as deployment of smart meters and smart grids has necessitated significant amount of investments in the grid. This has placed the issue of network investment at the core of recent energy policies and regulations in the power sector. The objective is to ensure sufficient investment in maintaining and modernising the grid and at the same time avoiding inefficiency in capital expenditures in order to protect the end-users against high electricity prices. This is because, in some countries, nearly one-third of final electricity prices are related to distribution and transmission network charges (Pollitt and Bialek, 2008) and investments lead to higher consumer bills.

The investment behaviour of firms in a competitive market is among the most studied areas of economics (Jorgenson, 1967). However, the results of competitive market may not be directly applicable to regulated industries such as network utilities. This is because investments in electricity networks, as regulated natural monopolies, are not driven by market signals where decisions are based upon the expected returns being higher than the incurred cost of capital. Instead, investments in networks companies respond to the regulatory framework and institutional constraints (Vogelsang, 2002; Crew and Kleindorfer, 1996). Therefore, regulators adopt various incentive mechanisms to ensure that there is no systematic underinvestment which jeopardises the reliability of grid.

The challenge of regulation is to provide effective incentives for delivery of right quality of services while reassuring investors of the profitability of economically justified investments (Newbery, 2004). The advantages of an effective regulatory framework include lower network costs, quality of service improvement, support of competitive wholesale and retail electricity markets and encouraging investments to address the changes in supply and demand for electricity services (Joskow, 2008). As a consequence, identifying the main drivers of investments can help regulators to understand the responsiveness of firms to regulatory incentives and hence, more effectively tackle the issue of investments under incentive regulation.

Despite the importance of investments in regulated industries, the empirical literature on the issue is rather finite. The current studies, except the work by Kinnunen (2006) which investigated the investment drivers in Finish electricity networks, do not analyse investment response to regulatory incentives. Instead the empirical research papers mainly aim to model the effect of certain regulatory features on investment. For example, some studies have attempted to explore the effect of public versus private ownership or unbundling of network utilities on investment (see, e.g., Gugler et al., 2013; Nardi, 2012). Another strand of literature has attempted to conduct cross country analysis in order to explore the effect of different regulatory regimes on investment (see, e.g., Cambini, and Rondi, 2010; Gugler et al., 2013). Also, some studies analyse investment indirectly as the cost of quality of supply improvement (see, e.g., Coelli et al., 2013; Jamasb et al., 2012).

Therefore, little effort has been made to identify and analyse the determinants of investments in electricity networks under incentive regulation. This chapter investigates the key factors that drive the amount and direction of the investments in electricity distribution networks using a case study of the Norwegian network utilities.The next section discusses network investment and associated incentives under regulation. Section 2.2 presents the empirical analysis. It briefly reviews the power sector reform and regulatory framework in Norway and then describes the methodology and data used in empirical analysis. The empirical method is based on a Bayesian Model Averaging technique. The results and discussion of major findings are presented in Section 2.3. Section 2.4 is conclusions.

2.1 Investment in electricity distribution networks

Electricity distribution companies are responsible to deliver energy to the end users and hence, they are required to have a reliable and available network at all times. These obligations are usually stated in the countries' regulation and standard of practice for the power sector. In the UK, for example, under the Electricity Act of 1989 which later modified by Utilities Act in 2000, distribution companies are obliged to support and facilitate a market-oriented electricity sector through developing and maintaining an economically and technically efficient distribution system (Shaw et al., 2010). The companies are also required to comply with additional standards such as those related to the environment, security of supply, safety and customer service. These challenges necessitate an investment plan that helps network companies to achieve their performance targets and at the same time ensure all statutory and legal responsibilities are met.

There are several technical and non-technical factors that can potentially drive investment in distribution network companies. The number of connected consumers and distribution of load, in a specific region, can change and hence require network reinforcement (Blokhuis et al., 2011). In these cases, distribution companies identify development of new residential or commercial sites, within their network area, and forecast future demand by taking into account the general macroeconomic and market conditions. Thus, a non-trivial part of investment of distribution companies is related to demand for new connections.

At the same time, the load profile of the existing customers can change and, over time, lead to lower or higher demand for electricity. For example, consumers may use more energy efficient equipment or appliances and therefore, cause the demand for electricity to decline. Similarly, consumers can use larger appliances and cause the demand for electricity to rise. Under the conditions that the load growth pushes the grid capacity to its limit, distribution companies need to carry out general reinforcement to enhance network capacity (Poudineh and Jamasb, 2014a).

The need for connection of supply side resources such as distributed generation is also another investment driver of distribution companies. Distributed generations mainly comprise renewable resources and combined heat and power (CHP) plants which are connected to distribution network and can bring the network to its operational limit (Vovos and Bialek, 2007).

Network companies are also responsible for quality of service and reliability of electricity supply at distribution level (Giannakis et al., 2005). This means the companies need to reduce progressively the frequency and duration of electricity supply interruptions as well as the number of affected consumers. The networks often experience technical faults which, in the worst case, can lead to power cuts. Thus, appropriate investment measures needs to be taken in order to rectify these faults which may damage consumers' appliances. In this respect distribution companies need to carry out frequent inspection and maintenance of network assets to ensure all devices work properly and provide a highly reliable service. This is specifically important with respect to those assets that are required to be switched off for maintenance. This is because due to asset specificity and the lack of redundancy their availability directly affects security of supply. Investment in remote control and power distribution automation systems are part of the solution to the network reliability (Liu et al. 2006). These systems send warning signals to replace the non-functional and faulty equipment and hence, can minimise the disruption to the consumers.

External factors can also necessitate network investment because they affect the operation of gird. For example, extreme weather conditions or proximity of distribution lines to trees increase the likelihood of power disruption (e.g., falling tree in the storm). In these instances, investment is necessary to protect the overhead lines against the risk posed by extreme events. The network companies are also required to invest in order to improve safety of grid. This, for example, includes horizontal and vertical clearance of overhead lines in accordance with national and international electricity standards and also protection of the equipment from theft and vandalism. This is because the increase in price of metals, in recent years, has made the distribution substations attractive targets for metalwork larceny.

Another important driver of investment, in electricity distribution companies, is network energy losses. Around 5% of electrical energy is lost in the distribution system due to conductors' natural resistance and/or technical problems (Shaw et al., 2010). Apart from the issue of energy inefficiency, these energy losses account for around 95% of operational CO_2 emission of distribution network companies (Shaw et al., 2010). Thus, network energy losses need to be reduced to the minimum feasible level.

The investment drivers in distribution network companies are not confined to technical problems. Non-technical factors can also potentially lead to capital investment. For example, network companies may need to invest in costly underground cables in order to avoid disturbing natural beauty areas or to reduce public opposition with respect to infrastructure development at local communities' proximity (Steinbach, 2013). Additionally, environmental legislation compliances such as reducing noise or oil leakage in substation can drive investments. Furthermore, distribution companies undertake investment in R&D activities and also facilities that support delivery of operational projects (e.g., buildings, computers, etc.).

2.1.1 Investment incentives under regulation

In order to enable distribution network companies to maintain their network, comply with regulation and standards and provide an acceptable quality of supply, the regulatory framework needs to incentivise "investment sufficiency". A "reasonable" rate of return on capital is a major incentive for network companies to undertake investment. The allowed rate of return, for efficient financing, is based upon the capital stock employed in production process and is at least equal to the estimated costs of capital of the notional company (Ofgem, 2013). The financing process is usually a combination of debt and equity and thence, a weighted average cost of capital (WACC) is calculated given different capitals have different costs of acquiring. Depending on the regulatory framework, the low risk and protected monopoly nature of the sector can cause the rate of return to be lower than unregulated companies

(Kinnunen, 2006).

However, the return on capital may not be sufficient to incentivise investment. This is because, for example, in remote rural areas the investment cost is usually higher and this can squeeze the companies' profits. Thus, in many countries, the regulatory frameworks are backed by legislations which oblige network companies to provide a fair and non-discriminatory grid access for both load and generations. These legislations also, oblige transmission system operator (TSO) to ensure that demand is met at all times. Under these legislations distribution network companies are legally responsible to maintain the connection of the current consumers and generation sources as well as those of new entrants who require grid access. These direct regulations play an important role in persuading network companies to undertake certain type of investment which may not be sufficiently incentivised through indirect incentive regulation.

Along with the incentives provided by return on capital and direct regulations, regulators often adopt additional instruments to ensure security of electricity supply. The need for additional instruments is highlighted when taking into consideration that the main aim of the incentive regulation is to promote cost efficiency. The incentive for cost reduction raises concerns about achieving cost efficiency at the expense of service quality. Thus, additional ad hoc instruments are designed to incentivise firms to improve their service quality by undertaking necessary investments. These incentives are normally provided through different approaches such as: (i) marginal reward and penalties, (ii) absolute fines, and (iii) quality incorporated regulatory models (Giannakis et al., 2005).

The marginal reward and penalties is based on the idea that the firm is rewarded or penalised for each unit of marginal improvement or decline in quality of service. Thus, firms undertake investments to the point where marginal benefit of quality improvement equals to the marginal cost of quality, at which point optimality will be achieved. In absolute fines approach regulator sets a target for service quality. A company that falls short of the target level will be penalised based on a predetermined amount per unit of service quality. Therefore, the firm has incentive to undertake investment in order to deliver the minimum required quality of service.

Finally, the quality incorporated regulatory models treat service quality as an integral part of regulation. For example, some countries evaluate the cost of energy not supplied at "consumer willingness to pay for reliable services" and add this to other cost categories when the companies' efficiencies are estimated. The companies' revenues, then, are set based upon their efficiency level. The quality incorporated regulatory model promotes competition among the firms for delivering the bundle of quantity and quality of service. This is because the firms will be rewarded or penalised when they outperform or underperform their peer respectively.

In a similar manner, regulators incentivise distribution companies to reduce network energy losses. The approaches for reducing network energy losses are similar to the case of service quality except that energy losses are often evaluated at a different price (e.g., system price) compared with energy not served.

2.2 Empirical analysis: The case of Norway

In this section the investment determinants of distribution networks are analysed, empirically, using the case of distribution network companies in Norway. First, a brief review of power sector reform and regulatory model in Norway is provided. Then, the empirical models and data are discussed.

2.2.1 Power sector reform and network regulation in Norway

Norway was among the first countries, after Chile and the UK, which embarked on power sector reform by unbundling the different elements of the electricity industry across the value chain. The generation and retail supply which are potentially competitive were separated from the transmission and distribution that are natural monopolies. Therefore, the distribution and transmission networks are subject to economic regulation. The Norwegian Water Resource and Energy Directorate (NVE)(Norges vassdrags- og energidirektorat) were appointed as the sector regulator since Norwegian Energy Act came into effect in 1991. Unlike the other countries where the regulatory reform was often accompanied by transfer of ownership, the

Norwegian power industry mainly remained under the state or local municipalities' control after the reform. Also, companies that are involved in both monopolistic (distribution or regional transmission) and competitive businesses (generation or retail supply) are required to keep them separated legally and/or financially[1].

At the early years of the reform, there were approximately 230 distribution networks and 70 generation units in Norway. The high number of utilities reflects the dispersed nature of the hydroelectric resources as the main source of power generation as well as the historical development of the sector in the country. In December 2010, around 167 companies were engaged in grid operation (NVE, 2010). The marked reduction in the number of distribution companies is the result of mergers and acquisitions among the network companies in pursuit of scale efficiency and other gains.

After the reform, initially, the distribution companies were operating under a rate of return regulatory regime. However, due to the lack of incentives for cost efficiency, since 1997, the regulatory regime was changed to incentive regulation. From 2007, NVE has implemented a new regulatory model which uses the Data Envelopment Analysis (DEA) as efficiency and cost benchmarking method (for details of DEA method see Charnes et al., 1978; O.Fried et al., 2008). The networks companies are regulated with a revenue cap regime that covers their costs annually based on their distance from the efficient frontier (best practice) in the sector.

Therefore, the Norwegian incentive regulation model treats investment in an ex-post manner. In this way the regulator sums all the costs incurred to the company including operating, capital and other controllable expenditures to construct one variable that reflects total cost. The total cost is, then, benchmarked against peer to obtain the efficient cost level. The revenue is set based on a weighted average of actual and benchmarked costs.

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[1] In 2010, about 67 companies were involved in generation, grid operation, and supply to the end users. Vertically integrated companies with more than 100,000 customers are obliged to separate their monopolistic operation from competitive activities (legal unbundling) (NVE, 2010). Also, the Energy Act requires the integrated companies to keep separate accounts for their monopoly and competitive businesses (NVE, 2010).

2.2.2 Investments under Norwegian regulatory regime

The investment incentives, under Norwegian regulatory regimes, are provided through a combination of economic and direct regulation (NordREG, 2011). Along with profit motivation, the network companies need to undertake substantial investments in order to meet their obligations as stated in the Energy Act. For example, Section 3-4 of the amended Energy Act states that distribution companies are obliged to connect new generation sources and consumers that are not covered by the supply requirement. In addition, a profit incentive is provided through a minimum guaranteed return on capital. The regulation states that all companies should achieve a reasonable (minimum 2%) return on capital, given effective management, utilization, and development of the networks[2].

The Norwegian regulator uses a quality incorporated regulatory model. The cost of energy not served (CENS) and network energy losses are included in the benchmarking model in order to provide incentives for service quality improvement and reducing energy losses. Moreover, regulator also deducts the CENS from the firms' revenue at the final stage of revenue setting. This is to strengthen the incentives for service quality improvement and prevent underinvestment. At the same time, under the Norwegian regulatory regime, investments are restrained indirectly such that overcapitalisation can lead to deviation from efficient frontier and consequently partial disallowance of investment costs (Poudineh and Jamasb 2013a).

Figure 2.1 shows total investments, new investments, and reinvestments by the Norwegian distribution companies between 2004 and 2010[3]. As shown in the figure, total investments are strictly increasing since 2006. The investment data indicates that the source of the increase is the reinvestments and not the new investments. Although new investments remained almost constant, they have had a higher share in total investments than reinvestments. For instance, 68% of the investments observations, during the period of study, have a share of new investments to total

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[2] A network that falls below this minimum level will receive a correction in its revenue to achieve a minimum 2% return on capital. The normal rate of return for Norwegian distribution networks is currently 5.62%.

[3] New investments and reinvestments can happen simultaneously in reinforcement projects.

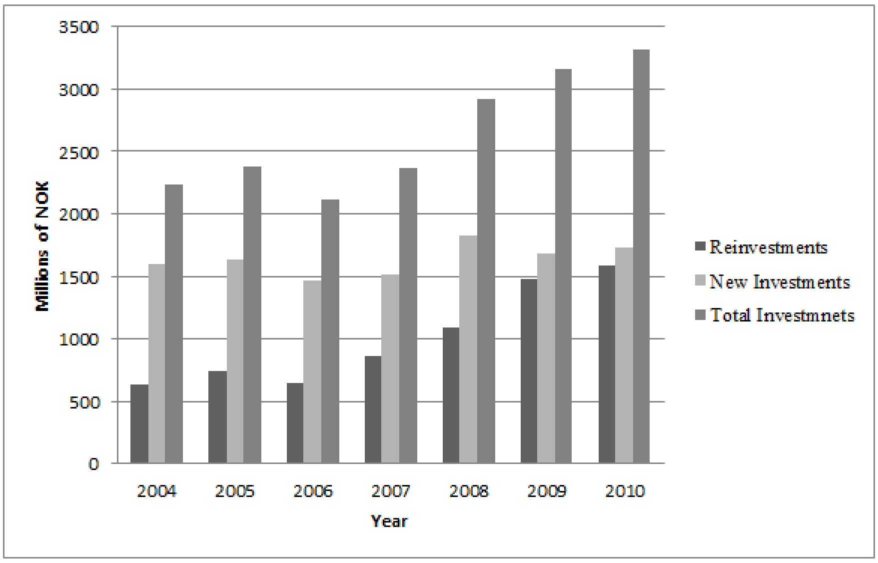

Figure 2.1: Investments in Norwegian distribution companies

investments higher than 50%. This can be an indication of strong investment incentives which have motivated some networks to undertake new investments, possibly beyond their minimum reinvestment needs. Such a change can be attributed to the view that social costs of underinvestment are higher than social benefits of overinvestment (Helm and Thompson, 1991).

2.2.3 Methodology

The classical investment models mainly revolve around the concept of Tobin's q which is defined as the ratio of the firm value in the stock market over the replacement value of installed stock of capital (Cuthbertson and Gasparro, 1995). The firm's Tobin q can be measured by regression and, in a pure theoretical form, should be a sufficient statistic for explaining the investment behaviour of firms (Cuthbertson and Gasparro, 1995). However, subsequent empirical models of adjustment cost showed that also other factors such as capacity utilisation, profit, cash flow and government investment policies have an independent effect on investment apart from their effect on q.

Moreover, Tobin's q models are developed in the context of competitive markets where the firms respond to the market signals whereas the regulated industries respond to the regulatory frameworks incentives. Additionally, in regulated industries such as electricity sector demand is inelastic, return on capital is guaranteed given the satisfactory performance of firm, and the industry is generally immune from the boom and bust of business cycle, due to protective role of regulation. Therefore, in a regulated environment, the factors that influence investment decision of the firms are not easily predictable especially if the firms are subject to a combination of incentives. Thus, due to the uncertainty around the response of the regulated firms to different incentive instruments we use a Bayesian Model Averaging (BMA) technique.

BMA is a powerful tool to examine the extent to which inclusion of a given factor improves the explanatory power of estimated models. The literature on the application of the Bayesian approach to investment analysis of electric utilities is limited but not new. Egert (2009) uses BMA to explore the effect of macro-factors such as joint introduction of independent regulator and incentive regulation on sector level investments. Peck (1974) employs a Bayesian method in order to investigate the association between return to scale characteristic and lumpy investments. He compares this with the result of a distributed lag model that complies with the smooth investment behaviour. In the present study we use BMA to examine possible factors that constitute firm level determinants of investments under incentive regulation.

BMA estimates the parameters of interest conditional on each model in the model space and then computes the unconditional estimates based on weighted average of these conditional estimates. The model averaging estimator takes into account the uncertainties around model selection and estimation whereas conventional estimators are based upon preliminary diagnostic tests. Hence, BMA provides a more robust method of inference on regression parameters. This is particularly relevant in the context of regulated networks where the regulator needs to take into account the shortcomings and revenue implications of using a specific model for a relatively heterogeneous set of networks. Hence, a practical approach by regulators to model selection can be to use the average of competing models (Jamasb et al., 2004).

The model space for a BMA estimator can be represented as in (2.2.1) (see De Luca and Magnus, 2011; Magnus et al., 2010).

$$y = \beta_0 + X\beta + u \tag{2.2.1}$$

where y is $n \times 1$ vector of dependent variable observations, X is $n \times k$ matrix of explanatory variables, β is $k \times 1$ vector of slope parameters, and, $u \sim N(0, \sigma^2)$ is an $n \times 1$ vector of error term that its elements are identically and independently distributed. As there are k regressors the number of possible models to be considered is $I = 2^k$. Therefore, the i^{th} model in the model space (model M_i) is achieved by inclusion of a subset of k $(0 \leq k_i \leq k)$ regressors and can be written as:

$$y = \beta_0 + X_i\beta_i + \epsilon_i \qquad i = 1, ...I \tag{2.2.2}$$

where X_i is an $n \times k_i$ matrix of observations for the included subset of regressors, β_i is the associated sub-vector of parameters and ϵ_i is the new error term after $k - k_i$ regressors are excluded. The weights used for averaging of possible models can be obtained using the Bayes' theorem. The posterior model probabilities are obtained by weighting the likelihood of each model by its prior probability as in (2.2.3).

$$P(M_i|y, X) = \frac{P(M_i)P(y|M_i, X)}{\sum\limits_{j=1}^{I} P(M_j)P(y|M_j, X)} \tag{2.2.3}$$

where $P(M_i)$ is the prior probability of model M_i and $P(y|M_i, X)$ is the marginal likelihood of y given model M_i. The estimator combines the prior belief on the known elements of model with the extra information coming from the data. The key elements include the sample likelihood function, the prior distribution on the regression parameters of model M_i and the prior distribution on the model space.

The posterior model probability (PMP) and thus the model weighted posterior distribution for any parameter such as β can be presented as in (2.2.4).

$$P(\beta|y, X) = \sum_{i=1}^{I} P(\beta|M_i, y, X)P(M_i|y, X) \tag{2.2.4}$$

Under the condition of no prior knowledge, a common choice of prior, $P(M_i)$ can be to assign the uniform probability to each model.

Following "Zellener's g prior" instruction, it is assumed that there is a normal error structure for each model M_i. A "non-informative" improper prior is chosen on the common intercept and error variance by assuming they are evenly distributed over their domain ($P(\beta_0) \propto 1, P(\sigma) \propto \sigma^{-1}$) (Zeugner, 2011). Moreover, since we do not know about the coefficients a priori, a common assumption is normal distribution with mean zero and a specified variance. Thus, according to Zellner's g the distribution of coefficients can be presented as in (2.2.5).

$$\beta_i|g \sim N(0, \sigma^2(\frac{1}{g}X_i'X_i)^{-1}) \tag{2.2.5}$$

The hyper parameter g shows the extent to which one is certain that the coefficients are zero. The posterior mean for β is a weighted average of the posterior means in each model as follows:

$$E(\beta|y, X) = \sum_{i=1}^{I} E(\beta|M_i, y)P(M_i|y, X) \tag{2.2.6}$$

The posterior distribution of coefficient also reflects the prior uncertainty and given g it follows a t-distribution with the expected value of $E(\beta_i|y, X, g, M_i) = \frac{g}{1+g}\hat{\beta}_i$. In a similar manner the posterior variance is also influenced by g as follows:

$$Cov(\beta_i|y, X, g, M_i) = \frac{(y - \bar{y})'(y - \bar{y})}{N - 3} \frac{g}{1 + g}(1 - \frac{g}{1 + g}R_i^2)(X_i'X_i)^{-1} \tag{2.2.7}$$

where $\bar{y}$ is the mean of the dependent variable, N is the number of observations and R_i^2 is the conventional R-squared for each model i. Considering this framework, we can write the marginal likelihood $P(y|M_i, X, g)$ with proportionality constant that is the same for all models, as in (2.2.8).

$$P(y|M_i, X, g) \propto \int_0^\infty (1 + g)^{\frac{N-1-k_i}{2}}[1 + g(1 - R_i^2)]^{-\frac{N-1}{2}}P(g|M_i)\, dg \tag{2.2.8}$$

where k_i is the size penalty factor adjusting for model size and $P(g|M_i)$ is probability of prior g which could depend on M_i. Popular value for the choice of g is to allocate $g = N$ for all models and thus assign the same information to the prior as it is contained in one observation (Ley and Steel, 2012). The detailed technical discussion of BMA estimator can be found in Hoeting et al.(1999).

Choice of model size prior

Following Zeugner (2011) and Amini and Parmeter (2011) we use three different priors for model size distribution in order to reduce the possibility of result bias from choosing a particular prior. These include, uniform prior, fixed prior and random prior. The uniform prior is to assign a common probability of 2^{-k} to all models, considering 2^k combinations of different models (”k” is the total number of explanatory variables). As this distribution has a mean of $k/2$ hence; we expect the mass of distribution concentrates around a model of size $k_i = k/2$, simply because the combination of $\binom{k}{k/2}$ is higher than other possible combinations.

The fixed prior places a common probability of inclusion, α , on each regressor. Therefore, the distribution of prior probability of model size k_i can be written as the multiplication of inclusion and exclusion probabilities as shown in (2.2.9).

$$P(M_i) = \alpha^{k_i}(1-\alpha)^{k-k_i} \tag{2.2.9}$$

The expected value of prior model size distribution in (2.2.9) is ”$k\alpha$”. This means specifying the expected value of prior model size distribution, by researcher, automatically determines the value of α. For example, choosing an expected model size of $k/2$ will convert it to the previous case of uniform prior because the inclusion probability of each regressor (α) will be equal to 1/2. Thus, specifying a prior model size lower than the mean of the regressors numbers ($k/2$) pushes the prior distribution towards a smaller model size and vice versa.

Finally, we adopt a ”random prior” in order to incorporate uncertainty and make the results as robust as possible to the prior selection. The random prior also has a binomial distribution such as (2.2.9). However, α is chosen randomly rather being fixed as in the case of fixed prior. If a Beta prior is chosen for α with hyperparameters $c > 0$ and $d > 0$ i.e., $\alpha \sim Be(c, d)$ then the expected value of prior model size is $\bar{q} = \frac{c}{c+d}k$ (Steel, 2011). The implied prior model size distribution would be a Binomial-Beta distribution. This prior, thus, depends on two parameters, c and d and Ley and Steel (2009) suggested to facilitate the prior elicitation by specifying $c = 1$. As noted in Steel (2011), this still allows for a wide range of prior behaviour and make it appealing to elicit prior in terms of the mean of prior model size distribution ($\bar{q}$). Any choice $0 < \bar{q} < k$ will determine $d = (k - \bar{q})/k$. Therefore, in order to set this, researcher only needs to specify the mean of model size prior which is exactly the same information one requires in the case of fixed prior. The resulting prior is less tight and reduces the unintended outcomes because of prior choice by decreasing the importance of the prior in estimation procedure[4] (Zeugner, 2011).

2.2.4 Data

The dataset used in this analysis is an unbalanced panel of 129 distribution companies observed from 2004 to 2010. All financial variables are presented in real terms and adjusted based on 2010 prices. There are ten independent regressors that constitute 13 factors by including three lag variables. The rationale behind these factors as potential investment drivers has been based on the economic theory, Norwegian regulatory model, technical characteristics of grid and previous studies of distribution networks. Overall, the factors that might affect investment behaviour of distribution companies in Norway can be categorised into four groups. Table 2.1 provides definition of these variable, method of calculation and their source. Table 2.2 presents the summary of descriptive statistics of them.

The first group of variables comprises "demand driven factors" which are related to demand for electricity. These are number of customers which in Norway includes conventional customers and leisure homes[5], number of stations (transformers)[6], and energy density. An increase in demand for energy may cause the network companies to raise the number of distribution feeders or to upgrade the capacity of transformers

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[4] In our analysis for both cases of fixed and random prior we chose the mean of model size prior equal to 6. The number of regressors in our case is 13 and consequently the mean of model size is 6.5. We choose 6 to have a prior model size lower than mean of regressors and consequently different from the case of uniform prior.

[5] The leisure homes are separated from conventional residential and commercial consumers as they have a different load profile which peaks over the weekends and is zero in other days.

[6] Network station or substation is the point that high voltage transmission grid connects to the distribution network.

which in both cases leads to capital investment. Energy density as the measure of energy delivered per unit of network length (Km) can be an investment driver as well. This is because an increase in energy density necessitates more advanced power electronic equipment to support power flows. Moreover, considering the geographic dispersion of load centres in Norway, energy density is a more important factor than the length of networks or energy distributed. There are some sparse areas towards the north with wider distribution networks (i.e., higher network length but lower energy density) whereas energy density is much higher in southern populated areas. Also, sometimes a single energy intensive commercial or industrial consumer can result in high energy density in the grid.

The second group termed "aspect factors" to refer to the characteristics of distribution networks such as the share of overhead lines and the total capacity of distributed generations connected to the grid. The share of overhead lines with respect to total length of network is calculated, for each distribution network, as these can potentially be exposed to environmental conditions and hence might need protective investments. Previous studies have shown that, for example, weather can affect the network physical condition (Yu et al., 2009). Distributed generations are also potential investment driver as the grid may require initial reinforcement to integrate these resources (Mendez et al., 2006).

The third group comprised of "quality driven factors" including the cost of energy not supplied ($CENS$) and cost of network energy losses ($CNEL$). $CENS$ reflects the socio-economic cost of energy not served to the consumers as a result of interruption. It is calculated based on the minutes of interruption multiplied with consumer willingness to pay for reliable service[7] . $CNEL$ shows the cost of energy lost in the grid because of the conductor resistance or other technical problems. It is computed by multiplication of physical network energy loss and annual average system price for electricity. $CENS$ and $CNEL$ related incentives are embedded in Norwegian regulation in order to encourage the network companies to maintain a high quality of supply. It is expected that threat of financial loss as a result of poor

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[7] Consumer willingness to pay is computed using costumer surveys and technical information.

Table 2.1: Definition of variables

Variable	**Definition**	**Method of calculation**	**Source**
Investment	The capital expenditure of companies	Report by companies	NVE
Energy density	Energy distributed per unit length of network	Energy distributed is divided by network length	NVE
Number of stations	It is the number of distribution network substations	Report by companies	NVE
Number of customers	It refers to the number of end-users connected to the grid	Report by companies	NVE
Number of lesiure homes	It refers to the number of holiday homes connected to the grid	Report by companies	NVE
Cost of energy not supplied	It is the socio-economic cost of outages	Energy interrupted times willingness to pay for reliable services	NVE
Cost of network energy loss	It is the cost of energy wasted in the grid	Energy lost times electricity system price	NVE
Distributed generation	Total capacity of distributed generation connected to the grid	Report by companies	NVE
Share of overhead lines	It is the share of overhead lines with respect to total length of network	Length of over headlines is divided by the total network length	NVE
Useful life of assets	It is the remaining life of assets	Calculated based on straight line depreciation formula	NVE
Operational expenditure	It refers to the operational cost of companies	Report by companies	NVE

Table 2.2: Descriptive statistics of variables

Group	**Variable**	**Name**	**Min**	**Max**	**Mean**
Dependent	Investment to capital stock ratio	IR	0	1.047	0.074
Group 1: Demand factors	Energy density (MWh/Km)	$DENS$	137	2234	552
	Number of stations (#)	NS	21	14405	965
	Number of customers(#)	NC	243	535443	19274
	Number of leisure homes (#)	RE	2	27307	2214
Group 2: Aspect factors	Distributed generation (MW)	DG	0	96.45	10
	Share of overhead lines (%)	OH	0.13	0.97	0.67
Group 3: Quality factors	Cost of energy not supplied*	$CENS$	10	58527	2844
	Cost of network energy loss*	$CNEL$	205	394127	14524
Group 4: Other factors	Useful life of assets (year)	UL	7.17	31.627	14.90
	Operational expenditure*	$OPEX$	878	854646	43917

*All monetary variables are in 000' NOK.

quality of service will encourage firms to undertake investment.

The forth category is related to "other factors" such as useful life of asset[8] and operational expenditures. The network companies are expected to replace depreciated assets hence, asset age can have an impact on investment. Operational expenditure may influence investment because the Norwegian distribution network companies operate under the ex-post review of investment using total cost benchmarking. Thus, we consider the possibility of a trade-off between capital expenditures and operational costs (Poudineh and Jamasb, 2013a).

The dependent variable is investment to capital stock ratio (investment rate) in order to define investment spikes and also be consistent with classical investment models in empirical literature (see e.g., Bloom et al., 2007; Morgado and Pindado, 2003). Furthermore, we include the lag of investment rate, $CNEL$ and $CENS$ as three additional factors. The lag of investment is included to controls for the

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[8] Useful life measures the remaining life of asset and is computed using straight line depreciation formula.

cyclical behaviour of investment. The large investment projects may last multiple years and hence, when firm-level data are used, spells of high investment rates are followed by spells of zero investment. The lags of $CNEL$ and $CENS$ are included to account for ”preventive investments” in pursuit of improving quality of supply proactively. The main quality factor variables capture ”corrective investments” where distribution companies respond to the current period events to reduce energy losses and interruptions (Jamasb et al., 2012).

