UNIVERSITY OF CAMBRIDGE
Electricity Policy Research Group

Quality of Supply in Energy Regulation Measurement, Assessment and Experience from Norway

EPRG Working Paper EPRG 0920

Cambridge Working Paper in Economics CWPE 0931

Christian Growitsch, Tooraj Jamasb, Christine Mueller, Matthias Wissner

Reform and liberalisation of electricity sectors around the world has motivated the search for regulation models that provide natural monopoly networks with incentives to improve their efficiency. However, experience with incentive regulation regimes has shown that utilities may pursue cost efficiency at the expense of quality of service. As a result, lower spending on quality can lead to more frequent as well as longer service interruptions.

The cumulative economic and social costs of network interruptions are significant. In order to prevent excessive maintenance reductions and insufficient network investments by electricity distribution companies, regulators throughout Europe have started regulating and incentivizing quality of service in the distribution networks.

In Norway, the regulator has internalized the cost of network service interruptions by incorporating customer willingness-to-pay (WTP) for better quality of service in the utilities' allowed revenues. In this paper, we discuss the issue of assessing and implementing quality-related incentives based on customers' WTP for network reliability and analyse the impact of such regulatory measures by means of a case-study of Norway.

In this paper we first survey the most widely used approaches to quantify customers' WTP for quality. We find that survey techniques such as contingent valuation and conjoint analysis are well suited for regulatory purposes. As Norway has put the measurement and assessment of quality of

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supply into practice, we then empirically examine how the network operators have adapted to quality-incorporated incentive regulation.

We use the Data Envelopment Analysis (DEA) technique, which is often used in regulatory benchmarking, to calculate efficiency scores for the utilities using both their total costs and social costs. We also use a boostraping technique in order to estimate confidence intervals for these. Overall, the findings of the paper indicate that incorporating the external cost of service quality has not played a major role in the perforrnace of the Norwegian electricity distribution utilities.

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Abstract

In order to overcome the incentive of excessive maintenance reductions and insufficient network investments in incentive regulation of electricity distribution companies, regulators throughout Europe have started regulating quality of service in the energy sector. In this paper, we discuss the issue of assessing and implementing quality-related incentives based on customers' WTP for network reliability and analyse the impact of such regulatory measures by means of a concrete case-study. Surveying the most prominent methodological approaches to quantify customers' WTP for quality we find that survey techniques such as contingent valuation and conjoint analysis cover regulatory purposes well. As Norway has put the measurement and assessment of quality of supply into practice, we empirically examine how network operators have adapted to quality-incorporated regulation. We find that the external cost for quality has not played a major role in Norwegian electricity distribution.

Keywords electricity, quality of service, willingness-to-pay, data envelopment analysis

JEL Classification L15, L51, L94

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Measurement, Assessment and Experience from Norway

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1. Introduction

The transition from cost-plus to incentive regulation of natural monopoly energy networks entails numerous new challenges for the regulators and network operators. In principle, the objective of incentive regulation is to encourage network operators to improve their cost efficiency towards a given target and to reward them for over-performance and penalize them for under-performance. The underlying parameter is a regulatory formula that caps the allowed prices (price-cap-regulation) or the allowed revenues (revenue-cap-regulation) of a network operator. This stimulus may, however, create perverse incentives as regards the level of quality of supply.

The network operator may focus solely on efficiency targets to the detriment of maintaining an adequate level of quality. In order to tackle this trade-off, some regulatory regimes have introduced incentive-based regulation schemes that also include quality of supply. The objective is to include the costs of (poor) quality in the profit optimisation calculus of the network operator. Thus the network operator will aim to provide quality up to the point where the marginal cost of quality equals the reward offered (Growitsch et al., 2005).

In order to steer the network operator's calculus towards a socially desirable outcome regulators face two major challenges. Firstly, they need to adequately

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define, incorporate and determine the financial incentives for quality. It is difficult, however, for the regulator to quantify the network operator's production costs of increasing quality. Modern regulatory practice therefore aims to include the social welfare surplus for quality (from a customer's point of view) into the network operator's decision-making. More specifically the *external* cost of energy not supplied (CENS), i.e. the cost incurred by network users due to energy not supplied (ENS) subsequent to an interruption is equated with the customer's willingness-to-pay (WTP) for network reliability. Within such an incentive scheme the regulated firm will aim to optimise its trade-off between CENS and total network expenditures (TOTEX). These together form the total social cost (SOTEX) of network provision. The more the network operators invest in network reliability to reduce CENS, the higher TOTEX becomes. At some point, the companies will – at least theoretically – reach an optimal quality level where the sum of CENS and TOTEX is lowest as illustrated in Figure 1. This implies that network operators will only increase quality as long as this leads to a net reduction in SOTEX, or if the marginal costs to provide more quality equal the reduction in CENS incurred by customers (Ajodhia, 2006).

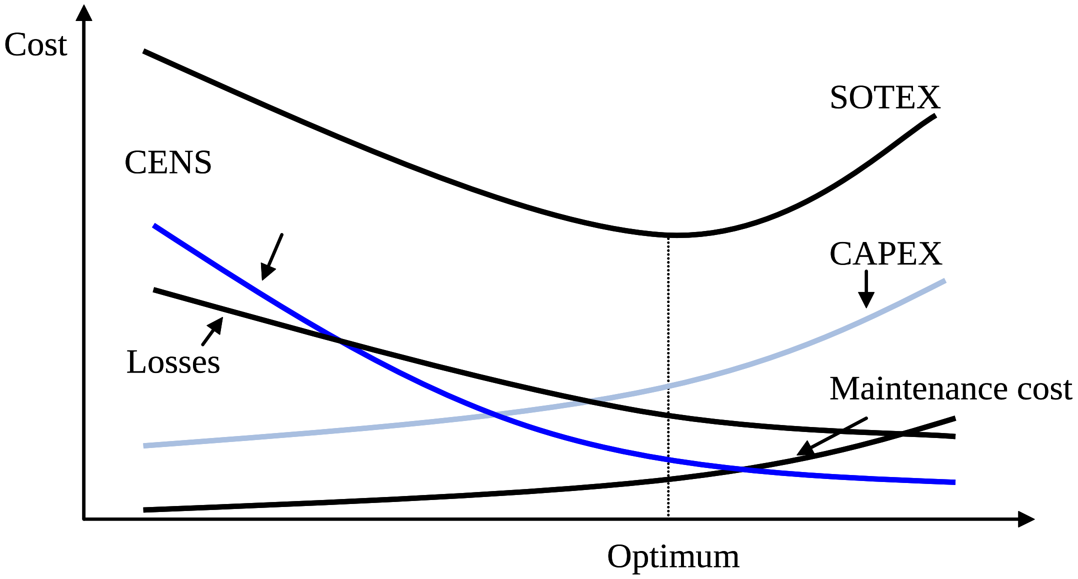

Figure 1: Trade-off between CENS and TOTEX

As a result, an increasing number of regulators aim to set quality incentives that are based on the customer's WTP for network reliability. The second regulatory challenge is to adequately quantify CENS for the regulatory formula by approximating the former with the customer's WTP for quality. There are different methods that can be used to measure WTP and these will be discussed in detail in this paper. In general, indirect approaches are easy to pursue; the more complex direct methods tend to be more challenging and costly. Against this background the objective of this paper is to further scrutinise the issue of assessing and implementing quality incentives based on customers' WTP for network reliability and to analyse the impact of such regulatory measures on the efficiency of network operators by means of a concrete case-study.

