Determinants of Investment under Incentive Regulation:
The Case of the Norwegian Electricity Distribution Networks

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Abstract

Investment in electricity networks, as regulated natural monopolies, is among the highest regulatory and energy policy priorities. The electricity sector regulators adopt different incentive mechanisms to ensure that the firms undertake sufficient investment to maintain and modernise the grid. Thus, an effective regulatory treatment of investment requires understanding the response of companies to the regulatory incentives. This study analyses the determinants of investment in electricity distribution networks using a panel dataset of 129 Norwegian companies observed from 2004 to 2010. A Bayesian Model Averaging approach is used to provide a robust statistical inference by taking into account the uncertainties around model selection and estimation. The results show that three factors drive nearly all network investments: investment in previous period, social-economic costs of energy not supplied and finally useful life of assets. The results indicate that Norwegian companies have, to some degree, responded to the investment incentives provided by the regulatory framework. However, some of the incentives do not appear to be effective in driving the investments.

Keywords: Electricity networks, investment incentive, regulation, Bayesian model averaging

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1. Introduction

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 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 study 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 investments and associated incentives under regulation and briefly reviews the Norwegian regulatory framework. Section 3 presents our methodology which is based on the Bayesian Model Averaging technique. Section 4 discusses the data used. The results and discussion of major findings are presented in Section 5. Section 6 is conclusions.

2. 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 the 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 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[2] 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 Investment under Norwegian regulatory regime

Under the Norwegian regulatory regime, the incentives for investments are provided through a combination of 'direct' and 'economic' regulation. The direct regulations, which are reflected in Norwegian Energy Act, oblige utilities to connect new consumers and generation sources and provide high level of power quality. In order to meet these requirements, companies need to carry out sufficient investments. On the other hand, network companies will receive a reasonable return (minimum guaranteed 2%) on their investments given effective management and utilisation of the network. Any company that falls short of the minimum return will receive compensation at the end of regulatory period.

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 peers to obtain the efficient cost level. The revenue is set based upon a weighted average of actual and benchmarked costs as in (1).

$$RC_t = C_t + \lambda(C_t^* - C_t) \qquad (1)$$

where RC_t is revenue cap, C_t denotes actual costs of firm including capital, operating, and maintenance costs as well as the cost of network energy losses and energy not supplied (CENS). C_t^* is the norm cost obtained by using frontier-based benchmarking method[3], and λ is the power of incentive in terms of the weight given to cost benchmarking vs. actual costs in

[2] Energy not supplied refers to the electricity which otherwise would have been served but is interrupted because of a power cut.
[3] Data Envelopment Analysis (DEA).

setting the allowed revenue of firm. The allowed revenue is then adjusted for tax and other non-controllable expenses. The shares of actual costs and norm costs, in determining the revenue, are currently 40 and 60% respectively (i.e. $\lambda = 0.6$). The regulator places more weight on the norm cost to encourage firms to move as close as possible towards the efficient frontier.

As seen from (1), 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 regulatory regime in (1), investments are restrained indirectly such that overcapitalisation can lead to deviation from efficient frontier and consequently partial disallowance of investment costs (Poudineh and Jamasb, 2014b).

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) (see De Luca and Magnus, 2011; Magnus et al., 2010).

$$y = \beta_0 + X\beta + u \qquad (2)$$

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 ith 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:

$$y = \beta_0 + X_i\beta_i + \varepsilon_i \quad i = 1, \dots, I \qquad (3)$$

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 (4).

$$P(M_i|y, X) = \frac{P(M_i)P(y|M_i, X)}{\sum_{j=1}^{I} P(M_j)P(y|M_j, X)} \qquad (4)$$

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 (PMPs) and thus the model weighted posterior distribution for any parameter such as β can be presented as in (5).

$$P(\beta|y,X) = \sum_{i=1}^{I} P(\beta|M_i, y, X)\, P(M_i|y, X) \qquad (5)$$

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 (6).

$$\beta_i|g \sim N(0, \sigma^2 \left(\frac{1}{g} X_i' X_i\right)^{-1}) \qquad (6)$$

The hyperparameter 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:

$$E(\beta|y,X) = \sum_{i=1}^{I} E(\beta|M_i, y) P(M_i|y, X) \qquad (7)$$

The posterior distribution of the 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:

$$Cov(\beta_i|y, X, g, M_i) = \frac{(y-\bar{y})'(y-\bar{y})}{N-3} (\frac{g}{g+1})(1 - \frac{g}{1+g} R_i^2)(X_i' X_i)^{-1} \qquad (8)$$

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 (9).

$$P(y|M_i, X, g) \propto \int_0^\infty (1+g)^{\frac{N-1-k_i}{2}} [1 + g(1 - R_i^2)]^{-\frac{N-1}{2}} P(g|M_i) dg \qquad (9)$$

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 product of inclusion and exclusion probabilities as shown in (10).

$$P(M_i) = \alpha^{k_i}(1-\alpha)^{k-k_i} \qquad (10)$$

The expected value of prior model size distribution in (10) 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 (10). 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 (Zeugner, 2011).[4]

[4] In our analysis for both the case 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 the mean of regressors’ number and consequently different from the case of uniform prior.