2.3 Results and discussions

Long-term planning and asset management are among the main priorities of distribution network companies. Investments in network companies are costly, long-lasting and irreversible. Hence, better information for the decision process is of essential importance to the both companies and regulators. This, in turn, relies on understanding and identifying the factors that drive long term investment of distribution grids.

The estimation to identify investment drivers of Norwegian distribution companies is carried out in a Bayesian framework. Table 2.3 presents the results of investment models estimated based on different priors (described in Section 2.2.3). The dependent variable is the investment rate (the ratio of investment to the stock of capital). For each prior and estimation three statistics are reported i.e. posterior inclusion probability (PIP), posterior mean of coefficient (Mean) for all models even those where the variable is not included (i.e., its coefficient is zero) and finally posterior standard deviation (SD). PIP shows the importance of the variable in explaining the investment behaviour of companies. It is also the sum of all Posterior Model Probabilities (PMP) wherein that particular variable is included.

As shown in Table 2.3, in the case of uniform prior, there are only three factors that have a PIP of higher than 50%. These are the lag of investment rate, cost of energy not supplied and asset useful life. Lag of investment rate has a PIP of 99% which is the highest among all other factors. This can be interpreted as a ranking measure of the extent to which the data favours inclusion of capital expenditures in the previous period as a determinant of investment behaviour.

The cost of energy not supplied ($CENS$) has a PIP of 62%, and asset useful life shows a PIP of 94%. There is no other significant factor that can be considered as investment driver under uniform prior. For example, there is no evidence of impact from "aspect factors" as neither overhead line nor distributed generation show any significance. The same applies to demand factors.

Table 2.3: Investment model estimation based on different priors

	Mprior=uniform			**Mprior=fixed**			**Mprior=random**		
Variable	**PIP**	**Mean**	**SD**	**PIP**	**Mean**	**SD**	**PIP**	**Mean**	**SD**
Constant	1.00	0.0107	NA	1.00	0.0108	NA	1.00	0.013	NA
IR_{it-1}	0.99	0.1289	0.027	0.99	0.1293	0.027	0.99	0.1314	0.027
$Log(DENS)_{it}$	0.26	0.0017	0.003	0.25	0.0016	0.003	0.18	0.0013	0.002
$Log(OH)_{it}$	0.05	0.0000	0.001	0.04	0.0000	0.001	0.02	0.0000	0.000
$Log(NS)_{it}$	0.10	-0.0004	0.002	0.08	-0.0003	0.002	0.05	-0.0001	0.001
$Log(NC)_{it}$	0.20	0.0010	0.002	0.19	0.0010	0.002	0.16	0.0007	0.002
$Log(RE)_{it}$	0.24	-0.0008	0.001	0.22	-0.0007	0.001	0.12	-0.0004	0.001
$Log(DG)_{it}$	0.05	0.0000	0.000	0.04	0.0000	0.000	0.02	0.0000	0.000
$Log(CENS)_{it}$	0.62	0.0028	0.002	0.61	0.0026	0.002	0.55	0.0022	0.002
$Log(CENS)_{it-1}$	0.07	-0.0001	0.000	0.06	0.0000	0.000	0.03	0.0000	0.000
$Log(CNEL)_{it}$	0.08	0.0000	0.001	0.08	0.0001	0.001	0.06	0.0001	0.001
$Log(CNEL)_{it-1}$	0.12	0.0004	0.001	0.12	0.0004	0.001	0.10	0.0004	0.001
$(UL)_{it}$	0.94	0.0016	0.000	0.93	0.0016	0.000	0.85	0.0015	0.000
$Log(OPEX)_{it}$	0.11	-0.0006	0.002	0.09	-0.0005	0.002	0.05	-0.0002	0.001

Moving away from uniform prior to the fixed prior based on binomial distribution of prior, Table 2.3 shows that there are no significant changes in the results. The PIPs of the main factors are almost identical to the case of uniform prior. Thus, the same three factors still have significant posterior inclusion probabilities under the fixed prior. In a similar manner, the identified factors under random prior match the cases of uniform and fixed priors. However, the PIPs of $CENS$ and UL variables are slightly lower, under random prior, compared with the other two priors. Nonetheless, their PIPs are still significant. Therefore, it can be concluded that the identified investment drivers are robust to the choice of prior. This highlights the importance of these factors in explaining the investment behaviour of Norwegian distribution companies.

The results in Table 2.3 are, to some extent, in line with the manner that investment incentives are implemented under the Norwegian regulatory regime. For example, the high PIP for $CENS$ is not an unexpected result given that the cost of energy not supplied is an important instrument used by the Norwegian regulator to incentivise quality of supply improvement. In effect, the regulator penalises the firms for poor service quality. On the other hand, the results in Table 2.3 show that other quality factors such as cost of network energy loss ($CNEL$) and the lag of $CENS$ and $CNEL$ variables are not significant.

The posterior model size distribution and cumulative model probabilities, under uniform prior, are illustrated in Figure 2.2. As seen from the figure and discussed previously, the mean of prior is 6.5[9]. However, the posterior distribution of model size has a mean of 3.88 (between three and four)[10]. This means that although we believed, a priori, that around 6 factors would be the final investment determinants, the data favours a number between three and four. In Bayesian parlance we have updated our prior belief about investment drivers through new information coming from the data. Overall, under uniform prior, three of the four factors are considered to be more certain. This is because many of the models estimated, under the uniform prior, have identified a weak response from investment with respect to forth factor with highest PIP-i.e., energy density ($DENS$). This can be seen from the unshaded area in cumulative model probabilities depicted for the best 500 models in Figure 2.2. A fully shaded area implies a PIP of 100% for the variable.

A similar result can be seen in Figure 2.3 for the case of fixed prior. The mean of the posterior model size distribution, under the fixed prior, is 3.76 whereas the mean of prior model size distribution is 6. The results of the estimations under uniform and fixed priors suggest that, on average, the response of investment to the

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[9] Recall that the mean of model size prior is 6.5 for uniform and 6 for the cases of fixed and random priors.

[10] The mean of posterior model size distribution is the weighted average of model sizes where posterior model probabilities acting as weights.

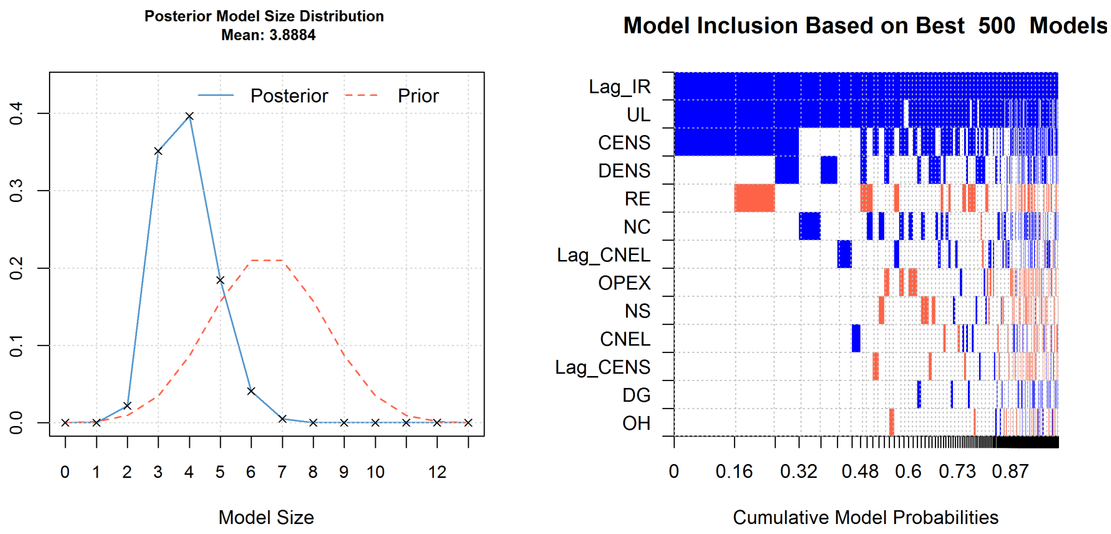

Figure 2.2: Model size distributions and cumulative model probabilities for a uniform prior

aforementioned three factors (i.e., lag of investment rate, cost of energy not supplied and useful life of the asset) are more certain. This is also reflected in the cumulative model probabilities in Figure 2.3 which shows less shaded areas for energy density (DENS) compared with other three factors.

The results indicate that the cost of current period interruptions can explain part of the variations in investments of distribution companies. This suggests that investment by the network companies mainly responded to interruptions and outages in the current period. In other words, interruption costs resulted in ”corrective investment”. There is no evidence of ”preventive investment” aiming at improving service quality proactively as lag of $CENS$ and $CNEL$ do not appear as investment drivers. The corrective nature of investment, in response to outages, can be explained by the fact that reducing the current period interruptions has a high priority from a regulatory perspective and thus needs to be dealt with in the shortest time.

It is likely that the most robust results stem from the random prior estimation. As seen previously from Table 2.3, under the random prior, the results follow the same pattern as the other two priors. Figure 2.4 illustrates the posterior distribution of model size and cumulative model probabilities for the random prior. As shown,

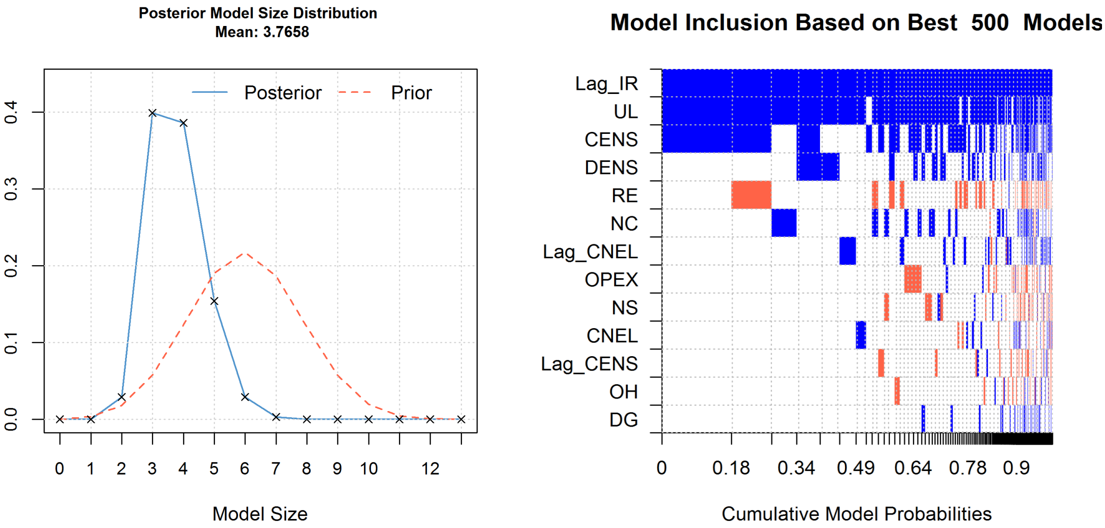

Figure 2.3: Model size distributions and cumulative model probabilities for a fixed prior

the prior distribution places more emphasis on small model sizes. However, the average of posterior model size distribution is 3.27 and thus close to the previous cases. The shaded areas in the cumulative model probabilities indicate that the random prior also identifies the same investment drivers. This strongly confirms that the results are not biased with the choice of prior.

Table 2.4 presents the summary of top 3 models based on different priors. It is evident from the table that in all cases the top model only includes lag of investment rate, $CENS$ and UL with posterior model probabilities (PMPs) of 15, 17 and 24% under uniform, fixed and random priors respectively. Considering high number of possible models (2^k) these constitute rather high probabilities.

The second and third best models, under uniform prior, pick up the same three factors (lag of investment rate, $CENS$ and UL) along with RE and $DENS$ as additional investment drivers respectively. This is also the case for the second best model under fixed prior. However, the third best model under fixed prior identifies lag of investment rate, useful life of assets and number of customers as determinants of investment. This again repeated for the case of second best model under random prior. The third best model, under random prior, only picks up lag of investment rate and $CENS$ as the main factors.

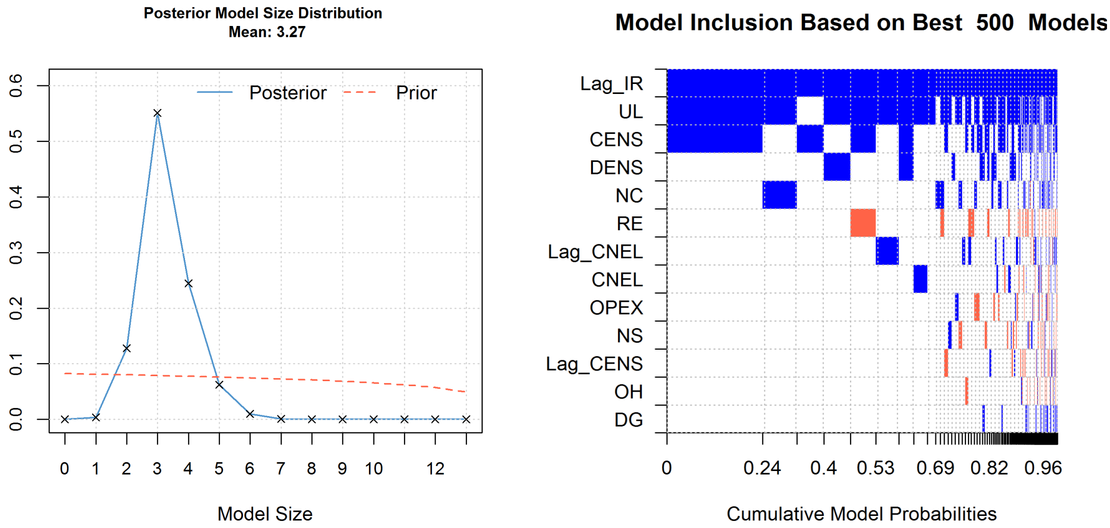

Figure 2.4: Model size distributions and cumulative model probabilities for a random prior

Overall, the second and third top models under all priors are associated with lower PMPs and hence, less probable. Therefore, the main drivers of investment in the distribution companies are investment rate in previous period, $CENS$ and UL. Among these, lag of investment rate is ranked highest and cost of energy not supplied has the lowest rank in terms of posterior inclusion probabilities.

The coefficients of identified investment drivers are positive but vary in magnitude as seen from Table 2.3. The largest coefficient is related to investment rate which is around 0.13. The useful life of asset has a coefficient of approximately 0.002 and coefficient of $CENS$ is around 0.001. This ranking of coefficients coincides with the importance of associated regressors in terms of variations they create in dependent variable. The fact that lag of investment rate explains a large portion of variation in investment behaviour of distribution companies is consistent with theory. The operating environments of distribution companies are dynamic so, demand, economic condition, technology, regulation etc. may change. The companies do not respond to these changes instantaneously rather the changes are likely to be spread over time and equilibrium position, if ever achieved, will be approached gradually. The slowness of response may be the result of time delays in information transmission and reception upon which the decision is based. It can also be

Table 2.4: Top three models based on different priors

Variable	**Mprior=Uniform**			**Mprior=Fixed**			**Mprior=Random**		
	Top1	Top 2	Top 3	Top1	Top 2	Top 3	Top1	Top 2	Top 3
IR_{it-1}	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$
$Log(DENS)_{it}$			$\otimes$						
$Log(OH)_{it}$									
$Log(NS)_{it}$									
$Log(NC)_{it}$						$\otimes$		$\otimes$	
$Log(RE)_{it}$		$\otimes$			$\otimes$				
$Log(DG)_{it}$									
$Log(CENS)_{it}$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$		$\otimes$		$\otimes$
$Log(CENS)_{it-1}$									
$Log(CNEL)_{it}$									
$Log(CNEL)_{it-1}$									
$(UL)_{it}$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	
$Log(OPEX)_{it}$									
PMP	0.155	0.105	0.060	0.176	0.102	0.063	0.244	0.087	0.068

attributed to adjustment costs which deter firms from rapid changes. In Chapter 4 we will show the effect of adjustment cost and slowness of investment response on dynamics of cost efficiency.

The positive coefficient for $CENS$ implies that the increase in interruption costs results in higher investment to reduce outages (due to adverse effects on the revenue of companies). Similarly, the positive coefficient for useful life of asset (UL) implies that firms with younger assets invest more compared with those that have older assets. This may be because firms with younger assets are in process of expansion or investment in older assets is more costly.

Contrary to $CENS$, the results show that the companies do not respond to energy loss reduction incentives embedded in the regulatory model. The lack of response of investment to $CNEL$, may signal that further reduction of network energy losses do not justify the required investments because the incentive for energy loss improvement has not been strong enough. This can also be attributed to the different treatment of cost of network energy loss ($CNEL$) and cost of energy not served ($CENS$) under Norwegian regulatory model. Both $CNEL$ and $CENS$ are part of controllable costs that are included in the benchmarking model. However, $CENS$ is also subtracted directly from the firms' allowed revenue at the final stage of revenue setting thus leading to a stronger incentive for service quality. Additionally, the regulator evaluates network energy losses at system price whereas energy not served is valued at "consumer willingness to pay for reliable services". As the costs of outages are higher to the residential, commercial and industrial users than the system price, network companies have more incentives to avoid interruption costs which affect their revenue base to a greater extent.

To sum up, we have investigated the effect of 13 factors which are categorised under four groups, on investment behaviour of distribution networks. Figure 2.5 summarises the impact of all factors across the all models. The results indicate that only a few factors drive most of the investments of the distribution companies. There are two sets of variables in the figure 2.5: those that are located in the far upper left with highest PIP and those that are in lower right and associated with lowest PIP. None of the investment determinants has a PIP of below 55%.

There is only one investment driver from service quality factors: the cost of energy not supplied. Among other factors asset useful life is identified as an important investment driver. There is no evidence of effect from operational costs on investment although there is a possibility of trade-off between operational and capital expenditures as the Norwegian regulatory model is based on the total cost benchmarking.

The investment is also not responsive to the number of recreational homes and number of customers. Moreover, as shown in Figure 2.5, distributed generation does not appear as an investments driver which, at first, seems counterintuitive. However, one explanation is that the Norwegian networks have already adapted to integrate the distributed generation resources. For example, the share of the dispersed hydroelectric plants accounted for around 95.1% of the total net generation in 2009 (NVE, 2011).

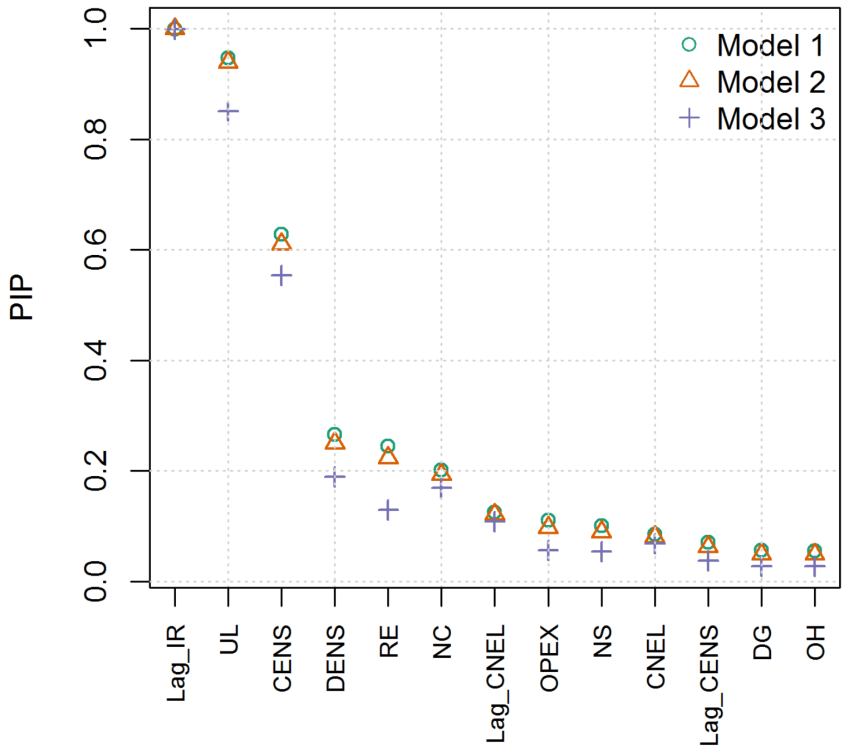

Figure 2.5: Comparison across models for the most important factors

The Norwegian Energy Act obliges distribution network companies to connect new consumers and generations as far as it does not compromise grid security. This is a form of direct regulation to ensure investment sufficiency with the objective of network access provision for all customers. If the request for connection comes from a production unit, and if there is not enough capacity in the grid, the firms are obliged to carry out necessary reinforcement. Under the condition that joint investment in grid and production unit is economically inefficient, the grid company can ask for exemption from obligation to provide grid access.

In addition, although Norway is located in the cold region with severe weather conditions over the large parts of year however; there is no evidence of overhead line driven investment. This is while overhead distribution lines are usually vulnerable to the effect of weather condition. One reason for this could be that environmental factors are already incorporated in the design and operation of networks and this reduces the need for subsequent reinforcement against severe weather conditions.

2.4 Conclusions

Achieving sufficient and efficient investments in the capital intensive electricity networks is a major challenge for electricity sector regulators. Over the coming years the need for significant levels of investment is envisaged, in distribution networks, as a result of sustainability policies aiming at a decarbonised electricity sector. Thus, understanding the response of companies to regulatory incentives enables the sector regulators to promote adequate and appropriate investments more effectively through incentive regulation.

This study investigated the determinants of investments in the Norwegian electricity distribution companies using a Bayesian Model Averaging (BMA) approach. BMA is a coherent method of inference on regression coefficients that takes into account the uncertainties around model selection and estimation. This is particularly relevant in the context of investment in regulated industries where the companies are subject to various incentive mechanisms and hence; there is uncertainty in model selection. The estimations were based on three priors in order to avoid bias in the findings as a result of selecting a particular prior.

The results indicate that, of the 13 potential factors explored, three factors constitute the main determinants of investments in electricity distribution networks. Due to the dynamic nature of investment decisions, a large part of variations in investment of firms can be explained by investment in previous period. The lag of investment to capital ratio is identified as the strongest factor which repeatedly shows a high posterior inclusion probability regardless of the choice of prior.

The cost of energy not supplied and useful life of asset are the other main drivers of investments. We find little evidence that the length of overhead lines drive investments though we expect network reinforcements to improve protection against severe weather conditions. Moreover, we find no investment effect from distributed generation sources connected to low voltage distribution grid. Furthermore, there is no evidence that the number of customers influences the investment by firms. Under the Norwegian regulatory framework, network reinforcement is the obligation of licence holders in order to ensure a fair and non-discriminatory network access for all types of users.

The study of investment response of firms to the four groups of factors in this chapter provides a picture of investment behaviour of distribution companies under Norwegian regulatory model. The results indicate that the Norwegian distribution companies have responded, to some degree, to the investment incentives provided by regulatory framework. Nonetheless, some of the incentives do not appear to have been effective. The quality of supply incentives embedded in the benchmarking model have motivated the firms to undertake investment to reduce service interruptions. However, the results show that these investments are more of a "corrective" nature and not of a "preventive" type. Moreover, the lack of investment response to energy loss reduction incentives show that the strength and type of incentives are important in promoting investment sufficiency and to reduce certain operational deficiencies. The results of this study suggest that network companies respond to investment incentives when the cost of inaction outweighs the investment costs.

The responsiveness of network companies to investment incentives gives an indication of "sufficiency" of investment. However, another major issue of regulation is to incentivise "efficiency" in capital expenditures. The challenge is how regulators can ensure that there is no systemic under- or over-investment. The next chapter provides an in depth study of the relationship between investment and efficiency under incentive regulation.

Chapter 3

Investment and efficiency under incentive regulation

Following the liberalisation of the electricity industry since the early 1990s, many sector regulators have recognised the potential for cost efficiency improvement in the networks through incentive regulation aided by cost benchmarking and productivity analysis. Although benchmarking has achieved efficiency improvements (mainly in operating costs), new challenges have emerged as how to address the issue of network investments. The challenge is to provide the right incentives for the delivery of cost effective services while ensuring there is no systematic underinvestment or overinvestment. Hence, regulators need to balance the cost and risk of underinvestment against the cost of overinvestment in maintaining and modernising the networks.

Incentive regulation accentuates static cost efficiency while investment is a dynamic and long term activity. On the other hand, benchmarking is a relative concept in the sense that a firm's efficiency depends not only on its own performance but also on the performance of other companies. The paradoxical effect of incentive regulation concerning investment and the peculiar specifications of total cost benchmarking complicate the relationship between investment and cost efficiency. This chapter analyses the relationship between cost efficiency and investments under incentive regulation with ex-post regulatory treatment of capital expenditures using the case of electricity distribution networks in Norway.

The contribution of this research is two-folded. Firstly, we introduce the concept of "no impact efficiency" as a revenue-neutral efficiency effect of investment under incentive regulation which makes the firm "investment efficient" and immune from cost disallowance in benchmarking process. Secondly, we estimate the "observed" efficiency effect of investment in order to compare this with no impact efficiency and discuss the implication of cost benchmarking for network investments in Norway. Despite the important role of regulatory treatment of capital expenditure, using total costs benchmarking, for investments behaviour and efficiency improvement in the networks, the topic has not been formally studied in the empirical literature.

The next Section discusses different approaches to regulatory treatment of investment and their effect on optimum capital expenditure. It also reviews the most important literature in this respect. Section 3.2 describes the methodology used to conceptualise the efficiency implications of investment under incentive regulation and also presents the stochastic frontier analysis procedure. Section 3.3 describes the data used in empirical analysis. The empirical results are presented and discussed in Section 3.4. Section 3.5 is the conclusions.

3.1 Regulatory treatment of investment

The regulatory treatment of investment is among the debatable issues in regulatory economics. Other controllable expenditures such as operating costs tend to be less critical as there is a consensus that these need to be minimised for a given level of output and service quality. However, due to the dynamic and long term nature of investments, minimisation of capital expenditures may not be possible or desirable. This is because it may lead to underinvestment which can endanger long term reliability of networks with significant socio-economic costs. Within this context, the challenge of regulation is to strike a balance between incentive for investment, and prevention of under- and over-investment.

The regulators of natural monopolies have adopted different models in order to address the issue of investment under regulation. Broadly, the regulatory treatment of investments can be viewed in terms of two main approaches: ex-ante and ex-post review of capital costs (Petrov et al., 2010).

3.1.1 Ex-ante review of capital costs

Under the ex-ante model of investment treatment, regulated companies submit their business plans for expected capital expenditures prior to the commencement of the next regulatory period. The regulator scrutinises the submitted plan to verify prudence of investments. As there is asymmetric information between the regulator and the firm, the former relies on engineering reports, auditing, and cost-benefit analysis for the need case and efficiency of investments (Petrov et al., 2010). Thus, the regulator needs to form an opinion, a priori, on the prudent level and type of investments required in the following regulatory period (Petrov et al., 2010). At the end of the regulatory period, the regulator evaluates deviations of actual investments from the investment plans and may disallow, partially or totally, the excess investments.

Likewise, in the case of downward deviation from projected investments, the regulator might reward the firm. This is the case in the UK under the RIIO-ED1 model where distribution networks receive financial incentive if they deliver the same output with less investment (Ofgem, 2012). Under this condition, regulator can lower the allowed revenue in the next regulatory period in order to better align the network's actual cost with their revenue and share the benefits of cost reduction with consumers.

The ex-ante method of investment treatment aims to secure adequate investment and quality of supply. This method has been adopted under rate of return regulation and also incentive regulations that are based on projected cost and not on historical costs. However, the effect on investments depends on the regulatory model as, for example, rate of return regulation increases observable investments, whereas price cap regime promotes cost reducing investments (Armstrong and Sappington, 2005).

The ex-ante model influences the investment behaviour of network companies in certain ways. Under the condition of guaranteed return, the utilities bear little risk for their investments. This makes it easier to compete with non-regulated firms, in the capital market, in order to finance investments. Additionally, under this regulatory model of investment treatment, the companies have incentive to inflate the capital cost by reporting high volume of work or by capitalising their operational expenditure especially when there is no incentive attached to downward deviation from the agreed level of capital expenditures in the business plan (Petrov et al., 2010).

The ex-ante model of investment treatment, under rate of return regulation, has been the subject of empirical and non-empirical research for many years. Averch and Johnson (1962) were the first who showed that under this model more capital will be employed compared to a non-regulated firm, given any level of output, especially when the regulator commits to a higher rate of return (than the cost of capital) in advance. This is because the regulator sets the revenue to cover the operating cost plus a return on capital stock. Therefore, the firms know that lower investments lead to lower regulatory asset base (RAB) and consequently lower revenues.

Since the formal presentation of Averch-Johnson effect, several methods have been proposed to overcome this issue. Gilbert and Newberry (1988) show that an approach based on "used and useful" rate-of-return regulation, applied strategically in an infinitely repeated game, can remedy the effect. The other suggested approach to alleviate the Averch-Johnson bias is that the regulator should offer a nonlinear rate-of-return in which return is decreasing in capital (Kle-vorick, 1966; Baumol and Klevorick, 1970). However, a non-linear rate of return might be an optimal solution to observe the capital costs of firms; it does not reduce the firms' incentive to inflate investment (Besanko, 1985).

Therefore, an operating environment which is regulated with ex-ante model of investment treatment can provide incentive for overinvestment. A shift in the regulatory regime which allows for the use of cost disallowance instruments will decrease the propensity to invest (Gal-Or and Spiro, 1992). Cost disallowance is an effective instrument to motivate firms move towards an equilibrium path when the regulator identifies undue investments. Lyon and Mayo (2005) demonstrate that the empirical consequence of large scale cost disallowance is a reduction in propensity to invest for the firms that have experienced such disallowances. Along the same line, Teisberg (1993) argues that under stringent cost disallowance, firms incline more towards smaller projects in order to reduce the chance of being penalised in regulatory process. Moreover, unlike larger projects that are prone to change in economic conditions; the short lead time of implementation does not change the "usefulness" of project from initial expectation.

The regulator commitment is another critical issue, under the ex-ante model, which has mainly been discussed in the context of rate of return regulation. The process of revenue setting under the rate of return regulation involves two stages. In the first stage firm chooses the level of capital and in the second stage regulator sets the regulated price based on the firm's capital stock (Besanko and Spulber, 1992). Due to irreversibility of investment, the issue of regulator commitment plays an important role in the investment decision of firm. Besanko and Spulber (1992) shows that lack of a credible commitment, by regulator, can create disincentive for investment.