Focussing on Norway, a pioneer country in electricity network regulation, we describe the current regulatory regime and carry out an empirical analysis on the impact of CENS-regulation on the quality-related optimisation calculus of the Norwegian network operators. We measure OPEX and SOTEX efficiency respectively by means of the Data Envelopment Analysis (DEA) technique for the first four years following the implementation of CENS-regulation. The Norwegian experience serves as an excellent example since the regulator was one of the first who incorporated customer valuation of service quality into the regulatory scheme. We examine whether the distribution network operators changed their quality-related optimisation strategy in response to efficiency developments and discuss the effectiveness of integrated CENS-regulation for our case study.

The paper is structured as follows: In Section 2 we review and evaluate the main methodological approaches to measure CENS. This involves a short overview of the less common indirect approaches and a more detailed synopsis of direct approaches such as insurance premiums, blackout analysis, conjoint analysis and contingent valuation. Section 3 describes how Norway has put into practice the measurement and assessment of quality of supply. Section 4 concludes.

2. Methodologies for the Assessment of Outage Costs

The determination of outage costs is pivotal to implementing a comprehensive quality regulation scheme. In this section we survey the main approaches used to assess these costs. Broadly, the methodologies can be divided into direct and indirect approaches. Direct approaches rely on outage data obtained from customers while indirect approaches often use highly aggregated data.

▪ Indirect Approaches

One way to measure outage costs is to approximate them by indirect methods. Since the results of this type of approach are not commonly used in quality regulation, we provide only a short overview here.

The first method is based on the **use of proxy values** that are deduced from indirect data sources. The first proxy value is “the ratio of the gross product of an area to the electrical energy consumed in that area” (Telson, 1975). However, this approach is controversial, and it is not clear whether household consumption should be included in this calculation or whether it should be limited to industrial and commercial customers. Only the latter may contribute to value added, i.e. a linear correlation is seen between the electricity consumption of these sectors and economic output. This ratio therefore forms an upper bound for the energy not supplied.

A similar approach for the calculation of the upper bound is to use the **labour costs of industry and businesses in relation to the energy consumed**

(Telson, 1975). For domestic customers, loss of leisure in the evening hours is also suggested as an approach to measure customers' costs (Munasinghe, 1980). As a lower bound the **ratio of electricity bill and electricity demand** can be set for industry and business as well as for household customers (Bental and Ravid, 1982).

Another proxy value is based on **back-up-technology** used in the case of non-supply (Bental and Ravid, 1982). A profit-maximising company using a back-up technology compares the marginal costs of its own generation with the marginal gain from an additional kWh. In a state of equilibrium these costs are equal so that marginal costs of own generation can serve as a proxy for marginal outage costs.

Another concept is that of **consumer surplus**. It is based on the assumption that the demand curve for electricity for different 'times of day' and different seasons contains information on WTP of customers for one unit within the respective period (Sanghvi, 1982). WTP depends on the corresponding time of demand, because demand elasticity behaves differently at different times. In the morning or evening hours it is much more difficult for households to shift loads, because certain essential needs must be met

All indirect approaches, however, suffer from a high level of data aggregation. This makes it difficult to implement the results into a quality regulation scheme. Direct approaches tend to be more commonly used for this purpose and are discussed in the next sub-section.

- ### Direct approaches

The second methodological category of measuring outage costs is through direct approaches. They do not fall back on more or less easily accessible auxiliary quantities as the indirect approaches do, but use data directly from end-users. Data collection can be carried out before (ex-ante) or after (ex-post) supply outages. We discuss the main features of direct approaches in the remainder of this section.

a) Insurance premiums

A direct method to identify outage costs is to offer customers individual insurance for the case of outages (Fumagalli et al., 2001). Grid users choose from a menu of different quality levels and related insurance premiums, i.e. the policy that conforms best to their desired reliability of supply and the relevant price. Revenues from insurance premiums are used to guarantee payment in the case of damages (i.e. in the case of non-supply) or to increase grid reliability. Thus, the preferences of the grid users are made known, i.e. their assessment of different quality levels, whereas the risk of outages is transferred to grid operators. The insurer may be the grid operator itself or an independent third party that possesses no influence on grid reliability. In Germany, for instance, some insurance companies offer blackout insurance policies for commercial customers while some local utilities implicitly insure their standard customers against

blackouts. In the latter case, customer preferences are not revealed directly, however, or only partially, if the indemnity limit is restricted.
If the grid operator is the insurer, it has the advantage of knowing polices in advance and – in the case of a blackout or with regard to its long-term investments – is able to set priorities accordingly. This means that it can take priority measures or investments for customers with a higher demand for reliability of supply. In general, the allocation of activities concerning reliability of supply corresponds to customer preferences. This mechanism leads to increased efficiency, because the grid operator receives correct price signals for its operative and investment activity.

The insurance approach can be an intelligent instrument to reveal customers' required reliability and for its efficient provision. If the customer has an insurance contract with an independent third party, however, this is beyond the control of the regulator who is then hardly or not at all able to access data for regulatory purposes. If the grid operator acts as insurer, more data is accessible but the regulator would have to confine itself to determining an average quality level as a basis for the calculation of insurance premiums.

b) Power System Interruption Analysis

This type of analysis collects information on costs emerging from actual power system interruptions. In doing so, a distinction can be made between direct and indirect costs. Furthermore, the social consequences of interruptions can be taken into account, from which costs can also arise.
A fundamental work in this area was a study for the US Department of Energy on the consequences of the New York Blackout in 1977 (SCI, 1978). As well as categorising costs as direct and indirect, the study uses the following classification based on the different parties involved:

- Businesses
- State
- Concerned Grid Operator
- Insurance Branch
- Public Health Service
- Other Public Service Institutions

Power system interruption analyses generally face some difficulties. Firstly, it is necessary to define clear cost categories in advance of the analysis and it may be difficult to avoid overlapping between categories, i.e. one has to understand complex economic correlations to avoid double counting. Secondly, it is often not possible to complete the different categories with the required data due to lack of availability. Even if the data were available, the fact that power system interruptions are often a regional phenomenon means that applying the results to other regions might be difficult due to different structural parameters. Furthermore, supply interruptions are rather infrequent in countries with high reliability of supply; because of this temporal transfer can be problematic as costs might change in character and level over time.

c) *Contingent Valuation*

Contingent Valuation is applied in many sectors to assess the value of non-market goods (Portney, 1994). In recent years the method has mainly been utilised to measure the value of (public) environmental goods (clean air, clean water etc.) (Hanemann, 1994). It has also been used in assessing quality of supply and regulation of electricity networks, for example in Italy in 2003. A typical questionnaire using contingent valuation comprises several steps, of which the core step involves the use of hypothetical scenarios that must be monetarily valued by respondents. Other elements that should be covered by the questionnaire include: the description of the survey's purpose, general questions on respondents' views on the relevant good, questions on the usage of the good and socio-economic data.

