Customer Costs Related to Interruptions and Voltage Problems: Methodology and Results

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***Abstract*—This paper presents the methodology and main results of the most recent Norwegian customer survey on consumer valuation of interruptions and voltage problems. The survey provided cost estimates that have been incorporated in the quality of supply regulation, in terms of the cost of energy not supplied. The data collected are also useful for different tasks related to value-based planning and operation of the electric power system. A combination of direct worth (DW) and willingness to pay (WTP) was used in the survey. The DW approach yielded significantly larger cost estimates than the WTP. The ratio of DW/WTP cost estimates varies in the order of 2–12 depending on customer group. There has been a real increase in the customers' costs since the 1991 survey for all groups and particularly for the agricultural group.**

***Index Terms*—Customer costs, interruptions, power system economics, quality of supply, voltage disturbances.**

I. Introduction

NETWORK companies are increasingly being subjected to regulatory regimes that explicitly take into consideration the quality of supply. One example is the Norwegian regulation scheme cost of energy not supplied (CENS) where the network companies' revenue caps are adjusted in accordance with the customers' interruption costs [1]. A critical parameter in a credible quality regulation scheme is information about customers' costs associated with alternative levels of quality of supply, including different levels of reliability of supply and power quality problems.

The costs of providing an acceptable quality should be balanced against the value of quality. See, for example, [2] and [3]. The value of quality may be measured in terms of customers' costs of interruptions and voltage disturbances. Customer surveys are typically used to collect such data. Considerable work has been done throughout the world on estimating customers' costs, particularly related to interruptions. CIGRE TF 38.06.01 summarizes this work in a report from 2001 [4], providing a basic reference within this area. The report gives an extensive discussion of the impact of interruptions for customers, methods to evaluate customer costs and applications of the data in planning and operation of the power system. Interruption cost data collected in various countries are also presented.

Two different customer surveys covering interruption costs have previously been conducted in Norway: The first one (with a rather limited extent) in the late 1970s and the second (nationwide) reported in 1991. The CENS arrangement implemented in 2001 was based on cost data collected through the 1991 survey. In addition it provided input to the Nordic survey from 1994 [5]. In year 2000 the Norwegian Water Resources and Energy Directorate decided, in cooperation with the electricity industry, to carry out a new survey on customers' costs covering not only interruptions but also power quality problems. During the past decade (after the deregulation in 1991) new purposes/applications (such as the CENS arrangement) had emerged revealing a need for more data. In addition a hypothesis to be tested was that there had been a real increase in the customers' costs caused by the increased dependence on electricity.

The objective of the new survey (2001–2003) was to generate quantitative indicators which could be used for designing "compensation schemes" in order to enable effective regulation of quality of supply provided by electricity networks. The survey data provided a basis for new cost rates in the CENS arrangement. These cost rates have been updated for the new regulation period from 2007.

The purpose and methodology for this customer survey is introduced in Section II. Section III describes the methodology for transforming the raw (surveyed) data to a useable form for different applications. In Section IV the main results from the survey are presented. A brief outline of possible applications of the transformed data is given in Section V.

II. Customer Survey

The methods to evaluate the impacts experienced by customers due to interruptions can be grouped into three categories: 1) indirect analytical methods, 2) case studies of blackouts, and 3) customer surveys [4]. Examples from the first category may be to derive a value of reliability of supply using the electrical tariff or taking the ratio of the annual gross product to the total electricity consumption. The second approach attempts to assess costs due to both direct and indirect societal impact of a specific interruption. This assessment can be performed after major blackouts. In the study reported here the postal survey approach was chosen. This approach is briefly outlined below, followed by a description of the purpose and scope of the survey and the methodology developed.

Manuscript received September 6, 2007; revised January 15, 2008. This work was supported in part by the Research Council of Norway, in part by Norwegian Water Resources and Energy Directorate, in part by Norwegian Electricity Industry Association, in part by Statnett (The Norwegian Transmission System Operator), in part by The Federation of Norwegian Process Industries, in part by Norsk Hydro, network companies, and in part bySINTEF Energy Research. Paper no. TPWRS-00626-2007.

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Digital Object Identifier 10.1109/TPWRS.2008.922227

A. Survey Approach

In the survey customers are asked to estimate their costs or losses due to supply interruptions of varying durations at different times of the day and year, etc. The survey method as opposed to the other two categories of evaluating costs can provide interruption cost data for planning purposes. The survey can be tailored to seek particular information related to the specific needs of network companies and authorities. A drawback of this method is that the costs and efforts are significantly higher than if using the other two approaches. Still the customer survey method is a widely recognized approach for the purpose of providing customer interruption cost estimates.

The survey approach was chosen both in the study from the 1970s and the one from 1991. The main objective of those two studies was to provide information about consumer valuation of quality of supply (QoS). Even at that time the need for interruption cost data for planning purposes was pointed out. The stepwise introduction of QoS regulations in Norway since the energy act was put into force in 1991, has led to new needs regarding this kinds of information. The objective of the survey in 2001–2003 was therefore to generate quantitative indicators not only for planning purposes but also with the purpose to enable effective regulation of QoS. According to this regulation, QoS covers reliability of supply, voltage quality, information, monitoring, etc. [6]. For the first time in Norway costs related to voltage problems were included in the survey. Until now these kinds of costs were only evaluated using the case studies approach, revealing that in particular voltage dips imposed considerable costs to the industry.