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 1 presents the summary of descriptive statistics of these variables.

The first group comprises of "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 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).

[5] The leisure homes are separated from conventional residential and commercial consumers as they have a different load profile which peaks during the weekends and is nearly zero in other days.
[6] Network station or substation is the point where high voltage transmission grid connects to the distribution network.

Table 1: 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 home (#)	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.

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 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, 2013).

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 cyclical behaviour of investment. The large

[7] Consumer willingness to pay is computed using costumer surveys and technical information.
[8] Useful life is computed using straight line depreciation formula.

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).

5. 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 presents the results of investment models estimated based on different priors (described in Section 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 (Po. Mean) for all models even those where the variable is not included (i.e., its coefficient is zero) and finally posterior standard deviation (Po. 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, 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: Investment model estimation based on different priors

Variable	Mprior=uniform			Mprior=fixed			Mprior=random		
	PIP	Po. Mean	Po. SD	PIP	Po. Mean	Po. SD	PIP	Po. Mean	Po. SD
$Constant$	1.00	0.0107	NA	1.00	0.0108	NA	1.00	0.0130	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 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 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 show that other quality factors such as cost of network energy loss ($CNEL$) and the lag of $CENS$ and $CNEL$ variables show no significance.

The posterior model size distribution and cumulative model probabilities, under uniform prior, are illustrated in Figure 1. 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 1. A fully shaded area implies a PIP of 100% for the variable.

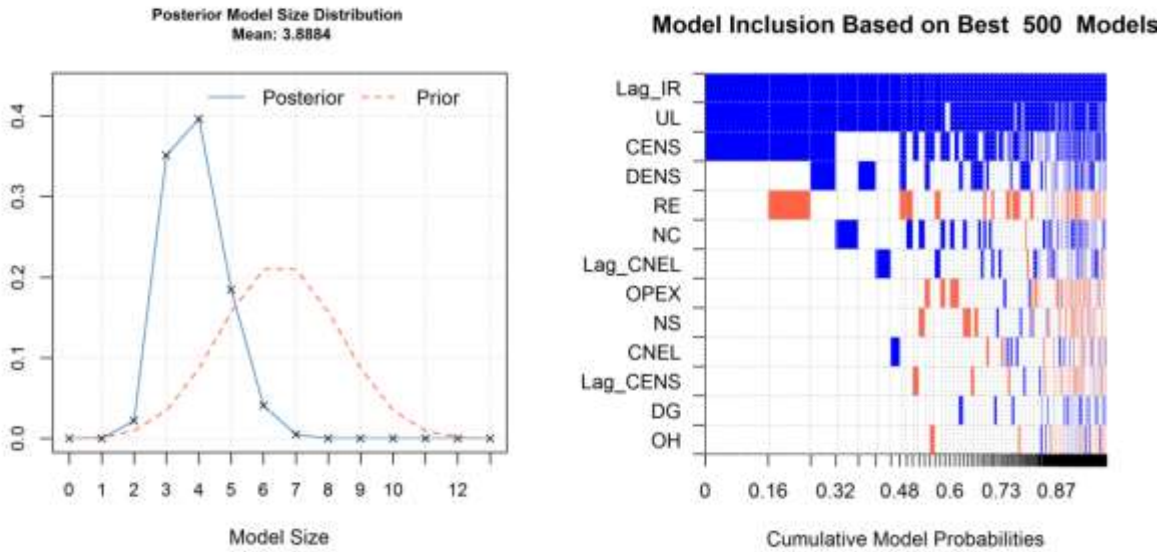

Figure 1: Model size distributions and cumulative model probabilities for a uniform prior

A similar result can be seen in Figure 2 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 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 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

[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.

$CNEL$ 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.

