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Assessment of electricity supply interruption costs under restricted time and information resources

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Abstract: - Customers' perceptions of reliability do not always reflect the level of reliability purported by traditional reliability indices. Thus the electricity supply industry strives 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 customer interruption costs in different customer sectors of Estonia due to electric service interruptions. Because the time frame stated for the study was relatively short for the comprehensive large scale customer survey the results of the preliminary pilot survey were complemented with indirect analytical methods on base of GNP and annual household income as well as on base of analysis of corresponding characteristics of other countries. The final estimates for different customer sectors as well as for the whole country were found averaging estimates found by different methods. Estimated were characteristics of cost models most widely used by power system planners.

Key-Words: - Worth of reliability, interruption costs, outage costs, interruption cost models, customer damage function, cost of energy not supplied, customer survey.

1 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. Power system planners need to determine an adequate balance between costs and reliability for satisfying the predicted load.

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 still used in utilities of many countries including Estonian Power System. It is however difficult to justify correctly the norms or standards, which have been set, based on rules of thumb, judgment and past experience.

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 underutilized 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 among 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 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 for estimating characteristics needed to evaluate electrical supply interruption costs associated with Estonian power customers 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 consists 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 electrical interruption and relate 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 customer outage costs (*COC*) are understood here, because in general they are much bigger than utility costs. If needed, the latter are included into operation costs of the utility.

In economies with high electricity use customer outage costs are considerable. Figure 1 can illustrate this, where average annual costs of outages and voltage dips for Estonian customers are presented.

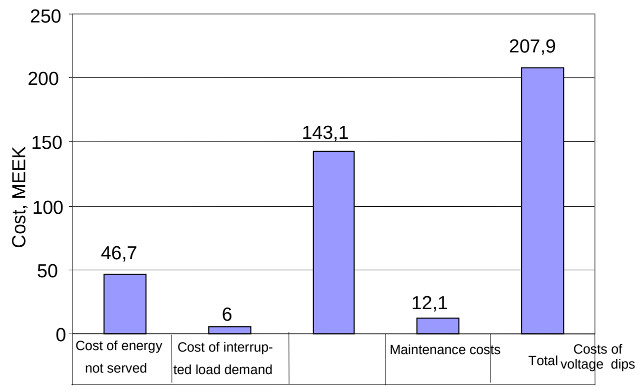

Figure 1. Outage and voltage dips costs in Estonian National Grid

To distinguish the perceived customer interruption costs (*CIC*) and the customer outage costs (*COC*) they are defined as follows [1]:

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

This paper is focused to estimation of system independent customer interruption costs *CIC*.

2 Interruption cost models

The cost models most widely used by power system planners are following.

1. *Customer Damage Function* (*CDF*) *Models* [1] – interruption costs are modeled as a function of the interruption duration. Typical interruption durations are 2 seconds, 1 and 20 minutes and 1, 4 and 8 hours.

To represent customers with different electrical consumption levels the costs are normalized, 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* are 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.

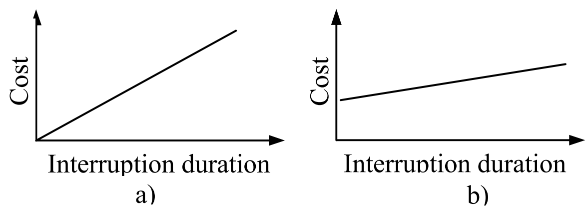

Figure 2. Interruption cost functions:
a) energy not supplied cost models and
b) combined cost model

The model implies that the cost function is a straight line passing through the origin, as is shown in Figure 2a [2].

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

If no information about the possible reliability performance of the system is available, then the interruption durations used to calculate *CENS* should be assumed to be evenly spaced over the time interval *D* of interest [2]:

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

where $CDF(r_i)$ is the ordinate of the annual peak demand normalized *CDF* 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 energy not supplied would take into account the interruption duration distribution, so representing the weighted average. The two such weighted averages in use have got specific names in the literature: Value of Lost Load (*VOLL*) [2] and Interrupted Energy Assessment Rate (*IEAR*) [3].