The arguments for choosing the survey approach were among others; the need for comparison with previous (survey-based) national studies, the assumption that the end-user is the best qualified for estimation of his/her losses, and finally the fact that the results were to be incorporated in the CENS-scheme and power network planning as such.

B. Purpose and Scope of Survey

The objective of the survey was to contribute to increased knowledge about socioeconomic costs related to interruptions and voltage disturbances, providing the necessary basis and incentives for authorities, system operators, network companies and customers to contribute to a socioeconomic optimal level of quality of supply. The results from the survey could serve various purposes related to planning, operation and maintenance of the power system, establishment of quality-dependent tariffs, further development of the regulation, load shedding, etc. The data needed to accomplish this were found to be the following:

- costs of long interruptions (>3 min);[1]
- costs of short interruptions (≤3 min);
- costs related to voltage disturbances;
- costs related to partial interruptions/load shedding;
- customers perceived QoS;
- consumer flexibility regarding price versus QoS.

In addition it was necessary to take into consideration that the cost of an interruption is a function of customer characteristics. These are: type of customer and energy requirements as well as interruption characteristics such as duration, frequency, time of occurrence, advance warning, etc. [4]. Costs related to for instance a voltage dip will similarly depend on the duration and the “depth” (residual voltage) of the dip.

The scope of the survey was to collect data for all types of customers, aggregated to six different customer groups:

- Industry;
- Commercial;
- Large industry;
- Public sector;
- Agriculture;
- Residential.

Regarding voltage disturbances the survey was limited to voltage dips with 50% reduced voltage in 1 s.

C. Cost Valuation Methodology

The project focused on development of methodology for empirical estimation, through customer surveys of interruption and voltage dip costs which reflect consumer valuation of QoS in a market-based power system. Survey-based methods include both direct and indirect methods. These are discussed in, e.g., [7]. The direct methods comprise the direct worth approach (DW) and the willingness to pay (WTP) or accept (WTA) approaches. In the DW approach different interruption scenarios are described and the respondents are asked to estimate the costs they would experience if the scenario occurs at a predefined reference time. Instead of asking about the direct costs one could ask the respondents to estimate how much they are willing to pay to avoid such an incident, alternatively how much they are willing to accept in compensation to be indifferent to the interruption. WTP and WTA are especially useful where intangible costs are present which are difficult to estimate using the DW approach.

One of the indirect methods is the preparatory action method (PAM) which evaluates the costs based on preparatory actions a customer would take for a given level of QoS. Imputation is another approach where one attempts to impute the costs from the choices customers make when presented different choices that involve tradeoffs between QoS and price.

The different methods described above are suitable for different customer groups. In this project a mix of the mentioned methods were chosen, mainly the DW and WTP. Elements of the PAM-approach were used in introductory questions enabling the respondent to see possible consequences of the interruption scenarios. Furthermore this triangulization of research was adopted to handle strategic response. The respondents might give strategic response if they have reason to believe that their response will influence the outcome of decisions affecting their situation. The different methods alone are not capable of revealing strategic response and it is therefore important to examine the results via other questions and variables.

D. Customer Sectors and Questionnaires

The national postal customer survey covered the six customer groups described above. An important part of a survey is the questionnaire used for collection of information from the respondents. In this study specific questionnaires for each customer group were developed to obtain information about cus-

[1]As defined by the European Standard EN 50160 (CENELEC).

TABLE I
SURVEY SAMPLE SIZE

Customer group	Resi-dential	Industry	Com-mercial	Agri-culture	Public sector	Large industry
Sample size	1000	2400	1800	800	800	220
Repeal	56	141	122	53	31	44
Real sample	944	2259	1678	747	769	176
Response rate	45 %	27 %	25 %	43 %	45 %	44 %
No of responses	425	618	425	321	347	78
Incentive (lottery tickets)	40			40		

TABLE II
CONTENT OF QUESTIONNAIRES

I	INFORMATION ABOUT THE RESPONDENT AND ELECTRICITY CONSUMPTION
	SIC business sector, business size, working hours, type of offices, other energy sources, etc. Yearly electricity consumption in kWh and NOK[2].
	Electricity usage. Perceived QoS (interruptions, voltage disturbances and information/notification)
II	COSTS OF INTERRUPTIONS AND VOLTAGE DIPS
	Total costs in NOK for different durations of incidents occurring at reference time: 50 % dip in 1 sec., interruption of 1 min., 1 hour, 4 hours, 24 hours[3]
	Costs divided in A) Damage of equipment, spoiled goods or raw material etc., B) Loss of production, C) Extra costs for lost hours of work, D) Starting costs, E) Other costs[4]
	Portion of costs related to space and water heating, cooling and freezing, production processes, electric boilers, data processing etc.
	Modification of costs in case of advance warning, necessary warning time
III	CHANGES IN COSTS FROM REFERENCE TIME
	By season (months), time of week (weekdays), time of day
IV	COST REDUCING ACTIONS
	Type of action: Reserve supply, UPS, protection, insurance etc.
	Cost of action and valuation of reserve supply possibilities (WTP)
V	CONSUMER FLEXIBILITY
	Willingness to accept compensation in case of load shedding
	Willingness to pay for reserve supply for parts of the electricity demand