3.1.2 Ex-post review of capital costs

An alternative regulatory option to treat investments is the ex-post review of capital expenditures. In this method, the regulator does not need to form an opinion, a priori, on the type and scale of investments required in the next regulatory period such that there is no need to project these (Petrov et al., 2010). The regulator uses the sum of all the costs incurred to the company (operational and capital expenditures, and other controllable costs) to construct a single variable that reflects the total costs. The total expenditure is then benchmarked against peer companies in each regulatory review period using frontier based benchmarking methods such as COLS, DEA, or SFA [1] (Petrov et al., 2010). Thus, the regulator does not interfere with the detail of investment plans of companies. The firms are free to decide whether or not to undertake a particular investment or what level of capital expenditure is needed. It is expected that companies will restrain their investments to the efficient levels, in order to avoid high costs in the benchmarking process. This is because high cost can reduce the relative efficiency score and consequently regulated revenue of company.

Under the ex-post method the regulatory period is normally shorter, compared

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[1] Corrected Ordinary Least Square (COLS), Data Envelopment Analysis (DEA), and Stochastic Frontier Analysis (SFA).

with ex-ante approach, in order to dissuade investment inefficiency. Also, similar to the ex-ante model, the ex-post regulatory treatment of investment creates incentives for certain types of strategic behaviour. For example, benchmarking total cost creates incentives for the firms to trade-off between capital expenditures (Capex) and operating expenditures (Opex) to avoid revenue loss when there is fear of cost disallowance. The effect of ex-post model on investment behaviour of regulated firms is not limited to trade-off between Capex and Opex. In this chapter (Sections 3.2 and 3.3) we analyse, in details, the impact of ex-post model on the investment behaviour through an empirical study of Norwegian distribution companies.

3.1.3 Optimum investment and regulation

The low-powered regulatory regimes such as pure "rate of return regulation" are often associated with poor incentive for efficiency. Incentive-based regimes such as price or revenue caps aim to overcome the efficiency problem by decoupling prices from utilities' own costs. However, they give rise to new challenges regarding the level of investments. The issue of cost efficiency at the expense of investments or service quality has been discussed in the literature (see e.g., Giannakis et al., 2005; Rovizzi and Thompson, 1995; Markou and Waddams Price, 1999). Therefore, regulators usually adopt quality incentives such as setting a performance target based on some estimated index of reliability (e.g., SAIDI and SAIFI [2]) or including the cost of energy not supplied and cost of network energy losses in the total benchmarked cost. This is to reduce the chance of underinvestment which endangers network reliability. However, under incentive regimes, when rewards and penalties are weak or uncertain, the incentives for cost reductions outweigh the inducement to maintain quality of service and investment (Burn, and Riechmann, 2004).

The empirical evidence concerning investment behaviour of firms under incentive regime is not conclusive. While some initially argued that incentive regulation

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[2] System Average Interruption Frequency Index (SAIFI). It is the equivalent of the ratio of total number of consumers interrupted to the total number of consumer served. The System Average Interruption Duration Index (SAIDI) is the ratio of the sum of all customer interruption duration to the total number of customers served.

will lead to underinvestment, subsequent empirical works demonstrated that the outcome of the incentive regulation concerning the investment behaviour can be in either direction. Waddams Price et al. (2002), state that a high-powered incentive regulation might lead to overinvestment. Roques and Savva (2009) argue that a relatively high price cap can encourage investment in cost reduction as in an unregulated company. Nagel and Rammerstorfer (2008), on the other hand, show that a strict incentive regulation regime is more likely to create disincentive for investment. However, it is generally agreed that in incentive regulation regimes, due to the separation of firms' own costs from prices, the motivation for cost reducing investment is higher than under the rate of return regulation models (Ai and Sappington, 2002; Greenstein et al., 1995; Cambini and Rondi, 2010).

From the regulatory viewpoint, it is important that decisions influencing the investment level of the firms are based upon economic efficiency. For example, the cost of reducing service interruptions through investments should be lower than the socio-economic costs of service interruption. In effect, the regulator seeks an efficient level of investment in the grid although realising this goal through regulation is a challenging task. On the one hand, theory does not provide clear indications of the conditions under which "efficient" levels of investment are achieved and which factors lead to over or underinvestment (von Hirschhausen, 2008). Meanwhile, the empirical evidence from cases of overinvestment or underinvestment is rare. Therefore, the outcome of incentive regulation regarding investments is ambiguous, and that regulators, in practice, tend to adopt a combination of different regulatory incentive mechanisms in order to achieve their objectives. Furthermore, implementing incentive regulation is complicated and an evaluation of the associated efficiency is more difficult than it is often implied (Joskow, 2008b).

Additionally, an important shortcoming of the current studies is that while they discuss the impact of main regulatory models on investment, they do not explore the nature of this relationship. In other words, the literature does not show, for example, how investment of network companies will be reflected in their efficiency level if capital expenditures are treated in an ex-post manner. Also, the empirical literature has not systematically categorised regulatory treatment of investment.

Therefore, the results of those empirical works that seem to investigate the investment behaviour under incentive models may not be directly comparable as they not necessarily study the same form of incentive regime.

All in all, the area of efficiency effect of investment under incentive regulation has been largely ignored in the empirical literature. One of the main reasons might be that quantifying the efficiency effect of investment can be a challenging task especially if the investments are treated in an ex-ante manner. In the case of ex-post, investigating this relationship requires an analytical framework and an appropriate empirical model that allows us to purge the effect of investment on efficiency. This chapter bridges this gap by providing the details for a theoretical framework and an empirical model that enable us to perform this task.

3.2 Methodology

In this section, we first present a model of the incentive regulation of electricity distribution networks in Norway and then analyse the relationship between investments by the utilities and the change in their relative efficiency under incentive scheme. We then describe the econometric approach and the models estimated in order to explore the efficiency effects of investments.

3.2.1 Modelling incentive regulation

The allowed revenues of regulated networks are determined by incentive regulation and cost efficiency benchmarking. Within this framework, investments are encumbered indirectly such that overinvestment can result in partial disallowance of investment costs. The Norwegian regulator computes the allowed revenue (RE_t) of the networks using Equation (3.2.1), which, in essence, is a generic incentive regulation formula representing the trade-off between cost reduction incentive and rent transfer to the consumers, given the presence of asymmetric information between the firm and the regulator (Newbery, 2002b; Joskow, 2005b).

$$RE_t = C_t + \lambda(C_t^* - C_t) \tag{3.2.1}$$

Where C_t is the actual (own) costs of a network company ($C_t > 0$), C_t^* is the norm cost obtained by using the frontier-based benchmarking method Data Envelopment Analysis (DEA), and λ is the power of incentive in terms of the weight given to benchmarked costs vs. actual costs in setting the allowed revenue. The power of incentive is important for motivating the firms to move as close as possible to their norm (benchmarked) cost as they lose revenue when deviating from the efficient frontier. The share of actual costs and norm costs in determining the revenue caps is currently 40% and 60% respectively (i.e. $\lambda = 0.6$) (NVE, 2008). Placing more weight on norm costs increases the incentive power of regulation and promotes indirect competition among the utilities to improve their cost efficiency relative to best practice.

Actual costs include operating and maintenance costs, capital costs, depreciation costs and cost of negative externalities such as network energy loss and service interruptions. In addition, the regulator deducts the cost of energy not supplied ($CENS$) from the firms' revenue cap[3] and adjusts the allowed revenue for tax and other non-controllable expenses. The regulator uses data with a two year lag which is updated with an inflation index. The allowed revenue is then adjusted at the end of the year when final actual data becomes available[4].

We divide both sides of (3.2.1) with C_t and rearrange such that it yields:

$$RE_t = C_t[1 + \lambda(e_t - 1)] \tag{3.2.2}$$

where $e_t = C_t^*/C_t$ is the efficiency of firm in period t ($C_t > 0$). When a firm invests the amount In, this will impact its revenue by changing its relative efficiency in cost benchmarking. The variables for before and after undertaking investments are denoted by subscripts 1 and 2 respectively. The change in a firm's revenue due to an investment can be computed from equation (3.2.3).

$$\Delta RE = RE_2 - RE_1 = C_2 - C_1 + \lambda[C_2(e_2 - 1) - C_1(e_1 - 1)] \tag{3.2.3}$$

The change in actual cost of the firms after undertaking investments is equal to the amount of investments ($\Delta C = C_2 - C_1 = In$). We substitute for C_2 in the bracket and rearrange (3.2.3) as presented in (3.2.4) to show the change in revenue as a result of investments.

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[3] In order to incentivise network companies to improve service quality (NVE, 2011).

[4] While the current and previous year investments (years t and t-1) are not included in the regulatory asset base (RAB) due to a time-lag, the companies can start to calculate a return on investment into their allowed revenue (i.e. tariff base) from the commissioning year. It is also important to note that investments enter the regulatory asset base and then capital cost is computed based on calculated rate of return and depreciations. So, the Norwegian regulator uses capital costs in the cost base for benchmarking model and not capital expenditures.

$$\Delta RE = \Delta C + \overset{\substack{\text{Revenue effect of}\\ \text{investments due to}\\ \text{benchmarking}}}{\lambda[C_1(e_2 - e_1) + In(e_2 - 1)]} \qquad (3.2.4)$$

Equation (3.2.4) presents the main framework for the network companies' incentive to undertake investments. In the absence of cost benchmarking (i.e., when $\lambda = 0$) the firm would automatically earn a return on its investments because the change in the firm's revenue is the same as the change in its cost ($\Delta RE = \Delta C$), and the company can pass all its investment costs to its customers. However, as investments are included in cost benchmarking, the firms' revenue also depends on their relative cost efficiency before investments (e_1) and after investments (e_2). This is reflected in the second component of (3.2.4), to which we refer as Q in (3.2.5), and shows the (gross) revenue effect of investments due to benchmarking.

$$Q = [C_1(e_2 - e_1) + In(e_2 - 1)] \qquad (3.2.5)$$

As seen from (3.2.5), the revenue effect of investments consists of two parts. Clearly, we always have $(e_2 - 1) \leq 0$. However, the outcome of the component $(e_2 - e_1)$ of (3.2.5) is not certain as it is not clear whether, following an investment, the cost efficiency increases, decreases, or remains constant[5].

Depending on the initial and after investment measured cost efficiency, Q can take different values. If $Q < 0$, the firm gains less from investing compared to the case of no cost benchmarking (ceteris paribus). However, when $Q = 0$ investment costs are fully recovered as there is no benchmarking. If $Q > 0$, investment creates synergy by excessive increase in efficiency although this may not happen under normal condition[6] so in most situations one expects $Q \leq 0$.

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[5] $(e_2 - e_1 > 0, e_2 - e_1 < 0$ or $e_2 - e_1 = 0)$

[6] The reason is that if the share of investments to other costs (before investments) increases, the efficiency required to satisfy the inequality rises considerably. However, under certain circumstance we can have $Q > 0$ which we refer to it in Section 3.4

$$\Delta RE = \Delta C + \lambda Q \tag{3.2.6}$$

Thus, as shown in (3.2.6), the change in revenue after investments is not necessarily equal to the change in cost and it crucially depends on the value that Q takes. Although the revenue also depends on the power of incentive (λ), it is a predetermined parameter which is beyond the control of the firm. Thus, a desirable outcome can be achieved when $Q = 0$ and benchmarking has no adverse impact on the firms' revenue. - i.e. when the efficiency after investments increases (due to productivity of capital) to an amount that results in $Q = 0$ (note that also when the firm is on the efficient frontier and remains there after investments, we have $e_2 = e_1 = 1$, and consequently Q becomes zero). This efficiency can be obtained by solving (3.2.5) with respect to e_2 as in (3.2.7).

$$e_{no\ impact} = e_2 = \frac{C_1 e_1 + In}{C_1 + In} \tag{3.2.7}$$

Equation (3.2.7) shows how the Norwegian incentive regulation links investments to efficiency improvement. In order for a firm to earn a profit on its investments as if there was no cost benchmarking (ceteris paribus), its efficiency should be, at least, $\frac{C_1 e_1 + In}{C_1 + In}$ after the investment. An efficiency level below this will result in lower revenue relative to the no benchmarking case. We use the term "no impact efficiency" to refer to the revenue-neutral efficiency effect of investment under cost benchmarking as presented in (3.2.7). In other words, a firm is considered "investment efficient" when it meets the "no impact efficiency" criteria under regulation[7].

The Norwegian incentive regulation links investment and efficiency to ensure that firms do not undertake undue investments. This means that the regulator does not need to interfere in the firms' investment decisions, but indirectly incentivises them to be investment efficient. A limit analysis of (3.2.7) shows that as C_1 increases, the efficiency e_2 will approach e_1. The opposite of this implies that when the ratio

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[7] For simplicity, we assume that the frontier firms are genuinely efficient. In practice, this may not be the case.

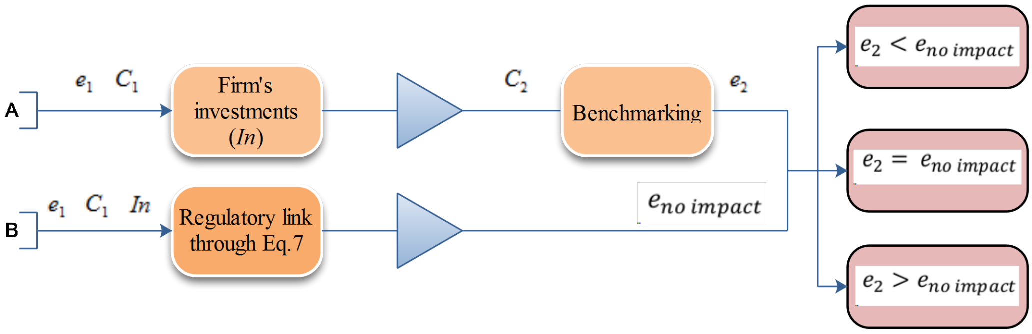

Figure 3.1: Possible efficiency effects of investment under Norwegian incentive regulation

of investment to other costs[8] increases, the firm needs to achieve a higher efficiency level (which in limits is equal to unity) in order to avoid revenue loss. This means that the expected interval of the no impact efficiency change is $e_1 \leq e_{no\ impact} \leq 1$, which depending upon the investment to cost ratio would be closer to lower or upper boundary.

Figure 3.1 shows the possible outcomes of efficiency effect of investment under Norwegian regulation as an ex-post regulatory model for treatment of investments. When a firm (with an initial cost and efficiency level) undertakes an investment, it achieves a new level of efficiency (A). On the other hand, regulation links the initial cost, efficiency, and investment to no impact efficiency and rewards or penalises the firm based on the efficiency effect of their investments (B). In practice, this reflects the incentive mechanism pertaining to investments.

3.2.2 Modelling a stochastic efficient frontier

This section presents the efficiency measurement techniques and empirical model estimated in this study. We estimate the efficiency of firms before and after investments and use the efficiencies to calculate the no impact efficiency for current investment levels of the networks.

The efficiency and productivity analysis has been based on parametric (Stochas-

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[8] The ratio of “investment to other costs before investments”, the average of this ratio for the Norwegian networks is currently 34%. The maximum is 168% and the minimum is 0.1%.

tic Frontier Analysis (SFA)) and non-parametric (Data Envelopment Analysis (DEA)) approaches or combination of these two. The advantage of non-parametric methods is that we do not need to assume a functional form and make assumption a priori about the nature of production technology except about convexity (Hjalmarsson et al., 1996). However, a major disadvantage of non-parametric methods is that they are deterministic and one cannot distinguish between noise and inefficiency. Parametric methods allow for separating noise from inefficiency but they need a functional form and thus there are always risks of misspecification and estimation issues. However, a main attraction of parametric methods is that they allow for statistical hypothesis testing and constructing confidence intervals (Hjalmarsson et al., 1996). In recent years significant efforts have been made to combine the advantages of both approaches which the most important estimator of this type is known as Stochastic Non-Parametric Envelopment of Data (StoNED) (A detailed comparison of SFA, DEA and StoNED can be found in Kuosmanen et al., 2013).

In the present analysis we use a fully parametric method because we are interested to measure the effect of investment on efficiency and this requires simultaneous estimation of two functions. Furthermore, for our analysis it is important to separate noise from inefficiency something which requires a parametric setting.

We use an input distance function which allows us to estimate the efficiency of the firms when input price data is not available (Färe and Lovell, 1978; Coelli and Perelman 1996). Other advantages of distance functions are that they do not depend on explicit behavioural assumptions such as cost minimization or profit maximization and they can accommodate multiple inputs and outputs (Kumbhakar and Lovell 2000; Coelli et al., 2005).

Input distance functions have been used in empirical studies for efficiency and productivity analysis of industrial units as in Abrate and Erbetta (2010) and Das and Kumbhakar (2012) as well as those of electricity networks such as Tovar et al. (2011), Hess and Cullmann (2007), and Growitsch et al. (2012). The output of electricity networks is determined exogenously by demand for energy and connections. Thus companies can only adjust their inputs (i.e. costs) to deliver a given service efficiently.

An input distance function can be defined as in (3.2.8):

$$D^I(x,y) = max\{\psi : (\frac{x}{\psi}) \in L(y)\} \tag{3.2.8}$$

where $L(y)$ represents the input vectors x that produce the output vector y, and ψ indicates a proportional reduction in input vector. The function has the following characteristics: (i) it is linearly homogenous in x, (ii) it is non-decreasing in x and non-increasing in y, (iii) it is concave in x and quasi-concave in y, and (iv) if $x \in L(y)$ then $D^I \geq 1$ and $D^I = 1$ if x is on the frontier of input set.

Input-oriented technical efficiency is defined as the inverse of the distance function and can be obtained from (3.2.9).

$$TE = 1/D^I(x,y), \qquad 0 < TE \leq 1 \tag{3.2.9}$$

When a firm is operating on the frontier it has a distance function value equal to unity and consequently has a technical efficiency score of 1. We use a flexible functional form for input distance function as in (3.2.10):

$$\begin{aligned} lnD^I_{it} &= \alpha_0 + \sum_{m=1}^{M} \alpha_m lny_{mit} + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \alpha_{mn} lny_{mit} lny_{nit} + \sum_{k=1}^{K} \beta_k lnx_{kit} \\ &+ \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} lnx_{kit} lnx_{lit} + \sum_{k=1}^{K}\sum_{m=1}^{M} \delta_{km} lny_{kit} lny_{mit} + \theta_1 t + \frac{1}{2}\theta_{11} t^2 + \nu_{it} \end{aligned} \tag{3.2.10}$$

where D^I_{it} represents the distance function, y_{mit} is output, x_{kit} is input, variable t represents the time trend, subscript $i = 1...N$ denotes the number of the firms and $t = 1...T$ indicates number of periods. Also, $m = 1...M$ and $k = 1...K$ show the number of outputs and inputs respectively. Parameters α, β, δ, and θ are to be estimated.

The flexible functional form relaxes the restrictions on demand elasticities and elasticities of substitution nevertheless; imposing appropriate curvature on translog models can be challenging (Greene, 2008)[9]. The time trend is included in order to capture technical change and also everything else that we cannot measure but varies

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[9] Some studies use the Bayesian approach to impose regularity conditions (Greene, 2008).

over time and has a common effect on all firms (e.g., price of capitals, change in the regulatory environment, etc.). This is common in efficiency analysis of network companies (see e.g., Growitsch et al., 2012).

The condition of homogeneity of degree one in inputs is imposed by the use of the following constraints:

$$\sum_{k=1}^{K}\beta_k = 1, \quad \sum_{k=1}^{K}\beta_{kl} = 0 \quad k = 1,2,...K \quad and \quad \sum_{k=1}^{K}\delta_{km} = 0, \quad m = 1,2,...M \tag{3.2.11}$$

The symmetry condition is met if: $\alpha_{mn} = \alpha_{nm}, \quad m,n = 1,2...M,$ and $\beta_{kl} = \beta_{lk}$ $k,l = 1,2...K$.

We transform the input distance function into econometric models to be estimated by the stochastic frontier analysis (SFA) method and to obtain technical efficiency of the firms. Imposing the homogeneity of degree one by deflating $K-1$ inputs by Kth input (we use other cost (C_1) to deflate) will lead to (3.2.12):

$$lnD_{it}^{I} - lnx_{Kit} = f[(lnx_{kit} - lnx_{Kit}), lny_{mit}, t] + \nu_{it} \tag{3.2.12}$$

where $f(.)$ is the translog functional form. For the purpose of estimation we rearrange the above equation as:

$$-lnx_{Kit} = f[(lnx_{kit} - lnx_{Kit}), lny_{mit}, t] + \nu_{it} - u_{it} \tag{3.2.13}$$

where $lnD_{it}^{I} = u_{it}$ represents the non-negative technical inefficiency. The error components have the following distributions:

$$\nu_{it} \sim iidN(0,\sigma_{\nu}^{2}) \qquad u_{it} \sim iidN^{+}(0,\sigma_{u}^{2}) \tag{3.2.14}$$

ν_{it} is a normally distributed random error term and u_{it} is a half- normal random error term that capture inefficiency. As the efficiency is affected by the investments we model the heteroscedastic inefficiency variance $\sigma_{u_{het}}^{2}$ as in (3.2.15).

$$Log\sigma_{u_{het}}^{2} = \rho_0 + \rho_1 Log(In) + \rho_2 Log^2(In) \Rightarrow \sigma_{u_{het}}^{2} = exp(\rho_0 + \rho_1 Log(In) + \rho_2 Log^2(In)) \tag{3.2.15}$$

where ρ_0, ρ_1 andρ_2 are parameters that need to be estimated and "In" is normalised investment level with respect to sample mean. As shown in (3.2.16) we can separate the heteroscedastic variance into its homoscedastic component ($\sigma^2_{u_{hom}}$) and the element related to investments.

$$\begin{aligned} \sigma^2_{u_{het}} = exp(\rho_0)exp(\rho_1 Log(In) + \rho_2 Log^2(In)) = \\ \sigma^2_{u_{hom}} \times exp(\rho_1 Log(In) + \rho_2 Log^2(In)) \end{aligned} \tag{3.2.16}$$

This allows us to purge the effect of investments on inefficiency as seen from (3.2.17). In terms of estimation, equations (3.2.13) and (3.2.15) are estimated simultaneously based on the only observed data in (3.2.13). Having estimated them, the homoscedastic inefficiency can be obtained as follows:

$$\begin{aligned} u_{it} &\sim N^+(0, \sigma^2_{u_{hom}} \times exp(\rho_1 Log(In) + \rho_2 Log^2(In))) \\ u_{it} &\sim N^+(0, \sigma^2_{u_{hom}}) \times exp(\rho_1 Log(In) + \rho_2 Log^2(In)) \\ \hat{u}_{it} &= exp(\hat{\rho}_1 Log(In) + \hat{\rho}_2 Log^2(In)) \times \hat{u}_{before} \end{aligned} \tag{3.2.17}$$

It is clear that $\hat{u}_{it} = E[u_{it}|\epsilon_{it}]$ where $\epsilon_{it} = \nu_{it} - u_{it}$, On the other hand, $\hat{u}_{it} = \hat{u}_{after}$ thus we can write:

$$\hat{u}_{before} = \frac{\hat{u}_{after}}{exp(\hat{\rho}_1 Log(In) + \hat{\rho}_2 Log^2(In))} \tag{3.2.18}$$

where, $\hat{u}_{before}$ is before-investment inefficiency and $\hat{u}_{after}$ is after-investment inefficiency ($\hat{u}_{it}$). The firm specific technical efficiency is then computed by $\hat{e}_1 = exp(-\hat{u}_{before})$ and $\hat{e}_2 = exp(-\hat{u}_{after})$. The "no impact efficiency" is calculated using Equation (3.2.7).

3.3 Data

We use a dataset comprising a weakly balanced panel of 129 distribution network utilities from 2004 to 2010. All monetary data are in real terms and adjusted to 2010 price level. The data is collected by the Norwegian Water Resource and

Energy Directorate (NVE) and used in order to set the networks allowed revenues. The data collection procedure is mainly through an electronic system named eRapp (NVE, 2007). These include both technical and economic data. The economic data gives detailed information on the costs and revenues with respect to different network activities. The technical data, on the other hand, include consumer specific information such as customer numbers at each category, energy distributed, network energy losses, and also technical information about the networks such as length, type and capacity of lines and cables, transformers, switches, number of meters and finally duration and frequency of interruptions (NVE, 2007).

The network companies are responsible for the accuracy of metering data within their grid area even for metering and collections that are outsourced to a third party. The only data that is not based on the firm's own report is the environmental data (see Footnote 12). Following the data collection, the economic data are verified by independent auditors and controlled by the regulator. Moreover, NVE controls the technical data by visiting the site and also auditing the technical components of distribution networks and other comparable sources (NVE, 2007).

Our distance function model consists of two inputs and two outputs. The inputs are capital expenditure (In) and other costs (C_1). Following the Norwegian regulatory approach, we incorporate quality of service into our benchmarking model by adding the cost of negative externalities (network energy losses and service interruptions) to the directly incurred elements of operating cost as presented in (3.3.19).

$$C_1 = Operational\ Expenditure + Cost\ of\ Losses + Cost\ of\ Energy\ Not\ Supplied \tag{3.3.19}$$

The cost of energy not supplied is calculated from the number of minutes of interruptions multiplied by consumer willingness-to-pay for a more reliable service[10]. The cost of network energy losses is computed by multiplying the physical losses with average annual system price of electricity.

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[10] Consumer willingness to pay for quality of service is derived from consumer surveys and technical analysis.

The standard outputs, in efficiency measurement of distribution companies, are the number of customers, energy distributed and network length (or the size of service area) (Coelli et al. 2012). We use total number of customers (residential plus recreational homes) and network length as outputs[11] . These two variables are commonly used in efficiency analysis of electricity networks (e.g., Growitsch et al., 2012; Miguéis et al., 2011; Coelli et al., 2012). In addition to the input and output variables we use three weather and geographical variables in order to capture the heterogeneity among firms[12] . These factors can impact cost efficiency of the networks and controlling for their effects can help to account for the heterogeneity in the operating environment of network companies (Growitsch et al., 2011; Jamasb et al., 2012)[13] . Table 3.1 summarises the descriptive statistics of the data used.

As we use "other costs" (C_1) to impose homogeneity of degree one, the dependent variable of model is $-Log(C_1)$. The parameters used in the model are obtained by maximum likelihood estimation procedure. The optimisation technique used is Berndt-Hall-Hall-Hausman (bhhh) algorithm. Furthermore, in order to facilitate the interpretation of the first order terms, all variables are divided by their sample mean prior to estimation.

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[11] We examined the case of using distributed energy as an output along with number of customers. However, due to the presence of sever multicollinearity between these two variables, the estimated function does not satisfy regularity conditions (i.e. monotonicity and concavity). This is also the case when we estimated with three standard outputs.

[12] The three environmental variables are: (1) snow conditions, in millimeters of snow per year at a given temperature (around 0 degrees C), (2) Wind and distance to coast, as a ratio (average extreme wind/distance to coast), and (3) forest productivity, a number between 0 and 1 showing the share of forest with this growth rate along the power lines.

[13] We examined the influence of asset age (ratio of depreciation to book value) as a control variable. However, the variable showed inconsistencies in the sign of the age variable itself as well as for first order terms of other variables. Other measures of age may produce different results but these were not available. At the same time, the results indicated that inclusion of age does not change the efficiency scores significantly.

Table 3.1: Descriptive statistics

Variable Description	Name	Min.	Max.	Mean	Std. Dev.
Inputs					
Other costs*	C_1	1205.25	1178987	41260.63	67709.02
Capital expenditures*	In	6.82	121042.4	13113.12	17518.02
Outputs					
Network length (Km)	NL	14	8111	558.27	779.13
Number of customers (#)	CU	18	515152	13054	26964
Geographical variables					
Snow condition (millimetres)	$snow$	0	1193.61	372.64	196.54
Wind / distance to cost (ratio)	$wind$	0	0.16	0.01	0.02
Forrest productivity (fraction)	$forest$	0	0.54	0.15	0.11

*Monetary variables are in 000' NOK.

3.4 Results and discussion

The profit motive implies that incentive regulated firms evaluate the costs and benefits of undertaking investments by comparing the possible reductions and increases in their allowed revenue as a result of efficiency effect of their investments in cost benchmarking. However, the outcome depends on the net efficiency effect achieved by the investments.

Table 3.2 presents the results of the input distance function and heteroscedastic variance model estimations[14]. As shown in the table, the coefficients of first order terms for the number of customers, network length and investments are statistically significant and have the expected signs. These coefficients can be interpreted as distance function elasticity with respect to outputs and inputs at sample mean. The first order coefficients for snow, wind and forest are significant and consistent in terms of sign indicating that these geographic variables are also cost drivers. Additionally, all interactions of the forest variable with outputs are significant. However, only one interaction term of wind and snow variables with outputs is statistically significant. The heteroscedastic inefficiency variance model shows significant coeffi-

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[14] For ease of interpretation, the model coefficients were multiplied by -1.

cients both for the first order and quadratic terms.

The translog functional forms do not satisfy monotonicity and convexity globally (regularity conditions) hence, these need to be verified a posteriori (Sauer et al., 2006). Monotonicity implies two conditions for partial derivatives of input distance functions: non-decreasing in inputs and non-increasing in outputs (Perelman and Santin, 2005). Appropriate curvature implies concavity in inputs and quasi-concavity in outputs which boils down to a negative definite Hessian matrix on inputs and a negative semi-definite bordered Hessian matrix on outputs (Perelman and Santin, 2005). The results of a posteriori check on monotonicity and concavity conditions are presented in Tables A1 and A2 respectively (Appendix).

The results show that monotonicity is satisfied at sample mean for all inputs and outputs. Moreover, for the inputs investment and other costs and output network length monotonicity is satisfied 100% over all data points. The figure is 99.6% for the other output number of customers. The Hessian matrix of inputs is negative definite at sample mean without violation of appropriate curvature over data points. The bordered Hessian matrix of outputs is, however, indefinite at the point of approximation and satisfies appropriate curvature only 18.7% of times over data points[15].

Figure 3.2 illustrates the changes in the efficiencies before and after investments. As shown in the figure, investments have impacted the efficiency of the networks and within a relatively wide range. It is evident that the impact of investments on the efficiency variation among the firms is not uniform, in the sense that some of the firms have gained while some others lost efficiency. This complies with the basic notion of ex-post regulatory treatment of investments based on benchmarking that efficiency effects influence investment behaviour of firms as undue investments face the risk of efficiency loss.

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[15] Appropriate curvature cannot be guaranteed at all data points due to the presence of trade-off between flexibility and theoretical consistency. It is, however, desirable to have these conditions at least at the vicinity of the approximation point (e.g., sample mean), or for a range of dataset in which case interpretation capabilities with respect to the data points far from point of approximation is restricted. For a detail discussion of the regularity conditions see Sauer et al. (2006).