Questioning techniques

Different questioning techniques have been developed for the monetary assessment of goods and services. The first of the techniques presented here is *open-ended elicitation*, where respondents are directly asked for their willingness-to-pay or willingness-to-accept (WTA) for a given increase or decrease in quality. The data analysis can, as a simple solution, contain average determination or estimation of data against explanatory variables such as socio-economic characteristics or attitudes of respondents by means of regression analysis (CIE, 2001).

Another technique is based on a *bidding game*. The interviewer sets an initial value for the good. If the respondent is willing to pay this amount the interviewer increases the amount until he gets a negative answer. The last answer indicates the so-called Hicksian compensation (Boyle et al., 1985). This can be interpreted as the amount that the respondent is willing to pay without changing his utility level (after realisation of the scenario, i.e. after the improvement of quality).

Using a *payment card* the respondents are offered a range of different values from which they can choose the maximum value they are willing to pay. The difference between the different values can either be held constant or increase exponentially.

The most commonly used contingent valuation method is called *referendum* and offers respondents an alternative: either no (additional) payment and perpetuation of the existing quality level; or payment of an (additional) amount and delivery of a higher quality. A typical question is: "Would you be willing to pay X € to receive a quality increase of Y units (Yes or No?)" (CIE, 2001). The parameters price and quality are thereby varied for all respondents. It is therefore assumed that respondents make their decision (payment yes or no) on the basis of individual utility maximisation with regard to their budget constraint. This questioning method is also called single-bounded dichotomous choice.

An important decision when designing a questionnaire using the dichotomous choice technique is to determine the number of given values and their distribution for respondents (Jakobsson and Dragun, 1996). Furthermore the level of the highest and lowest values and the distance between single values must be fixed. The calibration of these parameters can influence the level of the stated WTP.

Contingent Valuation and economic theory

Hanemann has linked dichotomous choice with theoretical welfare considerations, thus grounding the methodology in economic theory (Hanemann, 1984). According to these considerations respondents have individual utility functions containing different parameters. For questioning related to reliability of supply these might be: income y, state with higher reliability level z_1, state without higher reliability level z_0, and a vector containing further characteristics that can influence preferences (e.g. age, gender, previous experiences etc.).

The utility function is then U (y, z, s) with $\Delta U = U(z_1, y, s) - U(z_0, y, s)$. ΔU therefore describes the change in utility when changing the state of the environment. A crucial assumption is that only the respondent knows his/her utility function for certain but that it contains some unobservable parameters that can be regarded as stochastic from the questioner's point of view. The utility function can therefore be written as:

$U = (z, y, s) = V(z, y, s) + \varepsilon$
$U(z_1, y, s) - U(z_0, y, s) = (V(z_1, y, s) + \varepsilon_1) - (V(z_0, y, s) + \varepsilon_0)$

$\varepsilon_0$and ε_1 are independent and identically distributed random variables with zero means. Thus a respondent will accept paying the amount A if:

$(V(z_1, y\text{-}A, s) + \varepsilon_1) \geq (V(z_0, y, s) + \varepsilon_0)$

because only the respondent but not the questioner knows for certain what choice maximises his/her utility, the individual answer of the respondent is, from the questioner's point of view, a random variable with a distribution function:

$P_1 \equiv \Pr$ {respondent willing to pay}
$P_1 = \Pr\{(V(z_1, y\text{-}A, s) + \varepsilon_1) \geq (V(z_0, y, s)\ \varepsilon_0)\}$

Define $\eta \equiv \varepsilon_1 - \varepsilon_0$ and let F_η be the cumulative distribution function of η then the probability of WTP can be defined as:

$P_1 = F_\eta(\Delta V)$ with ΔV as utility difference
$\Delta V \equiv V(z_1, y\text{-}A, s) - V(z_0, y, s)$

It is necessary to assume a distribution function for the random variable η (Jakobsson and Dragun, 1996). This can typically be a standard normal cumulative distribution function (c.d.f.) or a logistic c.d.f. Hanemann (1984) showed that in the latter case the probability of a 'yes' response is:

$$\Pr\{\text{yes}\} = F_{\eta}(\Delta V) = (1+e^{-\Delta V})^{-1}$$

This formula can be used as a basis for calculating the expected WTP.

Closing questions

After the questions on monetary assessment the questionnaire should continue with questions that allow conclusions to be drawn on the potential motives for the answers given (Pearce et al., 2001). These questions can especially shed light on whether respondents have an objection to or an unwillingness to pay for the good in question and therefore give no answer or a willingness to pay of zero respectively.

d) Conjoint Analysis

Conjoint Analysis is rooted in marketing research. It is applied in particular in the planning phase of product launches (Wittink et al., 1994). The method is now also used in other areas such as the health sector or transport and environmental economics (Ryan and Farrar, 2000). The British regulator (Ofgem) used this particular method in a consumer survey in 2004 to obtain WTP for quality of supply in the electricity sector.

In contrast to the method of contingent valuation, respondents do not have to choose a binding and certain option or state concrete values. Instead they have to give relative assessments when comparing different options. Conjoint analysis is based on the assumption that goods and services can be described by their specific characteristics (parameters) that generate a specific utility for the buyer. The total utility is the sum of the single utilities of the different parameters. A rational buyer will thereby choose the product that maximises their total utility. Conjoint analysis attempts to measure the utility attached to a good or service by deducing the single utility values of its parameters. These utility values can then be used to generate a utility function that indicates WTP of buyers (Fumagalli et al., 2007).

As regards the data collection process within conjoint analysis, the structure of the questionnaire principally corresponds to that of contingent valuation and only differs in how the scenarios are structured and presented. We focus, therefore, only on the latter in the discussion to follow.

