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ASSESSMENT OF ELECTRICITY SUPPLY INTERRUPTION COSTS IN ESTONIAN POWER SYSTEM

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Customers' perceptions of reliability do not always reflect the level of reliability suggested by traditional reliability indices. Thus the electricity supply industry in Estonia intends to relate reliability investments with customers' benefits obtained from such investments. A difficulty encountered by such efforts is the lack of appropriate valuation of these benefits. With a view to correcting this paucity, the authors have conducted a study aimed at assessing the characteristics needed to estimate the expenses of customers due to electric service interruptions. Because the time frame stated for the study was relatively short for a comprehensive large-scale customer survey, the results of the preliminary pilot survey were complemented with indirect analytical methods on basis of GNP and annual household income as well as on basis of analysis of corresponding characteristics of other countries. The final estimates for different customer sectors as well as for the whole country were found as averages of estimates found by different methods. Estimated were the characteristics of cost models most widely used by power system planners and briefly overviewed also in the paper. The used methodology can be applied for evaluation of electricity supply interruption costs under restricted time and information resources.

Introduction

The basic purpose of a modern power system is to satisfy the system load and energy requirements as economically as possible and with a reasonable level of reliability. The requirements for the lowest possible costs and maintaining high reliability are generally antithetic. Therefore power system planners need to determine an adequate balance between costs and reliability for satisfying the predicted load.

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The traditional approach to consider the reliability requirements is establishing different reliability norms or standards like *n-1* criteria, normative level of loss of load probability (*LOLP*) or expected energy not served (*EENS*), permitted interruption frequency and duration per year, etc. that are treated as certain restrictions which have to be met with the lowest costs in planning and operation of a power system. Such approach is still used in utilities of many countries including Estonian Power System. It is, however, difficult to justify correctly the norms or standards, which have often been established somewhat arbitrarily.

At present, deregulation and competition in the electricity sector as well as increasing energy costs, concerns for the conservation of resources, and environmental awareness are forcing electric utilities to increase the market value of the services they provide. It means an increased concern to economically justify the level of reliability. Excessive reliability results in unnecessarily high capital and operation costs associated with redundant or underused physical plant. Conversely, the consequence of low reliability is the direct cost of lost productivity or business resulting from power interruptions. Hence, there is considerable impetus to strive for realistic and dependable reliability levels on the basis of cost/benefit analysis, and efforts within the electric power industry are being directed towards quantifying the worth of service reliability. Direct customer costs due to service interruptions are often used as an indirect measure of reliability worth.

So, in least-cost planning, the modern approach to consider the worth of reliability is accomplished by including interruption costs in the costs associated with the different engineering design and operation alternatives. Thereof there are ongoing efforts within the industry to expand and apply customer cost information.

Increased environmental concerns, public review procedures, uncertainty in growth of demand, increasing energy and capital costs, and recent developments in the electricity market liberalization have raised an interest of Estonian power utilities to interruption costs and including of them into the practice of power system planners in justifying investment and operating costs for a service area in question.

The object of this paper is to present the methodology and results of a study to estimate the characteristics needed to evaluate electrical supply interruption costs associated with customers of Estonian power in value-based reliability assessment and planning. The study was conducted by the Department of Electrical Power Engineering of Tallinn University of Technology on request of the Estonian National Grid.

In principle, electricity supply interruption costs consist of utility costs (revenue from unserved energy, costs of the supply restoration) and customer outage costs which can be broadly classified into

- direct costs, arising directly from the interruption of supply and related to such impacts as lost industrial production, spoiled food or raw materials, lost personal leisure time, injury or loss of life;

- indirect costs related to impacts arising from a response to the interruption, such as crime during a blackout and business relocation.

Under electricity supply interruption costs we understand here, like in most relevant publications, customer outage costs (*COC*) because in general they are much bigger than utility costs. If needed, the latter are included in operation costs of the utility.

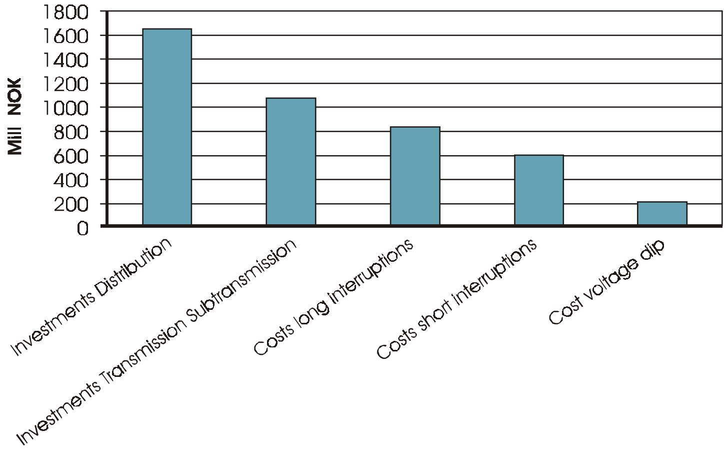

Fig. 1. Interruption costs versus investment costs of network companies in Norway in 2001 [1]

In branches of industry with high electricity use the customer outage costs are considerable. An example is given in Fig. 1, where the costs of interruptions and voltage dips for Norwegian customers are compared to the investment costs of network companies [1].