Table 3.2: Input distance function model estimation

Dependent variable: $-Log(C_1)$		
Variables	**Coefficient**	**Std. Err**
$Constant$	-5.799***	0.911
$Log(CU)$	0.428*	0.233
$Log(NL)$	0.625***	0.218
$Log(In)$	-0.924***	0.17
$0.5Log^2(CU)$	0.235***	0.025
$0.5Log^2(NL)$	0.134***	0.049
$0.5Log^2(In)$	-0.073***	0.016
$Log(CU) * Log(NL)$	-0.159***	0.036
$Log(CU) * Log(In)$	-0.007	0.02
$Log(NL) * Log(In)$	0.026	0.02
t	-0.01	0.01
$0.5t^2$	0.011***	0.003
$snow$	0.075***	0.021
$wind$	0.022***	0.005
$forest$	0.064***	0.013
$snow * Log(CU)$	-0.003	0.029
$snow * Log(NL)$	0.073**	0.035
$wind * Log(CU)$	-0.019**	0.008
$wind * Log(NL)$	0.014	0.009
$forest * Log(CU)$	0.077***	0.023
$forest * Log(NL)$	-0.067***	0.024
$Log(\sigma_u^2)$		
$Log(In)$	-1.801***	0.684
$Log^2(In)$	-0.261**	0.124
$Constant$	-5.605***	1.005

Note: $* \ P < 0.1$; $** \ P < 0.05$; $*** \ P < 0.01$

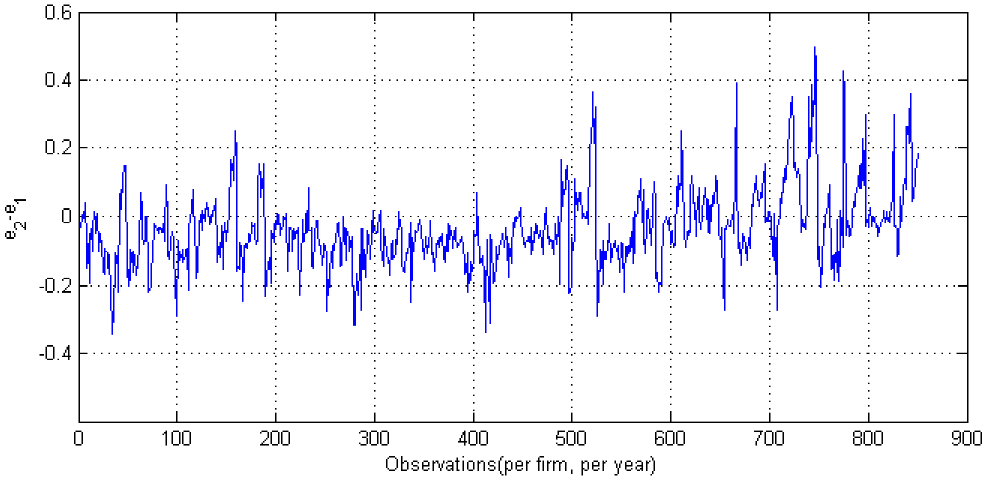

Figure 3.2: Efficiency change in firms before and after investments

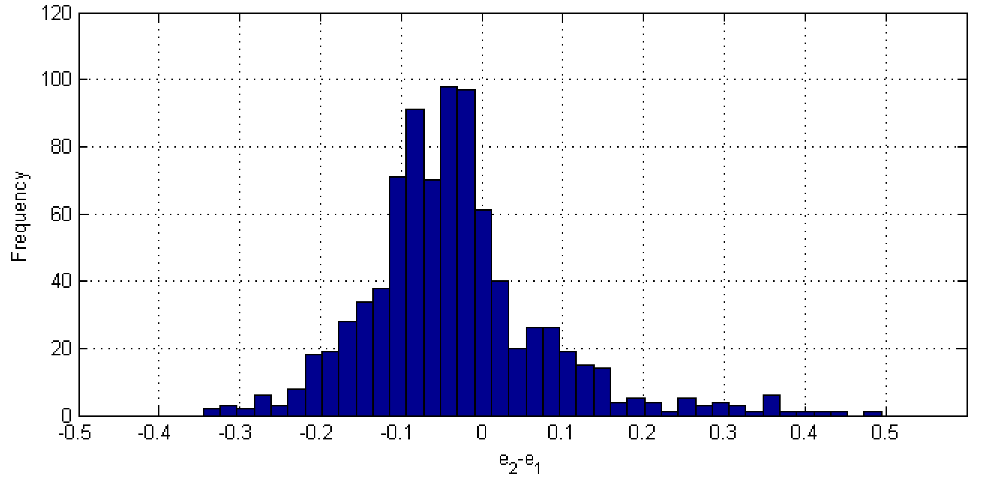

Figure 3.3: The distribution of efficiency change following investments

Figure 3.3 shows the distribution of efficiency variation following investments. The descriptive statistics of graph data is presented in Table 3.3. As seen from the graph and the table, the change in efficiency tends towards an asymmetrical distribution. The Jarque-Bera test of normality is rejected and distribution is right skewed. The maximum positive variation is 0.49 whereas on the negative side it is -0.34. Also, the majority of observations lie between -0.15 and 0.08 efficiency variations following investments (one standard deviation with respect to mean).

Furthermore, as illustrated by the scatter plot in Figure 3.4, efficiency loss after investments is more prevalent among the companies with lower investment to total

Table 3.3: Descriptive statistics of $e_2 - e_1$

Mean	-0.035
Median	-0.043
Maximum	0.496
Minimum	-0.345
Std. Dev.	0.112
Skewness	1.022
Kurtosis	5.711
Jarque-Bera	408.59
Probability	0.000

cost ratios. On the other hand, companies with average investment levels show more efficiency gain following their investments compared with companies with very high share of investment in total cost. This suggests that middle scale investments have generally been more productive than the larger and especially than the small ones.

One striking point is that the efficiency loss following investment is mainly related to the smaller companies. As seen from Figure 3.5, many of the utilities with a network length of less than 1000 km have lost efficiency following their investments. These companies have also lower investment to total cost ratios. On the contrary, the efficiency gain from investments increases with the size of firm, in the sense that highest efficiency gains are achieved by firms with a network length in excess of 1000 km. However, for very large firms, the efficiency gains from investments tend to decline again.

These observations suggest that smaller companies tend to be less productive and less able to absorb the full benefits of their capital expenditures. One reason can be that small companies are not operating at optimum size[16] . Moreover, the fact that lower investment to total cost ratio in these companies did not lead to an efficiency improvement indicates the complexity of the investment and efficiency

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[16] In the extreme, one network served 18 customers in a year and one with 14 Km of network length only (see Table 3.1). As seen from Figure 3.5, the majority of the companies have a network length of less than 1000 Km.

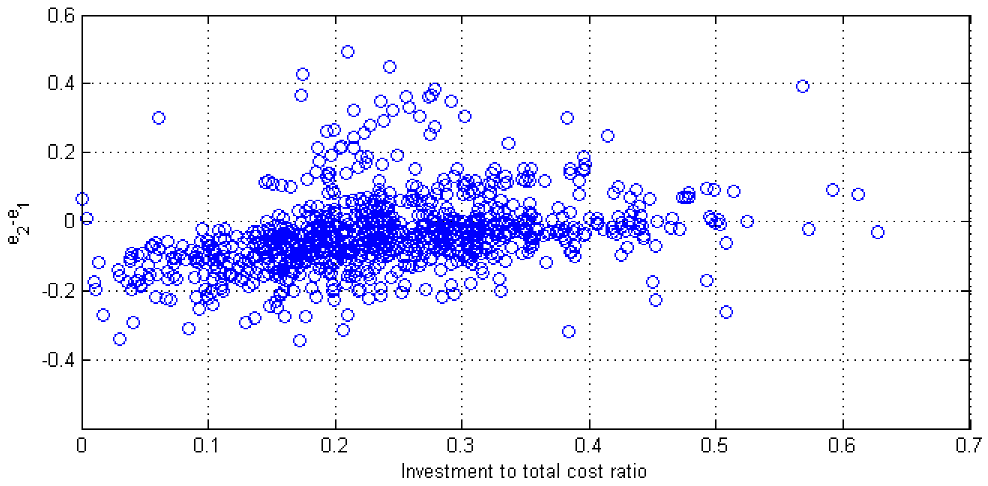

Figure 3.4: Efficiency change versus investments to total cost ratio

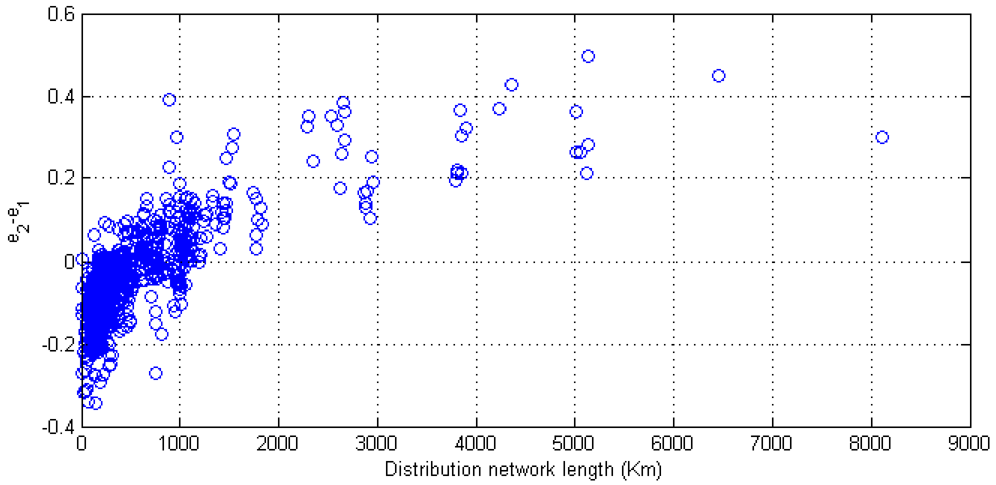

Figure 3.5: Efficiency variation versus network size (length)

relationship under benchmarking as lower investment levels might lead to an increase in other costs and may not help with efficiency improvement. This also implies that small scale investments may need better scrutiny prior to implementation in order to avoid lower allowed revenues as a result of cost benchmarking.

Figure 3.6 summarises the distribution of before investment, after investment and no impact efficiencies estimated in different years. As seen from the figure, in all cases, the distributions do not show zero skewness rather the mass of distribution is concentrated around the more efficient region without a noticeable change over different years. Additionally, the lower quartile is higher for the case of no impact efficiency compared with before investments and after investments efficiency, suggesting that given the current levels of investment efficiency improvement is required for many firms.

Table 3.4 compares the average of the same efficiencies in each year for all companies. As the table shows, the average efficiency declined following investments and it falls behind no impact efficiency in all years. This deviation varies between 3.7 to 6.2% in different years. Moreover, there is no stable pattern of change, in average efficiencies, over different years. However, the average becomes affected with outliers hence; in order to make a more reliable inference on the performance of sector we have weighted the efficiencies by the share of their corresponding investment in the total investment of the sector. This is to ensure that the weight effect of firms on total investment in the sector is taken into account when looking at the sector level. This is particularly relevant to the case of the Norwegian distribution companies which are diverse in terms of network size and customer density.

As shown in Table 3.4, the average efficiency gain following investments increased to around 10% when weighted. Additionally, there is a decline in weighted no impact efficiency. Also, the weighted average efficiency following investment exceeds the no impact efficiency by around 6.4%. This clearly indicates that equal treatment of firms to infer about their investment behaviour "at sector level" can result in biased conclusions. Moreover, the fact that the weighted average no impact efficiency declined below the weighted average after investment efficiency signals that the sector can still increase the level of investments, through new reallocation of investments, and without lowering the average efficiency gain of the sector.

Table 3.4: Average 'before investment', 'after investment', and 'no impact' efficiency

Efficiency measured	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Average e_1	0.951	0.953	0.948	0.949	0.947	0.946	0.943
Average e_2	0.912	0.908	0.898	0.911	0.925	0.922	0.913
Average $e_{no\ impact}$	0.962	0.965	0.96	0.962	0.962	0.962	0.959
Weighted average	$e_1 = 0.861$ $e_2 = 0.963$ $e_{no\ impact} = 0.899$						

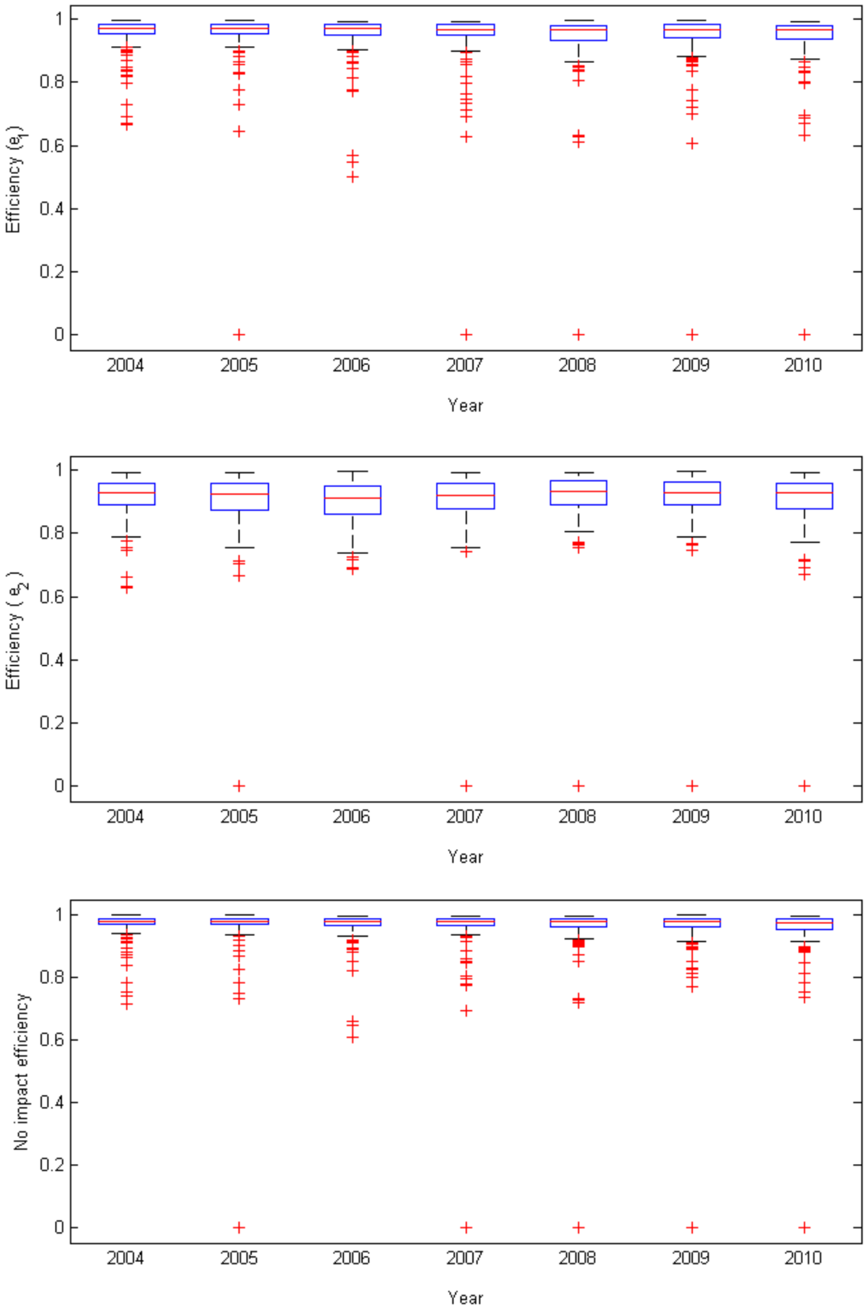

Figure 3.6: Distribution of efficiencies estimated

The reallocation of investments can increase the total investments in the sector because there are significant performance differences among the companies as depicted in Figures 3.3 and 3.4. The very efficient utilities that exceeded the no impact efficiency may wish to increase their investment in order to gain from their efficiency level. The investment increase can be continued until efficiency after investment declines to no impact efficiency, in which state, a form of optimality is achieved. On the other hand, those firms that their efficiency after investments falls short of no impact efficiency need to reduce their investment level in order to avoid inefficiency associated revenue loss[17] . The total capital expenditure of the companies that fall short of no impact efficiency accounts for 34% of the sector investment whereas this figure is about 66% for networks that obtained or exceeded no impact efficiency. Therefore, the net effect of the new reallocation is an increase in total investments without reducing the average efficiency of the sector.

As discussed above, the outcome of ex-post regulatory treatment of investments through total cost benchmarking is that some firms will lose part of their capital cost while some others recover all their investment and some make above normal profits. For example, the firms that appear to have outperformed the investment efficiency requirement i.e. their efficiency after investments exceeded the no impact efficiency considerably (the instance of $Q > 0$ discussed in Section 3.2.1) can earn more compared to the no benchmarking case. Under the circumstance that an "investment efficient firm" gains and an "investment inefficient firm" loses, the ex-post regulatory treatment of investment is effective in rewarding efficient and penalising inefficient firms.

However, this might not always be the case as the condition under which benchmarking produces reliable results does not always hold. This is because efficiency, in benchmarking terms, is a relative concept and only reveals information about firm

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[17] In this analysis we ignore the concept of dynamic efficiency hence; we do not take into account the cost effect of investments that takes more than one regulatory period to become realised. This is because our positive analysis is based on the current form of incentive regulation with ex-post regulatory treatment of investments as practiced in Norway and some other countries. The concept of dynamic efficiency is addressed in chapter 4.

performance in relation to other firms. Thus, the relative efficiency of a firm can also improve when the peer companies are not performing well. For instance, when companies are capital productive and their investments are used and useful, they might move to a higher level of relative efficiency after investments. However, the same can happen when they underinvest, something which gives them the appearance of cost efficiency. Therefore, unless the frontier firms genuinely represent the best practice, the results of benchmarking can be misleading.

The benchmarking limitation regarding investment embraces other cases such as when the firms' investments behaviour is harmonised in the sense that they are in the same phases of their investment cycles. This refers to the case that firms invest in similar periods and in proportion to their total cost levels but beyond their actual need. As the measure of efficiency is relative the firms tend to remain in a relatively similar efficiency position before and after investment. Under this condition, benchmarking can fail to identify the incidence of overinvestment.

The regulator expects that the threat of partial disallowance of capital expenditures built into the regulatory formula leads the firms towards efficient investments. However; the power of the model to detect overinvestments is limited to the case of 'out of phase' investments (i.e. when firms are not in the same investment cycle). Thus, sector-wide 'in phase' or cyclically harmonised overinvestments by the firms are not revealed in the process of benchmarking because the approach is based on between-firms comparisons. This will, in turn, limit the ability of the regulator to effectively address the issue of overinvestment. Harmonised investment behaviour can happen when many firms follow a similar investment policy. For instance, when a regulator guides the investment into a desired direction by, for example, offering a higher return for investments in innovation and particular types of technologies and activities (e.g., Smart Grids).

A parallel argument also holds in the case of harmonised underinvestment. This problem arises when the incentives to invest are not strong enough or the regulation is restrictive which causes firms to reduce their investments. In the short run, this can give the appearance of cost efficiency while, overtime, leading to gradual degradation of the networks and their reliability.

There are some possible remedies to address the cases of harmonised underinvestment or overinvestment. For instance, the regulator can use the power of incentive (λ) in order to influence the investment inefficient firms when there is evidence of overcapitalisation. The higher the power of incentive is the greater possibility of financial loss as a result of investment inefficiency. Thus, a high λ causes investment inefficient firms to reduce their investments and consequently improve their efficiency. Also, frontier firms need to follow the same path to maintain their position on the frontier. At present, λ is set at 60% for Norwegian distribution companies. A small increase in λ can reduce the net efficiency gains by the firms and create disincentive for investments. On the contrary, a reduction of the power of incentive aligns the revenue of the firm more with its actual cost and increases its propensity to invest. However, the power of incentive is usually set for a long period of time in order to make the investment behaviour of firms predictable and provide a stable regulatory environment. Therefore, the ability of the regulator to modify the power of incentive can be constrained[18].

In order to avoid underinvestment and deterioration of quality of supply induced by cost reduction incentives incorporated in incentive regulation, regulators adopt either quality performance targets or include the cost of network energy losses and cost of energy not supplied in benchmarking model as in the case of Norway. This is to prevent systematic underinvestment which can endanger network reliability over time. However, the issue is that underinvestment can have an immediate effect on efficiency improvement of the network whereas its impact on network reliability will be realised in the longer run.

Another possible problem of ex-post regulatory treatment of investment using benchmarking is that it can ease the strategic behaviour for trade-off between Capex and Opex[19] in order to avoid revenue loss from investment inefficiency when firms invest beyond their productive capacity. For instance, as shown in Table 3.2, invest-

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[18] This strategy can have significant side effects such as inducing uncertainty in regulation. Therefore, it needs to be used with strong evidence of persistent or systematic over or underinvestment in the sector.

[19] Capital expenditures and operational expenditures.

ments and other costs are negatively correlated in such a way that a 1% increase in investment with respect to the mean of the sector can result in 0.92% reduction of other costs. This in turn raises the regulatory issue of substitution of capital for labour introduced by Averch-Johnson (1962).

The regulatory treatment of investments involves a risk sharing dimension between the utilities and the consumers irrespective of being ex-ante or ex-post. The ex-post regulatory treatment of investment has the merit of being less interventionist. However, this comes at the cost of transferring investment risks to the companies. On the contrary, the ex-ante regulatory model is more interventionist but less risky for the investments of the network companies because risks are mainly transferred to the users of networks.

Thus, it is less likely that firms operating under a pure ex-ante regulatory regime (i.e., no ex-post evaluation of used and useful capital) peruse cost reducing investments as the investment cost is decoupled from their efficiency level. For example, in the UK, under the current regulatory framework for electricity and gas transmission networks, which are a form of ex-ante model (though subject to ex-post efficiency assessment), consumers are exposed to 75% of the companies 'actual cost' (Ofgem, 2010)[20] . Under the ex-post model it is more likely that consumers are exposed to the efficient cost of firms however, the implementation of this model has proven to be more complicated that initially perceived.

To sum up, the relationship between investment and efficiency under incentive regulation with ex-post regulatory treatment of investment is not straightforward. As efficiency is a relative concept in economics, performance of a firm is not only related to its own behaviour but also to that of other firms. The conditions under which overinvestment can reduce cost efficiency might not always hold. Moreover, it takes time for underinvestment to appear as cost in the form of quality of service deterioration. The Norwegian regulator attempts to incentivise the companies to operate and maintain their networks in an efficient manner and provide a high level of reliability. However, the use of total cost benchmarking does not necessarily

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[20] This figure is perceived to be lower for electricity and gas distribution companies (Ofgem, 2010).

lead to the socio-economic efficient level of investments. The implication of these for regulatory framework of network companies is that, there is no ideal measure to address the issue of investment under regulation given the trade-off between the level of intervention and risks of capital cost to the utilities or their consumers. Therefore, the regulator might choose to combine the effective elements of different approaches to balance between the benefits and shortcomings of taking up a particular method. Some previous works which have proposed such new approaches, in the context of transmission grid, include combining the merchant model with benchmark or price regulation models (see Hogan et al., 2010) or the design of network tariffs such as two-part tariffs as in Vogelsang (2001).

3.5 Conclusions

Contrary to the early years of electricity sector reforms when regulators were mainly concerned with cost efficiency, an emerging and pressing issue is how to ensure sufficient and efficient level of investments in the regulated networks. Over the years, efficiency of the natural monopoly power networks has been improving as a result of incentive regulation. However, the need for significant investments in the coming years combined with the incentives to reduce costs gives rise to new challenges regarding the efficiency and sufficiency of investments in the networks. In this study we analysed the relation between cost efficiency and investments in electricity distribution networks under ex-post regulatory treatment of capital expenditures using the case of Norway. We introduced the concept of ”no impact efficiency” as a revenue-neutral efficiency effect of investments under cost benchmarking which, if achieved, makes the firm ”investment efficient” and immune from cost disallowance in the benchmarking process. Also, we estimated the observed efficiency effect of investments in order to compare this with the no impact efficiency and discussed the implication of cost benchmarking for the investment behaviour of distribution companies in Norway.

The results show that the weighted average efficiency gain of the networks from investments is 10% reflecting the fact that more investment often resulted in higher efficiency. The results suggest that networks that fall short of the no impact efficiency need to reduce their capital expenditure in order to improve their efficiency following investment. On the other hand, firms that outperform the no impact efficiency may wish to increase their investment levels in order to gain from the efficiency they achieved. Overall, the new reallocation of investments increases the total investment of the sector as a whole but without lowering the average efficiency gain of the sector.

At the same time, there are significant variations in efficiency gain following investments at the level of individual companies. Firms with average investment to total cost ratio have gained more efficiency through their investments relative to those with higher or lower than average. Moreover, the efficiency loss following investments is mainly related to the smaller networks. An implication of this for regulatory framework can be that cost reducing incentives have adversely affected the smaller firms leading to lower level of investments and higher operating costs and consequently efficiency loss in these firms. Given that average investment levels have been more productive indicates that the incentives should prevent the network utilities from going below or beyond certain levels of capital expenditures.

The relationship between investment and efficiency under incentive regulation is not straight forward. The effectiveness of ex-post regulatory treatment of investments relies on the reliability of benchmarking results which are potentially vulnerable to certain trends and behaviours such as harmonised over- and under-investments. Despite these issues, under the ex-post regulatory treatment of investments, consumers are more likely to be exposed to efficient level of costs compared with the ex-ante model. At the same time, the networks bear a higher investment risk under the ex-post model. Thus, the regulatory treatment of investment always involves an element of risk sharing trade-off between the firms and their consumers.

This chapter analysed the relationship between investment and short run efficiency under incentive regulation. However, a serious shortcoming of regulatory models (both ex- ante and ex-post) is lack of an incentive mechanism for dynamic efficiency. Dynamic efficiency is concerned with the optimal rate of innovation and investment to improve production processes which help to reduce the long run average cost curves. Dynamic efficient behaviour, on the other hand, might cause the regulated firms to temporarily deviate from the static efficient frontier. This, however, is problematic especially under ex-post regulatory treatment of investment because it exposes the firms to financial loss and hence, creates disincentive for long term investment and innovation. The next chapter deals with the issue of dynamic efficiency under incentive regulation.

Chapter 4

Dynamic efficiency and incentive regulation

The pursuit of efficiency improvement is the main motivation for reform and incentive-based regulation of infrastructure and network industries such as electricity, gas, water, and telecommunications. The expectation is that incentive regulation mechanisms would provide more powerful incentives for regulated firms to deliver the objectives of regulators (Joskow, 2005b). Due to asymmetry of information between regulators and regulated firms, the former often rely on sector level information (benchmarking) in order to determine the firms' efficient levels of cost. This is because the business plan of a regulated company can be strategically distorted in pursuit of profit. Furthermore, the incentive regulatory regimes tend to remunerate firms based on their performance and not their actual cost. Thus, incentive regulation models almost invariably involve efficiency and productivity analysis using benchmarking techniques (Jamasb and Pollitt, 2001).

In theory, regulators would be expected to pursue multiple aspects of efficiency when regulating natural monopoly industries (Coelli et al., 2003). An important aspect is the concept of dynamic efficiency. Dynamic efficiency can be described as a state where the short run and long run objectives of firms are balanced. It also tends to promote longer term investment in technology and research and development, which are the key factors for the success of a business. The resulting innovation often helps an economic decision making unit to smoothly address its future challenges.

This is particularly the case in a capital intensive sector such as electricity networks. This is because the industry is regulated and the operating environment of network companies is highly dynamic as a result of increasing penetration of distributed energy resources, smart grid deployment, electric vehicles' uptake and demand side management.

Thus, regulation should incentivise distribution networks to undertake innovation, make sufficient investment, promote their technical level and improve their management practices. In other words, regulators need to promote dynamic efficiency in regulated firms. However, until recently the dynamic aspect of efficiency analysis was absent from the efficiency and productivity literature and, in particular, in the context of the regulated industries (Serra et al., 2011).

This chapter introduces the concept of dynamic efficiency under incentive regulation with ex-post regulatory treatment of investments using the case of electricity distribution networks in Norway. We show that incentive regulatory models based on benchmarking total cost are problematic for investment and optimal inter-temporal accumulation of capital of regulated firms. This is because they induce an autoregressive process in the level of cost efficiency and expose firms to financial losses following investment and capital stock adjustment. The study demonstrates that, in a given period, cost inefficiency of regulated utilities is a combination of period-specific effects (shocks) and a carry-over component from previous periods. The latter component is due to the sluggish adjustment of outputs in the presence of investment and the associated adjustment costs. Additionally, we estimate these two components of inefficiency along with the rate of inefficiency transmission across periods (adjustment towards the long run equilibrium). Finally, we show that there is a positive relationship between the investment level and period specific inefficiency shocks and also the rate of inefficiency transmission across periods.

The next section provides a theoretical framework for the effect of adjustment cost and incentive regulation of electricity distribution networks on the dynamics of inefficiency. Section 4.2 discusses the empirical model adopted to estimate the two components of inefficiency (i.e., period specific shock and carry-over) and the rate of inefficiency transmission. The empirical results are presented and discussed in

Section 4.3. Section 4.4 provides the conclusions.

4.1 Theoretical framework

In this section we develop a simple framework to describe the process of capital stock adjustment of a firm and its effect on the evolution of inefficiency under incentive regulation with ex-post regulatory treatment of investment such as (4.1.1).

$$RE_t = C_t + \lambda(C_t^* - C_t) \tag{4.1.1}$$

In the above model, t indexes time periods, RE_t is regulated revenue, C_t represents the actual costs of the firm,C_t^* is the efficient cost obtained from efficiency analysis of regulated firms (i.e., $C_t^* = e_t C_t$ where e_t is the cost efficiency of the firm) and λ is the power of incentive[1] . Actual cost includes capital expenditures and other costs (operation and maintenance, etc.).

The relation in (4.1.1) presents a generic form of incentive regulation model with ex-post regulatory treatment of investments. It is an incentive regulatory model because the revenue of the firm is partially (or totally) decoupled from its actual (own) cost depending on the magnitude of the power of incentive [2]. This amounts to a non-zero value for λ within its feasible boundary ($0 \leq \lambda \leq 1$).

The regulatory model presented in (4.1.1) has also two important specifications. First, it constructs the allowed revenue of firm based on a weighted average of firm specific information (actual cost obtained from business plan) and sector level information (efficient cost obtained from benchmarking). Second, revenue crucially depends on the firm's cost efficiency. This implies that any factor which affects the

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[1] The aim of this regulatory model is to incentivise efficiency improvement in regulated utilities. In theory, a higher than optimum level of cost (C_t^*) means revenue loss to the firm. Thus, the regulated firms have incentive to move as closely as possible to the production frontier (Poudineh and Jamasb, 2013a, Newbery, 2002b).

[2] Depending on the value of λ, the model in (4.1.1) represents an spectrum of incentive regulations ranges from a high powered incentive regulation (i.e., $\lambda = 1$) where the firm's cost is fully decoupled from the revenue to a low powered incentive regulation (i.e., λ=0) where the firm's revenue is the same as the actual cost (i.e., rate of return regulation).

cost efficiency of a firm will also affect its revenue. Additionally, as the revenue of a firm is linked to the cost efficiency, it promotes an indirect competition among regulated firms to reduce their cost for given levels of outputs or maximise the outputs for a given level of cost (Müller et al. 2010).

Under the ex-post regulatory model of investment treatment the regulator does not interfere directly with the investment level of regulated firms. The regulator, however, evaluates the companies' performance, ex-post, using benchmarking techniques and sets their allowed revenues based on their deviation from the sector best practice. In this approach, the investment level of regulated firms will impact their revenue through its effect on cost efficiency.