On the one hand the questionnaire design can adopt a so-called "Full-Profile-Approach" especially where there are only a few characteristics and parameters. This approach compares all of the different combinations for a chosen set of characteristics. Alternatively, combinations can be ranked directly in an order that reflects the respondent's preferences, assuming again that there is a limited number of parameters and characteristics. This procedural method is known as "Two-Factor-at-a-Time-Approach" and can be traced to an approach proposed by Green and Srinivasan (1978). However, a decision that accounts for several parameters contemporaneously is more consistent with reality than the two-factor-at-a-time-approach. When there are high numbers of parameters and parameter values, choice of data may be reduced systematically to a manageable number by so-called "Fractional Factorial Design". This implies that the interviewer is aware that only the main influences are estimated (Dijkstra and Timmermanns, 1997). In summary the full-profile-approach has become more dominant in the last years.

Following data collection as described above data evaluation takes places. Evaluation normally proceeds in two steps: computation and aggregation of utility values (Backhaus et al., 1994). Computation is carried out on the basis of the respondent's assessments. As a first step, partial values are formed for all parameter values. With these, the total utility value of single combinations of parameter values (stimuli) is deduced. In the simplest case, an additive model is taken as the basis, i.e. with two parameters (A and B):

$y = \beta_A + \beta_B$
with y = total utility value of a stimulus
β = partial value of the relevant parameter value
or in a more general form:

$$y_k = \sum_{j=1}^{J} \sum_{m=1}^{M_j} \beta_{jm} \cdot x_{jm}$$

with:

y_k= estimated total utility value of stimulus k
β_{jm} = partial value of parameter value m of parameter j

$$x_{jm} = \begin{cases} 1 & if\ stimulus\ k\ has\ parameter\ j\ with\ parameter\ value\ m \\ 0 & otherwise \end{cases}$$

Basically, metric or non-metric approaches may be used to find the solution for the assessment of the partial values (for further details see, for example, Backhaus et al., 1997).

As a second step, the interpretation and aggregation of utility values follows. In order to make the values of the different respondents comparable, they must first be standardised. In order to do this, a "zero-point" must be defined which usually means that the parameter value delivering the smallest utility contribution is adjusted to zero. Other utility values are transformed accordingly by subtracting the smallest partial value. Further adjustment of the scaling unit may then be undertaken. The most preferred stimulus is set to one for all respondents. On this basis, standardized partial values can be deduced. Once standardisation is complete, the assessments of respondents can be compared. Finally, single partial values can be aggregated over all respondents by taking the arithmetic average.

- **Section Conclusions**

We conclude this section by summarizing the most pertinent aspects as regards the methods of measuring and assessing customer preferences for quality of supply (cp. Table 2).

	Pros	**Cons**
Indirect Approaches		
Ratio of gross output to energy consumed	Data relatively easy to access	High aggregation, unclear role of households, only upper bound
Ratio of labour costs to energy consumed	Data relatively easy to access	High aggregation, unclear role of households, only upper bound
Ratio of energy bill to energy demand	Data relatively easy to access	High aggregation, only lower bound
Back-Up-Technology	Data relatively easy to access	High aggregation
Consumer Surplus	Data relatively easy to access, time dependent values	High aggregation
Direct Approaches		
Insurance Premiums	Customers' "real" WTP is revealed	Regulator must set average quality level
Power System Interruption Analysis	"Real world" values	Data difficult to access, potentially not transferable from one region to another
Contingent Valuation	Representative sample	Survey necessary, Different potential biases
Conjoint Analysis	Representative sample	Survey necessary Different potential biases

Table 1: Summary table of different measurement approaches

In principle, we find that indirect approaches such as the use of proxy values or the concept of customer surplus are less appropriate for quality regulation as these methods suffer from high data aggregation. As a result the actual WTP is hard to detect and therefore results do not fulfil the requirements of a sophisticated quality incentive mechanism. By contrast, direct methods are more valuable in the context of quality regulation. The insurance premium approach is quite appealing since the network users directly reveal their WTP for a given insurance contract whilst the network operator receives direct price signals concerning its investment and maintenance activities. Although it is an intelligent instrument for revealing the customers' WTP for quality, the information exchange happens beyond the regulator's control and is therefore less applicable for regulatory purposes.

Likewise the method of blackout analysis suffers from a lack of data availability and the fact that results are not necessarily transferable given the different structural parameters that cause and accompany blackouts in different regions. By contrast, the methods of contingent valuation (especially the referendum approach) and conjoint analysis which apply different questionnaire techniques to reveal customer WTP are more commonly used in electricity and gas regulation.

Regulatory regimes that have already used methods to reveal customer preferences for grid reliability are for example the UK, Italy and Norway. The application of such techniques in practice varies, however, across countries. In the UK, OFGEM commissioned a survey to improve quality of service in the electricity sector based on conjoint analysis in 2004. Following the survey, OFGEM criticised the questionnaire technique on the basis that the relationship between network reliability and service quality was too strong in the questions. As a result, customer WTP and WTA were much higher compared to the results of other European surveys. OFGEM decided not to implement the results of the survey in their bonus / penalty scheme and refrained from applying such regulatory techniques (Merz, 2008). Italy, by contrast, has applied the results of a survey conducted by means of contingent valuation to calibrate the Q-factor within the Price-Cap-Scheme for the regulation period from 2004 on (Bertazzi et al., 2005). In summary, these regulatory experiences show that the quality of the outcome of such survey techniques crucially depends on the appropriate design of the questionnaire; ensuring that all parameters are set appropriately and do not bias customers towards an incorrect perception of quality. Moreover the need for expertise (e. g. market research) and associated costs need to be taken into account.

Another country that has conducted surveys to measure customer preferences for network reliability and has used the results for the purpose of quality regulation is Norway. The method chosen was contingent valuation (Samdal et al., 2006). Since Norway seems to be one of the most pertinent and elaborated regulatory regimes in this field, the next section is dedicated to the Norwegian application of quality regulation. In particular, we analyse how Norwegian network operators reacted to quality incentives based on customers' willingness-to-pay.

3. Norwegian example

▪ Overview

This section explores and assesses the development path of quality regulation in Norway, one of the pioneering countries in this field. The objective is to further scrutinise the issue of implementing quality incentives based on customer WTP for network reliability, and to analyse the impact of such regulatory measures on the efficiency of the Norwegian network operators by means of a concrete case study. After a brief description of Norwegian quality regulation, we analyse the adaptation of the network operators in terms of their improvement in social cost efficiency. Comparing this with the development of private cost efficiency provides evidence of the effectiveness of quality regulation in Norway.

a) Quality regulation in Norway – development and status quo

The first features of quality regulation were introduced after regulatory reform in 1991 by the Norwegian regulator (NVE). In 1995, NVE implemented a standardized reporting system for interruptions and outages called Fault and Supply Interruption and Information Tool (FASIT). As a result network operators were obliged to report all interruptions and outages longer than three minutes (Brekke, 2007). In 1997, network operators at 33-420 kV were required to report any incidents, disturbances and system failures. Simultaneously, a revenue cap was introduced but without any incentive for quality management, thus leading to a tendency towards underinvestment. Likewise standardised methods to compute the ENS per customer category were set up and a reporting system was made mandatory. Eventually in 2001, a quality term based on the CENS was incorporated into the regulatory formula to determine the revenue cap for the second regulatory period (2001 to 2006). The former was adjusted in accordance with the customers' interruption cost. In pursuing this approach all planned and unplanned interruptions longer than three minutes in networks over 1kV were considered. Based on estimates of expected ENS and average outage costs per customer group, the underlying model annually computes the expected outage costs per network operator. The latter particularly depends on two determinants: the customer group and the type of interruption (planned or unplanned) as illustrated by Equation (1):

$$IC = \sum_{n,m} ENS_{n,m} \cdot c_{n,m} \tag{1}$$

with:

IC = Cost of energy not supplied/Outage cost (€)

ENS = Energy not supplied (kWh)

c = average specific outage costs

n = customer group

m = planned, unplanned interruption

ENS is defined as the amount of energy that would have been supplied to the customer if there had been no interruption. This amount can be estimated by means of FASIT, which provides a uniform standardised methodology. The average specific outage cost (c) can however be appraised based on customer surveys that have been conducted since 1991 (Langset et al., 2001).

illustrates the respective values per customer group resulting from a survey conducted in 2002.

Customer group	Planned outage costs	Unplanned outage costs
Industry	5,8	8,3
Trade and Services	8,5	12,4
Agriculture	1,9	1,3
Households	0,9	1,0
Public Facilities	1,3	1,6
Wood Processing	1,4	1,6

Table 2: Specific outage costs in the Norwegian CENS system (€/kWh)
Source: Brekke (2007), own translation

Network operators are also set individual quality targets. In other words, the outage costs for all customers that are connected to the distribution networks are capped at a specific sum. To this end the expected value for ENS for each network is estimated by means of regression analysis (Equation 2). This analysis uses parameters such as network structure, number of transformers, geographic and climatic factors. Panel data from previous years provide the historical values for ENS. Consequently, quality targets can be derived from the expected value of outage costs.

$$E(IC) = \sum\nolimits_{n,m} E(ENS)_{n,m} \cdot c_{n,m} \tag{2}$$

with

E (IC) = Expected outage costs [NOK]

E (ENS) = Expected ENS [kWh]

$C_{n,m}$ as above

It is noteworthy that the expected outage costs E (IC) do not reflect an optimal but rather the current average quality level. Hence, the resulting values oscillate below and above the optimal quality level. However, the CENS scheme encourages network operators to move towards an optimal level. At the end of the year the difference between expected and actual outage costs is calculated. In the case of a positive difference, i.e. the reliability is higher than expected, the difference is added to the revenue cap. In the case of a negative difference, the amount is subtracted from the revenue cap. This mechanism is illustrated by Equation (3) and Figure 2.

$$dR = E(IC) - IC \tag{3}$$

with dR = change in Revenue Cap

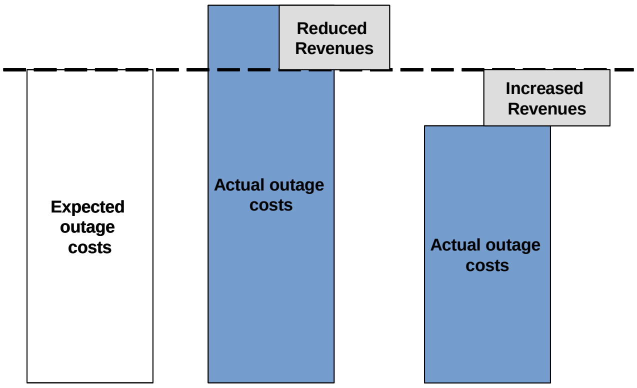

Figure 2: Outage costs and revenues (Brekke, 2007)

The calculations described above are carried out one year after the determination of network charges by the network operator. Therefore a gap usually occurs between the expected (allowed) revenues and the actual revenues as already illustrated in Figure 2. If the difference is to the benefit of the network operator, the firm is obliged to pay back the windfall profit through lower network charges to its customers in the following years. Conversely the firm is allowed to be compensated for a potential loss through higher network charges. Thus an increase in reliability (i.e. a decrease in outage costs IC) leads to higher revenues whilst a decrease in quality leads to lower revenues. Given this mechanism Equation (4) applies:

$$R' = IC' \tag{4}$$

with

R’ = marginal revenue

IC’ = marginal outage costs for a specific customer group

Moreover the economic costs for network operation can be considered as the result of company specific capital expenditures (CAPEX) and operational expenditures (OPEX) as well as the outage cost of the customers as shown under Equation 5.

$$C = OPEX + CAPEX + IC \tag{5}$$

The economic optimum for marginal outage costs results from a minimisation of Equation (6), given that
$OPEX' + CAPEX' = IC'$ (6)

Consequently the profit of a network operator can be expressed as:
$\Pi = R - OPEX - CAPEX$ (7)

Therefore a profit maximising network operator would act on the assumption
$OPEX' + CAPEX' = R'$ (8)

Taking these assumptions into account as per Equations (4), (6) and (8) we deduce that a profit-maximising network operator under the Norwegian regulatory regime would also maximise social welfare by minimising overall economic costs.

Brekke (2007) concludes that the implementation of the quality regulation system has sensitised the network operators to outage costs incurred by their customers. This motivated a change in the operation and management of their assets. Moreover the regulatory regime allows for a clear definition of responsibilities in the network and therefore higher operational performance. Brekke detected, however, some shortcomings in the system such as the unsatisfactory recovery time following an interruption for those clients for whom the CENS-regulation does not set strong enough incentives. Moreover, short interruptions are not taken into account which may lead to higher costs to those customers concerned.

The shortcomings detected by Brekke (2007) have partly been addressed by amendments to the regulatory regime with the start of the new regulatory period in 2007. For example outage costs have been integrated into the calculation of the revenue cap (Figure 3). Thus, the costs incurred for the provision of a certain quality level are considered as part of OPEX and feed into the DEA-based benchmarking (Sand, 2007); and the revenue caps are adjusted on an annual basis.

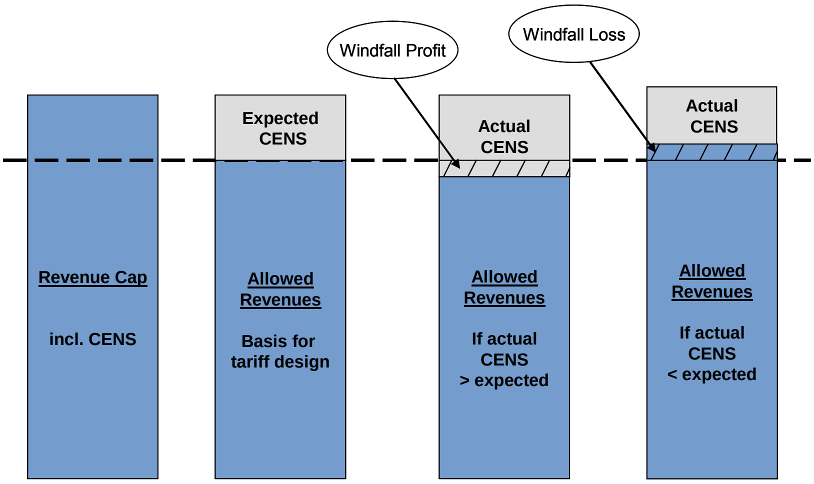

Figure 3: Revenue Cap and outage costs since 2007 (Brekke, 2007)

In parallel, another component of quality regulation has been introduced, namely direct compensation payments. As a result, network operators are obliged to pay direct compensation to those customers affected by interruptions longer than 12 hours (Brekke, 2007).