[2] $8 \text{ NOK} \approx 1 \text{ euro}$
[3] For large process industry: Costs of interruptions of 1 s, 3 min., etc. and more detailed questions about voltage disturbances
[4] For public, residential, and agricultural sectors: Consequences of interruptions and dips for heating, cooking, washing, data communication, lighting, ventilation, elevators, safety and security, etc. Costs indicated in check boxes. Willingness to pay for reserve supply.

tomer costs associated with interruptions and voltage dips in Norway. Design of questionnaire involved making tradeoffs between details on one hand, and response rates to questionnaires on the other. The final set of questionnaires used in the study was chosen through an iterative process which included a pilot survey covering two customer groups.

A total number of 7000 respondents were randomly sampled using the Standard Industrial Classification (SIC) within each group based on the European NACE standards [8]. The sample sizes, response rates, etc. for the different customer groups are shown in Table I. For the residential and agriculture groups it was chosen to provide incentives for response offering lottery tickets to the respondents.

Table II shows the different main parts of the questionnaires, while Table III gives the reference time used for the interruption scenarios for the different groups. The reference time is usually chosen to represent the worst case of an incident, typically the heavy load situation.

TABLE III
REFERENCE TIME FOR THE INTERRUPTION SCENARIOS

Industry	Commer-cial	Large industry	Public sector	Agriculture	Residential
Thursday in January at 10 a.m.	Thursday in January at 10 a.m.	Thursday in January at 10 a.m.	Working day in January at 10 a.m.	Thursday in January at 6 a.m.	Working day in January at 4 p.m.

E. Lack of Responses

As shown in Table I there was a response rate of 25%–45% depending on group, meaning that more than half of the mailed questionnaires were not returned. In addition some of the questions of those received were not replied at all or not answered properly. It is questionable whether or not the real collection of responses is representative for the random samples. Lack of responses might give misleading estimates in case of systematic repeal. Statistical t-tests were performed along the geographical dimension as well as within each group according to size. It was for instance a tendency that small sized enterprises in the commercial sector were more willing to respond than larger companies, while it was the opposite for the industrial sector. However, the tests showed that the lack of responses did not lead to any significant imbalance according to the size of the enterprises or, e.g., the age of residential customers, neither according to the geographical dimension. Combining the test results with the censoring of outliers in the sample (see Section III) there was no reason to believe that the missing questionnaires would give significant and systematic deviations.

Extensive data quality analysis was carried out, sorting out "careless respondents." Missing data about electricity consumption were imputed where possible, according to the following procedure: If the consumption was given in monetary values (NOK) only, it was calculated dividing by the tariff (sum of energy cost tariff and network tariff). In cases where both kWh and NOK for the electricity consumption were missing, the consumption was estimated using average load data.

III. Methodology for Estimating Cost Data

The raw data obtained through the customer survey were the basis for estimating average cost data for the different sectors. This section provides a description of the assessment of specific costs related to interruptions and voltage problems.

A. Normalization of Individual Cost Data

The raw data were given as a monetary value in NOK per voltage dip or interruption for different scenarios (see Table II). This is the "actual" cost a particular respondent will experience if the scenario occurs. The raw (surveyed) data need to be transformed into normalized data that can be used to represent customers within the same sector and to provide cost data on a useable form for different applications.

For most of the applications regarding planning and operation of the power system it is appropriate to use a measure of installed/demanded power or energy for the normalization [4].

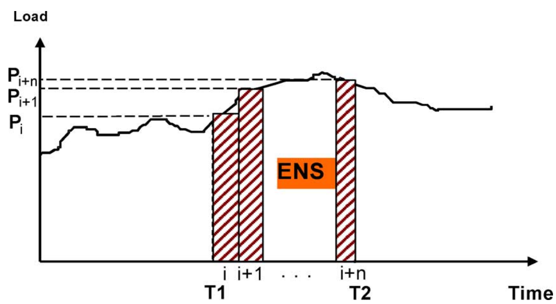

Fig. 1. Approximation of ENS based on hourly average load.

Interruption cost data from customer surveys are typically reported as specific costs referred to the maximum load, the annual electricity consumption or energy not supplied. The normalization parameter used for the Norwegian data was energy not supplied (ENS) in kWh for long interruptions (>3 min) and the interrupted power in kW for dips and short interruptions (≤3 min), both at reference time. ENS and interrupted power was estimated using the FASIT standard [16] for collection and reporting of reliability data as specified in the Norwegian regulation [6]. The procedure is described in the following.