Poudineh and Jamasb (2014b) show that, under the incentive regulation model in (4.1.1), firms need to achieve a certain level of cost efficiency, following investment, in order to avoid cost disallowance in the benchmarking exercise. This level of efficiency, which is termed "no impact efficiency", depends on the investment level (In), cost and efficiency of the firm before investment (i.e. C_1 and e_1 respectively) and can be presented as in (4.1.2) (see Poudineh and Jamasb 2014b; 2013a).

$$e^* = \frac{C_1 e_1 + In}{C_1 + In} \tag{4.1.2}$$

Alternatively, it can be shown that there is a certain level of investment (In^*), for a given level of no impact efficiency (e^*), that can be done without reduction in profits. This investment level can be obtained by solving (4.1.2) with respect to In as in (4.1.3).

$$In^* = \frac{C_1(e^* - e_1)}{1 - e^*} \qquad e^* \neq 1 \tag{4.1.3}$$

As seen from (4.1.3), as no impact efficiency moves towards unity (though never equals one), the optimum level of investment for the firm will be higher. In practice, the regulated firm neither observes nor can choose the level of no impact efficiency whereas it only adjusts the investment level (and other costs). However, the firm knows that high level of investment involves the risk of cost disallowance because it requires a higher level of efficiency achievement following investment. Moreover, as shown in Poudineh and Jamasb (2014b), in a static setting, the lower than optimum level of investment can increase other costs and hence, reduces efficiency in the benchmarking process, which consequently will be reflected in the firm's revenue.

Therefore, the firm conjectures the optimum level of investment, given its current level of efficiency and other costs. The capital accumulation process follows the following relation:

$$K^*_{t+1} = (1 - \varphi)K^*_t + In^*_t \tag{4.1.4}$$

where K is the stock of capital of the firm, φ is the depreciation rate of capital and the star superscript indicates optimally. In theory, deviation from the optimum investment level (i.e., under- or over-investment), under the incentive model in (4.1.1), will be translated into a cost to the firm in the form of efficiency loss. Thus, regulated firms have an incentive to adjust their level of capital stock employed in the production process.

However, there are two barriers to the full and fast adjustment of capital stock towards the optimum level. First, the regulated firm needs to take into consideration the revenue effect of investments and possible cost disallowance in the benchmarking practice. This is because the firm carries out investment based upon an ex-ante prediction of the optimum level of investment. However, the firm's actual investment can turn out to be lower or higher than the optimum level following the ex-post efficiency benchmarking (for a detailed discussion see Poudineh and Jamasb, 2013a). Second, the adjustment costs as a result of changing capital stock (e.g., cost of installation, disturbing the production process, personnel training, etc.) manifest themselves as reduced output or resource cost and lead to sluggish capital stock adjustment[3]. Adjustment costs are often modelled as either explicit resource cost or as output-reducing cost incurred by firms as a result of diversion of resources from production to investment support activities (Silva and Stefanou, 2007).

Therefore, in any regulatory period, the firm's objective (with regard to investment) is to minimise the cost of deviation from the optimum capital stock, as well as,

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[3] In this analysis we do not consider external adjustment costs which are related to market for capital goods (i.e., monopsony in the market for supply of capital goods).

the cost of adjustment. In the context of incentive regulated firms, it is reasonable to assume that adjustment cost appears as a resource cost to the firm rather than an output-reducing cost. This is because output is determined by demand which is exogenous and hence, the utilities adjust their input to deliver a given level of output and service quality.

Following Pereira (2001) we adopt a quadratic loss function to represent the firm's decision for investment and capital level adjustment. In our model we interpret the loss function components in the context of a regulated industry as previously mentioned. Within this framework, the firm minimises the expected sum of future adjustment cost and the cost of deviation from the optimal path of capital stock, which are discounted appropriately, subject to a capital accumulation process as follows:

$$\begin{aligned} Min\ E_t \sum_{i=0}^{\infty} \eta^i [(K_{t+i} - K^*_{t+i})^2 + b(In^2_{t+i})] \\ s.t. \quad K_{t+i+1} - K_{t+i} = I_{t+i} - \varphi K_{t+i} \end{aligned} \tag{4.1.5}$$

where $0 < \eta < 1$ is the discount factor and $b(In^2_{t+i})$ is a quadratic function representing the adjustment cost, with b denoting the importance of adjustment cost in disequilibrium cost. E_t is the expectation operator conditional on the information set available to the firm at time t. The quadratic nature of the function ensures that any deviation from the optimum level of capital (under- or over-investment) appears as a cost to the firm (Freiesleben, 2008).

Expectations play an important role in investment decision of firms under regulation. The economic actions concerned with the future are not strictly determined by a set of objective data whereas often decided upon in a shadow of doubt and uncertainty. Under uncertainty the optimisation is based on the expectation of future relevant variables for rationally by agents. The optimum capital adjustment path (Euler equation) can be obtained from the decision of firm based on the forward solution procedure.

Using discrete time calculus of variations, the first order condition for the dynamic optimisation problem in (4.1.5) will lead to the Euler equation in (4.1.6), which shows the optimal path for capital stock (Pereira, 2001).

$$E_tK_{t+1} - \frac{[(1-\varphi)^2 + b^{-1} + \eta^{-1}]}{1-\varphi}K_t + \frac{1}{\eta}K_{t-1} = -\frac{b^{-1}}{(1-\varphi)}K_t^* \tag{4.1.6}$$

Using a simplifying assumption of zero depreciation rate ($\varphi = 0$)[4] and the conditional expectation operator converts (4.1.6) into the following:

$$(B^2 + \zeta B^{-1} + \frac{1}{\eta})E_tK_{t-1} = -b^{-1}E_tK_t^* \tag{4.1.7}$$

where $\zeta = -[1 + b^{-1} + \eta^{-1}] < 0$ and B represents an operator defined as $B^{-j}E_tx_t = E_tx_{t+j}$.

The equation (4.1.7) can be further decomposed into its factors as follows:

$$(\theta_1 - B^{-1})(\theta_2 - B^{-1})E_tK_{t-1} = -b^{-1}E_tK_t^* \tag{4.1.8}$$

where $\theta_1 + \theta_2 = -\zeta$ and $\theta_1\theta_2 = 1/\eta$. As the sum and product of roots are positive we can conclude that the roots θ_1 and θ_2 are both positive. Furthermore, Pereira (2001) shows that one of these roots is smaller than unity and the other is larger than one. Solving (4.1.8) for the unstable root, say θ_2, leads to the equation of motion for capital stock in (4.1.9):

$$K_t = \theta_1K_{t-1} + \theta_1\eta b^{-1}\sum_{i=0}^{\infty}(\theta_1\eta)^iE_tK_{t+i}^* \tag{4.1.9}$$

If we multiply both sides of (4.1.9) with $(B^{-1} - 1)$ a similar equation of motion for investment can be obtained as follows:

$$I_t = \theta_1I_{t-1} + \theta_1\eta b^{-1}\sum_{i=0}^{\infty}(\theta_1\eta)^iE_tI_{t+i}^* \tag{4.1.10}$$

where $I_t = K_{t+1} - K_t$ and $I_t^* = K_{t+1}^* - K_t^*$.

Therefore, the level of investment (or capital stock), in the current period, is directly influenced by its value in the previous period and also related to the current and expected future levels of optimum investment (capital). In other words,

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[4] This assumption is just for simplicity in working with the equations and has no effect on the nature of the autoregressive process we will obtain for investment or capital in the following equations.

the equation of motion, for investment (capital) of the regulated firm, follows an autoregressive process.

The presence of an autoregressive process in investment (or capital) evolution induces a similar relationship in state of the firm's cost inefficiency as well. In order to show this we construct the total costs of firm using the relation in (4.1.10). According to incentive regulation model in (4.1.1), the total cost of firm includes investment and other costs (operation and maintenance etc.) as in (4.1.11).

$$C_t = I_t + Other\ costs_t \tag{4.1.11}$$

If we substitute for I_t from (4.1.11) into (4.1.10) we will have:

$$C_t = \theta_1 I_{t-1} + Other\ costs_t + \theta_1 \eta b^{-1} \sum_{i=0}^{\infty} (\theta_1 \eta)^i E_t I^*_{t+i} \tag{4.1.12}$$

which can be presented as follows:

$$C_t = \theta'_1 C_{t-1} + V_0 + \theta_1 \eta b^{-1} \sum_{i=0}^{\infty} (\theta_1 \eta)^i E_t I^*_{t+i} \tag{4.1.13}$$

where $\theta'_1 C_{t-1} + V_0 = \theta_1 I_{t-1} + Other\ costs_t$ and $1 - \theta'_1$ shows the rate of adjustment of total cost. The equation in (4.1.13) can be further simplified and presented in term of an autoregressive process for total cost as follows:

$$C_t = \theta'_1 C_{t-1} + C_0 \tag{4.1.14}$$

where $C_0 = V_0 + \theta_1 \eta b^{-1} \sum_{i=0}^{\infty} (\theta_1 \eta)^i E_t I^*_{t+i}$ and shows the cost level of firm if there was no transfer from previous period.

Cost efficiency (CE_t) is defined as the ratio of minimum cost (C^*) over actual cost of the firm (C_t). Also, for any given level of cost inefficiency (z_t), the cost efficiency (CE_t) is defined as $CE_t = exp(-z_t)$. Therefore, we can write:

$$\begin{aligned}
CE_t = \frac{C^*}{C_t} &= \frac{C^*}{\theta_1' C_{t-1} + C_0} \\
\frac{1}{CE_t} = \frac{\theta_1' C_{t-1} + C_0}{C^*} &= \theta_1' \frac{C_{t-1}}{C^*} + \frac{C_0}{C^*} \\
\frac{1}{CE_t} &= \theta_1' \frac{C_{t-1}}{C^*} + \frac{C_0}{C^*} \\
exp(z_t) &= \theta_1' exp(z_{t-1}) + \frac{C_0}{C^*} \qquad (4.1.15)
\end{aligned}$$

The relation in (4.1.15) clearly shows that inefficiency in the current period is correlated to the inefficiency in the previous period. Thus, the firm decision with respect to optimal capital stock adjustment, under regulatory model in (4.1.1), will lead to an autoregressive process in the level of cost inefficiency [5].

Econometric version

Taking the logarithm of both sides in (4.1.15), and appending a random term (ϵ_t) we can present the econometric version of this relation for z_{t-1} as follows:

$$z_t = \alpha + (1 - \psi) z_{t-1} + \epsilon_t \qquad (4.1.16)$$

where α is a constant which is related to the $\frac{C_0}{C^*}$ in (4.1.15), $1 - \psi$ shows the persistence of inefficiency[6] and is related to θ_1' (i.e., ψ is the speed of adjustment of inefficiency). Finally, ϵ_t is a random shock to the level of inefficiency in the current period.

The term $\alpha + (1 - \psi) z_{t-1}$ in (4.1.16) is the expected value of z_t given z_{t-1}. In other words, given the previous level of inefficiency and presence of an autoregressive process, firm inefficiency is expected to be composed of a constant term (α), and its inefficiency in the previous period (z_{t-1}) which is partially adjusted ($-\psi z_{t-1}$).

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[5] While we demonstrate that investment behaviour of firms under regulation model in (4.1.1) will lead to an autoregressive process for inefficiency, we do not claim presence of such a relationship is solely due to investment.

[6] The value of ψ can be common or different for every observation. The empirical model in the next section is setup to enable an observation specific estimation of ψ.

However, in practice, the observed level of inefficiency can be higher or lower than the expected value due to period specific shocks (i.e., ϵ_t). These shocks have a zero expectation and cause inefficiency to deviate from its expected path. Ahn and Sickles (2000) attribute these shocks to emergence of new technologies, regulation or deregulation and changes in behaviour of competitors. Investment also is an important factor that introduces period specific shock to the current level of inefficiency which persists over subsequent periods.

It is evident from (4.1.16) that inefficiency transmission across periods exists only when $\psi \neq 1$. A value between zero and unity ($0 < \psi < 1$) means that the rate of inefficiency transmission is diminishing as time passes. Under this condition, a higher ψ (or a lower $1 - \psi$) implies a faster adjustment towards the long run equilibrium and a lower level of inefficiency persistence. On the contrary, a lower ψ implies prolonged persistence of inefficiency and hence; inability of producers to optimise their cost quickly. A value of $\psi = 0$, on the other hand, implies that there is no tendency for inefficiency to revert back to an equilibrium point.

Although, in the short run, inefficiency depends on its past values, in the long run it is a function of α and ψ. If $0 < \psi < 1$ and ϵ_t is a white noise process, the expected long run inefficiency would be $\frac{\alpha}{\psi}$[7].

Therefore, in any given period, cost inefficiency has two components. One element is related to period-specific effects (ϵ_t) and the other is the inefficiency carried over from previous periods ($\alpha + (1 - \psi)z_{t-1}$). This implies that inefficiencies which are related to sluggish adjustment of capital and the associated adjustment costs persist over time, without firms having much control over them in the short run. At the same time, the incentive regulation model in (4.1.1) penalises and rewards firms based on their observed levels of efficiency which, in effect, includes an uncontrollable component due to investment cycles. This is problematic for optimising investment and capital as it exposes the regulated firm to revenue loss following

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[7] ***Proof***: a recursive substitution for (4.1.16) gives $z_t = (1 - \psi)^n z_{t-n} + \alpha[\sum_{i=0}^{n}(1 - \psi)^i] + [\sum_{i=0}^{n}(1 - \psi)^i \epsilon_{t-i}]$ on the other hand $E(z_t) = (1 - \psi)^n E(z_{t-n}) + \alpha[\sum_{i=0}^{n}(1 - \psi)^i]$ because ϵ_t is assumed to be a white noise process and $E(\epsilon_t) = 0$. Thus, the cumulative effect when $n \to \infty$ is $E(z_t) = \frac{\alpha}{1-(1-\psi)} = \frac{\alpha}{\psi}$.

investment.

4.2 Empirical model

This section presents a parametric method to estimate the two components of inefficiency and the rate of inefficiency transmission, across periods, as described in Section 4.1. Application of parametric methods to address the dynamic aspect of inefficiency is relatively new. Ahn and Sickles (2000) were the first to use a dynamic model to provide a structural explanation for variations in the efficiency levels of a firm. They assume that technical inefficiency evolves over time in an autoregressive manner due to the firm's inability to adjust its efficiency in a timely manner. This model is reduced to a normal dynamic panel data model if the speed of inefficiency adjustment is assumed to be the same for all firms. Emvalomatis et al. (2011) use a similar dynamic efficiency model based on the standard stochastic distance function model, but allow the efficiency scores of the firms to be correlated through time. The autocorrelated inefficiency model is developed in a state-space framework and nonlinear Kalman filtering is used to evaluate the likelihood function and obtain the efficiency scores.

Tsionas (2006) proposes a stochastic frontier model that allows for inefficiency effects and dynamic technical inefficiency by adopting Bayesian inference procedures based on Markov chain Monte Carlo (MCMC) techniques. Emvalomatis (2012) considers the implications of stochastic frontier models with autocorrelated inefficiency in the presence of unobserved heterogeneity. The study specifies random- and correlated random-effects models and proposes a Bayesian estimation approach to measure dynamic efficiency.

4.2.1 Model development

The empirical model is developed in a cost function framework. The cost function, $C(\mathbf{w}, y)$, gives the minimum possible cost of producing output y given the observed input prices, $\mathbf{w}$. The cost efficiency of firm i in period t is defined as the ratio of minimum possible cost relative to the observed cost, $\mathbf{w}_{it}'\mathbf{x}_{it}$, as follows:

$$CE_{it} = \frac{C(\mathbf{w}_{it}, y_{it})}{\mathbf{w}'_{it}\mathbf{x}_{it}} \tag{4.2.17}$$

where $\mathbf{x}$ is the vector of input quantities used. Thus, cost efficiency is always between zero and one ($0 < CE_{it} \leq 1$). Taking the logarithm of both sides in (4.2.17), appending a noise error term $\nu_{it} \sim N(0, \sigma_\nu^2)$ and rearranging will lead to relation in (4.2.18).

$$logTC = logC(\mathbf{w}_{it}, y_{it}) - logCE_{it} + \nu_{it} \tag{4.2.18}$$

where $TC = \mathbf{w}'_{it}\mathbf{x}_{it}$ represents total observed cost of the firm, $C(\mathbf{w}_{it}, y_{it})$ is the cost function and $logCE_{it}$ is an one-sided error term which enters the equation as the logarithm of cost efficiency. According to economic theory, the cost function is required to be concave and linearly homogenous in input prices and non-decreasing in input prices and outputs (Chambers, 1988).

Equation (4.2.18) assumes that all firms have access to the same technology and operate under similar conditions. As this assumption may not be realistic, we add a firm specific term ω_i to (4.2.18) in order to account for unobserved heterogeneity among the firms, assuming $\omega_i \sim N(0, \sigma_\omega^2)$ (Emvalomatis, 2012). Thus, the cost frontier in (4.2.18) can be written in terms of an estimable linear function of $\boldsymbol{Q_{it}}$ as the logarithm of matrix of independent variables and a vector of coefficients $\boldsymbol{\beta}$ as follows:

$$c_{it} = \boldsymbol{Q'_{it}}\boldsymbol{\beta} - log(CE_{it}) + \omega_i + \nu_{it} \tag{4.2.19}$$

where c_{it} is the logarithm of total cost[8].

Following Emvalomatis et al. (2011), we assume an autoregressive process for the cost efficiency by making non-linear transformation of inefficiency as in (4.2.20)-(4.2.22)[9].

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[8] Although the model is developed in the context of cost function however, a distance function approach can also be used.

[9] This transformation is for estimation purposes and allows us to have observation specific inefficiency transmission. Thus, equation (4.2.21) is comparable to equation (4.1.16) in Section 4.1

$$s_{it} = log(\frac{CE_{it}}{1 - CE_{it}}) \tag{4.2.20}$$

$$s_{it} = \delta + \rho s_{it-1} + u_{it} \qquad u_{it} \sim N(0, \sigma_u^2) \tag{4.2.21}$$

$$s_{i1} = \mu_1 + u_{i1} \qquad u_{i1} \sim N(0, \sigma_{u1}^2) \tag{4.2.22}$$

where s_{it} is the logarithm of the ratio of efficiency to inefficiency and ρ is an elasticity that measures the percentage change in the ratio of efficiency to inefficiency that is transferred from one period to the next. Equation (4.2.22) initialises the stochastic process and assumes stationarity. Stationarity also implies that, in the long run, the expected value of s_{it}, unconditional on s_{it-1}, is the same for all firms and the possible observed differences are due to shocks or the difference in the stage of the path towards long run equilibrium. Under this condition (stationarity), the two additional parameters can be obtained by (4.2.23) and (4.2.24).

$$\mu_1 = \frac{\delta}{1 - \rho} \tag{4.2.23}$$

$$\sigma_{u1}^2 = \frac{\sigma_u^2}{1 - \rho^2} \tag{4.2.24}$$

If the process is not stationary the expected value of the firms' efficiency, over time, tends towards unity or zero. Similarly, the expected value of s_{it} can incline towards positive or negative infinity. As suggested in Tsionas (2006), it is unlikely that the data are generated by a process with a unit root, especially when efficiency approaches zero. This is because we normally expect inefficient firms to fall out of a competitive market or, in the case of regulated firms, suffer from financial losses as their revenue is directly linked with their efficiency level. Thus, the number of

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in the following way (subscript i is removed for simplicity): $\frac{dz_t}{dz_{t-1}} = 1 - \psi = \frac{dz_t}{ds_t} \times \frac{ds_t}{ds_{t-1}} \times \frac{ds_{t-1}}{dz_{t-1}} = \frac{exp(s_t)}{(1+exp(s_t))^2} \times \rho \times \frac{1}{z_{t-1}(1-z_{t-1})}$. For the above relationship we have used $z_t = 1 - CE_t$ which approaches $z_t = -log(CE_t)$ for low values of inefficiency. This is because based on the Taylor series of e^{-z_t} we have: $e^{-z_t} = \sum_{n=0}^{\infty} \frac{(-z_t)^n}{n!} = 1 - z_t + \frac{(z_t)^2}{2!} - \frac{(z_t)^3}{3!} + ...$ and hence, $Lim\ e^{-z_t} = 1 - z_t$ because all the higher order terms will approach towards zero quickly as $z_t \rightarrow 0$.

very inefficient firms will be small. Given stationarity, the long run cost efficiency can be obtained by (4.2.25)[10].

$$Long\ run\ CE = 1/[1 + exp(-\frac{\delta}{1-\rho})] \tag{4.2.25}$$

In terms of estimation our empirical analysis involves estimation of two models simultaneously. In other words, we estimate the parameters of the hidden state model (4.2.21)[11] and of the measurement equation (4.2.19) simultaneously using only the observed data in (4.2.19). In order to estimate the vector of all parameters, $\boldsymbol{\theta} = [\boldsymbol{\beta}, \sigma_\nu, \delta, \rho, \sigma_u, \sigma_w]'$ we set up the likelihood function by letting s_i denote the $T \times 1$ vector of the latent state variable for the firm i as in (4.2.26).

$$\begin{aligned} p(\boldsymbol{c}, \{w_i\}, \{s_i\}|\boldsymbol{\theta}, \boldsymbol{Q}) &= p(\boldsymbol{c}|\{w_i\}, \{s_i\}, \boldsymbol{\beta}, \sigma_\nu, \boldsymbol{Q}) \times p(\{s_i\}|\delta, \rho, \sigma_u) \times p(\{\omega_i\}|\sigma_\omega) \\ &= \frac{1}{(2\pi\sigma_\nu^2)^{NT/2}} exp\{-\frac{\sum_{i=1}^{N}\sum_{t=0}^{T-1}(c_{it} - \omega_i - \boldsymbol{Q'_{it}\beta} + logCE_{it})^2}{2\sigma_u^2}\} \\ &\times \frac{1}{(2\pi\sigma_{u1}^2)^{N/2}} exp\{-\frac{\sum_{i=1}^{N}(s_{i1} - \delta_1)^2}{2\sigma_{u1}^2}\} \\ &\times \frac{1}{(2\pi\sigma_u^2)^{N(T-1)/2}} exp\{-\frac{\sum_{i=1}^{N}\sum_{t=1}^{T-1}(s_{it} - \delta - \rho s_{i,t-1})^2}{2\sigma_u^2}\} \\ &\times \frac{1}{(2\pi\sigma_\omega^2)^{N/2}} exp\{-\frac{\sum_{i=1}^{N}{\omega_i}^2}{2\sigma_\omega^2}\} \end{aligned} \tag{4.2.26}$$

where c and Q represent the vector and matrix of dependent and independent variables respectively and δ_1 and σ_{u1}^2 are the mean and variance of s_{i1} in equation (4.2.22). The last term in likelihood function captures the heterogeneity effects. This likelihood function enables a simultaneous estimation of equations (4.2.19) and (4.2.21).

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[10] ***Proof***:we know s_{it} has the following process $s_{it} = \delta + \rho s_{it-1} + u_{it}$. Thus, the log run value of s_{it} is $\frac{\delta}{1-\rho}$ (The proof of this is exactly similar to the footnote 7). On other hand,we know that s_{it} is defined as $s_{it} = log(\frac{CE_{it}}{1-CE_{it}})$. Thus we can obtain the long run efficiency by $log(\frac{CE_{it}}{1-CE_{it}}) = \frac{\delta}{1-\rho}$, hence, $\frac{CE_{it}}{1-CE_{it}} = exp(\frac{\delta}{1-\rho})$ and therefore, $Long\ run\ CE = 1/[1 + exp(-\frac{\delta}{1-\rho})]$.

[11] Equation (4.2.21) is called hidden (latent) state because we do not observe the data in this equation.

The estimation is carried out in a Bayesian framework. For β and δ, normal priors are selected. For the variance parameters the inverted Gamma has been chosen because it is conjugate. Moreover, for ρ a Beta prior has been used to restrict it in unit interval. In order to estimate the posterior moments of the model's parameters a posterior simulation based on Markov chain Monte Carlo (MCMC) is employed.

4.2.2 Data and model specification

The dataset used for the application is a balanced panel of 128 Norwegian electricity distribution networks observed from 2004 to 2010. All financial data are in real terms which are adjusted based on 2010 prices. The Norwegian distribution companies are working under incentive regulation with ex-post regulatory treatment of investment based on the formula given in (4.1.1). The power of incentive (λ) in the Norwegian regulatory model is currently 60% in order to motivate companies to move as close as possible to the efficient frontier.

Following the Norwegian energy regulator, our total (social) cost includes capital costs, operating costs as well as cost of network energy losses and cost of energy not supplied. Cost of network energy loss is computed by multiplying physical network energy loss with annual average system price. Cost of energy not supplied is computed by multiplying the energy not served (interrupted) with consumer "willingness to pay for reliable service". The Norwegian regulatory framework adds the aforementioned two costs to other controllable costs categories in order to incentivise service quality (Poudineh and Jamasb, 2013b).

Other variables include in the model are the number of customers and energy distributed. These are considered as standard outputs of networks in productivity and efficiency analysis of distribution companies (e.g., Growitsch et al., 2012; Miguéis et al., 2011). The number of customers reflects the total number of connected consumers to the grid including holiday homes[12]. The summary statistics of model's variables are presented in Table 4.1.

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[12] The Norwegian regulator has separated holiday cottages from other customers as they have a different load profile compared with conventional consumers.

The equation in (4.2.19) requires a functional form for the cost function. The translog functional form has appropriate characteristics because it does not impose restrictions on the nature of technology a priori. Due to unavailability of input price data we construct our cost frontier without input prices assuming every firm faces the same input prices. This approach is theoretically consistent and has been used in several efficiency studies of electricity distribution networks (e.g., Filippini and Wetzel, 2013; Nillesen and Pollitt, 2011). Therefore our cost frontier model becomes:

$$\begin{aligned} log(TC_{it}) = \beta_0 + \beta_1 log(DE) + \beta_2 log(CUS) + \frac{1}{2}\beta_3 log^2(DE) + \frac{1}{2}\beta_4 log^2(CUS) \\ + \beta_5 log(DE) log(CUS) + \omega_i + \zeta_1 t + \frac{1}{2}\zeta_2 t^2 + \nu_{it} - logCE_{it} \quad (4.2.27) \end{aligned}$$

where t is a time trend which captures technical progress and also everything else that we cannot measure but varies over time and has a common effect on all firms (e.g., input prices).

Given the possibility of the presence of correlation between the firm effects (ω) and cost efficiency, two models are estimated based on the method proposed by Emvalomatis (2012). In the first model we assume that the firm specific effect is uncorrelated with the independent variables (simple random effects). For the second model we take into account the possibility of correlation between the firm specific effects with the independent variables using the technique in Mundlak (1978). For ease of interpretation of the first order terms, all data are divided by their sample mean prior to estimation.

Table 4.1: Descriptive statistics

Variable Description	**Variable**	**Min.**	**Max.**	**Mean**	**Std. Dev.**
Total cost (000' NOK)	TC	1474.6	1509458	80960.7	167738.9
Distributed energy (MWh)	DE	6915	1.68E+07	561877	1575379
Number of customers (#)	CU	18	544925	21115	55979.07

4.3 Results and discussions

4.3.1 Empirical results

Table 4.2 presents the results, of the models estimated, based on the posterior mean of the parameters and their standard deviation. Results of an analysis of the monotonicity condition are presented in Table 4.3. As seen there, monotonicity is satisfied at the sample mean for both models. Also, monotonicity is satisfied over a wide range of data values with respect to each output. The first order parameters, in both models, can be interpreted as the elasticities of total cost with respect to distributed energy and number of customers, evaluated at the sample mean.

The estimated parameter ρ is around 72% for the simple random effect model and 71% for the correlated random effects model, which are quite similar and fairly high. The value of ρ directly influences the rate of inefficiency transmission $(1-\psi)$ (discussed in Section 4.1) across periods. We have used their relationship, as the way shown in Footnote 9, to obtain the rate of inefficiency transmission for each observation. Unlike ρ which is common to all firms in the sector, the inefficiency transmission rate $(1-\psi)$ is observation specific and has a mean of 69%.

However, the distribution of the inefficiency transmission rate $(1-\psi)$, as presented in Figure 4.1, shows significant variation among individual firms. A small value implies short duration of problematic inefficiency persistence and hence, speedy adjustment. A large value of $1-\psi$ indicates that inefficiency transmission between periods affects the performance of firms significantly over a period of years. The magnitude of inefficiency transmission rates is influenced by the scale of investment.

In any given regulatory period, investment appears as a shock to the current level of the firms' inefficiency whose duration of inefficiency persistence depends on gestation period of the investment projects undertaken. Thus, firms remain under financial constraints due to inefficiency induced by investments. This effect exists until the firm reaches the long run equilibrium. The estimates of long run efficiency of the distribution networks under simple and correlated random effects are close and, as seen from Table 4.2, approximately 81% and 85% respectively.

At the same time, Figure 4.1 shows that the rate of inefficiency transmission is

Table 4.2: The posterior mean of parameters and their standard deviation

	Simple random effect		Correlated random effect	
Variable	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
β_0	-0.154	0.055	-0.324	31.16
β_1	0.073	0.082	0.016	0.140
β_2	0.801	0.084	0.276	0.278
β_3	0.035	0.068	-0.041	0.093
β_4	0.172	0.019	0.053	0.054
β_5	-0.098	0.035	0.002	0.070
ζ_1	-0.010	0.008	-0.003	0.008
ζ_2	0.009	0.002	0.010	0.002
δ	0.416	0.108	0.507	0.121
ρ	0.721	0.055	0.710	0.055
σ_ν	0.082	0.006	0.086	0.005
σ_u	0.479	0.069	0.532	0.078
σ_ω	0.177	0.015	0.182	0.014
Long run Efficiency	**0.812**		**0.8495**	

Table 4.3: Monotonicity condition

Model	**Variable**	**Monotonicity at sample mean**	**% violated over data points**
Simple random effect	DE	satisfied	27%
	CUS	satisfied	0.00%
Correlated random effect	DE	satisfied	12.50%
	CUS	satisfied	0.00%

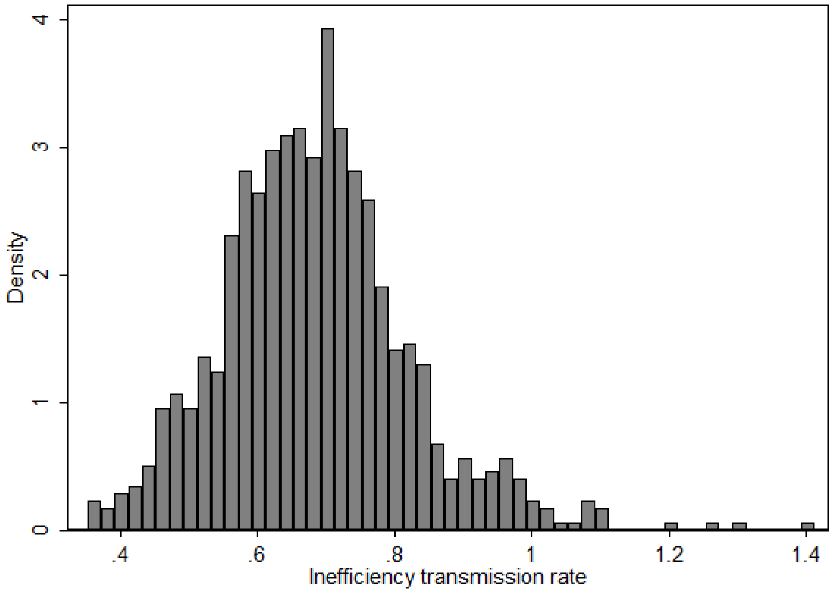

Figure 4.1: Distribution of inefficiency transmission rate $(1-\psi)$

less than one for the majority of observations. This means inefficiency shocks fade-off over time. However, few firms show an inefficiency transmission rate higher than one which is not persistent over the studies period and hence, can be attributed to the observations being far from the point of approximation (mean). This is because a value of inefficiency transmission rate higher than one suggests that the firm becomes progressively more inefficient over time, something which is very unlikely under the reward and penalty scheme of incentive regulation (because revenue is directly linked with efficiency as shown in relation 4.1.1).