These payment obligations follow the schedule below:

- For 12 to 24 hours: 600 NOK (app. 70 €)
- For more than 24 till 48 hours: 1.400 NOK (app. 160 €)
- For more than 48 till 72 hours: 2.700 NOK (app. 310 €)

Additionally, 1.300 NOK (app. 150 €) applies to each subsequent 24-hour period. However, the payments should not exceed the annual tariff payments. Moreover, short interruptions lasting from one to three minutes are planned to be integrated into the CENS-system as from 2009.

The previous sub-section provided an overview of the evolution of quality of supply regulation in Norway. In summary we conclude that Norway has a mature system for determining the external costs of quality and for incorporating them into the regulatory formula.

It is also worthwhile to look behind the scenes of the Norwegian system in order to gain empirical evidence of the actual impact of quality regulation on the efficiency situation of Norwegian network operators. This review is carried out in the following section.

▪ Method and data

In order to examine the performance of the Norwegian approach to service quality regulation, we use a panel dataset for 131 Norwegian distribution utilities from the period 2001 to 2004 and productivity analysis models[5]. The method used is based on the Data Envelopment Analysis (DEA) technique (Coelli et al., 2005; Greene, 2007).

DEA is used to measure the relative efficiency of a company relative to the best performing companies (peers) by means of a non-parametric, linear frontier over the sample. This piece-wise approach aims at fitting a linear “hull” around the data assuming that this hull adequately forms the frontier of the most productive firms by means of a deterministic approach with multiple inputs and outputs. The resulting efficiency score reflects the amount by which a given company could improve its productivity relative to its peers. The most efficient company is assigned an efficiency score of one given that it scores best by minimising its inputs for a given level of output. In the following example, we assume constant returns to scale (CRS) since the networks operators may, in general, be able to optimize their size and scale. A CRS input-oriented frontier is

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[5] For the following discussion, it should be noted that the time horizon of the analyzed date ends at 2004. Hence the companies within our sample could not react to the latest features of quality regulation that were introduced in the second regulatory period.

calculated by solving the linear optimization program in Equation (4) for each of N companies. Moreover, it is assumed that the companies use K inputs and M outputs (Shephard, 1970):

$$\begin{aligned} \max \quad & \theta, \\ \text{s.t.} \quad & -y_i + Y\lambda \geq 0, \\ & x_i / \theta - X\lambda \geq 0, \\ & \lambda \geq 0, \end{aligned} \tag{4}$$

where X is the K N matrix of inputs and Y is the M N matrix of outputs. The i-th company's input and output vectors are represented by x_i and y_i respectively. λ is a N 1 vector of constants and θ is the input distance measure.

DEA in its original form, however, is unable to provide unbiased efficiency estimates and confidence limits for the efficiency scores. The theoretical bias is evident since the observed input-output combination is just a fraction of any possible one: $(x, y) \subseteq (X, Y)$. This implies that the estimated production set $\hat{\psi}$ is a just a subset of Ψ, $\hat{\psi} \subseteq \psi$. Efficiency is estimated and compared within a restricted sample and the estimator is upward biased as a result. We apply a bootstrap procedure suggested by Simar and Wilson (1998) to overcome this problem. It provides an estimate for DEA's upward efficiency bias and confidence intervals by drawing random samples from the efficiency scores' truncated probability density functions.

This DEA bootstrap algorithm is applied to a data set of 131 electricity distribution companies published by the Norwegian regulator NVE. As highlighted above, DEA determines the efficiency score of a firm compared to its peers and therefore indicates the catch-up potential within a given sample. For the purpose of this paper the cost of service quality is incorporated into the benchmarking. Therefore it is crucial to provide for the ambivalent relationship between productive efficiency and quality. In general one may assume that higher quality levels lead to higher costs. In a cost-based DEA, companies operating at higher quality levels would therefore likely score worse than their efficiency-oriented counterparts albeit running their business to the benefit of quality. This potential trade-off can be reduced by incorporating SOTEX into the DEA and thus accounting for the provision of quality (Ajodhia, 2006).

The model specification incorporates total expenditures TOTEX and SOTEX respectively. These are considered separately as a single input in monetary terms. Hence, we use two models, one with TOTEX and the other one with SOTEX as input variable. In Model 1 TOTEX describes the sum of OPEX and CAPEX, both influencing the productivity of the network operator without explicitly considering quality aspects. By contrast, Model 2 incorporates SOTEX as the input variable in order to reflect the impact of quality incentives. SOTEX is the sum of TOTEX (corporate production costs) and the external costs of low quality, i.e. the CENS incurred by customers. Thus, the resulting efficiency scores of

SOTEX reflect the ability of the network operator to balance the trade-off between efficient costs and quality (Ajodhia, 2006).

We use a simple model with one input and two outputs. The outputs consist of energy supplied and the number of customers. Although the two cost drivers form one joint service in electricity distribution they are considered separately since they drive different cost categories, namely fixed and variable costs (Growitsch et al., 2005). The model assumes input-orientation, i.e. the efficiency score depends on the ability of the network operator to minimise its inputs given a fixed vector of outputs. Table 2 shows the descriptive statistics of our sample aggregated for the considered period and individually for the respective years. Table 4 exhibits the mean for the years 2001 to 2004.[6]

Variable	Mean	Std. Deviation	Minimum	Maximum	Cases
SOTEX (k€)	76,406	166,517	2,074	1,598,890	524
TOTEX (k€)	74,067	161,395	2,074	1,561,140	524
Final Customers (n°)	19,784	52,854	429	516,339	524
Energy Supplied (MWh)	523,231	1,481,630	7,470	15,482,400	524

Table 3: Descriptive statistics of the sample (aggregated)

Variable	Mean 2001	Mean 2002	Mean 2003	Mean 2004
SOTEX (k€)	77,830	79,224	76,646	75,857
TOTEX (k€)	75,783	77,372	73,396	73,510
Quality cost	2,047	1,852	3,249	2,348
Final Customers (n°)	19,912	19,956	20,083	20,216
Energy Supplied (MWh)	559,071	540,384	501,420	520,255

Table 4: Mean for the period 2001 to 2004

With regard to SOTEX we find that costs slightly increase in 2002 followed by a decline in the following years. A similar development can be observed for TOTEX. Accordingly the cost of quality decreases in 2002 followed by a significant increase in 2003. Simultaneously the standard deviation and the maximum more than double compared to 2002. This development suggests that a significant event took place in 2003 featuring increased prices. Looking at the output variables, the final customers slightly increase after an initial stagnation, whilst the energy supply declines over the period. Overall we show in Table 4

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[6] For an overview of the descriptive statistics per year, see Appendix.

that there is only a marginal gap between TOTEX and SOTEX. Moreover homogenous trends can be reported for SOTEX and TOTEX.