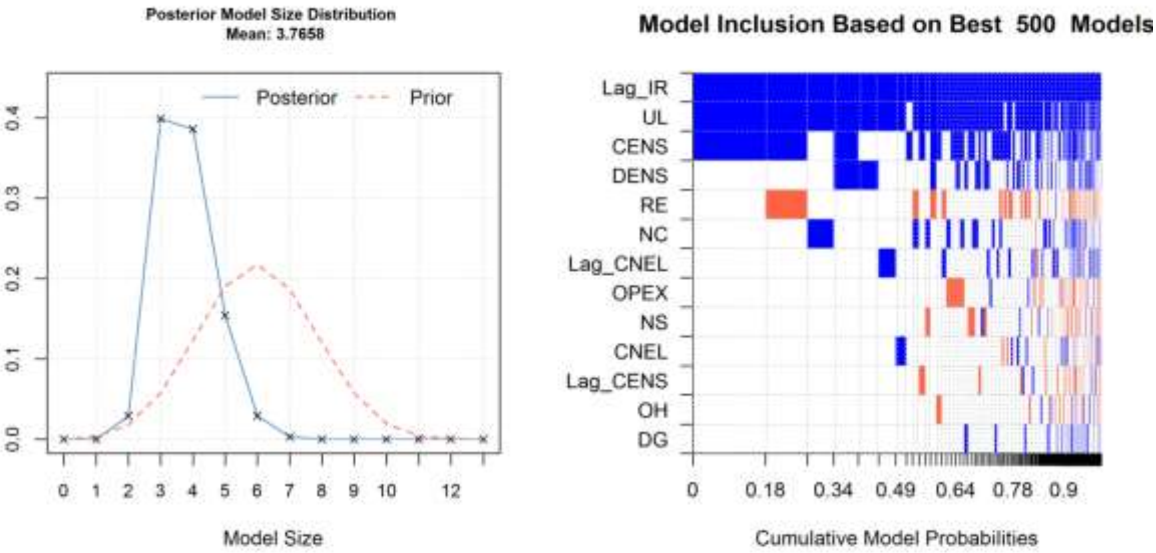

Figure 2: Model size distributions and cumulative model probabilities for a fixed prior

It is likely that the most robust results stem from the random prior estimation. As seen previously from Table 2, under the random prior, the results follow the same pattern as the other two priors. Figure 3 illustrates the posterior distribution of model size and cumulative model probabilities for the random prior. As shown, 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.

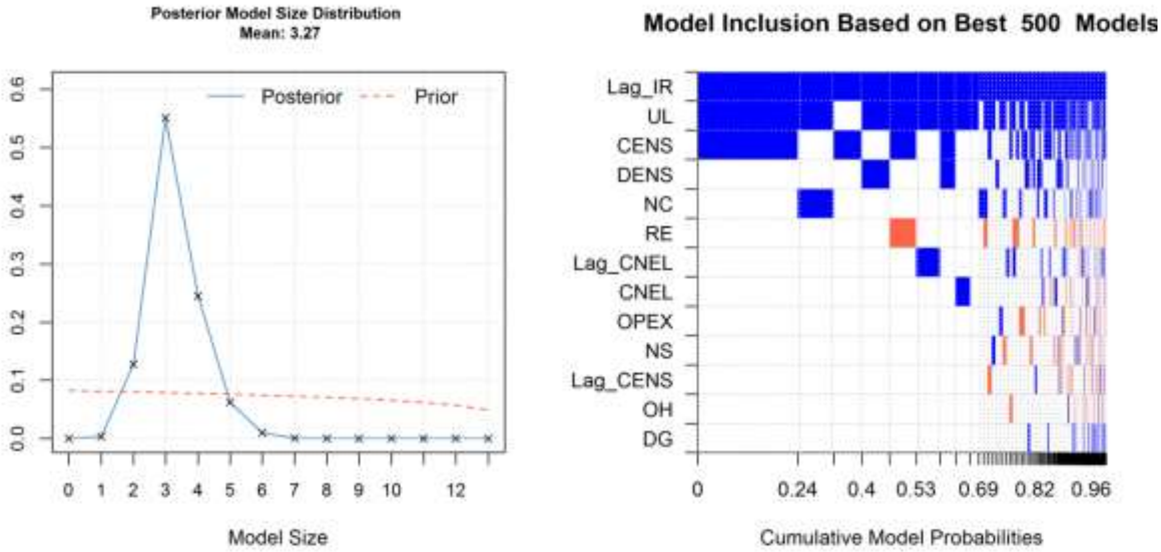

Figure 3: Model size distributions and cumulative model probabilities for a random prior

Table 3 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.

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 1. 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. The fact that the 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 attributed to adjustment costs which deter firms from rapid changes.

Table 3: 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
$(IR)_{it-1}$	*	*	*	*	*	*	*	*	*
$Log(DENS)_{it}$			*						
$Log(OH)_{it}$									
$Log(NS)_{it}$									
$Log(NC)_{it}$						*		*	
$Log(RE)_{it}$		*			*				
$Log(DG)_{it}$									
$Log(CENS)_{it}$	*	*	*	*	*		*		*
$Log(CENS)_{it-1}$									
$Log(CNEL)_{it}$									
$Log(CNEL)_{it-1}$									
$(UL)_{it}$	*	*	*	*	*	*	*	*	
$Log(OPEX)_{it}$									
PMP	0.155	0.105	0.060	0.176	0.102	0.063	0.244	0.087	0.068

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). However, the positive coefficient for useful life of asset (UL) may seem counterintuitive. This is because it 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.