To distinguish the perceived customer interruption costs (*CIC*) and the customer outage costs (*COC*) they are defined as follows [2]:

- *CIC*: the perceived individual customer or average sector customer costs resulting from electricity interruptions. They are therefore system-independent costs.
- *COC*: the expected total annual costs incurred by all the customers connected to a particular network or service area. They are calculated from the *CIC* and take into consideration the network performance data and loading information, and are therefore customer-mix and system-dependent costs.

This paper is focused on the estimation of system-independent interruption costs for main customer sectors and for the whole country.

Interruption Cost Models

The most widely used cost models are:

1. *Customer Damage Function* (*CDF*) *Models* [2] − interruption costs are modeled as a function of the interruption duration. Specific interruption duration times widely used are 2 seconds, 1 minute, 20 minutes and 1, 4 and 8 hours.

To represent customers of different electrical consumption levels, the costs are normalized by dividing them by the annual peak load in kW, or by the annual energy consumption in kWh. To get a customer sector *CDF* the normalized *CIC* values for customers within the sector are averaged.

To yield the composite *CDF* for the whole country, the sector *CDF* is appropriately weighted.

2. *Cost of Energy not Supplied* (*CENS*) *Models* − interruption costs are modeled as a function of the unsupplied energy, regardless of the interruption duration and frequency. *CENS* represents the average cost over the interruption duration interval. The model implies that the cost function is a straight line passing through the zero, as is shown in Fig. 2*a* [3].

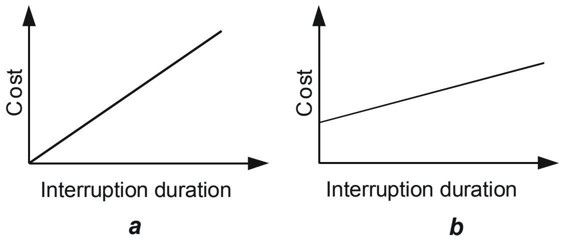

Fig. 2. Interruption cost functions: (*a*) cost models of energy not supplied and (*b*) combined cost model

There are several ways to calculate the cost of unsupplied energy.

If no information about the possible reliability performance of the system is available, the interruption durations used to calculate *CENS* should be assumed to be evenly spaced over the time interval *D* of interest [3]:

$$CENS = \frac{1}{n}\sum_{i=1}^{n}\frac{CDF(r_i)}{LF \times r_i} \tag{1}$$

where $CDF(r_i)$ is the ordinate of the *CDF* normalized by annual peak demand corresponding to the interruption duration r_i;

LF designates the load factor of the customer sector or mix considered;

n is the number of interruption durations $r_i \in D$.

The *CENS* would then represent the ordinary average.

A more realistic assessment of cost of the energy not supplied would take into account the interruption duration distribution, so representing the weighted average. These two weighted averages in use have got specific names in the literature: Value of Lost Load (*VOLL*) [2] and Interrupted Energy Assessment Rate (*IEAR*) [4].

Starting from the *CDF,* normalized by annual peak demand, *VOLL* can be calculated as the average cost over the interruption duration interval *D*, for each $r_i \in D$:

$$VOLL(r_i) = \sum_{i=1}^{n} \frac{CDF(r_i)}{LF \times r_i} \times p(r_i) \approx \sum_{i=1}^{n} \frac{CDF(r_i)}{LF} \times f_i \tag{2}$$

where $p(r_i)$ is the probability of an interruption of duration r_i;
f_i is the frequency of that interruption.

IEAR can be calculated as the average cost over the interruption duration interval *D*, for each $r_i \in D$, by dividing total expected customer outage cost *ECOC* by total expected energy not served *EENS*:

$$IEAR = \frac{ECOC}{EENS} = \frac{\sum_{i=1}^{n} m_i f_i CDF(r_i)}{\sum_{i=1}^{n} m_i f_i r_i} \tag{3}$$

where m_i is the value of the deficiency for each interruption *i*, the other variables being defined above.