Starting from the annual peak demand normalized *CDF*, *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*, another is a function of the expected energy not served *EENS* [2]:

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

The model has two parameters that ascribe a cost to the interrupted demand, *CID* (€/kW interrupted), and to the unsupplied energy, *CENS* (€/kWh unsupplied).

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

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

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

3 Approach

To implement any of the models treated in previous section for assessment customer outage costs in specific practical tasks a system planner have to know 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 [4].

In general, the customer survey approach is favored by utilities. At the same time the cost and effort of conducting surveys are significantly higher than of other methods. The time frame 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 complemented with indirect analytical methods.

Case studies of particular outages were not performed, as there have not happened major, large-scale blackouts in Estonia, allowing authentic conclusions.

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

Interruptions 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.

4 Customer survey

The primary aim of the customer survey was to compose the customer damage functions for different customer sectors. Questionnaires for different sectors were designed proceeding the direct costing, indirect costing and contingent valuation methods [5]. In designing the survey experience of UK [1] and Canadian [6] as well as Denmark, Finland and Island [7] was used.

The questionnaires for residential and agricultural customers were quite similar. Besides of the direct costing the WTA (willingness to accept) and WTP (willingness to pay) approaches of indirect costing [6] were used.

The questionnaires for industrial and commercial customers were based mainly on the direct costing approach. Respondents were asked to estimate costs to their companies during various interruption scenarios including such components as lost sales, damaged goods or equipment, restarting costs, availability of standby equipment, and others. Into commercial sector were included also public customers like hospitals, churches, public transport, etc. To estimate 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 market information company TNS Emor. Residential survey was carried out by CATI (Computer Assisted Telephone Interviewing) method. For other sectors Internet survey was used. Responding rate in commercial and residential sector was low (correspondingly 26 and 46 %).

In Figure 3 the annual peak demand normalized CDF obtained by the surveys are shown. For comparison the average curves of corresponding functions of other countries are shown as well.

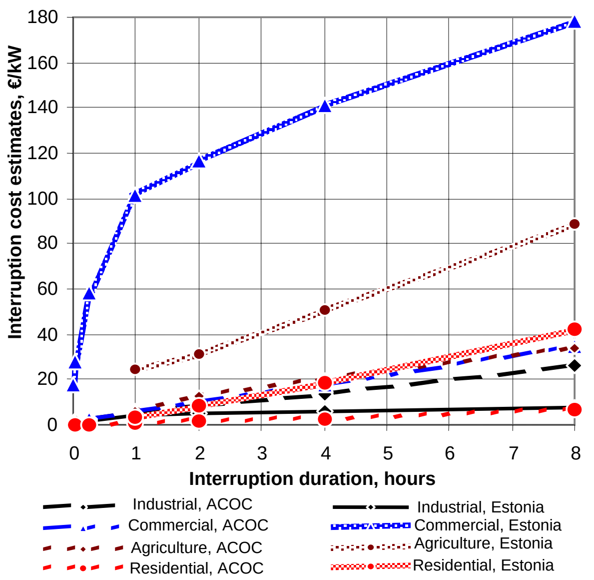

Figure 3. Peak demand normalized *CDF* obtained by the surveys. In dotted lines – the average curves of corresponding functions of other countries (ACOC)

Regrettably, practicalities did not allow realizing all of customers survey principles properly. Main reasons of that were following.

- The time frame for the surveys was much less than it has used to be in practice of other countries.
- Short time frame and limited financial resources as well did not allow conducting sufficiently bulk surveys needed to obtain reliable results.
- In spite of reference that such kind of customer surveys can be performed competently only by specially instructed personnel (e.g. by the service staff of the utility) the survey was performed without any special training of questioners. So the additional competent explanations often needed were not available.
- Questionnaires were considerably simplified to be suitable for telephone or Internet survey.
- Lists of possible answers were complemented with the answer “I can not say”. This gave to 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 the Figure 3) that respondents, particularly in commercial and agricultural sectors, strongly overestimated their costs. Realistic and relatively reliable results were obtained in industrial sector.

So, the customer survey concerned can be treated as a pilot one, which results, except in industrial sector, were not authentic. However, the survey gave substantial experience for conducting more extensive surveys in future.