B. Estimating Energy Not Supplied

ENS is defined as *the estimated energy that would have been supplied if the interruption did not occur*. Estimating ENS would ideally be carried out by finding the integral under the load curve for equivalent conditions (customer type, temperature and season). Due to lack of such detailed information ENS is estimated by means of hourly average load, as illustrated in Fig. 1.

Estimation of ENS for an interruption with duration from T1 until T2 (Fig. 1) is carried out by the following approximation:

$$ENS = \int_{T1}^{T2} P(t) \approx \sum_{h=i}^{h=i+n} P_h \quad [\mathrm{kWh}] \tag{1}$$

where $\mathrm{P_h}$ is the average load in any hour h [kWh/h].

The electricity consumption in Norway (heating in particular) is highly dependent on outdoor temperature. Consequently, temperature dependent load profiles have been established for all the surveyed end-user groups and for all climatic zones. For the purpose of estimating normalized cost data per respondent, the load profiles were combined with information from the questionnaire about yearly electricity consumption, category of end-user and climatic zone.

The average load $(\mathrm{P_{c,z,h}})$ in any hour h for end-user of category c in climate zone z is estimated according to

$$P_{c,z,h} = a_{c,z,h} \cdot t + b_{c,z,h} \quad [\mathrm{kWh}] \tag{2}$$

where

$\mathrm{a_{c,z,h}}$	coefficient for hour h for end-user of category c in climate zone z [kWh/°C];
t	daily mean outdoor temperature [°C];
$\mathrm{b_{c,z,h}}$	average load at 0°C for end-user of category c in climate zone z [kWh/h] for hour h.

Since the questionnaire asked for electricity consumption for year 2000 the normal yearly electricity consumption for each respondent for this year $(\mathrm{W_{c,z,2000}})$ was estimated based on (2) and the temperature-series for year 2000.

The percentage $(\mathrm{p_{c,z,h}})$ of the yearly consumption per hour in year 2000 is considered to be the same as in a normal year, and is found by

$$p_{c,z,h} = \frac{(a_{c,z,h} \cdot t_{n,z,d} + b_{c,z,h})}{W_{c,z,2000}} \cdot 100\% \tag{3}$$

where $\mathrm{t_{n,z,d}}$ is the daily mean temperature on day d in climate zone z in a *normal year*.

$\mathrm{p_{c,z,h}}$ values were calculated for all climate zones and different end-user categories. Each set consists of a full year time-series (8760 values).

Energy not supplied (ENS) in hour h for a respondent i of end-user-category c, located in climate zone z, can then be estimated using the formula in

$$ENS_{i,c,z,h} = p_{c,z,h} \cdot W_{i,2000}/100\% \quad [\mathrm{kWh}] \tag{4}$$

where $\mathrm{W_{i,2000}}$ is the yearly electricity consumption in year 2000 for respondent i (from questionnaire).

Furthermore ENS for an interruption of duration r occurring at time t is given in the following, using (1):

$$ENS_{i,c,z}(r,t) = \sum_{h=t}^{h=t+r} ENS_{i,c,z,h} \quad [\mathrm{kWh}]. \tag{5}$$

This expression gives the normalization factor for long interruptions (>3 min) for a given respondent i of end-user category c and climate zone z.

The normalization factor for dips and short interruptions (≤3 min) is the interrupted power in kW, defined as *the estimated power that would have been supplied at the time of interruption* (or voltage dip) *if the interruption* (dip) *did not occur* [16]. The interrupted power is similarly estimated using hourly loads according to the above procedure.

ENS and interrupted power was estimated for each individual respondent and each scenario in the customer survey. Missing data for yearly electricity consumption were imputed when possible as described in the previous section.

C. Customer Damage Functions

The individual normalized cost for long interruptions (>3 min) was presented in terms of specific cost of energy not supplied, as a function of an interruption scenario of duration r occurring at time t. Similarly the normalized cost for short interruptions (≤3 min) and voltage dips was presented in terms of specific cost of interrupted power as defined above. The normalized (specific) cost $c_{N,i}$ for respondent i is given by

$$c_{N,i}(r,t) = \frac{C_i(r,t)}{N_i(r,t)} \quad [\mathrm{NOK/kWh\ or\ kW}] \tag{6}$$

where

$c_{N,i}(r,t)$ normalized (specific) cost for respondent i for an interruption of duration r or voltage dip occurring at time t [NOK/kWh or kW];

$C_i(r,t)$ monetary value of respondent i (from the survey) for an interruption of duration r or voltage dip occurring at time t [NOK];

$N_i(r,t)$ normalization factor for respondent i: $\mathrm{ENS_i(r,t)}$ for an interruption of duration $r > 3\ \mathrm{min}$ at time t [kWh] $\mathrm{P_{int,i}(t)}$ for an interruption of duration $r \leq 3\ \mathrm{min.}$ or voltage dip at time t [kW];

$ENS_i(r,t)$ energy not supplied for respondent i for an interruption of duration r at time t [kWh];

$P_{\mathrm{int},i}(t)$ interrupted power for respondent i for a short interruption or voltage dip at time t [kW].