Figure 4.2 presents the mean of decomposed inefficiencies for the whole sector in different years. Inefficiency decompositions include two terms: inefficiency carry-over from previous periods and period-specific inefficiency shocks which jointly construct the observed inefficiency of the period. It is worth noting that period-specific effects are different from uncontrollable noise that affect inefficiency, as our model controls for noise and unobserved heterogeneity [13].

As seen in Figure 4.2, the mean of period specific term can be positive, negative

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[13] The noise and unobserved heterogeneity are reflected in the idiosyncratic error term (ν_{it}) and the firm specific term (ω_i), respectively, in equation 4.2.27.

and zero in different years. For example, in 2008, the mean of observed inefficiency increased by about 4.7% with respect to its expected value as a result of the period-specific term. Similarly, the mean of observed inefficiency remained unchanged in 2005 and declined very slightly in 2006 and 2010. Cyclical investment is the most important factor in introducing period-specific positive shocks which persist over time. On the contrary, underinvestment, cost reducing measures, and innovative managerial practice can impact the period-specific term negatively.

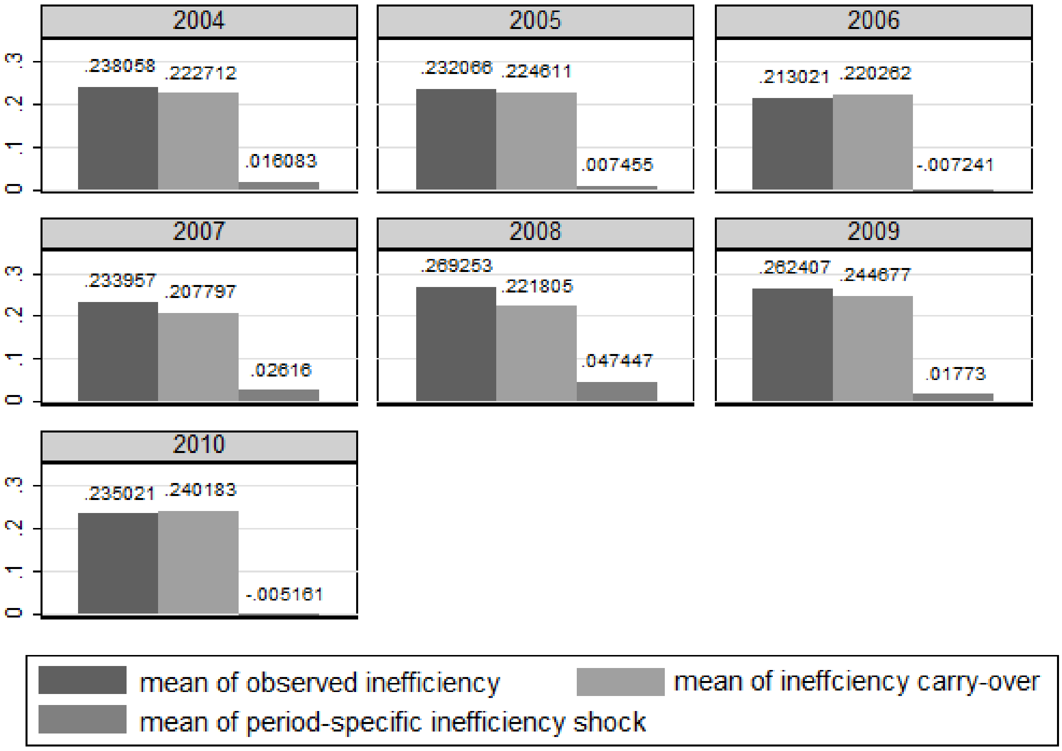

Figure 4.2: Inefficiency decomposition in different years

At the same time, there are significant variations in the components of decomposed inefficiency at the level of individual companies. Figure 4.3, shows the distribution of inefficiency decomposition for each year. As it is evident from the figure, the share of components of inefficiency in constructing the observed inefficiency varies across years. In some years firms are affected considerably by period-specific shocks which are eventually reflected in their observed inefficiency. For instance, in 2004, a major share of observed inefficiency of the firms was related to the period-specific effects. The positive shocks again manifested themselves as increased share of inefficiency carry-over in subsequent years. Although under the condition of stationarity these shocks fade-off over an infinite time horizon, in practice their residual effects remain in the observed inefficiency of the firms.

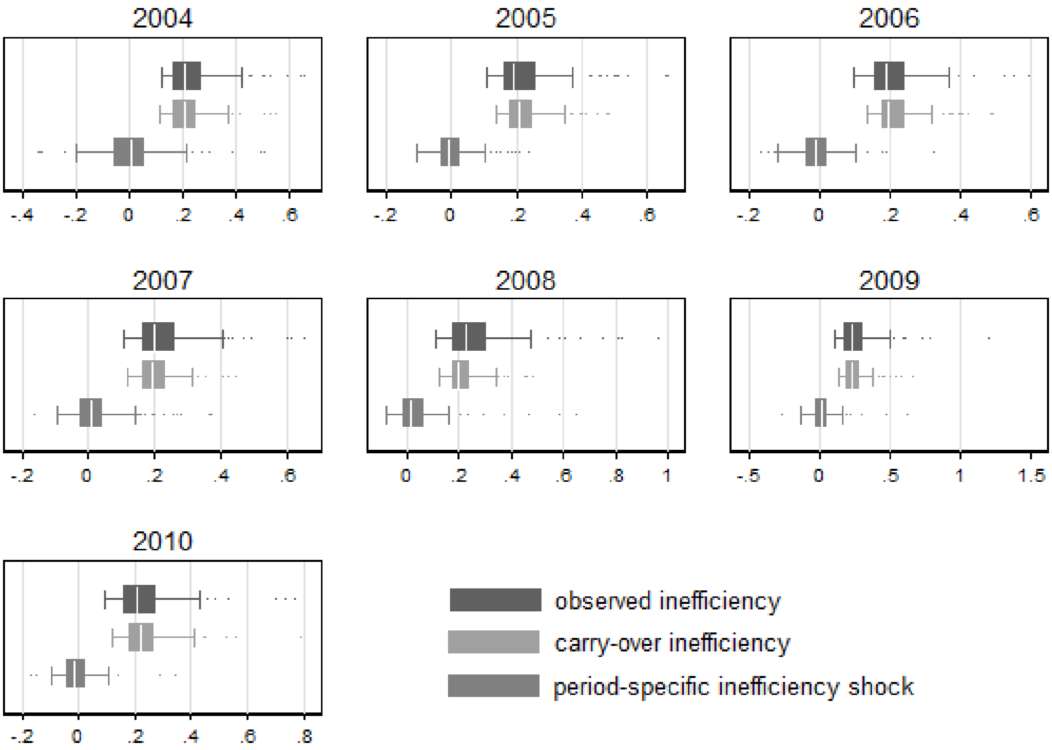

Figure 4.3: Distribution of inefficiency decomposition in different years

The intertemporal nature of the autoregressive process for inefficiency implies that one-time shocks can affect the value of evolving inefficiency far into future. In other words, the value of the current level of inefficiency is affected by past shocks because of investment or other reasons.

The impact of period specific effects (shocks) on the evolution of inefficiency can be computed by taking the derivative of the left hand side term in equation (4.1.16). The marginal effect can be obtained using $\frac{\partial z_{t+j}}{\partial \epsilon_t} = \rho^j$, where$j$ denotes the length of time that separates a disturbance to input (ϵ_{it}) and the observed value of the outputs (Hamilton, 1994). The sum of consequences for all future values (cumulative effect) of inefficiency, z_{it}, as a result of a transitory disturbance to ϵ_{it}, can then be computed from $\sum_{j=0}^{\infty} \frac{\partial z_{t+j}}{\partial \epsilon_t} = \frac{1}{1-\rho}$ (Hamilton, 1994).

In order to illustrate this effect, consider the year 2004 which has a mean of period-specific shock of 0.016 and average inefficiency transmission rate of 0.72. The expected change in efficiency in subsequent years as a result of this average shock would be $\Delta z_{t+j} = 0.016(0.72)^j$. This means that in 2005 the shock will become 0.0115 and in 2010 would be 0.002. Also, the cumulative effect would be 3.57 which is much higher than the initial perturbations. Therefore, when the initial shock is larger, the effect on firm's efficiency will also be higher. These indicate that historical shocks play a major role in the current and future level of firms' inefficiency. This also marks the importance of investment as a factor which gives rise to period specific effects.

The investment level can affect the process of inefficiency evolution in two ways. First, it is one of the factors which give rise to period specific inefficiency shocks. Second, under the condition that the initial shock is due to investments, the scale and type of investment will impact the elasticity of inefficiency persistence. These two effects can be seen from Figure 4.4 that shows the scatterplots for the rate of inefficiency transmission and period-specific inefficiency shock versus investment to total cost ratio. As seen from the graphs, in both cases, the higher share of investment in total costs of firms is generally associated with higher rate of inefficiency transmission and also higher period-specific inefficiency shocks.

However, it should be noted that investment does not explain all the variations in the inefficiency transmission rate or period-specific inefficiency shock. This is because investment is not the only factor that can result in period specific inefficiency shocks or inefficiency transmission across periods. Period-specific shocks can also happen because of emergence of a new technology or sudden changes in the firms' operating environment, such as introduction of a new regulatory regime. In a similar manner, inefficiency persistence can be the result of sub-optimal technology level employed by the firm. However, the extent to which these effects are the result of cyclical investments, they are problematic for incentive regulation models that use total cost benchmarking.

The firm can opt for smaller projects which take less time to produce results. However, once inefficiency transmission begins, the process of adjustment is not

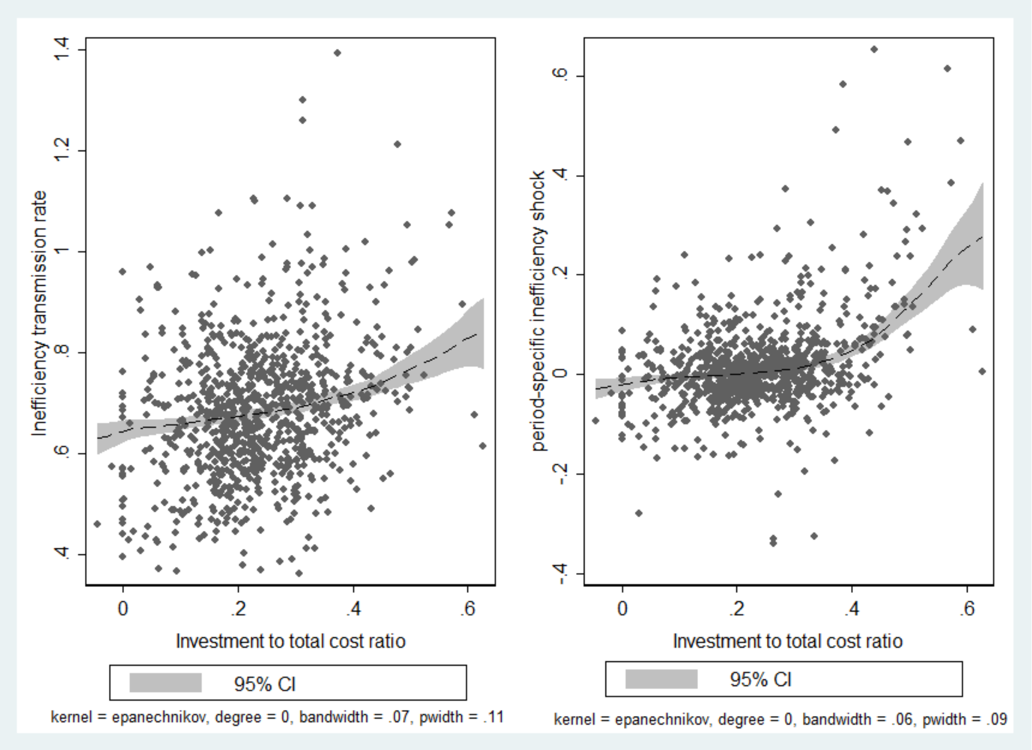

Figure 4.4: Inefficiency transmission rate $(1-\psi)$ and period-specific inefficiency shock (ϵ_{it}) versus investment to total cost ratio

completely under the control of the firm because it depends to the nature of investment. This is against the very basic assumption of incentive regulation model in (4.1.1) which assumes that the evolution of inefficiency is entirely controllable and, based upon that, links the revenue of firm with its observed efficiency. The presence of a positive relationship between investment and period-specific inefficiency shocks and also the rate of inefficiency transmission limits the firms' ability to improve their productivity in a timely manner because of the inefficiency induced by investment. This result is also consistent with previous arguments that under the incentive regime the immediate efficiency gains are achieved from operating costs and not from capital costs (Müller et al., 2010).

4.3.2 Regulatory challenges and the way forward

The implication of persistent inefficiency is crucial for incentives regulation based on (4.1.1), which is currently being practised in Norway and many other countries.

Under this model of incentives regulation, efficiency loss is equivalent to revenue loss for the firms. The theory behind the short run efficiency assumes that firms are profit maximisers and the regulatory regime implies that cost minimising is valid under all conditions. However, due to the presence of dynamic aspects in the firms' decision concerning investments and innovation, static efficiency is an inadequate measure of investment behaviour and performance of utilities[14]. Therefore, ex-post regulatory treatment of investments through benchmarking total cost distorts the long run objectives of the firms and might expose them to financial loss. Although, this approach has been adopted to deter overcapitalisation considering asymmetric information between the firm and the regulator, it will not necessarily lead to an efficient level of investment.

The inefficiency persistence also has implications for innovation. Innovation is the outcome of firms' efforts to produce new or improved products and services, introduce more efficient and productive design processes and implement organisational or managerial changes. Innovation generation and adoption by the firms depends, among other factors, on the market structure and the cost of resources. The innovative behaviour entails complementary investment to the more traditional R&D concept such as investment in innovation-related training and design, investment in machinery, equipment and software. However, these types of investments can induce a prolonged inefficiency and expose the distribution companies to substantial financial losses under the penalty and reward schemes of the incentives regime.

This study identifies the problems with ex-post regulatory treatment of investment. However, the regulatory solution is not straightforward. This is because regulating the capital cost of companies is the matter of trade-off between using information from the firm itself (i.e. project the cost) and from its peers (i.e. through benchmark). The fact is that there is asymmetric information between the regulator and the regulated company. Thus, a regulated firm may use the information advan-

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[14] This is because in a dynamic context the firms' inefficiency can take a different meaning as in the short run (the measure of deviation from the optimum frontier). Emvalomatis (2009) describes the inefficiency, in dynamic setting, as the deviation of the "observed path" with respect to "optimal capital stock adjustment".

tage to exploit the regulatory process in order to increase its profit or achieve other managerial objectives (Joskow, 2008b). Benchmarking of regulated firms can help the regulator reduce, to some degree, the issue of imperfect information. However, as mentioned previously, it gives rise to new challenges including those related to quasi-fixed inputs.

An approach used by some sector regulators to address the issue of quasi fixed inputs is to exclude capital expenditures from the benchmarking models. That is to rely on firms' own information regarding capital expenditure (Capex) and benchmark only operating cost (Opex)[15] . However, this approach received several criticisms. Burn and Riechmann (2004) argue that Capex and Opex should be treated equally because benchmarking only one cost category such as Opex and different treatment of Capex creates incentives for companies to transfer costs from the “yardstick” category to ”firm specific” category. The firm is aware that lower investment leads to lower regulatory asset base and consequently lower return, and may, therefore, engage in strategic behaviour in pursuit of gold plating capital costs.

Furthermore, as argued in Besanko and Spulber (1992), firms might choose a higher than optimal level of capital in order to persuade the regulator to allow higher operating costs and price on their product. Furthermore, Averch and Johnson (1962) showed that under this model, more capital will be employed by the regulated firm compared to a non-regulated firm, given any level of output. Additionally, from a practical point of view when the number of regulated companies is large (as in the case of Norway which are around 130 companies), scrutinising the investment plan of each individual firm might not be feasible considering the length of regulatory period.

Another approach that can be considered but needs further investigation is to use directional contraction of inputs where both operating and capital costs are part of the benchmarking practice. In this case the, the inputs are contracted only in the direction of operational expenditures assuming convexity between operational and capital expenditure as two inputs. This is in contrast with the current form of radial

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[15] This approach is being practised in the UK in which the companies submit their business plan to the regulator before the next regulatory period to be examined and approved if justified.

contraction of both inputs being used in the benchmarking exercise. However, the convexity constraint between operating and capital expenditures might not always hold in which case this approach can be problematic. Another possibility is to develop statistical approaches that allow for controlling inefficiency persistence due to investment such that firms are only penalised for the controllable part of their inefficiency evolution. At the same times, regulators need to ensure that approaches used to ease the process of investment and innovation will not lead to overcapitalisation.

The area of dynamic efficiency under incentive regulation requires further research to address the issues of investment and innovation and also strike a balance between firms' own information, sector information, investment incentives and the possibility of over- and under-investment. Regulators also need to understand the long term consequences of the regulatory framework for investment and innovation and make informed decisions regarding the way incentives are implemented.

4.4 Conclusions

The use of efficiency and productivity techniques such as total cost benchmarking, is becoming now common practice in incentive regulation to induce cost efficiency and prevent firms from overcapitalisation. However, benchmarking only captures short run efficiency of network companies while they operate in a dynamic environment where technology, regulatory standards, demand and economic conditions are changing. In response to this, the utilities reorganise their production process to become more efficient in the short run.

However, the factors that affect the short term efficiency of the firms (i.e. network inputs and outputs) may not be adjusted instantaneously when firms invest in new and costly technologies and practices, which take time to produce result. Under this condition, in the short run, investment induces inefficiency which persists for some time until the inputs and outputs are fully adjusted. On the other hand, under incentive regulation, the firms' revenues crucially depend on the level of efficiency achieved in the benchmarking process.

The current form of incentive regulation with ex-post regulatory treatment of investment, employed by many European regulators, does not take this effect into account and, hence, there is a risk of financial loss for regulated companies when undertaking investment. Therefore, the simultaneous incentives for investment and static cost efficiency can send inconsistent signals to regulated firms. This potentially limits the companies' incentives for investment and innovation.

This chapter analysed the concept of dynamic efficiency under incentives regulation with ex-post regulatory treatment of investment. We have shown that, in any given period, a firm's inefficiency consists of two components: the period-specific shocks and the carry-over from previous periods. The period specific inefficiency shocks can be created by investment or other factors that affect inefficiency and the carry-over effect is due to the inability of firms to adjust their inputs in a timely manner. Additionally, we estimated a dynamic stochastic frontier model in a Bayesian framework for a balanced panel of 128 Norwegian electricity distribution companies from 2004 to 2010.

The results show that, at the sector level, around 72% of the efficiency to inefficiency ratio is transferred from one period to another. At the level of individual companies, however, the variation is significant. There are firms with very low or very high elasticity of inefficiency transmission. The high magnitude of elasticity causes the effect of the shocks to die out over a longer period. The distribution of inefficiency decomposition shows that the share of carry-over effects, in the observed level of firms' inefficiency, is considerable.

The results demonstrate that investment to total cost ratio is positively associated with period-specific inefficiency shocks and also the inefficiency transmission rate across periods. Therefore, those firms with higher investment share have experienced higher inefficiency persistence. This is problematic for benchmarking based revenue setting of network companies as both the cumulative effect as well as the duration of inefficiency persistence will increase by the magnitude of initial perturbation caused by investment. Finally, the results indicate that the long run cost efficiency of the sector is approximately 81% and 85% based on the simple and correlated random effects models respectively.

An important dimension of dynamic efficient behaviour, for a company, is to adapt to its dynamic operating environment. This is particularly relevant to the distribution network companies as power sector, currently, is experiencing rapid changes with increasing penetration of distributed energy resources. The issue is that network companies cannot continue relying only on their current business model while the traditional paradigm of generation-transmission-distribution is changing. This is because, due to proximity of generation and demand, penetration of distributed energy resources reduces the volume of energy transmitted in the network and consequently shrinks the revenue base of distribution companies over time. Therefore, the network companies need to accommodate themselves in the new environment and utilise distributed energy resources for efficient planning and operation of their network.

A promising and yet underdeveloped area is to utilise the synergy between integration of distributed resources and reducing the need for network capacity investment as a result of demand growth. This, however, requires innovation at regulatory level as well as business model of distribution companies. The next chapter explores this issue and introduces an innovative market-oriented approach, which enables integration of distributed resources as alternatives to demand driven network investment.

Chapter 5

Improving efficiency of electricity networks utilisation

A conventional power system is characterised by large scale generation sources that inject large amounts of power into the transmission grid, which in turn is transported to passive distribution networks, and then delivered to the end-users. A key feature of the low-carbon future power systems is that they will perform in an operating environment and paradigm in which distributed generation (DG), demand response, and storage facilities are important components of the system (Soares et al., 2012). These resources are connected to low (and medium) voltage networks thus making the distribution grid a crucial element of sustainable electricity sectors of the future. These changes are driven by climate and sustainability policies along with affordability and reliability of electricity supply. Thus, the future power systems will be based on coexistence of conventional and distributed generation sources, and tap into demand response and storage as network resources for efficient planning and operation.

The electricity distribution network operators (DNOs) are responsible for, expansion, reinforcement and maintaining the safety and reliability of the network to support power flows and ensure quality of supply. Integration of distributed resources[1] introduces new challenges and opportunities that require innovative technical, economic and regulatory solutions to overcome the barriers and utilise possibilities. This includes enabling distributed resources to compete with alternatives in providing network and non-network services to the DNOs. In the context of non-network solutions, there is an opportunity for replacing or deferring grid reinforcement by meeting demand locally through deployment of DGs, storage and reducing peak demand through demand response and energy efficiency[2] . In effect, due to potential benefits of distributed resources for the grid, especially at distribution level, they are natural alternatives to conventional network capacity enhancement (Sheikhi Fini et al., 2013).

From an economic viewpoint, a challenge is how to value these alternative energy resources. At present, there are no established methods to value the complex set of technical and financial opportunities (and challenges) arises from the integration of these resources. This stems from the lack of a market mechanism that supports this process. Moreover, adopting distributed resources to defer demand driven grid reinforcement requires extending the traditional business model of distribution utilities in a consistent manner with the unbundled sector. Thus, along with technical concerns, there is a need for innovative economic and regulatory solutions. For example, issues such as ownership model of resource facility, differentiating between costs of capacity and energy, dispatchable and non-dispatchable generation, possibility of trade in other markets, managing storage and demand response are important and need to be addressed. Moreover, the presence of uncertainties such as the sustainability of costs and possibility of demand reduction over time constitute some risk elements.

This study proposes a three stage market-based approach termed as "contract

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[1] Throughout this chapter we use the term "distributed resources" to refer to distributed generation, storage facilities, demand response and energy efficiency that interact with distribution network.

[2] Energy efficiency, as a permanent reduction in energy demand, is emerging as a resource in capacity markets along with behavioural (temporary) demand response.

for deferral scheme" (CDS) in order to employ an economically efficient portfolio of distributed generation, storage, demand response and energy efficiency to supply network capacity and to defer demand driven investments.

The next section discusses the need for innovative network solutions and explores the previous studies on the effect of distributed resources on network investment deferral. An extended business model of distribution companies including the contract for deferral scheme has been introduced in Section 5.2. Section 5.3 discusses the details of CDS market model in three steps: pre-auction stage, auction stage and post-auction stage. Finally, the study concludes with Section 5.4.

5.1 Demand driven network investment

A feature of the traditional approach to upgrading the network is that as demand grows gradually, network reinforcement is carried out in large increments requiring lumpy investments. As a result, a portion of grid capacity remains idle for long periods in anticipation that demand will eventually increase (Hoff et al., 1996). Therefore, in a network reinforcement cycle, the total capital employed, to deliver a given amount of output, can be higher than the theoretical optimum needed at any given time. At the same time, due to adverse effect of asset utilisation rise on energy loss; the network utilities face a trade-off between the rate of asset utilisations and reducing network energy losses (Ofgem, 2003). Figure 5.1 presents the demand growth path and a corresponding network capacity enhancement schedule. C_i denotes the initial capacity and C_r represents the added capacity as a result of reinforcement.

Inefficient utilisation of assets, in traditional demand driven network investments, is exacerbated when the mid- or long term development of demand are uncertain. As demand grows, the output of network, for a given level of capacity, also increases. However, demand for electricity can also decline, in which case the idle capacity and consequently the operating cost of network, per unit of output, raises (Jamasb and Marantes, 2011). The case of an upward deviation of demand from projections is less critical for asset utilisation, as it is normally possible to carry out investment such that the shortages in network capacity can be avoided.

An alternative to the traditional network enforcement is to meet part of the demand for energy services locally through DGs, storage and managing demand through demand response and energy efficiency measures. This is to use distributed resources whether on the supply side (DGs and storage) or on the demand side (demand response and energy efficiency) to avert the need for lumpy investment in costly redundant transformers (Hemdan and Kurrat, 2011). These resources can be procured to meet the extra demand projection plus a reserve margin for contingencies. The advantages of distributed resources are not limited to the deferment of network reinforcement but also include, peak shaving, spinning reserve, voltage and frequency regulation, and dealing with variability of supply side (Zafirakis et al., 2013).

From a regulatory perspective, integration of distributed resources as an alternative to conventional network reinforcement is in concert with the innovation incentives embedded in the regulatory frameworks of distribution companies. For example, in the UK, under the RIIO-ED1 regulatory model, innovative solutions are incentivised by rewarding the downward deviation from the expected capital expenditure in business plan of DNOs (Ofgem, 2012). These financial incentives play a pivotal role in directing the network companies towards implementing smart solutions.

There is an extensive body of literatures that evaluates the effect of distributed resources on investment deferral of grid capacity, in particular with respect to integration of distributed generation. These studies explore different perspectives of this issue such as cost-benefit analysis, size, siting and type effect of generator as well as implication for the regulatory model of network companies.

Pudaruth and Li (2007) investigate the costs and benefits of DG for investment deferral of distribution companies in terms of thermal capacity limits of lines and assets. Mendez et al. (2006) assess the medium and long term impact of DGs on investment deferral of radial distribution networks. The study demonstrates that after initial investment for connection of DGs, their net effect is to defer capacity enhancement driven by natural demand growth. They also show that the intensity

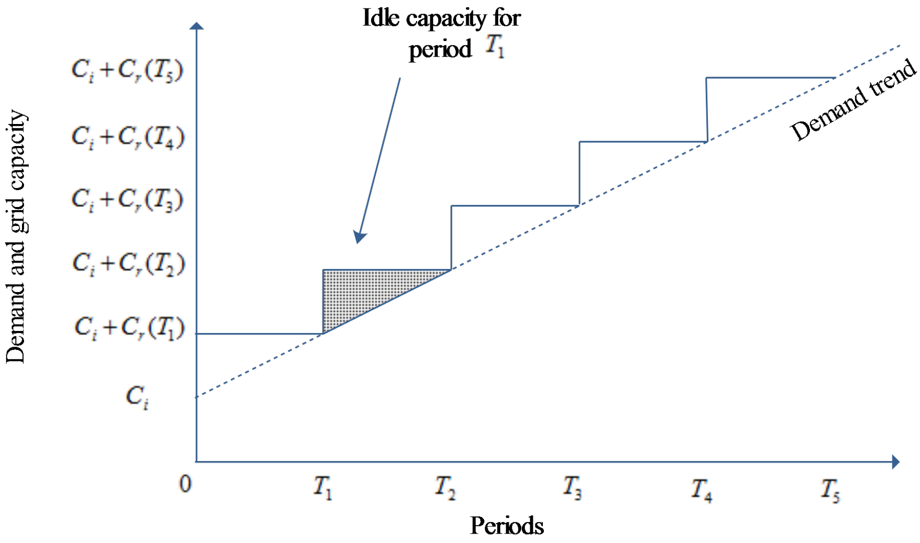

Figure 5.1: Demand growth and network capacity enhancement

`[Source:Adapted from Hoff et al. (1996)]`

of the effect depends on the type of distributed generation (e.g., wind power versus combined heat and power (CHP)).

The effect of siting on investment deferral of distributed resources has been discussed in several studies. Gil and Joos (2006) find that the benefits are maximised, if DGs are sited at the end of long feeder and near load pockets because of their effect on energy losses and congestion reduction. Zhang et al. (2010) show that effective site reallocation will increase the benefits of capacity deferral for the same amount of DGs connected. Moreover, Wang et al. (2009) demonstrate that significant benefits, in terms of investment deferral, can be harnessed if the DG contribution to system security is taken into account. They also show that the deferment varies significantly with location and size of the generator.

Although DGs are promising and reliable resources for investment deferral; this effect is not limited to these resources. In effect, storage facilities, demand response and energy efficiency are also potential resources that, along with DGs, can lead to grid investment deferral. Schroeder (2011) argue that demand side management and storage also constitute important tools in operation of distribution networks that could benefit system operation by avoiding capacity shortages. The study shows that, in the case of storage, for example, grid reinforcement can be avoided at some voltage level without harming system security because network capacity utilisation rate will remain well below the threshold. Also, the study noted that the effect of demand side management is stronger when more flexible demand, such as electric vehicles, is available.

These studies show there exists an opportunity for taking the advantage of the synergy between investment in distributed resources and the obligation of network companies with respect to network reinforcement. However, the effect of these resources on grid depends on many factors such as location, technological specification and timing of investments (Vogel, 2009). An effective regulatory framework, thus, is required to align these benefits between resource developer and network companies. In the absence of such mechanism, penetration of these resources can, sometimes, lead to adverse effect on the network. For example, DGs uptake can expose the grid to induced energy losses when installed capacity exceeds the demand (Harrison et al., 2007).

Distribution utilities can influence the siting of distributed energy resources such as DGs through connection and use-of-system charges (which could be based on their capacity and the sole-use network asset used) and reward when DG installation is in line with optimal operation of the network (Jamasb et al., 2005). The rewards can be grounded on generator exported power at system peak, proximity to the frequently congested zones and the network asset utilised. The implication of DNOs preferences for size and location of DGs and the effect of regulatory model on optimal connection of DG within existing networks have been examined by Piccolo and Siano (2009).