Based on this first impression, we hypothesize that the external costs of quality have a small effect on the cost and, as a result, the incentives of the Norwegian network operators. In the following section we test this hypothesis by analysing the results of the DEA regarding the efficiency of the sample of Norwegian network operators.

- **Estimation and results**

Table 4 and Table 6 show the bootstrap results of the DEA for Model 1 (input: TOTEX) and Model 2 (input: SOTEX) respectively. In order to test whether the annual average efficiency scores for TOTEX and SOTEX differ significantly from each other, we use the non-parametric Wilcoxon ranksum test.[7] We find that TOTEX efficiency decreases significantly after the first year and remains statistically constant from 2002 to 2004.

In another series of Wilcoxon mean comparison tests we also find that average SOTEX efficiency is significantly lower than TOTEX efficiency. Comparing average efficiencies from 2001 and 2004 indicates marginally but statistically significantly lower social cost efficiency four years after the introduction of the CENS regulation.

Variable/Year	Mean	Mean* (unbiased)	Std. Deviation	Minimum	Maximum
2001	62.76%	60.97%	14.71%	28.44%	100%
2002	58.15%	55.81%	15.50%	25.81%	100%
2003	56.45%	53.58%	14.36%	26.44%	100%
2004	57.31%	54.22%	14.25%	24.94%	100%

Table 5: Technical efficiency for Model 1 (TOTEX)

* **Efficiency score bias corrected via bootstrap (100 replications).**

Variable/Year	Mean	Mean* (unbiased)	Std. Deviation	Minimum	Maximum
2001	62.12%	60.33%	14.68%	28.56%	100%
2002	58.91%	56.64%	15.60%	26.47%	100%
2003	56.51%	53.82%	14.97%	26.80%	100%
2004	57.81%	55.16%	14.65%	25.48%	100%

Table 6: Technical efficiency for Model 2 (SOTEX)

***Efficiency score bias corrected via bootstrap (100 replications).**

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[7] The Wilcoxon ranksum test, also Mann-Whitney-U-Test, is a non-parametric test that analyses whether two independent groups belong to the same population (see Cooper et al., 2006)

Overall we find that TOTEX and SOTEX almost develop in similar manners, corroborating the initial hypothesis we made. Moreover, the Wilcoxon ranksum test showed that there is no significant difference in the efficiency score between the years 2002 and 2004, neither for TOTEX nor SOTEX. The reduction in SOTEX efficiency in 2004 relative to 2001 coincides with the development of SOTEX as illustrated in the descriptive statistics.

A closer examination of efficiency scores on a per company basis, however, shows that the efficiency scores for individual firms can change significantly from year to year. At the same time, the TOTEX and SOTEX scores, for a given year, are rather similar. Figures 3 and 4 show the utilities' efficiency scores (Y-Axis) for 2001 in increasing order relative to those of 2002-2004 (Company ID, X-Axis). Moreover, the figures show that the scores of more efficient utilities (i.e. right hand side of the figures) in 2001 also tend to be higher than in subsequent years.

Analysis of the technical efficiency development shows that the introduction of quality regulation did not significantly change the efficiency scores of the companies. Moreover, it appears that the external costs for quality are quite low which is proven by the fact that the difference between TOTEX and SOTEX is nearly zero. These findings are substantiated by the fact that the costs of energy not supplied in Norway only amounted to 0.37 € per kWh in 2004 (Ajodhia, 2006).