The reference time used in the survey (see Table III) represents the time t in (6). The interrupted power $\mathrm{P_{int,i}}$ used to normalize the costs of short interruptions and voltage dips was estimated according to the above definition and procedure, representing a constant hourly load for respondent i at the time of the incident, referred to reference time. $\mathrm{P_{int,i}}$ does not represent the load for an actual interruption or a voltage dip.

The *sector* customer damage functions (SCDF) are determined as average (arithmetic mean) normalized costs based on the individual specific costs from (6) for the respondents belonging to the group, as shown in the following:

$$c_{SCDF}(r,t) = \frac{1}{m}\sum_{i=1}^{m} c_{N,i}(r,t) \quad [\mathrm{NOK/kWh\ or\ kW}] \tag{7}$$

where

$c_{SCDF}(r,t)$ sector customer damage function (SCDF) for sector s for an interruption of duration r or voltage dip at time t [NOK/kWh or kW];

m number of respondents in sector s.

The SCDFs are calculated for long (>3 min) and short interruptions (≤3 min) and voltage dip, respectively, as presented in Tables IV and V in Section IV.

Furthermore the *composite* customer damage functions (CCDF) are found from the following, representing an average specific cost for a composition of customer groups:

$$c_{CCDF}(r,t) = \sum_{s=1}^{S} c_{SCDF}(r,t)\cdot W_s \quad [\mathrm{NOK/kWh}] \tag{8}$$

TABLE IV
NORMALIZED COSTS OF INTERRUPTIONS, CENSORED DATA, MEAN VALUES (STANDARD DEVIATION IN PARENTHESIS). COST LEVEL 2002

Interruption duration		1 min. NOK/kW	1 hr NOK/kWh	4 hrs NOK/kWh	24 hrs*) NOK/kWh
Industry N ≈ 280	DW	38.4 (56.4)	123.0 (140.5)	107.3 (137.5)	65.3 (77.7)
	WTP	5.8 (26.5)	17.5 (32.1)	13.9 (25.5)	8.0 (14.3)
	M	16.6 (34.3)	70.5 (94.8)	57.1 (81.6)	36.1 (46.2)
Commercial N ≈ 160	DW	34.6 (61.3)	201.5 (246.4)	166.5 (196.9)	98.9 (110.3)
	WTP	7.1 (30.3)	22.9 (53.8)	15.5 (31.4)	8.0 (14.6)
	M	18.7 (43.5)	99.6 (156.2)	97.1 (152.3)	56.1 (78.0)
Large ind. N ≈ 35	DW	8.2 (11.0)	23.8 (37.0)	20.7 (38.9)	7.4 (11.3)
	WTP	4.4 (11.0)	9.8 (17.5)	10.2 (19.2)	4.1 (8.0)
	M	5.6 (8.0)	14.4 (21.8)	10.8 (20.0)	8.8 (18.1)
Public N ≈ 85	DW	1.4 (5.8)	19.9 (45.5)	25.6 (52.3)	15.3 (26.4)
	WTP	0.8 (3.4)	1.6 (3.7)	2.3 (3.8)	1.2 (2.2)
	M	1.1 (5.2)	11.9 (31.6)	14.8 (30.3)	7.9 (11.5)
Agriculture N ≈ 155	DW	4.5 (13.4)	16.6 (31.0)	13.8 (16.4)	12.3 (18.5)
	WTP	1.6 (9.9)	15.7 (39.6)	9.2 (13.7)	4.2 (5.7)
	M	4.2 (14.6)	16.2 (34.6)	11.8 (15.1)	8.6 (13.0)
Residential N ≈ 325	DW	-	11.5 (20.0)	12.7 (13.8)	11.1 (12.1)
	WTP	-	5.0 (10.7)	4.5 (7.0)	4.1 (5.6)
	M	-	8.6 (14.9)	8.7 (9.9)	7.4 (7.6)

*) For the residential sector: 8 h

TABLE V
NORMALIZED COST OF DIP (50%, 1 s), DW ESTIMATE. COST LEVEL 2002

Customer group	N	Normalized cost NOK/kW	Standard deviation NOK/kW
Industry	123	30.4	47.1
Commercial	128	22.1	50.5
Large ind.	13	5.6	8.5
Public	86	1.6	6.8
Agriculture	83	13.6	38.9
Residential	-	-	-

where

W_s sector s' proportion of the annual electricity consumption;

S number of sectors.