3. *Combined Cost Model* (CCM) – interruption costs are modeled as a sum of two components: one is a function of the interrupted load demand *ILD*, the other is a function of the expected energy not served *EENS* [3]:

$$COST = CID \times ILD + CENS \times EENS \tag{4}$$

The model has two parameters that ascribe a cost to the interrupted demand, *ICD* (€/kW interrupted), and to the energy not supplied, *CENS* (€/kWh not supplied).

The CCM assumes that the interruption cost versus time curve is a straight line, which does not pass through the origin as shown in Fig. 2*b*. The parameter *CID* determines the intersection of the cost curve with the ordinate. Starting from the *CDF*, normalized by annual peak demand, *CD* could be determined as

$$CID = CDF(0) \tag{5}$$

The second parameter, *CENS*, determines the slope of the cost curve and is exactly the same as in the previous model.

Approach

To implement any of the models treated in the previous section for assessment customer outage costs in specific practical tasks, a system planner havs to know the characteristics of the models, i.e. customer damage functions *CDF*, cost of energy not supplied *CENS*, and/or cost of the interrupted demand *CID* for different customer sectors and/or for the whole country.

A variety of methods have been utilized to estimate these characteristics, which can be conveniently grouped into three broad categories: (i) customer surveys, (ii) indirect analytical evaluations, and (iii) case studies of actual blackouts [5].

In general, the customer survey approach is favored by utilities, who require outage cost data for planning purposes. At the same time the cost and effort of conducting surveys is significantly higher than those of the other methods. The time frame stated by the sponsor for the customer survey in the study under discussion was relatively short to obtain sufficient, comprehensive and trustworthy results. Therefore the survey conducted should be treated rather as a preliminary pilot one. To achieve more reliable results the customer survey was decided to be complemented with indirect analytical methods.

Case studies of particular outages was not performed because there have been no major, large-scale blackouts in Estonia allowing to make authentic conclusions.

Final results were determined as mean values of estimates obtained by different methods.

Interruption cost characteristics were estimated for residential, industrial, commercial and agriculture sector. Estimates for the whole country were found as weighted averages of different sector values.

Customer Survey

The primary aim of the customer survey was to compose the customer damage functions for different customer sectors. Questionnaires for different customer sectors were designed proceeding the direct costing, indirect costing and contingent valuation methods [6]. In designing primarily the experience of UK [2] and Canadian [7] surveys were issued from, patterning from questionnaires of the surveys performed in Denmark, Finland and Island [8] as well.

The questionnaires for residential and agricultural customers were relatively similar. Besides the direct costing the WTA (willingness to accept) and WTP (willingness to pay) approaches of indirect costing [7] were used.

The questionnaires for industrial and commercial customers use an approach different from the previous two. Quantitative assessments were based mainly on the direct costing approach. Respondents were asked to estimate the costs of their companies during various interruption scenarios including such components as lost sales, damaged goods or equipment, restarting costs, availability of standby equipment, and others.

Commercial sector included also public customers like hospitals, churches, public transport, etc. Estimation of the interruption costs of such customers is very complicated. Often the damage is caused to the third party persons, or it is very difficult to evaluate damage in monetary terms.

As the results were wanted in a short time frame, the National Grid ordered the real implementation of the survey from the Estonian largest full service marketing research and consulting company *TNS Emor*. The survey was conducted in February and March 2004. The residential survey was carried out by CATI (Computer Assisted Telephone Interviewing) method, using software Ci 3 WinCATI to control the run of interview and proportions of the sample. For other sectors Internet survey was used. Responding rate was low in commercial and residential sector (26 and 46 %, respectively).

In Figure 3 the CDF normalized by annual peak demand obtained by the surveys are shown. For comparison the average curves of corresponding functions of other countries (ACOC – see the section *6*) are shown as dotted lines as well.

Regrettably, practicalities did not allow realizing all of customers' survey principles properly. The main reasons were as follows.

- The time frame for the surveys was too short, being much less than it has used to be in practice of other countries.
- Short time frame and limited financial resources did not allow conducting sufficient bulk surveys needed to obtain reliable results.

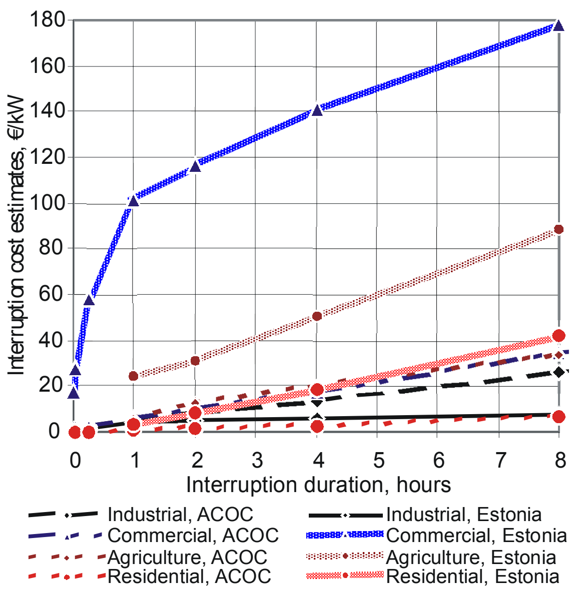

Fig. 3. CDF normalized by peak demand obtained by the surveys. Dotted lines – the average curves of corresponding functions of other countries (ACOC)