5 Use of analytical methods

First, the costs of energy not supplied were determined using simple macro methods [5]. In industrial, commercial and agricultural sector *CENS* were calculated by dividing the annual *GNP* in a sector by electric energy sold to 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 deriving interruption cost characteristics from corresponding values of other countries. In this purpose customer damage functions *CDF* in different customer sectors of

Canada [6,8], UK [1], Finland, Denmark and Island [7], Greece [9], Tai and Nepal [10] and India [11] were analyzed.

The *CDF* of different countries can be easily and directly compared using prevailing exchange rates (ER). As an example, Figure 4 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.

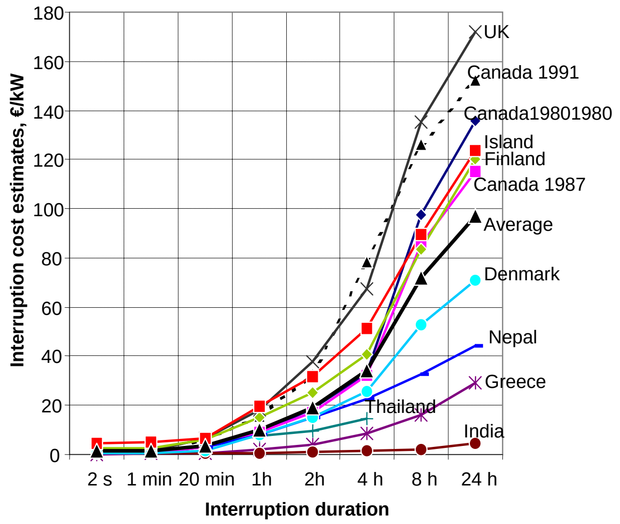

Figure 4. Commercial sector CDF based on exchange rates

However, comparing interruption costs on base 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 meaningful approach to compare the worth of electric service reliability in various countries is to incorporate the prevailing socioeconomic conditions of each country into the analysis using a purchasing power parity (PPP) estimate [10]. A PPP estimate reflects the purchasing power of the inhabitants of a country and depends on market value. So a more meaningful quantitative comparison across countries is possible. As an example, Figure 5 shows the comparison of commercial sector *CDF* based on PPP estimates.

It can be seen from Figures 4 and 5 that the curve shapes for the two methods are similar, but placement of curves for different countries is not the same. 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 other sectors.

The customer damage function estimates for Estonia were derived from the average curves of PPP estimates as more meaningful ones were issued.

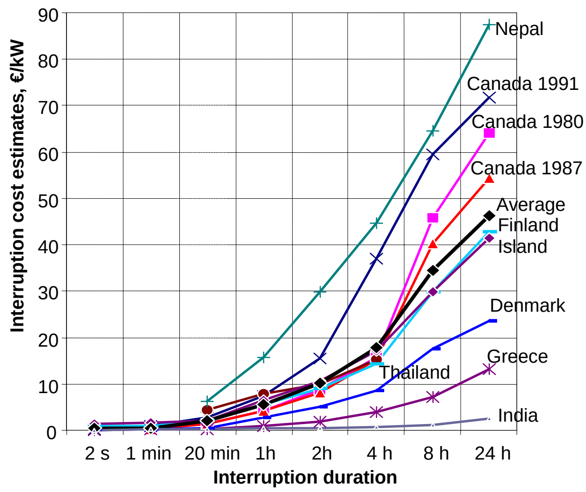

Figure 5. Commercial sector CDF based on PPP estimates

6 Final results

From results obtained by aforesaid methods, estimates of annual peak demand normalized *CDF*, annual energy consumption normalized *CDF*, cost of energy not supplied and cost of interrupted demand were derived.

Figures 6-9 show the peak demand normalized *CDF* obtained in different ways as well as the final estimate for different customer sectors. Surveys of commercial and agricultural customers practically failed (see Figure 3), whereby they are not taken into account.

Results of residential customers survey are obviously overestimated as well. Nevertheless they are considered, but with lower weigh, taking into account answers on willingness to pay for avoiding interruptions.