D. Censoring of Normalized Data

To reduce bias in the final estimates it is important to censor observations related to outliers in the sample. The key issue is to define an objective rule for identification of outliers. A widespread approach is to censor outliers with reference to the standard normal distribution. The survey results showed however

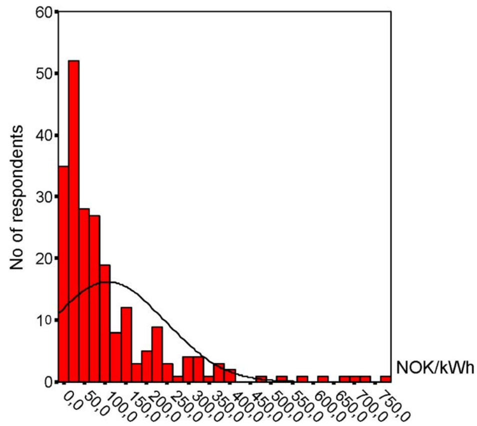

Fig. 2. Normalized data: example of distribution of costs for 4 h duration at reference time in NOK/kWh for the industrial sector.

- Data segmentation into sectors
    - Industry
    - Large industry
    - Commercial
    - Residential
    - Agriculture
    - Public sector
- Logical tests to handle
    - Careless response
    - Misinterpretation
- Lognormal transformation of sector normalized sample data
- Censoring of outliers based on pre-defined criteria
- Re-transformation [a'= exp(a)].
- Result: Censored normalized data in original format.

Fig. 3. Algorithm for censoring raw data.

that neither the monetary values nor the normalized data were normally distributed. The distributions were highly skewed as illustrated in Fig. 2 and a lognormal distribution was found to give a good approximation to the data. A similar distributed nature of interruption cost data is also discussed in, e.g., [11] and [12].

Before censoring of outliers the normalized data were transformed to a normal distribution using a lognormal transformation. Examples of distributions of the cost data and the normalization factor ENS are given in [9] together with a thorough description and discussion of the censoring procedure. The algorithm for censoring raw normalized data is shown in Fig. 3.

IV. Main Survey Results

This section gives the main results from the Norwegian customer survey of costs related to interruptions and voltage dips.

A. Cost Valuation Estimates

Due to the triangulization of research principle, it should be possible to test a variable directly or indirectly using other variables. Therefore a mix of methods were chosen in this study; see Table II. The results from the study are reported as DW estimates and WTP estimates for all customer sectors, based on the normalized costs and the normalized willingness to pay.

The DW approach yielded as expected significantly larger values than the contingent WTP valuation. This is in accordance with results from other surveys as well as from other markets (e.g., [10]). WTP tends to be underestimated while the direct worth costs tend to be overestimated. It was an aim in this project to reveal the different customers accurate valuation of QoS. As there is no market for QoS it is not possible to establish the market price directly. It is however difficult to quantify the deviation between reported and real WTP. Therefore the *estimated* willingness to pay (M) was introduced, defined as the average of DW and WTP, as follows:

$$M = (DW + WTP)/2. \tag{9}$$

If the respondent reported the DW estimate only, the M estimate was set equal to DW. The same procedure was applied if only the WTP estimate was reported. Otherwise M was determined on a per respondent basis according to (9).

B. Costs of Interruptions and Voltage Dips

Table IV gives the results for the normalized costs after censoring according to (6) and (7) for the DW, WTP and M estimate, respectively. The results for voltage dips (50%, 1 s) are given in Table V. These costs are given as DW estimates only. All results (cost estimates) are referred to the cost level January 2002 and the reference time given by Table III.

The total number of responses included in the cost estimates in Tables IV and V is reduced compared to the total number of survey responses shown in Table I and varies within each group for the different interruption scenarios. This is partly due to lack of data and partly due to the censoring. The N-number in Table IV represents the approximate number of responses used for calculation of the cost estimates. Cost estimates like those in Tables IV and V are mean values for broad customer categories. The dispersions in costs are considerable among the SIC groups within each of the six major groups as well as within each SIC group. This is in accordance with findings from similar surveys in other countries, see, e.g., [15]. The standard deviations for the normalized costs in Table IV are about 1–2 times the mean values. For the uncensored costs the standard deviations are in the order of 2–5 times the mean values for the six groups. The largest deviations are found for the cost of short interruptions. A division of the major group cost estimates per SIC group might lead to a reduced standard deviation. However, the sample sizes in this survey did not allow for a sufficient number of responses to provide an adequate level of significance per SIC group.

From Table IV it can be seen that the DW estimates are considerably higher than the WTP estimates. The ratio DW/WTP is about 5–12 for the interruption scenarios in the commercial sector and 6–8 in the industrial sector, while the ratio is 2–3 in the residential and agricultural sectors.

The major portions of the total cost (DW-estimates) are for the commercial sector constituted by loss of production and "other costs," each by approximately 30%. For the industrial

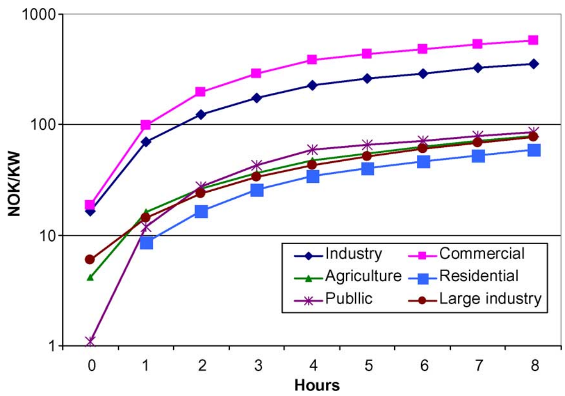

Fig. 4. Sector customer damage functions. M estimate, cost level 2002.