- In spite of recommendation that such kind of customer surveys can be performed competently only by a specially instructed personnel (e.g. by the service staff of the utility) the survey was ordered from the *TNS Emor* without any special training of questioners. So the additional competent explanations often needed were not available.
- Questionnaires with relatively sophisticated structure are not suitable for telephone or Internet survey, and they were considerably simplified.
- Lists of possible answers to the question about the values of interruption cost were complemented with the answer “I cannot say”. This gave respondents an easy opportunity to use this answer in many cases, and so turns very many answers (in commercial sector even 60–70%) useless.
- Telephone interviewing with request to answer immediately is not suitable for such kind of surveys.

It is obvious (see Fig. 3) that respondents, particularly in commercial and agricultural sectors, strongly overestimated their costs. Realistic and relatively reliable results were obtained in industrial sector. So, in conclusion, the customer survey concerned can be treated as a pilot one, whose results are not representative, except in industrial sector. Nevertheless, the survey allowed gaining substantial experience for conducting more extensive surveys in future.

Use of Analytical Methods

First, the costs of energy not supplied were determined using simple macromethods [6]. In industrial, commercial and agricultural sector *CENS* were calculated by dividing the annual *GNP* in a sector by electric energy *A* sold to the customers of the sector. *CENS* for domestic customers was determined by dividing annual household income by annual domestic electricity consumption. From the obtained values rough customer damage functions were derived using similarity principle.

One way, which can be treated as a distinctive analytical method, is to derive interruption cost characteristics from the corresponding values of other countries. For this purpose customer damage functions *CDF* in different customer sectors of Canada [7, 9], UK [2], Finland, Denmark and Island [8], Greece [10], Tai and Nepal [11] and India [12] were analyzed.

The *CDF* of different countries can be easily and directly compared using prevailing exchange rates (ER). As an example, Fig. 4*a* compares *CDF* in the commercial sector for the above-mentioned countries. The cost data for all countries were converted to €2003/kW using US price deflators and prevailing exchange rates. Similar comparisons were made for the industrial, agricultural and residential sectors.