5.2 An extended business model

Integration of distributed resources to defer demand driven network investment requires both technical and economic changes to the current operational paradigm of distribution networks. From a technical perspective, network management needs to evolve from passive to active by using real time control and management of distributed resources and network equipment based on real time measurement of

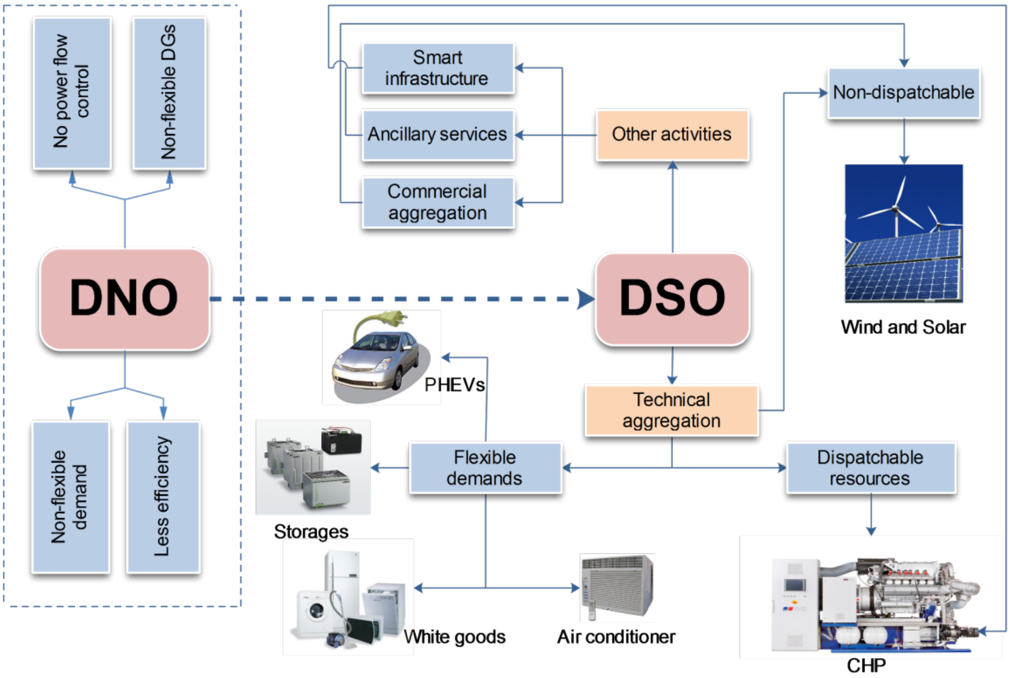

Figure 5.2: The transition from DNO to DSO model

`[Source:Author]`

primary system parameters such as voltage and current (Zhang et al., 2009). From an economic perspective, the business model of distribution companies is required to evolve and expand beyond the current only connection and use-of-system charges. The new economic and technical models will shift the operation of distribution companies from network operators (DNO) to distribution system operators (DSO). Figure 5.2 illustrates this paradigm shift.

Currently, the revenue sources of distribution utilities have comprised of the regulated connection charges and use-of-system charges. Based on the type of consumer and regulatory framework model, new connection fees consist of shallow and deep cost charges (Jamasb et al., 2005). In an environment with high penetration of distributed resources the DSOs should be allowed to expand their revenue sources beyond provision of connections and energy transport charges only. This is because, over time, the presence of distributed energy resources close to the site of demand reduces the volume of energy transmitted in the grid and consequently, shrinks the revenue base of network companies (van Werven and Scheepers, 2005).

The extended business model of DSO includes interaction with different consumer categories, transmission system operator (TSO), distributed energy operators and retail suppliers. DSO can offer certain services to these players that construct extra sources of revenue and receive certain services from them that will constitute part of its costs. These services will include local balancing in the distribution network, premium reliability for some commercial or industrial customers and also offering system data to the DGs operators and retail energy suppliers as DSO is the only party that have such information (van Werven and Scheepers, 2005). These will bring new stream of revenue for the DSOs which are not currently possible under the DNO business model.

DSO will contribute to national load balancing and will be compensated for that by the TSO. This will be done through dispatchable DGs (and, where possible, storage and demand response resources) that are under the control of distribution system operators. Moreover, many commercial and industrial users need premium reliability as their production process is sensitive to the electricity input (Poudineh and Jamasb, 2013c). DSOs will be reimbursed by those industries for providing highly reliable connections. Furthermore, with the use of information and communication technologies, valuable system data will be available that can be shared with DG operators and retail suppliers for efficient planning and operation in return for a payoff.

At the same time, the costs to DSO will include operation and maintenance, grid reinforcement (which can be either in a traditional approach or by procurement of distributed resources), acquisition of ancillary services from DGs and TSO, use of system charges and finally cost of energy losses. Figure 5.3, illustrates the existing and new services, flow of revenue, costs, and interaction of key players in an extended business model of DSO.

An important part of the extended business model is the possibility to integrate distributed resources as alternatives to grid capacity enhancement. This however, requires an economic model that is consistent with the regulatory framework of an unbundled sector. Moreover, the model must allow the DSOs to procure these resources cost efficiently and ensure compliance by resource providers. The rest of the chapter introduces a new approach that enables the DSOs to utilise this

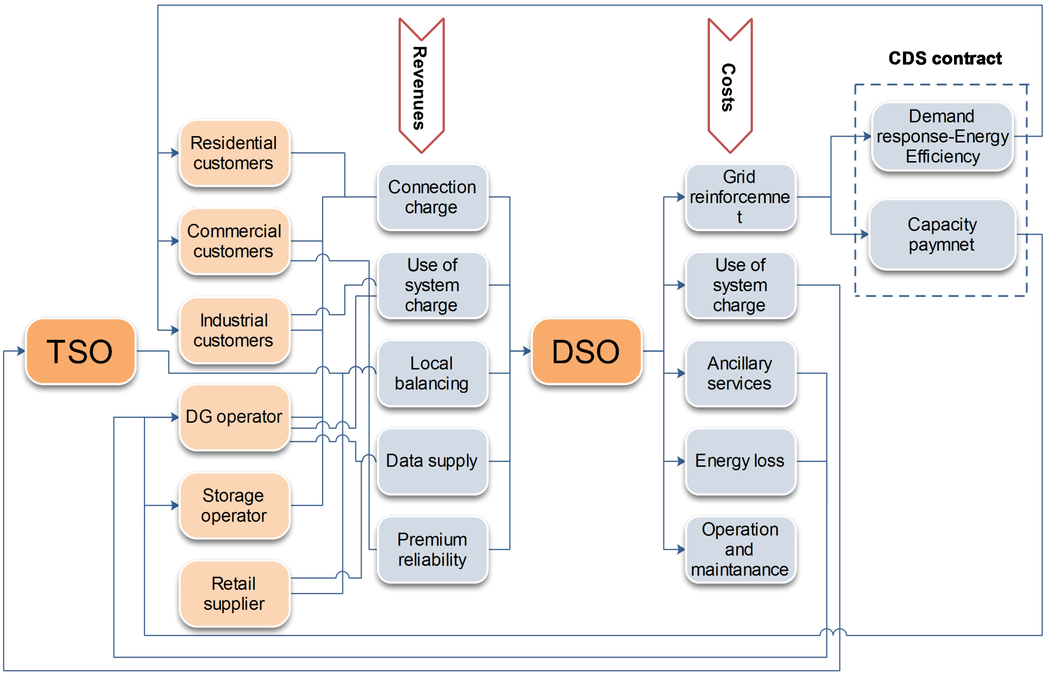

Figure 5.3: The extended business model for DSO

`[Source: Author, information partially from van Werven and Scheepers (2005).]`

possibility.

5.2.1 Contract for deferral scheme (CDS)

A challenging task is to design an economic model that delivers network service (network capacity) cost effectively using alternative resources (DGs, storage, demand response and energy efficiency). Provided the regulatory issue concerning the ownership of distributed resources by the network companies, under an unbundled power sector paradigm, our proposed model is based on a ”contract for deferral scheme” (CDS). Under the CDS scheme, the DSOs can enter into contract with distributed generations, storage facilities operators, demand response and energy efficiency providers, which offer available capacity when needed. The market participants that enter a contract will be obliged to have available the required capacity at the time of network constraints (or upon being called). In return, the DSO offers them a capacity payment. The CDS contract acts as a proxy for vertical integration and, at the same time, it is procured on a competitive basis.

CDS is considerably different from both administrative and market based methods that have been introduced previously. CDS differs from the administrative approach proposed in Hof et al. (1996) which calculates a break-even price at which a distribution company is indifferent between undertaking conventional reinforcement and alternative approach. This is because their approach does not achieve economic efficiency as it ignores market mechanisms and opportunity cost of scare resources to the society and hence, it is not welfare maximising. Furthermore, their administrative approach has only been discussed in the context of DG whereas CDS is a market-based approach for integration of a portfolio of distributed resources which are treated equally.

CDS also differs from the market based approach proposed in Trebolle et al. (2010) termed as reliability options for distributed generation (RODG). Firstly, the CDS model takes into account the investment deferral effects from all types of distributed resources irrespective of being on the supply side (DG and storage) or demand side (demand response and energy efficiency) whereas the RODG model focuses on distributed generation only. Secondly, the auction structure proposed for RODG is based on a version of sealed bid auction which might not be suitable for acquisition of renewable resources (e.g., Gottstein and Schwartz, 2010). In contrast, the CDS contract is based on a model of descending clock auction (presented in the next section) used in some countries for capacity procurement and in particular for renewable resources acquisition (e.g., NYSERDA, 2004). Thirdly, the RODG model does not specify how this model fits into the wider business model of distribution utilities whereas CDS emerges out of an extended business model within the unbundled power sector paradigm.

The advantages of the CDS approach can potentially go beyond investment deferral by providing value added benefits to the power system. For example, following the market deregulation and liberalisation, the reserve capacities of large scale power generation is declining in many countries (Gordijn and Akkermans, 2007). This creates new business opportunities for small scale distributed resources that could supply some system reserve. Additionally, CDS motivates investment in storage technologies which currently their uptake is sensitive to a range of uncertainties such as future resource mix, technology development, market structures and the uncertainty of returns (Grunewald et al., 2011). Moreover, CDS give a boost to the integration of demand response and energy efficiency, which are currently perceived to be underutilised resources because the electricity markets and reliability requirements have been designed for, and evolved under, a generator supply paradigm (Capper et al., 2012).

In summary, CDS is a mechanism for procuring, on a non-discriminatory basis, a portfolio of capacity resources through a competitive forward auction process. The auctions can reveal the value of the product (capacity) and maximize the revenue obtained, if a sufficient number of non-colluding bidders participate (Newbery, 2003). The selected resource portfolio will act as a substitute for conventional demand driven network reinforcements.

5.3 CDS procurement procedure

Procurement of CDS contracts, by DSO, needs to be based on a well-designed and implemented auction. Overall, the process of CDS contracts acquisition can be described in terms of three stages: pre-auction stage, auction stage and post-auction stage. In the pre-auction stage (stage one), eligibility of potential suppliers needs to be verified with respect to certain requirements. Stage two, is the implementation of auction and process of price discovery. Stage three (post-auction), corresponds to the signing and implementation of CDS contract. Figure 5.4 schematically illustrates the process of CDS contract procurement.

5.3.1 Pre-auction stage

In this stage the DSO forecasts demand growth over the subsequent years and projects the required network capacity. That is to identify the constrained zones and the locations which can potentially experience distribution bottleneck, for delivery to the consumers. DSO often investigates the load duration curve of distribution facilities to find out possible over-load condition and also assesses the grid reliability to ensure that a component failure will not cause a long term interruption (Trebolle et al., 2010).

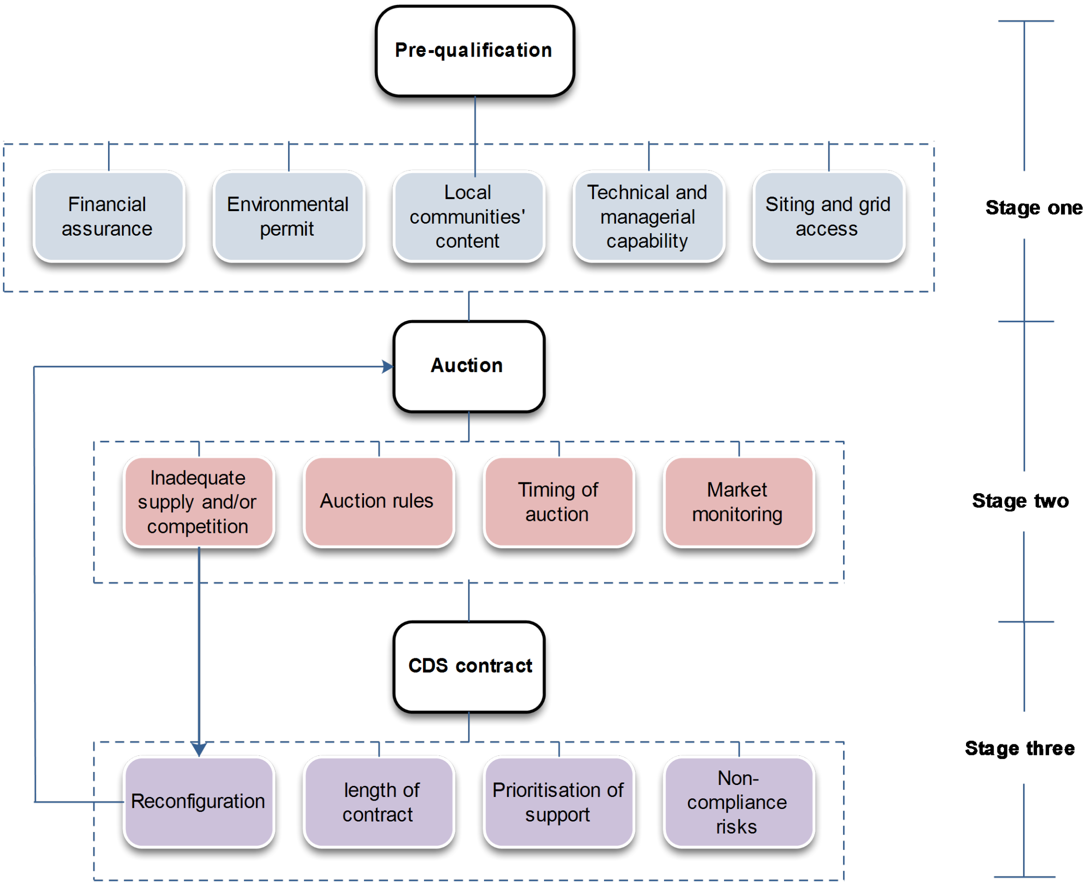

Figure 5.4: The procedure of CDS contract procurement

`[Source: Author, information partially from IRENA (2013).]`

The major task at this stage, however, is to identify and evaluate resource suppliers. This means the DSO needs to initially decide which resources are eligible to submit offer. For example, the DSO needs to determine whether to allow only existing capacities or that both existing and new capacity providers can participate in the auction and also specifying type of resources.

The resources that are eligible to participate in the auction can be different based on the feasibility, regulation and institutional framework as well as technical condition of power system. In the UK, the upcoming capacity auction is technology neutral and includes both the existing and new resources except those that are operating under contract for difference (CfD), feed-in-tariff or renewable obligation, and interconnected capacity (DECC, 2013)[3]. The eligible resources include traditional

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[3] This is to avoid overpayment because these are already under a form of capacity payment.

generation plants as well as demand response (behavioural demand reduction) and storage technologies.

Furthermore, energy efficiency (permanent demand reduction through adoption of more efficient processes and appliances) is being considered for inclusion in this list. ISO New England and PJM forward capacity markets[4] in the US, however, view energy efficiency as an eligible resource which can participate in the auction along with the other resources (Gottstein and Schwartz, 2010). Nevertheless, energy efficiency is treated differently in these markets. PJM allows energy efficiency to receive capacity payment, up to four years of their measured life, whereas ISO NE remunerate for its full measured life to encourage long-lived energy efficiency assets (Gottstein and Schwartz, 2010).

As the CDS contract aims to attract new investment in distributed resources, eligible bidders should be selected from both existing and new capacity providers, in a non-discriminatory and technology neutral manner. This will include, distributed generation, storage facilities, demand response and energy efficiency.

Depending on the nature of resources connected to the distribution network, the feasible options for CDS auction are: dispatchable distributed generations (e.g., CHPs), fairly electricity intensive and electricity dependent consumers (industrial and commercial consumers) which might be able to provide demand response and/or energy efficiency, and also storage facilities operators. Moreover, the DSO can set a minimum eligible volume of capacity to make the participation of small resources (e.g., residential consumers, small back-up generations, and small storages such as PHEVs' battery) possible only through an aggregator.

A DSO might allow intermittent resources such as wind and solar power to participate. However, these need to be treated differently due to their stochastic nature of outputs. For example, the DSO may need to exclude the intermittent resources from availability penalties and/or the poor performing as this is beyond the control of the resource provider. DSO can establish the value for winter and summer

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This is worth mentioning that the UK capacity auction is for non-distributed assets.

[4] ISO New England (ISO NE) market serves Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont. PJM is Pennsylvania-New Jersey-Maryland Interconnection.

qualified capacity of intermittent resources such as wind based on the methods that have been developed for this purpose. One approach that has been studied for ISO NE forward capacity market is to identify the set of reliable hours that deliver the most reliable estimator of median generation during the system peak (IRWGM, 2006). PJM capacity market, however, adopts a different method by applying a 13 percent reduction factor on peak capacity of wind intermittent resources (Gottstein and Schwartz, 2010).

Therefore, CDS can take the advantages of all available resources whether on supply side or demand side including those with stochastic output. Particularly, participation of demand side resources (demand response and energy efficiency) along with supply resources (distributed generation and storage) can significantly improve efficiency of CDS acquisition. The evidence from ISO NE first capacity auction demonstrates that participation of demand side resources saved rate payers $24 million by making the market clearing price lower than it would have been otherwise (Jenkins et al., 2009)[5] . Additionally, demand side resources are carbon free (when it leads to demand reduction) and thus, in harmony with environmental policies. Furthermore, they improve system reliability by relieving the load at congested circuits and also reduce market power of supply side resources in determining market clearing price.

Following the initial identification of potential bidders, the DSO needs to verify the eligibility of resources providers with respect to conditions such as financial ability of new capacity providers, environmental compliance, siting and grid access etc. Below are the most relevant conditions which need to be verified before potential suppliers enter into the auction stage. The DSO

i) should ask for supply of financial assurance, by potential bidder, in case of a new resource which needs to be constructed.

ii) should demand potential bidders for submission of relevant environmental

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[5] The ISO NE accounts DG as a demand side resource as well thus, in practice, the total saving from pure demand resources (demand response and energy efficiency) can be lower than this amount. Demand side resources (inclusive of DG in the case of ISO NE) made 2554 MW of 39142 MW offered capacity in the first auction (Jenkins et al., 2009).

compliance documents as specified by the regulator for each type of generation technology.

iii) should investigate the siting of distributed resource and grid access condition especially for new resources. For example, position of resource with respect to frequently congested circuits and cost of grid connection.

iv) should ask for submission of relevant documents, in the case of new resources, that indicates local communities living at development proximity are content.

v) can ask for proof of technical expertise and managerial capability of resource provider.

Potential suppliers that are qualified in terms of type and capacity volume and also meet the aforementioned criterions will be invited to submit their bids. In order to help the auctioneer to choose the starting price, the DSO might include other requirements in this stage such as rendering an indicative bid (the approximate quantity of supply and price).

5.3.2 Auction stage

Several different auction designs can potentially be employed in this stage. These include: sealed bid, descending clock auction, hybrid, combinatorial and two-sided designs (Maurer and Barroso, 2011). Sealed bid auction can be in the form of uniform pricing, pay-as-bid or generalised Vickrey style in which the winner pays the social opportunity cost of the item won (Fabra et al., 2002). In the combinatorial auction, auctioneer sells multiple goods simultaneously where bidders are only allowed to place a bid on bundle of items and not the individual items. A two-sided auction allows both bid and ask so as to deal with multiple sellers and buyers at the same time and is proved to be effective in reducing market power when there are few seller and many elastic demands (Zou, 2009). Descending clock auction, on the other hand, is a dynamic simultaneous multi-round Dutch auction in which bidders submit quantity supplied at each price until no excess supply exists (Rego, 2013). Hybrid auction is the combination of different auction forms.

As the CDS contract acquisition is a form of single buyer model (i.e., DSO as the sole emptor deals with many potential suppliers), descending clock auction is the method of choice because of appropriate market characteristic. These characteristics, which are noted in NYSERDA (2004), make the descending clock auction a suitable approach for the CDS contract procurement. Firstly, it is an open auction with uniform pricing that discovers price with transparency and improves investment efficiency. Secondly, this auction only identifies the least cost suppliers as inefficient suppliers will withdraw from the auction when the clock ticks down (i.e., price starts to fall). Thirdly, this type of auction determines the winner in a simple manner and averts the need for complex comparisons of competitors' bids which, in turn, reduces the probability of subsequent disputes. Fourthly, under this auction both price and quantity of capacity committed are known at the end of the auction which allows the DSO to project more accurately future financial obligation as a result of CDS contacts acquisition.

Descending clock auction has previously been used successfully in various public and private procurement contexts[6] . In the power market, this approach is used for procurement of renewable portfolio standard by New York State Energy Research and Development Authority (NYSERDA, 2004). Moreover, ISO New Englands Capacity Market uses a descending clock auction in which, energy efficiency, demand response, and distributed generation compete for capacity contract on an equivalent basis (Gottstein and Schwartz, 2010).

The DSO will execute a descending clock auction in multiple rounds with the following procedure. In the first round the auctioneer (DSO in this case) begins with a "starting price" (P_{start}) which is a fairly high price. The DSO can use information obtained during pre-auction stage such as indicative bid and breakeven price to choose the starting price. The resource suppliers, have some time (often between a quarter to few hours) to bid for the quantity of capacity they are willing to supply at this price. Then, the DSO adds up all the committed quantities and compares these with required network capacity to estimate the excess capacity.

In the second round the DSO reduces the price and allows resource providers

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[6] Descending clock auction has been used in US, Spain, Columbia, and the reverse form of it (ascending clock auction in which auctioneer sells) has been adopted in France, Spain, US and Canada (Maurer and Barroso, 2011).

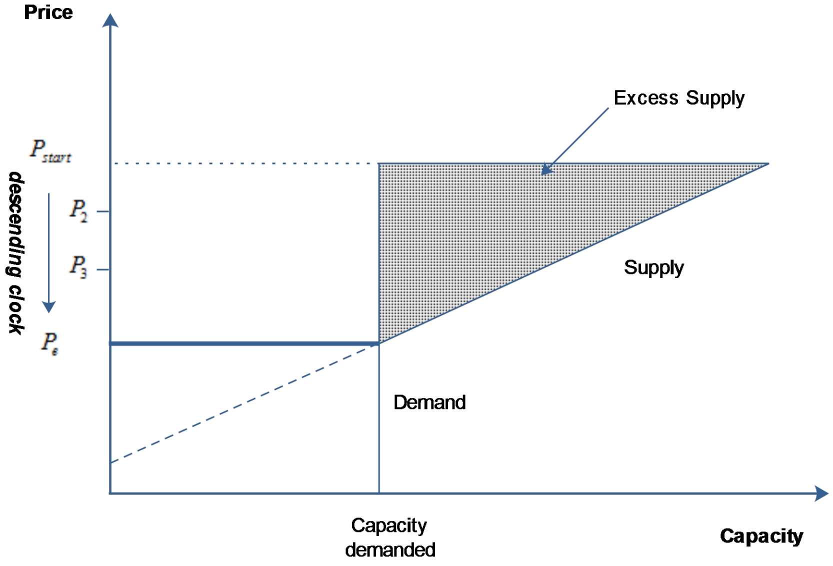

Figure 5.5: The descending clock auction

`[Source: Author]`

to bid again for capacity they are willing to supply at the new price. The new quantity will be lower, or the same as before (but not larger), because of the lower price compared with the previous round. If the excess capacity reaches zero, the auction terminates and the winners will be the suppliers that placed a bid in the last successful round. However, if the excess capacity is still not zero, the DSO will continue the auction over subsequent series until excess capacity is eliminated[7] . The winning suppliers receive the last price cleared by auctioneer. Figure 5.5 illustrates the procedure of a descending clock auction.

The descending clock auction is an effective process for price discovery compared with the sealed bid auctions. Moreover, the dynamic nature of the auction allows the bidders to continuously adjust their bids based on the information revealed during the auction so that they can reduce the so called ”wining curse”. Although the descending clock auction appears to be more complicated than the sealed bid auctions however, the past experience shows that it is not difficult to implement and also, the practitioners are more in favour of this model (Maurer and Barroso, 2011).

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[7] If in round n the committed capacity falls short of demand then auctioneer announces the price in round $n-1$ as the market clearing price and allocate demand among successful bidders pro rata.

However, the main weakness of the descending clock auction is that it increases the possibility of collusion among the bidders under the condition of weak competition. The case of insufficient competition is addressed in Section 5.3.2.3.

5.3.2.1 Auction rules

In order to conduct the CDS auctions in an effective and efficient manner, a number of rules need to be in place. These rules need to be transparent and known to all participants as they embrace the conditions to run the auction. The main auction rules, in the context of CDS procurement, are outlined in the following.

i) The rule concerning the information to be released at the end of each round (e.g., whether or not participants can see the bids submitted by other bidders).

ii) Withdrawal and re-entering in a multi-round auction (e.g., whether the winners must participate in all rounds of auction).

iii) The incremental quantity of price decline in each round (e.g. this can be specified as a constant or as an interval).

iv) Whether a bid can be modified after it is submitted.

v) The format of bid submission such as bidding on an electronic platform provided by the auctioneer or in a different form.

vi) The "bidding window" of the auction (i.e. specifying when the bidding round starts and ends).

vii) The minimum volume of capacity that supplier can bid in each round. This is to prevent inefficient bids and to allow aggregators to take part on behalf of many small scale storages and demand response providers.

viii) Indication of minimum price at which the bidder would be willing to commit supplying capacity in the round that bidder has withdrew because of low price.

ix) Rules concerning disqualification of bidders and allowing the auctioneer to remove a bid from the current or future submission.

5.3.2.2 Auction lead time

The time of the auction depends on several factors such as the prediction of demand growth in distribution network and the presence of new resources in the auction and their associated technology. The DSO will determine the lead time that new projects need to be completed and hence, fulfil their obligation for supplying capacity. However, if the bidders are existing resources only, the lead time will be shorter (e.g., the following year). Therefore, taking into consideration the different lead times for existing and new projects, the auction needs to be held well in advance of demand growth to allow sufficient time for the construction of new capacity if required.

A short lead time can become a problem for capacity market design as it deters new entry even with high prices. A short lead time might also incentivise resource providers to withhold strategically in order to raise the price. The decision to run the UK capacity market with a four-year lead time between auctioning time and delivery period is to mitigate the impact of withholding and make the market sufficiently contestable by attracting new investment (see DECC, 2012).

In the context of CDS auctions, the lead time should be based on the gestation period of energy-based distributed resources such as CHP plants or storage facilities which are often shorter compared with conventional power plants (e.g., coal or nuclear plants). Also, DSO can differentiate between existing and new resources to prevent a long lead time come at the cost of undervaluing the investment of existing resources. Moreover, specifying different delivery periods will facilitate the participation of demand response as they will not be constrained by the lead time of constructing projects.

5.3.2.3 Inadequate supply and weak competition

In CDS contracts, the issue of inadequate supply can occur if at the starting price, in the descending clock auction, the total capacity offered (by existing distributed generation, storage facilities, demand response and energy efficiency) is less than the network capacity demanded. Insufficient competition, on the other hand, occurs when the number of bidders is limited (this can be accompanied with inadequate supply as well, though not necessarily).

The issue of inadequate supply due to insufficient existing resources can be alleviated by changing the auction parameters such as price and lead time. One approach to modify descending clock auction is to differentiate between existing and new resources based on the price. For instance, allowing existing resources to have market clearing price but the new resources to collect the penultimate round price in the first year of delivery and market clearing price thereafter (i.e., if the market clears after n rounds; this corresponds to the price in round $n-1$ and since the auction is descending in price we always have $P_{n-1} > P_n$). This approach provides incentive for new resources to participate and thus, attracts more new developers into competition and can potentially reduce probability of inadequate supply. The discriminatory price descending clock auction can be accompanied with a suitable lead time to incentivise investors.

The second approach to address the issue of inadequate supply is to include the amount of inadequate supply in the subsequent reconfiguration auction to correct for the inadequacy(NYSERDA, 2004). This auction will cover both inadequate supply and change in the position of potential suppliers due to unpredicted circumstances. The reconfiguration auction has been explained in Section 5.3.3.4.

As mentioned previously, the descending clock auction is vulnerable to weak competition. That is the bidders can misuse the available information during the auction to coordinate their actions and raise the market clearing price. One approach to address the issue of weak competition is to carry out a hybrid auction in which the first phase starts with a descending clock auction followed by a sealed bid auction(Maurer and Barroso, 2011). The advantage of this approach is that it attracts more of small bidders and hence, strengthens competition. This form of hybrid auction has been used in Brazil to auction hydro power resources and has proved to be effective, to some extent, in handling market power and weak competition(Maurer and Barroso, 2011). However, a weakness of hybrid auction is that it can increase complexity of auction process and raises transaction cost. Therefore, it can be difficult to implement a hybrid auction.

Another approach, to address the market power, would be to use a single round sealed bid auction. Herrera-Dappe (2013) demonstrate that a sequence of two uniform price auctions gives lower expected revenue than a single uniform price auction when the market is not sufficiently competitive.

Despite these possible remedies, under insufficient competition, the DSO might seek permission from regulator not to run an auction. In this case the DSO can adopt alternative approaches to procure capacity which have been suggested to developing countries in these circumstances. Some of these alternatives are: negotiations between the DSO and potential suppliers, using an administratively set price such as feed-in tariff on a first-come-first served basis until the demand is met, or using a "beauty contest form of allocation" in the sense that DSO defines the criteria and conditions for contract with some room for discretion and subjective evaluation (Maurer and Barroso, 2011).

5.3.2.4 Market monitoring

A competitive process can result in an undesirable outcome, if it is not appropriately designed, implemented and monitored. There are a number of potential obstacles such as liquidity, market power, collusion, gaming etc., from which the CDS auction is not necessarily immune. These highlight the need for oversight. Therefore, regulator needs to appoint a third party, as the auction monitor, to superintend the CDS acquisition process.

The task of the auction monitor is to oversee the procurement process and report any evidence of breach of rule or non-conformity to the regulatory body(Maurer and Barroso, 2011). This includes all the stages from pre-auction to post-auction phase. The market monitor identifies the structural deficiency of CDS market design and the way these deficiencies can be misused by market participants. Moreover, the market monitor provides regulator with an assessment of market outcome to ensure they are consistent with a competitive process and policy objectives. Furthermore, the regulatory body can consult with the auction monitor in case that the conduct of the auction is disputed by a bidder.

The auction monitor can also help with designing the auction procedure for the specific contract procurement. However, the tasks of auction design and auction auditing should ideally be delegated to two independent entities, as in the case of PJM capacity market, to reduce possibility of conflict of interest and increase transparency.