Figure 4 shows the useful life of asset versus network length which is a standard proxy for the firm size. As shown, larger firms usually have an average useful life of around 15 years. The smaller firms, however, vary between very low to high useful life span. The graph confirms that the firms with higher than average useful life are mainly smaller size companies (i.e., have a network length less than 1500 Km).

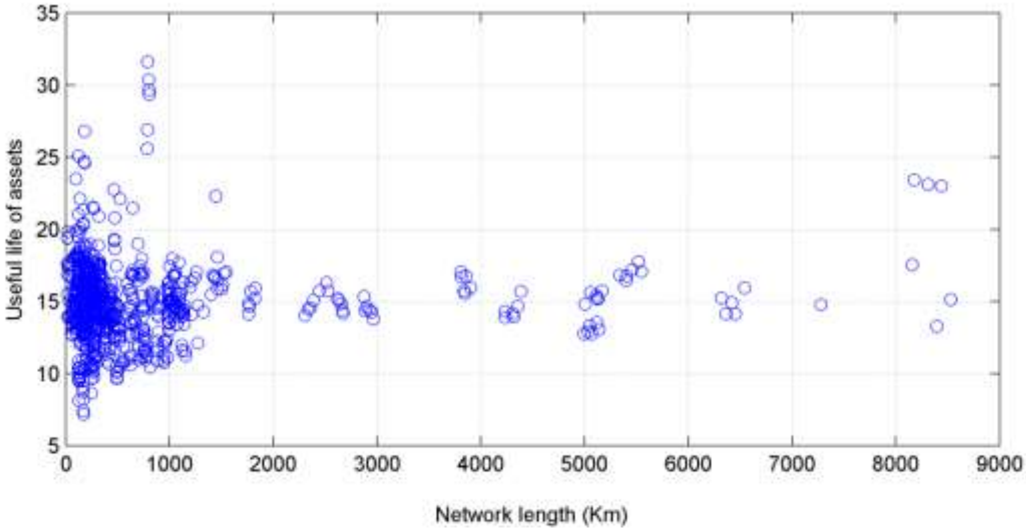

Figure 4: Useful life of asset versus network length (Km)

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 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 Figure 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 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).

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.

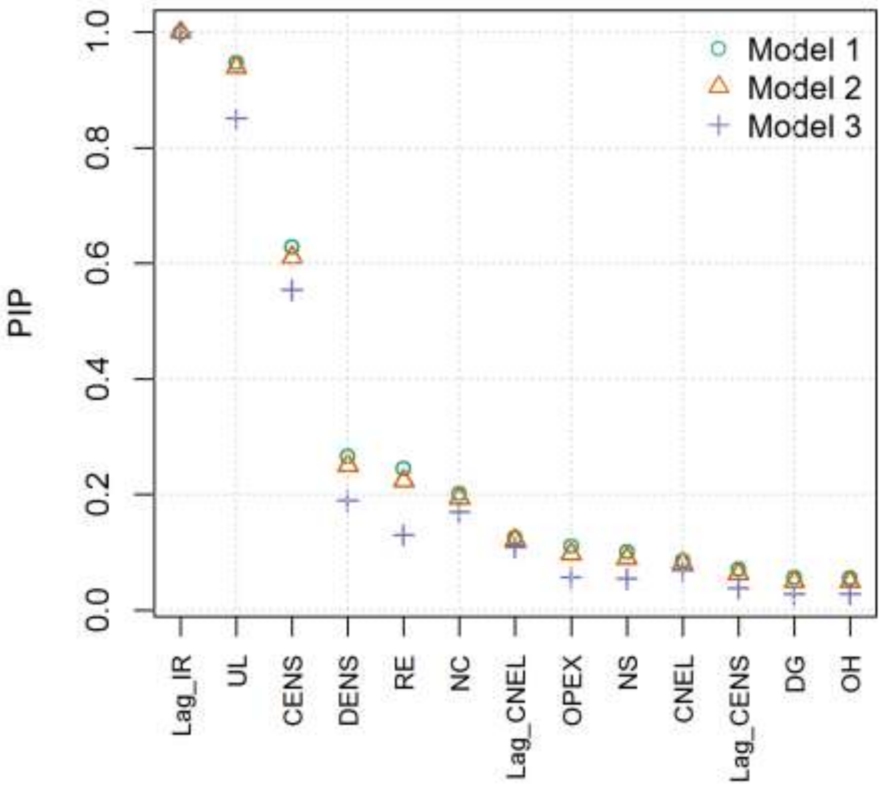

Figure 5: Comparison across models for the most important factors

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.

6. 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 paper 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 shows 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.

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