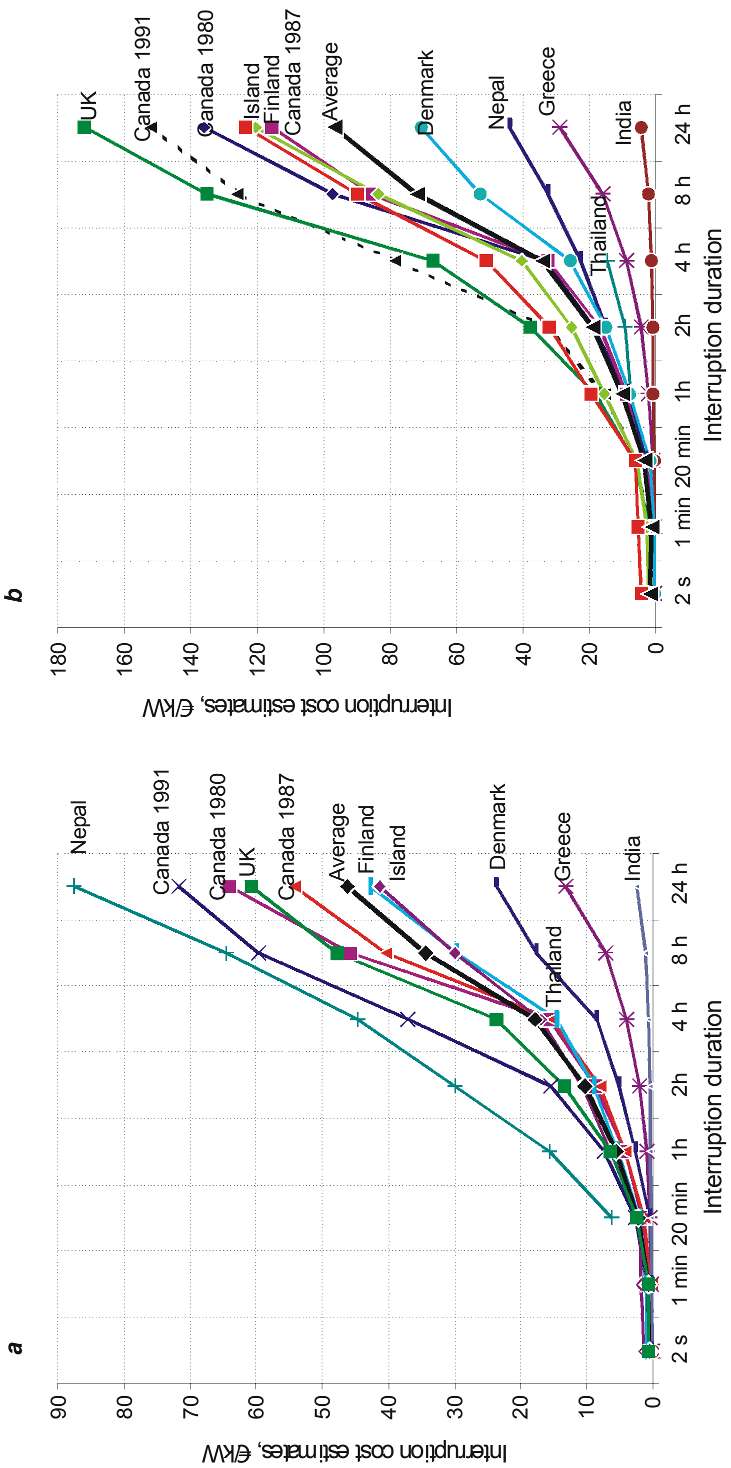

Fig. 4. Customer damage functions of commercial sector based on (a) exchange rates and (b) purchase power parity estimates

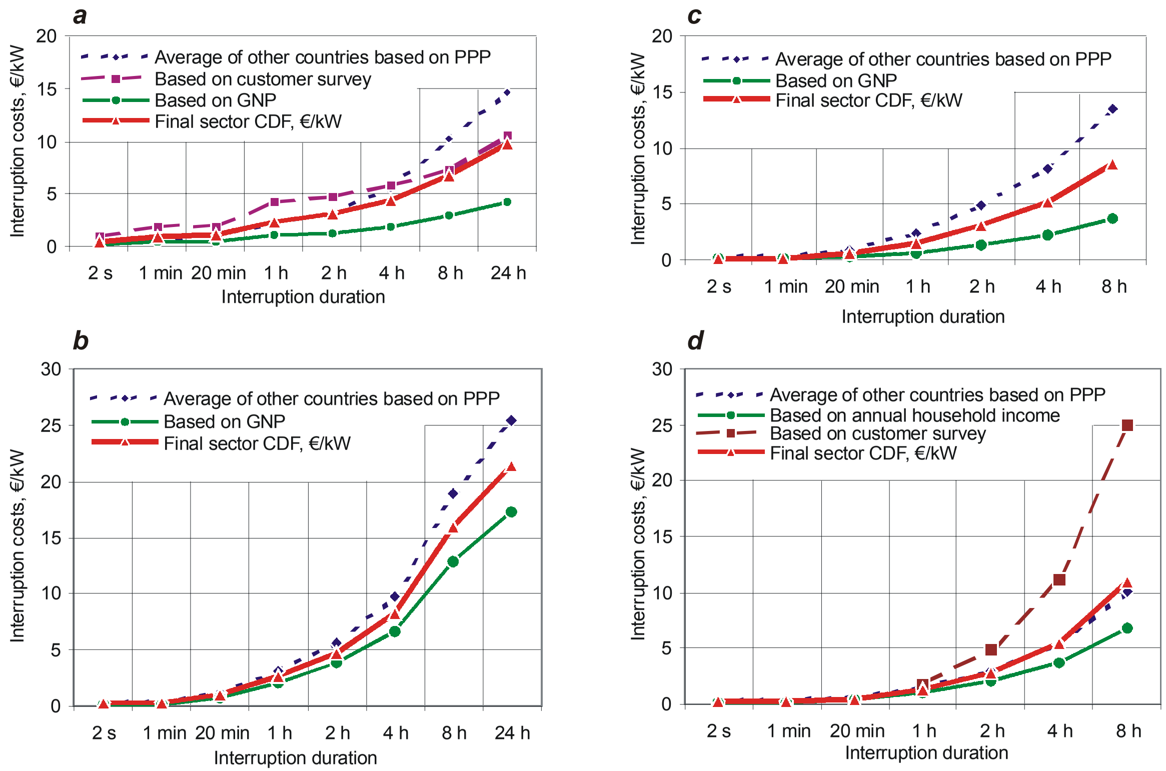

Fig. 5. Customer damage functions normalized by peak demand determined in different ways, and the final estimates for different customer sectors: (a) industrial; (b) commercial; (c) agricultural; and (d) residential