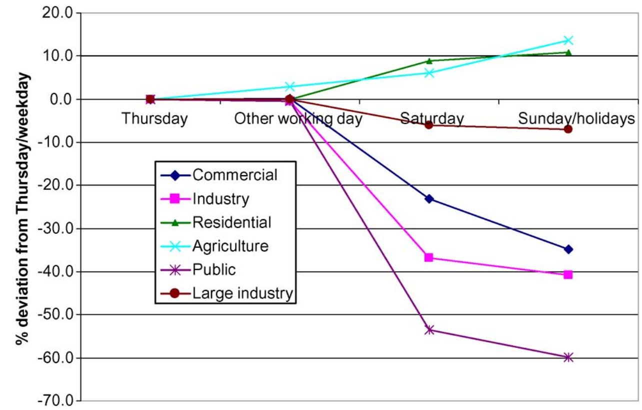

Fig. 5. Deviation (%) in cost from Thursday or other working day.

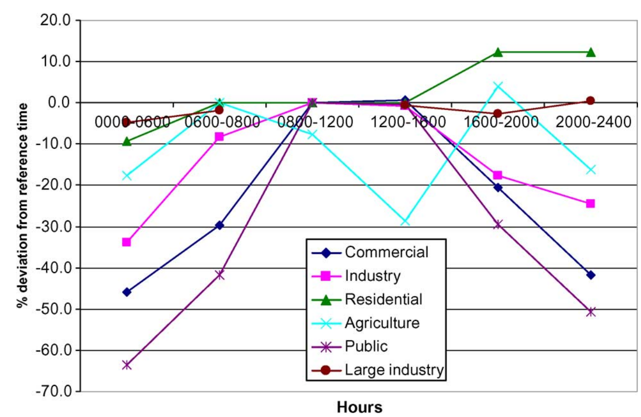

Fig. 6. Deviation (%) in cost from reference time.

sector the largest contributor to the total cost picture is the re-starting costs by 33%. Loss of production allows for 20% of the costs for the industrial sector and more than 60% for the large industry sector. Cost composition was not surveyed in the public, agricultural and residential sectors.

The cost estimates in Table IV represent the sector customer damage functions given by (7). The cost functions are further represented as continuous functions based on linear interpolation between the discrete surveyed data estimates in Table IV. The costs functions are shown in Fig. 4 (logarithmic scale) for durations up to 8 h. The table and figure both shows that the normalized cost for the public, agriculture, residential and large industrial groups are quite equal and very low compared with the corresponding normalized costs for the commercial and industrial groups.

The large industries (wood processing and power intensive industry) have on average surprisingly low normalized (specific) cost compared with the other industry and commercial groups. The main reason for this is the energy intensive production in this group resulting in very high normalization factors in terms of electricity consumption.

In case of advance warning (notified interruptions) the cost per interruption may be modified for all groups (part of questionnaire in Table II). The largest reduction in costs may be obtained in the commercial and public sectors by almost 30%. In the large industry group the cost will be only slightly reduced for notified interruptions.

C. Time Dependency in Interruption Costs

The cost estimates presented in the previous section are given for the reference time of the survey, see Table III. The reference time is assumed to be the worst case, i.e., January on working days and in the working hours (different for the six sectors). The survey also gave information about variation in interruption costs by season, weekdays and time of day (Table II). The time dependency in the interruption cost was found to be significant, especially for the industrial, commercial and public sectors over the week and by time of day. Weekly and daily variation in the cost per interruption (monetary value) is shown in Figs. 5 and 6.

The figures show that the cost per interruption is rather constant over the week and day for the large industry sector. The production in these industries is typically in continuous progress. For the commercial, public and other industrial groups the cost per interruption will be reduced in the order of 30%–60% from the cost at reference time if the interruption occurs on Sundays/holidays compared with Thursday/working day or during night compared with 10 a.m. The variation by season was found to be rather insignificant (±10%) except for the public group where the cost reduction is up to 40% during summer.

In order to determine the time variation in the normalized cost one should take into account the variation in the normalization factor [13], [14].

D. Comparison With the Survey in 1991

The results of time dependency in cost per interruptions were rather similar to the findings in the 1991 survey. In order to investigate whether there has been any real change in costs within the different groups from 1991 until 2001, the cost estimates from the 1991 survey were updated to cost level 2002 to account for an inflation of nearly 30% during this period. The cost valuation methods were slightly different in the two surveys: While the 2001 survey utilized a combination of DW and WTP for all groups, the results from the 1991 survey were reported as WTP for the residential group and DW for the other groups. The public group was not included in the 1991 survey. Table VI

TABLE VI
COMPARISON OF COST ESTIMATES FROM 1991 AND 2001 SURVEYS SPECIFIC COSTS FOR 1-H INTERRUPTION, COST LEVEL 2002

Customer group	Estimate	1991*) [NOK/kWh]	2001 [NOK/kWh]	Relative increase
Industry	DW	68.6	123.0	1.8
Commercial	DW	47.8	201.5	4.2
Large ind.	DW	19.3	23.8	1.2
Agriculture	DW	1.4	16.6	11.9
Residential	WTP	3.0	5.0	1.7

*) Updated to account for inflation

gives a comparison of the specific costs for a 1-h interruption based on comparable cost estimates.