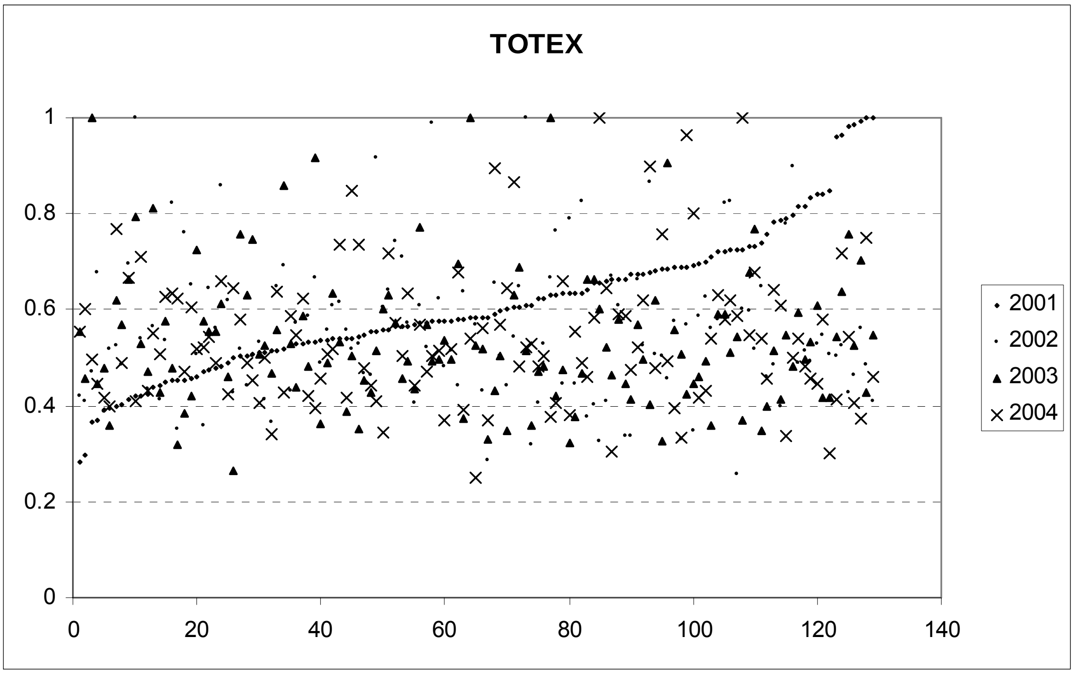

Figure 1: TOTEX efficiency scores by company and year

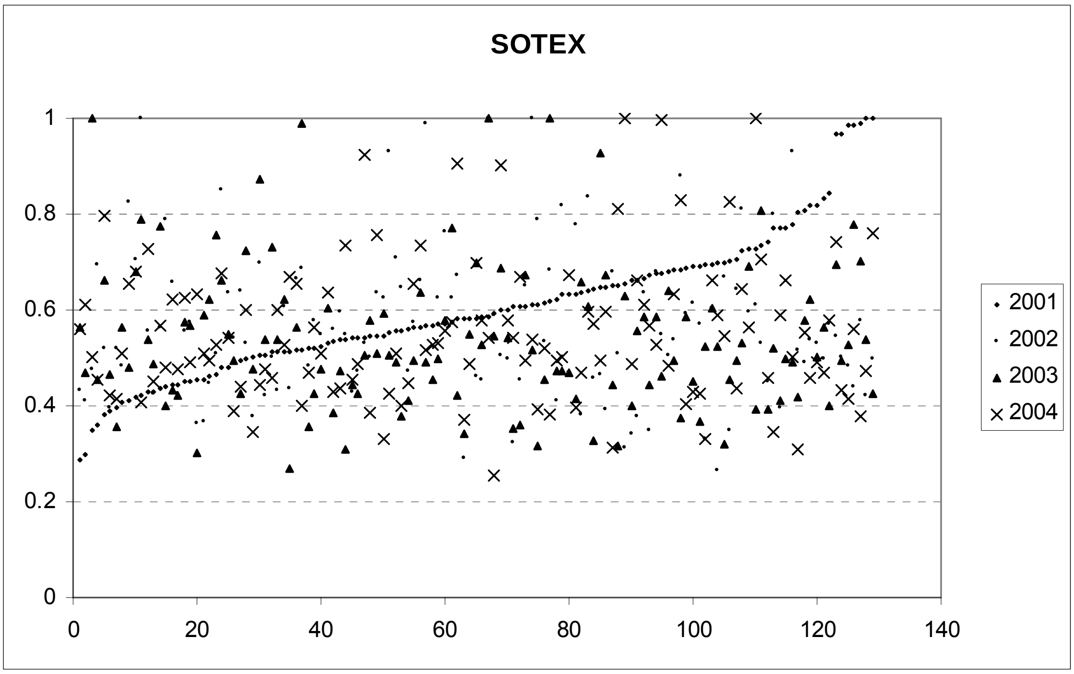

Figure 4: SOTEX efficiency scores by company and year

The results suggest that the introduction of quality regulation in Norway does not have a negative impact nor does it conflict with cost efficiency of the networks – i.e. the external quality costs play a relatively minor role. Moreover the level of quality appears to be reasonably high from a customer perspective, which explains the limited impact of the external cost of quality on the efficiency scores. However, benchmarking results in general and the empirical findings for the Norwegian example in particular have to be treated prudently since they only provide a first quantitative approximation of the implications of quality of supply regulation.

Our results contrast those of Burger and Geymüller (2007a), who find that quality regulation induced Norwegian network operators to optimise their quality strategy from a social point of view based on a DEA analysis and Malmquist indices for the period 1999-2005. As their sample covers a rather limited number of observations and not – as ours – a nearly full census of Norwegian electric utilities, differences might be explained by sample selection. Our findings are, however, more in line with Edvardsen et al. (2005) who found, for a similar sample, a flattening productivity increase since the year 2000 and another paper by Burger and Geymueller (2007b) which finds that ENS was reduced more significantly prior to the introduction of quality regulation than afterwards.

4. Conclusions

The objective of this paper was to scrutinise the issue of assessing and implementing quality-related incentives based on customers' WTP for network reliability and to analyse the impact of such regulatory measures by means of a concrete case-study. Our first step was to survey and evaluate the most prominent methodological approaches to quantify customers’ WTP for quality. Overall we find that direct methods seem to be more accurate than indirect methods. In particular survey techniques such as contingent valuation and conjoint analysis are suitable and have been used for regulatory purposes. However, an appropriate calibration of the different parameters is pivotal to an adequate outcome as regards the assessment of customer preferences and hence ample incentives for grid reliability.

In the second part of this paper we described how one country, Norway, has put the measurement and assessment of quality of supply into practice. The Norwegian experience is an excellent example as it was one of the first to incorporate customers’ quality of supply valuation into the regulatory scheme. We empirically examined how the network operators adapted to the new quality-incorporated regulation. In order to do this, we analysed whether the distribution network operators changed their quality-related optimisation strategies reflected by their efficiency developments. The results show that the external cost for quality has not played a major role in the current regulatory regime in Norway. This may be due to the comparatively high quality level prior to the implementation of quality regulation. Our results should, however, be treated with caution since our data panel only consisted of the period from 2001 to 2004. Moreover, we focused only on TOTEX and SOTEX efficiencies and did not further elaborate on productivity developments and welfare implications due to limited data availability. This caveat indicates that data availability (especially for a longer time horizon) and robustness are limiting factors for this kind of analysis. Moreover, there is a time lag between the introduction of quality regulation and its impact on the investment decisions of network operators. Thus, the full impact of quality and asset management related strategies of network operators might not yet be reflected in the efficiency scores within the time horizon considered in the Norwegian sample. Future research should in particular address the issue of delayed reactions of utilities and grid reliability and should also incorporate a parallel analysis of productivity developments.

Appendix

Variable	Std. Deviation	Minimum	Maximum	Cases
SOTEX (k€)	174,288	5,045	1,561,070	129
TOTEX (k€)	170,237	4,949	1,525,533	129
Quality cost	4,384	22	35,537	129
Final Customers (n°)	53,461	936	516,339	129
Energy Supplied (MWh)	1,571,051	18,720	15,500,000	129

Table A-1: Descriptive statistics year 2001

Variable	Std. Deviation	Minimum	Maximum	Cases
SOTEX (k€)	177,614	5,153	1,598,891	129
TOTEX (k€)	173,678	5,054	1,561,144	129
Quality cost	4,198	27	37,747	129
Final Customers (n°)	53,073	925	508,393	129
Energy Supplied (MWh)	1,525,085	17,557	15,000,000	129

Table A-2: Descriptive statistics year 2002

Variable	Std. Deviation	Minimum	Maximum	Cases
SOTEX (k€)	161,219	5,574	1,361,567	129
TOTEX (k€)	153,243	5,385	1,273,104	129
Quality cost	8,847	39	88,463	129
Final Customers (n°)	53,298	927	511,374	129
Energy Supplied (MWh)	1,420,952	16,708	14,100,000	129

Table A-3: Descriptive statistics year 2003

Variable	Std. Deviation	Minimum	Maximum	Cases
SOTEX (k€)	158,467	5,807	1,356,415	129
TOTEX (k€)	153,452	5,798	1,307,400	129
Quality cost	5,507	9	49,015	129
Final Customers (n°)	53,671	969	515,152	129
Energy Supplied (MWh)	1,463,252	16,504	14,400,000	129

Table A-4: Descriptive statistics year 2004

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