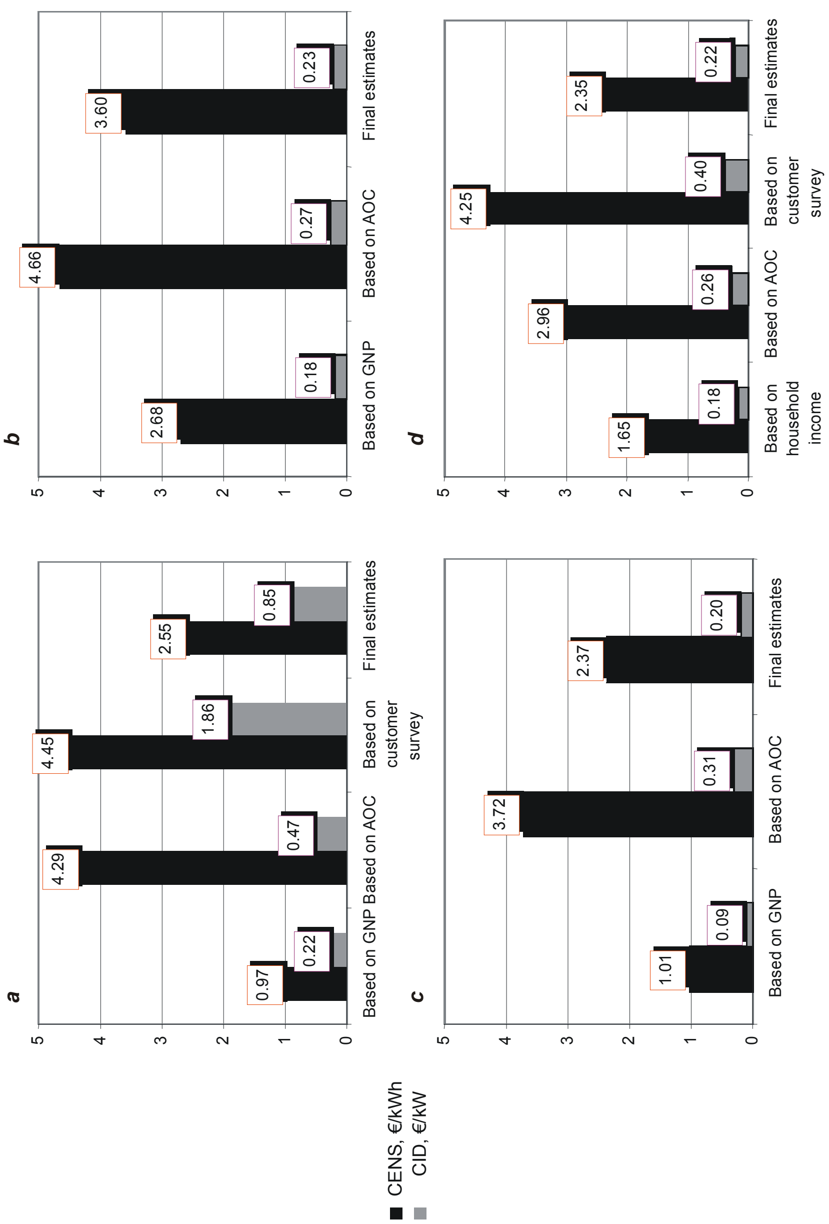

Fig. 6. Costs of energy not supplied and interrupted demand obtained in different ways, and their final estimates for different customer sectors: (a) industrial; (b) commercial; (c) agricultural and (d) residential