The table shows that the normalized costs at reference time for a 1-h interruption found in the survey in 2001 was 12 times higher on average in the agricultural group compared to the 1991 survey. One reason for this may be that there has been a marked industrialization in this group during the period 1991–2001. All the groups have increased their costs. The cost is four times higher in the commercial group and nearly twice as high in the residential. For a 4-h interruption the relative cost increase is reduced to about three times both for the commercial and the agricultural group.

V. APPLICATIONS

A. Quality of Supply Regulation

As mentioned in the introduction the objective of the 2001 customer survey was to generate quantitative indicators to enable effective regulation of QoS, such as the CENS arrangement. CENS was introduced in 2001 based on updated data from the 1991 survey and the customers were divided in two groups. The latest survey provided new cost rates from 2003. At the same time the customers were divided in six groups. CENS is based on the mandatory reporting of interruptions for end-users at all voltage levels >1 kV and the standardized method for estimation of ENS as outlined in Section III [1], [9]. CENS comprises both notified and non-notified interruptions. The cost rates utilized in the regulation are calculated for an average duration of the two types of interruptions based on the cost functions (SCDFs) in Fig. 4 and Table IV. In order to use the normalized cost data appropriately and adequately for an actual interruption or voltage dip, the data should be used in conjunction with the standardized method for estimation of ENS and interrupted power to arrive at a cost estimate in absolute terms (NOK).

The total CENS cost for Norway has been in the order of 400–500 million NOK per year, while the total costs of interruptions and voltage dips are estimated to 1030–1350 million NOK/year [9]. These figures are calculated on basis of the actual ENS and dips per customer group, thus indirectly taking into account the differences in number and duration of interruptions and dips. The value of lost load (VOLL) for the Norwegian power system can be estimated to about 20–25 NOK/kWh, based on CENS and a total ENS in the order of 15–20 GWh/year. This number includes both notified and non-notified interruptions. Similarly VOLL for the residential sector and commodity trade was about 8 and 90 NOK/kWh in 2006, respectively, according to the interruption statistics.

So far, only long interruptions (>3 min) have been included in the CENS arrangement. The regulator has proposed to include short interruptions (≤ 3 min) from 2009. This will provide the foundation for using the cost functions in NOK/kW (Fig. 4) to determine a specific cost as a function of the duration of the interruption. Furthermore the regulator proposes to take the time dependency (Figs. 5 and 6) of the costs into account in the calculation of the cost per interruption. Application of cost data collected through customer surveys to handle duration and time variation in normalized costs is described in, e.g., [13] and [14].

B. Planning and Operation

Cost data collected through customer surveys serve a wide range of purposes related to planning and operation of the power system. Examples are given in, e.g., [4] and [7]. The surveyed data have not just provided new cost rates for the QoS regulation and planning purposes. The data basis is also useful for designing efficient rationing (load-shedding) or priority-pricing schemes to meet energy or network capacity shortages. The survey allowed for considerations regarding costs associated with demand response, i.e., costs associated with the disconnections of loads (space heating, water heating and cooling and freezing processes), see Table II. The findings from these analysis show that there are large differences in the normalized costs (NOK/kW interrupted power of the partial loads) for such disconnections, both for the different consumption purposes and customer categories. Such findings can be valuable information when establishing tariffs encouraging end user flexibility, and also indicates for what types of consumption the cost/benefit ratio is most beneficial (where you can disconnect the most load for the least costs). In our survey, the "cheapest" consumption to disconnect was space and water heating in the industrial and commercial groups.

VI. CONCLUSIONS

This paper has presented the methodology and main results from the most recent Norwegian customer survey on consumer valuation of interruptions and voltage problems. The survey was based on a combination of DW and WTP approaches. The raw data were normalized by energy not supplied and interrupted power, providing cost estimates that are incorporated in the quality of supply regulation and usable for various purposes in value-based planning and operation of the power system.

Customer costs collected by surveys are characterized by considerable dispersions among groups and within each sector. The standard deviations of the normalized cost data were found to be in the order of one to two times the mean values. The DW approach yielded significantly larger cost estimates than the WTP valuation as the ratio of DW/WTP normalized and censored cost estimates varies in the order of 2–12 depending on customer group. Therefore the estimated willingness to pay was introduced as the arithmetic mean of DW and WTP. The time dependency in the interruption cost was found to be significant especially by weekdays and time of day.

The survey confirmed the hypothesis that there has been a real increase in customers' costs along with the increased dependence on electricity. All groups have increased their costs and in particular the agricultural group where it has been a marked industrialization.

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