5.3.3 Post-auction stage: Awarding CDS contract

Following the acceptance of offers and clearing price, DSO will enter into CDS contracts with successful bidders. According to the CDS contract, the capacity supplier will be paid based on the price in the agreement and the resource operator is obliged to deliver capacity or to reduce demand when called by the DSO. As CDS is a contract, many of the relevant issues in the context of contracts theory (i.e., principal-agent relationship such as information asymmetry, moral hazard etc.), are also applicable to CDS. Moreover, in practice writing a complete contract (taking all contingencies into consideration) for CDS is both unfeasible and costly. However, the following important issues need to be elucidated in a CDS contract.

5.3.3.1 Length of CDS contract

An important feature of the CDS contracts is the duration of agreement between DSO and capacity provider. Short agreements have the advantage that they are more easily tradable in a secondary market and also there is no long term financial obligation for DSO. However, long term agreement gives more financial security to capacity providers and avoids boom and bust in capacity market(DECC, 2012). In practice, a uniform contract length for all resources is not feasible, given the different cost structures, technology and asset age of capacity resources. Thus, in order to encourage investments and reduce the risk to investors, the DSO needs to differentiate between the existing resources and new capacities. It may be preferable to give more time to new capacities because a longer term agreement will enhance the certainty of return to investment and reduce the cost of capital.

A possible risk of differentiating between the existing and new capacities based on contract length is that the projects that are under construction at the time of the auction will be treated as existing resources. This creates incentive for investors to withhold new investments until an auction is announced. In order to mitigate this effect, the definition of existing and new resources should be based on the capability to deliver at the time of the auction so as to treat only those resources that are operational as existing resources.

5.3.3.2 Prioritisation of support

Under the CDS contracts, resource operator, DSO and TSO are the entities that will have control over the operational status of distributed resource. In order to improve coordination among these players and avoid conflict of interest, prioritisation of support needs to be clearly determined. The form of allocating priority can be based on the type of resource and the initial purpose of developing the resource. For example, if the resource is a DG which was originally installed to satisfy the developer's own demand, a feasible arrangement would be to give the owner of DG resource priority because it is usually needed as backup power supply. The DSO would then be the second entity that has priority to call the generation for local balancing as no other alternative is available, and finally the TSO is the third entity. Where the resource output is not required locally or nationally, the energy produced can be sold into the wider electricity market.

5.3.3.3 Non-compliance risks

There are several sources of non-compliance risks such as the failure of successful bidder to sign the CDS contract, failure to complete the project (for new resources), risks related to the delays and failure of supplier to deliver the committed capacity, risk of underbidding and finally regulatory and administrative risks(IRENA, 2013). As in other contracts, the CDS needs to address these issues at an appropriate stage. For example, the risk of delay and underbidding can be reduced by applying stringent compliance rules. Frequent monitoring of project development can reduce the risk of failure with respect to construction of new resources. Moreover, strict qualification checks at pre-auction stage reduce regulatory and administrative risks such as those related to the project siting, grid connection and environmental obligations.

A challenging issue from the perspective of the DSO is the commitment of the capacity provider to deliver when needed. Uncertainty in this will undermine the effectiveness of smart solution as alternative to grid capacity enhancement. Therefore, the DSO needs to ensure that a credible, effective enforcement and compliance mechanism is in place that guarantees a timely delivery and applies a penalty in the event of non-compliance. Drawing on the experience from the established capacity markets, there is a spectrum of approaches to reduce probability of non-compliance. The market-based methods rest at one end and the administrative approaches are located at the other end of the spectrum. The hybrid methods lay somewhere in between.

One market based approach is to pin the terms of CDS contracts to some reference electricity market such that when the reference price is above the contract price, the resource operator is required to pay the difference. This incentivises the resource owners to deliver at the time of network constraint and peak demand, because even if they do not operate they still need to pay the difference(DECC, 2012). The price spikes usually coincide with time of peak demand and network constraints. However, if they do not coincide this method can be problematic. Moreover, in some countries such a market might not be available to provide a reference price.

The administrative approach would be that the resource owners receive a capacity payment for their availability period, as specified in CDS contract, and to be penalised based on an administratively set price if they fail to deliver when they are called or fail a spot check by DSO. This method is more straightforward and easier to be implemented(DECC, 2012). However, the total annual penalties should be capped to avoid unquantifiable risk to the investors. For example, the penalty could be proportional to the volume of capacity (e.g., a percentage of the annual payment for that resource during the capacity commitment period). Moreover, the DSO should offer the option to resource provider to default on its commitment, when called, and pay the penalty if unexpected faults developed.

The compliance monitoring approach that the DSO can adopt is context bounded. However, regardless of the approach chosen; it needs to take into consideration several aspects, such as the possibility of strategic behaviour and gaming the DSO, allowing for maintenance planning of energy-based resources, and linking the size of penalties to total volume of capacity payment etc. Moreover, in many capacity markets the penalty price is not uniform across different resources. For example, the PJM and ISO NE capacity markets differentiate between supply side resources and demand side resources for non-compliance and associated penalties (Gottstein and Schwartz, 2010). This differentiation can also be helpful in the context of CDS contract given different nature of energy based and non-energy based resources.

5.3.3.4 Reconfiguration auction

Due to the possibility of unpredictable circumstances and change in economic factors, there might be discrepancies between the contractual obligation of bidders and the actual cost of their contract fulfilment(NYSERDA, 2004). Thus, when there is evidence of such condition, a reconfiguration auction should be held in an appropriate time, ex-post, in order to allow suppliers to correct for these differences. For example, the ISO New England's capacity market runs monthly and yearly reconfiguration auctions to allow deficient suppliers procure replacement capacity (Gottstein and Schwartz, 2010). The lack of such a mechanism increases probability of unavailability of resource in the time of need.

Other situations that require reconfiguration auction include the state of inadequate or excess supply of capacity. As mentioned in Section 5.3.2.3., the inadequate supply dominates when there is insufficient supply from the existing capacities at the first round of the descending clock auction. The excess supply can prevail when there is a decrease in load forecast[8] following the auction and capacity acquisition. Under these conditions, the reconfiguration auction can help the DSO to buy or to sell CDS contracts and match supply with demand more accurately. The reconfiguration auction, for a specific target, can be held close to the year of delivery. The price in the reconfiguration option can be higher or lower than the initial CDS auctions.

5.4 Conclusions

The power sector is evolving with anticipation of increase in penetration of distributed generation, storage technologies and demand side participation. Distribution networks which were originally designed as passive and one way transporters of electrical energy are entering a new era in which operational philosophy will change

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[8] The error in forecast is natural when looking far into the future i.e. the CDS auction has been held few years in advance of delivery period.

to the bi-directional power flows and the use of information and communication technologies. These will bring new opportunities for implementing innovative solutions for traditional issues such as demand driven network reinforcement, through locally satisfying of demand, using distributed resources.

This chapter proposed a new market-based model termed "contract for deferral scheme" (CDS) to integrate an economically efficient portfolio of distributed resources including distributed generations, storage technologies, demand response and energy efficiency, as an alternative to demand driven network investment. The concept of CDS is consistent with an unbundled power sector paradigm, and lies within the wider context of an extended business model of distribution utilities. The details of the CDS procurement were discussed in three stages: pre-auction, auction and post-auction. The pre-auction stage explored the conditions for resource eligibility; the auction stage discussed the process of price discovery and market rules and finally post-auction stage addressed issues such as the length of contracts and compliance monitoring.

The CDS contracts present several potential advantages. Firstly, they protect the developers of distributed resources from market risks, decrease the financing cost and improve commercial bankability of investments. Secondly, they improve competition, encourage investments and hence; speed up the deployment of DGs, storage facilities and demand side participation. Thirdly, CDS auctions help with creating an integrated market for substitution of a resource portfolio as a virtual network capacity, at distribution level, and simplifying the process of valuing alternative solutions to grid reinforcements. Fourthly, CDS helps, to some extent, alleviating the gradual reduction of reserve margin which is currently a major issue in the post-liberalisation power sector.

Chapter 6

Conclusions

Distribution networks are an important part of power systems, which deliver electricity to consumers and, at the same time, they play a principal role in the integration of renewables, demand side management, security of electricity supply, market competition, *inter alia.* The increase in demand for electricity as a result of consumption growth along with environmental policies aiming at a decarbonised electricity sector strain the power grid more than ever. Additionally, the anticipated shift in the operational paradigm of the power system, through the use of information technologies, implies the need for considerable automation and communication, especially at the distribution level where the concept of smart grid comes to play an important role. Therefore, development of a modern, flexible and reliable grid is essential and among the crucial challenges of the power sector in coming years.

The issue of network development requires sizable investments and innovation by grid companies, which are natural monopolies and, hence, subject to economic regulation. The motivation behind the regulation of the industry is to improve economic efficiency and to ensure sufficient investment in a segment which lacks competition. However, in practice, designing a regulatory system that provides the right incentives for investment and innovation, without compromising other objectives such as economic efficiency is more difficult than often perceived. Accordingly, this research was designed to address some of the most relevant regulatory, economic and policy challenges pertaining to grid development. More specifically, the thesis aimed at developing an understanding of investment drivers, the relationship between investment and static/dynamic efficiency and innovative alternatives to traditional network reinforcement, within the context of incentive regulation. The general theme of the thesis was broken down into four research questions, which were addressed in Chapters 2,3,4 and 5.

This chapter synthesises the empirical findings as well as the results from other methodological approaches used in the thesis. The outline of the chapter is as follows. The next section reflects on the main findings and results with respect to individual research questions posed at the beginning of the thesis. Section 6.2 presents the implications of research results for policy and practice in regulation of electricity networks. Finally, the limitations of thesis and the areas of further research have been discussed in Section 6.3.

6.1 Research findings and reflection

The investment drivers and responsiveness of companies to the regulators' incentives with regard to investment have been investigated in Chapter 2. The chapter provides an insight into investment behaviour of network companies under incentive regulation with ex-post regulatory treatment of investment.

The aim of incentive regulation is to set up a penalty and reward scheme that directs companies toward an efficient level of investment and operating cost. The response of regulated firms to investment incentives depends on the net effect of the costs and benefits resulting from their response. For example, the empirical findings of Chapter 2 showed no response from Norwegian distribution companies to incentives for network energy loss reduction, suggesting that these incentives do not justify investments. Although technical reasons might also explain this (i.e., reducing energy loss below a certain threshold is not possible due to the natural resistance of physical materials), from an economic perspective, the companies respond to an incentive only when the cost of taking measures is lower than ignoring the incentive.

Another example along the same line is the cost of service interruptions. The incentive for reducing outages, under the Norwegian regulatory framework, is stronger because the cost of energy not served is part of the benchmarking model and, at the same time, directly deducted from the companies' revenue at the final stage of revenue setting. Therefore, unlike the case of network energy losses, the cost of inaction is not trivial. The empirical evidence in chapter 2 confirms that Norwegian distribution companies have strongly responded to outage-reducing incentives.

The results of Chapter 2 also show that the investment rate in the previous period explains a large part of variations in capital expenditure of firms. The importance of lagged dependent variable (i.e., investment rate) in explaining investment behaviour of network companies suggests that the response of firms to information is slow. This can be because of adjustment costs and/or the nature of the ex-post regulatory model in which investment spikes can result in cost disallowance (i.e., cause the firms with high investment rate to look inefficient). Therefore, the network companies try to avoid instantaneous responses and instead spread their investment plan over multiple periods. Both of these effects motivates the autoregressive process developed for inefficiency, in chapter 4.

The incentives to maintain and modernise the grid can be provided through different instruments which vary in terms of strength, effectiveness and the degree of intervention. The economic incentives have the advantage of being unintrusive. Nonetheless, the response of firms is not guaranteed because it depends on the cost of action versus that of inaction. The economic incentives can be strengthened with direct instruments in order to secure investments prioritised by the regulator (e.g., network access).

A challenge, from a regulatory perspective, is how to adjust the incentives at the right level so as to deter inefficient behaviour. This is because strengthening the incentives increases the probability of overcapitalisation. In a parallel argument, weak incentives raise the chance of underinvestment. On the other hand, frequent adjustment of incentives can create regulatory uncertainty and, over a longer term, results in disincentives for investment.

A stable regulatory framework is a prerequisite for predicting the behaviour of regulated firms. Therefore, adjustment of incentives should be based on the strong evidence of systematic over or under-investment and after periods of observing the firms' behaviour.

From a regulatory point of view, investment incentives are designed and implemented in order to achieve two specific objectives. The first one is the objective of "investment sufficiency" which has been discussed in Chapter 2. The second one is "investment efficiency" which ensures that capital expenditures will not come at the expense of cost efficiency. This is the topic of Chapter 3 in which the relationship between investment and efficiency under incentive regulation has been explored.

Understanding the relationship between investment and efficiency is instrumental in addressing the issue of investment under regulation. The method of regulatory treatment of investment, under incentive regulation, determines the way investment and efficiency are related. Under the ex-ante regulatory treatment of investment, there is no clear quantifiable relationship between investment and efficiency, as capital costs are excluded from the benchmarking model. Thus, it is often hard to measure the efficiency effect of investment as the operating and capital costs are treated differently and the regulatory regime implies that efficiency gains can mainly be achieved from operating costs.

Unlike the ex-ante approach, under the ex-post regulatory treatment of investment there is a quantifiable relationship between investment and efficiency. This is due to the fact that capital cost is part of the benchmarking model and investment behaviour of network companies will be reflected in their observed efficiency. However, the characteristic of this relationship is more complex than previously thought. While it is possible to conclude that a lower level of investment will result in lower total cost and consequently higher efficiency, the empirical evidence of Chapter 3 showed that this is not necessarily true. The largest efficiency losses after investment were related to the firms with lower levels of capital expenditures to total cost ratio. This is partly due to fact that benchmarking is a relative concept and behaviour of firms is evaluated in relation to their peers and not in isolation. Thus, the behaviour of competitors also affects the benchmarking results.

This indicates that the relationship between investment and efficiency is far from linear under incentive regulation with ex-post regulatory treatment of investment. Thus, it is difficult to infer about the firms' investment efficiency *a priori*, based only upon their investment levels.

The presence of a relationship between firm investment level and cost efficiency increases the incentives for cost-reducing investment. This stems from the fact that inefficiency causes revenue loss but at the same time, firm has an incentive to invest in order to benefit from the return on capital. The concept of no impact efficiency introduced in Chapter 3 can be a useful benchmark to infer about the investment efficiency of individual firms in an ex-post manner. However, it has the same limitations of efficiency as a relative concept.

The implications of the relationship between investment and efficiency studied in Chapter 3 illuminated the difficulties of achieving investment efficiency. Along with regulatory invectives for investments, the actual capital cost needs to be controlled in order to deter strategic behaviour in pursuit of supernormal profit. This is why the ex-post regulatory treatment of investment links the capital cost of companies to their efficiency level. Although this approach can reveal more information about the firm's investment behaviour in relation to other companies, the possibility of harmonised overinvestments reduces the effective range of this approach.

Moreover, investment is a dynamic and long term undertaking, whereas efficiency obtained from benchmarking is a measure of the short-term behaviour of a firm. Therefore, the simultaneous incentive for investment and cost efficiency can send inconsistent signals to the regulated firm. This is the subject of Chapter 4 in which the dynamic aspect of efficiency in regulated firms, with ex-post regulatory treatment of investment, has been investigated.

The lack of incentives for dynamic efficiency is a major disadvantage of incentive regulation. In essence, incentive regulation is designed and applied to incentivise cost reducing measures. The cost of regulated companies, which mainly comprised operating and capital expenditures, does not have a uniform structure as these cost categories serve different purposes with different time scales. On the other hand, the incentives for cost reduction can only target those costs that have a short term nature such as operating costs. This is because the incentive regime seeks short run efficiency gains, which is only possible with respect to adjustable costs and is problematic with quasi-fixed inputs such as capital costs. This makes the incentive regulation a tool for short term objectives which does not take into account the long term nature of investment and innovation.

Although this is a common feature of incentive regulation models, the extent to which it impacts the dynamic behaviour of companies varies between the ex-ante and ex-post regulatory approaches. The empirical evidence from Chapter 4 shows that, under ex-post model, inefficiency persistence due to sluggish adjustment of quasi-fixed inputs, in the short run, is a critical issue. The persistent inefficiency can seriously affect the companies' short run productivity and consequently their regulated revenue. The benchmarking methods are unable to distinguish between the controllable and uncontrollable parts of inefficiency evolution. Therefore, the incentive to reduce the total expenditures of a firm to the efficient level can come at the cost of compromising the long term objectives of investment and innovation.

Under the ex-ante regulatory model of investment treatment, the issue of dynamic efficient behaviour is less critical compared to the ex-post model. This is because the length of the price control review period is usually higher and static efficiency is decoupled from capital expenditure by excluding investment from the benchmarking model. However, the advantage of this approach is relative as it suffers from several drawbacks discussed in Chapter 4. These shortcomings include the incentives for strategic behaviour in terms of cost transfer between cost categories and also gold plating of capital.

The lack of incentive for dynamic efficiency in incentive regulation hampers the objective of grid development as it affects the process of cost recovery in network companies. The solution to this problem is not straightforward. A shift to the ex-ante approach as well as the introduction of complementary incentives for innovation can, to some extent, reduce this problem. However, the regulator needs to deal with the side effects of the ex-ante method as well.

The design of incentives such as that of RIIO-ED1 regulatory model in the UK, which rewards the downward deviation of investment costs from the agreed level of capital expenditures in the business plan might encourage innovation by regulated companies. These innovations can reduce inefficient capital expenditures which prevail under the traditional operating paradigm of electricity networks. This is the topic of Chapter 5, which explores a practical solution to bring down inefficiency in network capacity enhancement. This approach takes advantage of distributed energy resources penetration to reduce the need for network reinforcement and improve the efficiency of asset utilisation.

The integration of distributed resource, as an alternative to traditional network reinforcement, not only improves efficiency of network utilisation but also minifies the problem of public opposition with respect to grid infrastructure expansion. A shift in the operating paradigm of distribution companies from network operator to system operator is helpful to enable an effective use of distributed resources. This implies major changes in the technical and the business operation of these companies. From a technical viewpoint, distribution network management, which traditionally has been passive, needs to become active. In this way, the distribution companies will have more control over the power flows and dispatchable demand and supply. This allows distributed resources to be used for efficient balancing of the system at the distribution level. It also avoids network congestions and thereby averts the need for costly redundant transformers. From an economic perspective, the business model of distribution companies needs to be extended as suggested in Chapter 5. The new business model includes market operation for integration of distributed resources, and utilising the new possibilities arising from active network management.

The contract for deferral scheme (CDS), introduced in Chapter 5, enables firms to optimise on asset-based network services and, at the same time, provides a sustainable business model for integration of distributed resources. Under the CDS contract, the process of price discovery is based upon a competitive forward auction which is an economically efficient way of revealing the real value of network services. Additionally, the CDS contract reduces the cost of financing renewable projects and encourages new investment through providing a sustainable cash stream for the resource developer. Furthermore, the financing source of CDS contracts is, in fact, the avoided costs of network reinforcement. Therefore, CDS is appealing from a regulatory perspective because it reduces the capital cost of companies. Moreover, CDS is part of an extended business model for distribution network companies which requires going beyond connection and use of system charges. This allows distribution network companies to take on a new and active role and helps them to fend off shrinking of their revenue as a result of distributed generations' uptake close to the demand site.

6.2 Policy implications

The outcome of this research has some policy implications concerning the regulation of natural monopoly electricity networks. A key regulatory challenge is the issue of investment in power network companies. The ability to adapt to the dynamic environment of the power sector is particularly important as lack of flexibility, in the current forms of incentive regulation, caused the network companies to lag behind the frontier. The climate policy objectives initiated a new trend in the power system operation in the form of renewable integration and decentralised generation. Thus, the incentive regulation needs to offer sufficient level of flexibility to allow distribution companies to play a more active role and at the same time evolve synchronously with the rest of the power sector. In what follows, the implications of the thesis results for policy and practice are discussed.

6.2.1 The concept of no impact efficiency as a benchmark

In theory, incentive regulation with ex-post regulatory treatment of investment, can incentivise investment efficiency as, for example, overinvestment will increase the total cost of regulated companies and lowers their efficiency. However, the previous studies using this model of incentive regulation do not explain the nature of the relationship between investment and efficiency. The theoretical framework, introduced in Chapter 3, bridges this gap. According to that framework, there is a minimum level of efficiency that a regulated firm, with ex-post regulatory treatment of investment, needs to achieve in order to pass a benchmarking exercise without cost disallowance. This productivity level, which is the revenue neutral efficiency effect of investment, was termed "no impact efficiency".

The concept of no impact efficiency illuminates the process under which incentive regulation seeks investment optimality. This concept can help with addressing the issue of investment under regulation and thus has several advantages. First, it improves our understanding of investment behaviour of firms under an incentive framework. The incentive to invest in cost-reducing capital is the direct consequence of incentive regulation. This effect, which is embedded in incentive regime, can be explained through the no impact efficiency concept.

Second, it provides a benchmark for the sector regulators to examine the firms' investment efficiency and design more effective policies with regard to investment and associated incentives. This is particularly important given that the assessment of investment behaviour of firms and identifying the incidence of overinvestment under total cost benchmarking is difficult. Third, the measure of no impact efficiency can be used by regulated firms to adjust their investment level accordingly.

Nevertheless, it should be noted that no impact efficiency is also a relative concept and has all the limitations of efficiency measurement. For example, the behaviour of peer companies can move the reference point for a particular firm regarding the investment. Thus, although no impact efficiency reveals information about the investment behaviour of firms; it should be applied with same level of cautiousness as the conventional efficiency measurements.

6.2.2 Harmonised investment behaviour

A common perception in incentive regulation with ex-post regulatory treatment of investment is that overinvestment behaviour will be identified in the benchmarking exercise as it reduces the efficiency score of the firms. However, as discussed in Chapter 3, under the condition of harmonised investment behaviour by regulated companies, the benchmarking practice fails to detect the incidence of overinvestment. This is because harmonised investments change the cost of all firms uniformly and within-group comparison does not reveal much information about their investment behaviour.

Harmonised investment behaviour can be the result of two circumstances. First, when the regulated firms are working under a similar investment policy, an unwanted policy effect might harmonise their investment behaviour over time. The second case is related to collusion among the regulated firms. The presence of any of these conditions is sufficient to create harmonised investment behaviour among the firms and reduce the power of benchmarking to detect the incidence of overcapitalisation.

The harmonised investment behaviour is a caveat on the effectiveness of incentive regulation and the extent to which it can address overinvestment through total cost benchmarking. The regulators who have adopted this approach assume that benchmarking will provide them with necessary information about investment efficiency of the firms. However, the success of incentive regulation to address the incidence of overcapitalisation, to some extent, depends on the investment behaviour of firms. The notion of harmonised behaviour draws a boundary around the incentive regulation and specifies the edge beyond which the reliability of information from total cost benchmarking, with respect to investment behaviour of companies, diminishes. This indicates the necessity of between-group comparisons (as opposed to within-group) by, for example, using information from similar companies outside the sector or perhaps, where feasible, international benchmarking.

6.2.3 The concept of inefficiency persistence

An important side effect of incentive regulation with ex-post regulatory treatment of investment is the issue of adjustment of quasi-fixed inputs such as capital expenditures. This arises from the short-term nature of incentive regulation which seeks to contract inputs for a given quantity and quality of outputs or maximise outputs for given levels of inputs. The concept of inefficiency persistence which was introduced and measured in Chapter 4 indicated that incentive regulation disregards the dynamic aspect of firms' behaviour.

The common application of incentive regulation, based on output maximisation or input minimisation, is insufficient to mimic the outcome of a competitive market. The empirical results of Chapter 4 provided new insights into the way that inefficiency should be defined as the basis for assessment of firm investment performance. Traditionally, the inefficiency of regulated firms is viewed and estimated as the measure of deviation from the static optimum frontier. This is in contrast to the concept of dynamic efficiency which defines inefficiency as a measure of deviation from “optimal capital stock adjustment”. This perspective provides more flexibility for regulated firms and does not detach them from their history and future when their investment performance is evaluated.

The insufficiency of efficiency measures with the static nature calls for the extension of incentive regulation. This includes the introduction of incentives for dynamically efficient behaviour, as opposed to static efficiency, which is problematic with respect to investment and innovation. The firm inefficiency evolution is currently considered to be completely under the control of the firm whereas the empirical results in Chapter 4 suggest that this is not necessarily true. The presence of quasi-fixed inputs reduces the control of firms on inefficiency evolution. The evolution of inefficiency, under this condition, depends upon the scale and type of investments. A modified incentive regulation, which takes into account the dynamic dimension of firm business, promotes flexibility in investment and innovation and helps the regulation outcome to better mimic a competitive market.

6.2.4 Distribution-managed market model for renewable integration

Although penetration of renewable energy resources has generally been considered to be policy oriented, the market approaches should be given priority where feasible. There is a significant scope for the contribution of distribution companies on the problem of renewable integration which can be achieved. For this to happen, the operation and organisation of these companies require reshaping and restructuring. This is to divert the concentration from physical asset-based network services to a combination of traditional network operation and alternative solutions such as procurement of distributed resources that provides network services. There is also a need for evolution of power distribution companies from network operator to system operator which implies market operation along with physical operation of the grid. At the same time, it is crucial to distinguish between regulated and non-regulated activities of distribution networks and allow them to have an active role in the process of electricity service supply.

The introduction of a new market, based on the contract for deferral scheme

(CDS) discussed in Chapter 5, to facilitate integration of renewable resources at distribution level, is among those possibilities that are yet to be utilised. There are significant advantages, both technically and economically, in a distribution-managed market model for distributed resources integration. From a technical point of view, integration of renewable resources under management of the distribution system operator allows distribution companies to contribute to national balancing services, quality of supply improvement, maintaining the voltage profile, among other things. Form an economic point of view, the CDS approach based on the long term contract will lower the cost of capital and will improve efficiency of network asset utilisation.

6.3 Limitations of research and the path forward

There are two types of possible limitations in this research. One pertains to those topics which are not covered here but are still related to the overall theme of the thesis (i.e., grid development). The second type is concerned with the methodological or data-related limitations.

The overall theme of the thesis includes areas which have not been covered thoroughly as any of them can be the subject of another PhD thesis. Areas such as social acceptability of grid development, the effectiveness of different investment models, network security and resiliency enhancement, among other topics require detailed investigation. Despite this, the research has attempted to address several key issues on the problem of grid development. These issues embrace a wide range of sub-topics from economic and market modelling to regulation and policy aspects of sustainable grid development.

A cross-country analysis will probably enrich the empirical findings with respect to models and concepts introduced in this thesis. This can be useful for all three empirical chapters in general, and Chapters 3 and 4 in particular which introduce and discuss new concepts and theoretical frameworks. Application of the approaches and concepts introduced in Chapters 3 and 4 to other countries would allow controlling for some of the differences and would provide a new insight into the problem under investigation. At the same time, it should be noted that the dataset adopted for empirical works in the thesis represents a leading country in power sector reform and regulation of distribution companies. The Norwegian regulator (NVE) regulates around 130 distribution companies and constitutes one of the world richest datasets in this area.

The methodological approaches adopted in the thesis can be compared with other feasible techniques to examine the robustness of the introduced concepts with respect to estimation methods. In chapter two, for example, although the adopted methodological approach was based on a thoughtful economic and statistical reasoning, a comparison of estimation results with non-Bayesian approaches can further underpin the outcomes. The same applies to Chapter 4 which uses a Bayesian technique for estimation of a dynamic stochastic frontier model. In Chapter 3, however, a comparison with non-parametric methods would be beneficial as it could reveal more information about the robustness of the approach taken. The conceptual market model developed in Chapter 5 can be further enriched by economic and mathematical modelling in order to develop and conduct scenario analysis.

The area of grid development is receiving increased attention in energy economics because of its relevance for a sustainable power sector and the significant scope for further works. For example, the issue of social acceptance of grid infrastructures is set to become a major challenge which can increase the cost of projects significantly. This area requires economic thinking and research to reduce the transaction costs and provide incentives for affected communities to become involved in the process of decision making.

Another important aspect of grid development is the issue of network protection against low probability, high impact events as other critical infrastructures heavily rely on a reliable power supply. The interdependency among critical infrastructures makes the total societal cost of electricity supply interruption, higher than expected. This is particularly due to lack of substitutes for electricity and also instantaneous failure spread of a triggered event. This area requires investigation to understand the impact of power supply interruptions on the system of interdependent critical infrastructures. Such studies can help to explore the ways to use the indirect and higher order effects of electricity supply interruptions to incentivise investment in resiliency enhancement.

Finally, the necessity to develop interconnectors and offshore transmission lines is becoming a pressing issue. There is currently a growing interest among the European countries to become interconnected and create a single electricity market. This is to utilise the renewable resources more efficiently, improve security of supply and boost deployment of low carbon technologies. Achieving these objectives, however, requires a regulatory model that overcomes obstacles and ensures investors of profitability of economically justified investments. The design of innovative regulatory models that consolidate the process of decision making with respect to both onshore and offshore lines can create synergies.

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Appendix A

Regularity conditions

Table A1: Regularity conditions (monotonicity)

Variable	Derivative		Value (at sample mean)	Percentage violated over data points
Outputs	$bh_m = \frac{\partial D^I}{\partial y_m} = \frac{\partial lnD^I}{\partial lny_m}\frac{D^I}{y_m} = \left(\alpha_m + \sum_{n=1}^{M}\alpha_{mn}\ lny_n + \sum_{k=1}^{K}\delta_{km}\ lnx_k\right)\frac{D^I}{y_m} \leq 0$	CU	-0.428	0.0035
		NL	-0.6257	0.00
Inputs	$h_k = \frac{\partial D^I}{\partial x_k} = \frac{\partial lnD^I}{\partial lnx_k}\frac{D^I}{x_k} = \left(\beta_k + \sum_{l=1}^{K}\beta_{kl}\ lnx_l + \sum_{m=1}^{M}\delta_{km}\ lny_m\right)\frac{D^I}{x_k} \geq 0$	In	+0.924	0.00
		C_1	+1.00	0.00

Table A2: Regularity conditions (concavity)

Curvature	**Corresponding matrix**	**Value at sample mean** **($K = M = 2$)**	**Definiteness At sample mean**	**Percentage with appropriate curvature over data points**
Quasi-concave (Outputs)	$BH = \begin{bmatrix} 0 & bh_1 & \cdots & bh_M \\ bh_1 & bh_{11} & \cdots & bh_{1M} \\ \vdots & \vdots & \vdots & \vdots \\ bh_M & bh_{1M} & \cdots & bh_{MM} \end{bmatrix}$	$\begin{bmatrix} 0 & -0.530 & -0.711 \\ -0.530 & 0.271 & 0.175 \\ -0.711 & 0.175 & 0.564 \end{bmatrix}$	Indefinite	18.7%
Concave (Inputs)	$H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1K} \\ h_{21} & h_{22} & \cdots & h_{2K} \\ \vdots & \vdots & \vdots & \vdots \\ h_{K1} & h_{K2} & \cdots & h_{KK} \end{bmatrix}$	$\begin{bmatrix} -0.936 & 0 \\ 0 & -1.101 \end{bmatrix}$	Negative definite	100%