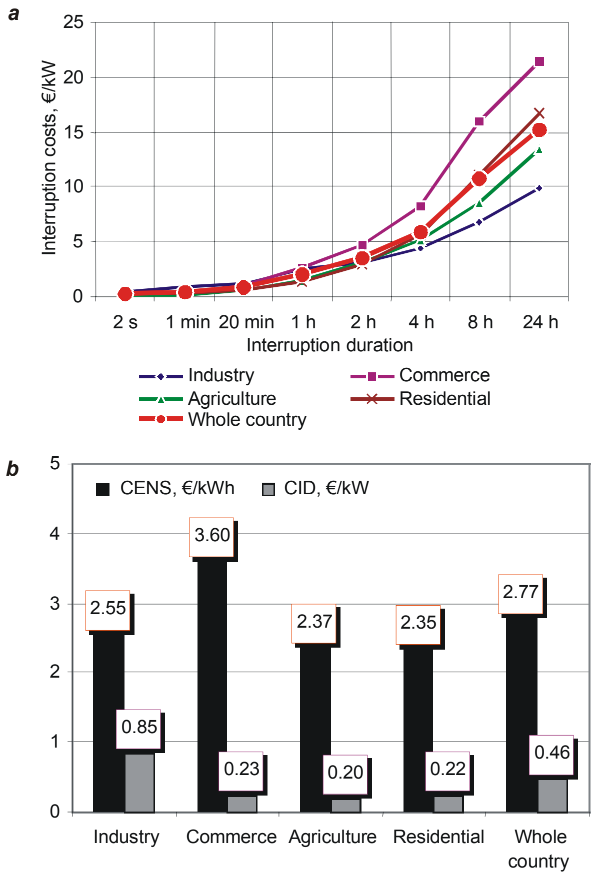

Fig. 7. Final estimates of interruption cost characteristics for different sectors and for Estonia as a whole: (*a*) customer damage functions normalized by peak demand; (*b*) costs of energy not supplied and costs of interrupted demand

However, comparing interruption costs on the basis of exchange rates is quite misleading, as, in general, an exchange rate does not reflect accurately the worth of electrical energy in the country in question. A more appropriate approach to compare the worth of electric service reliability in various countries is to incorporate the prevailing socio-economic conditions of each country into the analysis using a purchasing power parity (PPP) estimate [11]. A PPP estimate reflects the purchasing power of the inhabitants of a country and depends on market value. So, better quantitative comparison across countries is possible. As an example, Fig. 4*b* shows the comparison of commercial sector *CDF* based on PPP estimates.

It can be seen from Fig. 4 that the shapes of the curves obtained by the two methods are generally similar, but the sequence of the curves for different countries is not exactly the same. At the same time dispersion of PPP estimates is considerably less, and the average curve is much lower than in the case of ER estimates. Similar results were got for the industrial, agricultural and residential sectors.

For deriving estimates of customer damage function for Estonia from the average curves of PPP, estimates as more appropriate ones were issued.

Final Results

Thus, from the results obtained by the above-mentioned methods, the estimates of *CDF,* normalized by annual peak demand and by annual energy consumption, the cost of energy not supplied, and cost of interrupted demand were derived.

The relationship between the corresponding values of *CDF,* normalized by peak demand (CDF_D) and by annual energy consumption (CDF_E), for any sector *y* can be expressed by Equation 6 [2]:

$$CDF_{E,y}(r_i) = \frac{CDF_{D,y}(r_i)}{LF_y \times 8760} \text{ (€/kWh)} \tag{6}$$

where LF_y is the load factor for sector *y*.

Figure 5 shows the *CDF* normalized by peak demand obtained in different ways, as well as the final estimate for different customer sectors.

As one can see from Fig. 3, surveys of commercial and agricultural customers practically failed, so they are not taken into account. The results of residential customers' survey are obviously overestimated. Nevertheless, they are considered, but with lower weight, taking into account answers on willingness to pay for avoiding interruptions.

Shares of sectors in the total consumption were used as weight coefficients. Figure 7*a* shows the final estimates of *CDF* normalized by peak demand for different sectors and for whole Estonia.

As for the Estonian power system, information about the possible reliability performance of the system is not available, costs of energy not supplied *CENS* were calculated by the Formula (1). Costs of interrupted demand *CID* were found as intersections of the corresponding CDF_D with the ordinate. Figure 6 shows the values of *CENS* and *CID* for different customer sectors obtained in different ways as well as their final estimates. Calculations were based on *GNP*, on annual household income (for residential customers), on average *CDF* of other countries (*AOC*), and on the results of customer survey (for industrial and residential customers). Final estimates were determined as averages on base of the final sector *CDF*.

Customer damage functions for the whole country were determined as weighted average of sectors' *CDF*.

CENS and *CID* for the whole country were determined on the basis of the whole country's *CDF* as weighted average of sectors' values. Figure 7*b* shows the final estimates of *CENS* and *CID* for different sectors and for Estonia as a whole. Final numerical results of the study are presented in the Table.