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

Shares of sector consumptions in the total consumption were used as weight coefficients. Figure 10 shows the final estimates of peak demand normalized *CDF* for different sectors and for Estonia as a whole.

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.

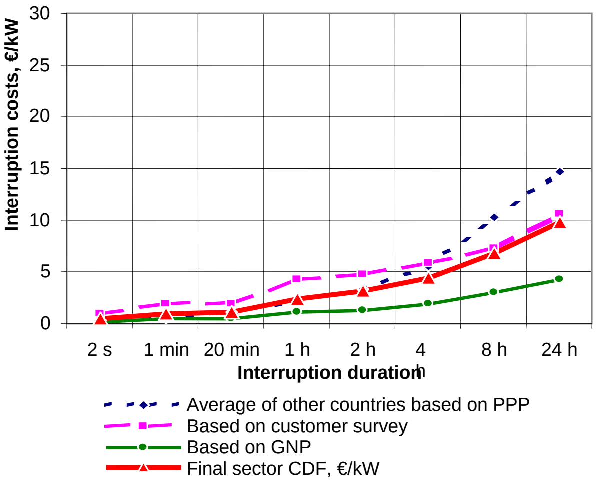

Figure 6. Peak demand normalized *CDF* for industry

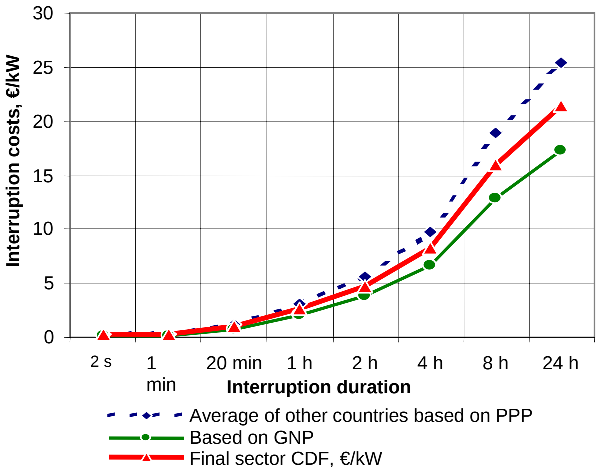

Figure 7. Peak demand normalized *CDF* for commercial sector

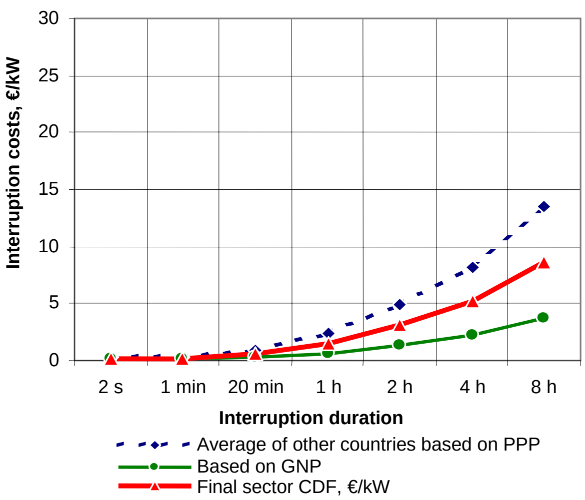

Figure 8. Peak demand normalized *CDF* for agriculture sector

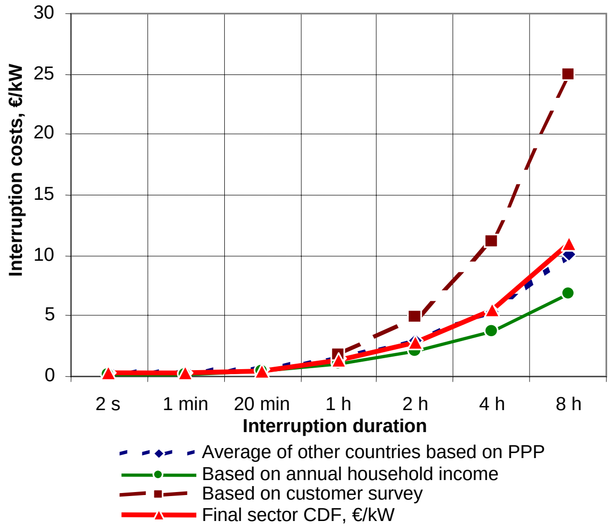

Figure 9. Peak demand normalized *CDF* for residents

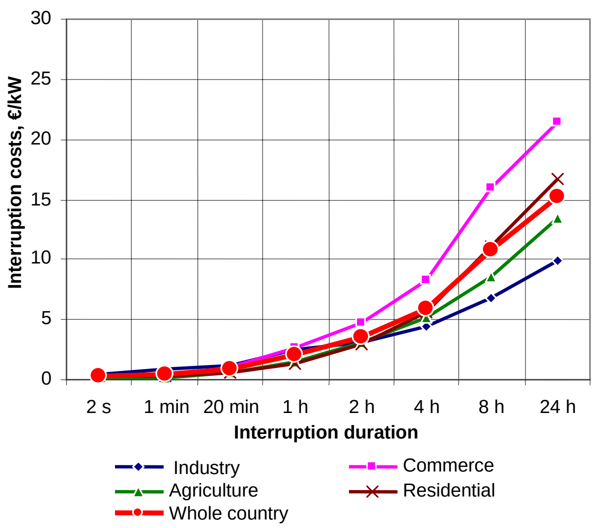

Figure 10. Final estimates of peak demand normalized *CDF* for different customer sectors and whole Estonia

The values of *CENS* and *CID* for customer sectors were obtained in different ways. Calculations were based on *GNP*, on annual household income (for residential customers), on average *CDF* of other countries (*AOC*) and on results of customer survey (for industrial and residential customers). Final estimates were determined as averages on base of final sector *CDF*.

CENS and *CID* for the whole country were determined on the base of whole country's *CDF* as weighted average of sectors' values. Figure 11 shows the final estimates of *CENS* and *CID* for sectors and for Estonia as a whole.

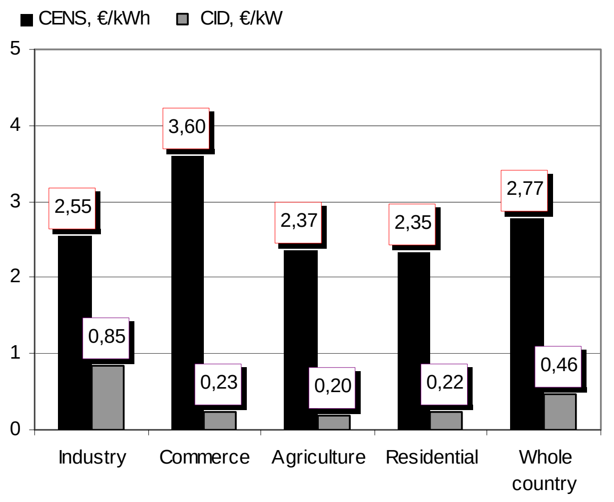

Figure 11. Final estimates of *CENS* and *CID* for different customer sectors and for whole Estonia

7 Conclusions

Evaluation of the costs associated with future expansion/reinforcement options is a standard planning procedure amongst power utilities. There is now a growing recognition of the need to consider the economic link between the cost of providing a certain level of reliability and its value to customers. The evaluation of the societal worth of electric service reliability, i.e. the cost of unreliability, however, is still in its infancy in many countries including Estonia.

Use of different reliability worth evaluation models briefly overviewed in the paper need certain interruption cost characteristics such as customer damage functions, cost of energy not supplied and cost of interrupted demand. This paper presents the outcome of the study provided to estimate these characteristics for main Estonian customer sectors as well as for the whole country. Due to a short time frame given for the study a preliminary small scale customers survey was complemented with indirect analytical methods on base of GNP and annual household income as well as on base of analysis of corresponding characteristics of other countries. Though such approach is rather approximate, the results were relatively realistic and made available a set of generic data that can be used in initial stages of reliability worth evaluation. Additionally, the study gave a valuable experience for providing comprehensive large-scale customer surveys in future to achieve more accurate results.

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