Estimates of interruptions cost characteristics

Characteristics for different sectors								
Industrial sector								
Sector customer damage function *CDF*								
Interruption duration r_i	2 s	1 min	20min	1 h	2 h	4 h	8 h	24 h
$CDF_{D,y}(r_i)$,€/kW	0.50	0.95	1.18	2.44	3.11	4.40	6.85	9.84
$CDF_{E,y}(r_i)$, c/kWh	0.0115	0.0216	0.0269	0.0558	0.0710	0.1005	0.1564	0.2246
Cost of energy not supplied *CENS*					2.55 €/kWh			
Cost of interrupted demand *CID*					0.85 €/kW			
Commercial sector								
Sector customer damage function *CDF*								
Interruption duration r_i	2 s	1 min	20min	1 h	2 h	4 h	8 h	24 h
$CDF_{D,y}(r_i)$, €/kW	0.23	0.26	1.00	2.60	4.74	8.27	15.91	21.36
$CDF_{E,y}(r_i)$, c/kWh	0.0043	0.0050	0.0190	0.0495	0.0901	0.1573	0.3027	0.4064
Cost of energy not supplied *CENS*					3.60 €/kWh			
Cost of interrupted demand *CID*					0.23 €/kW			
Agricultural sector								
Sector customer damage function *CDF*								
Interruption duration r_i	2 s	1 min	20min	1 h	2 h	4 h	8 h	24 h
$DF_{D,y}(r_i)$, €/kW	0.20	0.22	0.54	1.54	3.14	5.19	8.57	
$CDF_{E,y}(r_i)$, c/kWh	0.0038	0.0041	0.0102	0.0293	0.0597	0.0988	0.1630	
Cost of energy not supplied *CENS*					2.37 €/kWh			
Cost of interrupted demand *CID*					0.20 €/kW			
Residential sector								
Sector customer damage function *CDF*								
Interruption duration r_i	2 s	1 min	20min	1 h	2 h	4 h	8 h	24 h
$CDF_{D,y}(r_i)$, €/kW	0.22	0.24	0.52	1.37	2.89	5.56	11.06	
$CDF_{E,y}(r_i)$, c/kWh	0.0043	0.0046	0.0099	0.0260	0.0550	0.1058	0.2104	
Cost of energy not supplied *CENS*					2.35 €/kWh			
Cost of interrupted demand *CID*					0.22 €/kW			
Whole country								
Average customer damage function *CDF*								
Interruption duration r_i	2 s	1 min	20min	1 h	2 h	4 h	8 h	24 h
$CDF_{D,y}(r_i)$, €/kW	0.33	0.51	0.90	2.13	3.50	5.86	10.72	15.27
$CDF_{E,y}(r_i)$, c/kWh	0.0070	0.0111	0.0189	0.0440	0.0711	0.1179	0.2138	0.3048
Cost of energy not supplied *CENS*					2.77 €/kWh			
Cost of interrupted demand *CID*					0.46 €/kW			

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REFERENCES

1. *Sand, K*. The Use of Payment for Electricity not Delivered in Norway: Is It Enough to Give Incentives for Investments? SINTEF Energy Research, Norway, 2003.
2. *Kariuki. K. K., Allan, R. N*. Evaluation of reliability worth and values of lost load // IEE Proc. Gener. Transm. Distrib. 1996. Vol. 143, No. 2. P. 171–180.
3. *Božič, Z*. Customer Interruption Cost Calculation for Reliability Economics: Practical Considerations // Proceedings of the IEEE. PowerCon 2000. Vol. 2. P. 1095–1100.
4. *Billinton, R., Chan, E., Wacker, G*. Probability distribution approach to describe customer costs due to electric supply interruptions // IEE Proc.-Gener. Transm. Distrib. 1994. Vol. 141, No. 6. P. 594–598.
5. CIGRE Task Force 38.06.01 Report "Methods to Consider Customer Interruption Costs in Power System Analysis". (R. Billinton, Conveyor), August 2000.
6. *Billinton, R., Tollefson, G., Wacker, G*. Assessment electric service reliability // 3rd International Conference on Probabilistic Methods Applied to Electric Power Systems. London, July 1991. P. 9–14.
7. *Tollefson, G., Billinton, R., Wacker, G., Chan, E., Aweya, J*. A Canadian customer survey to assess power system reliability worth // IEEE Trans. on Power Systems. 1994. Vol. 9, No. 1. P. 443–450.
8. *Lemström, B., Lehtonen, M*. Electricity Supply Interruption Costs. Nordic Council of Ministers, Copenhagen, 1994 [in Swedish].
9. *Allan, R.N., Billinton, R*. Probabilistic assessment of power systems // Proceedings of the IEEE. 2000. Vol. 88, No. 2. P. 140–162.
10. *Dialynas, E.N., Megaloconomos, S.M., Dali, V.C*. Interruption cost analysis for the electrical power customers in Greece. CIRED 2001, 18–21 June 2001, Conference publication No. 482, IEE 2001, Billinton R., Ali S.A., Wacker G. Reliability worth comparisons. IEEE Power Engineering Review, May 2001. P. 3–9.
11. *Kaur, N., Singh, G., Bedi, M.S., Bhatti, E.T*. Customer interruption cost assessment: an Indian survey // Proceedings of the IEEE. PowerCon 2002. Vol. 2. P. 880–884.

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