ISSN 1330-3651
UDC/UDK 621.311 : [657.47 : 519.248]

SURVEY ON CUSTOMER POWER SUPPLY INTERRUPTION COSTS AND CALCULATION OF EXPECTED CUSTOMER DAMAGES

Damir Šljivac, Zdenko Šimić, Marinko Stojkov

Original scientific paper

The paper presents the methodology on survey of the customer power supply interruptions and the results of the conducted survey in order to assess the customer interruption costs (*CIC*) depending on the interruption duration. The survey was conducted in 2004 and 2005 on over 100 households mostly from the city of Osijek and other urban and rural areas in Eastern Croatia. In addition one large industrial user has been surveyed in order to compare the results of different types of power system customers (consumers). Customer damage functions (*CDF*) have been determined and the calculation of expected damages, i.e. overall expected customer outage costs (*COC*) is presented using a developed Visual Basic algorithm for customer supply reliability analysis.

Key words: *power supply, customer, interruption costs, survey, households, expected damages*

Anketa o troškovima prekida opskrbe električnom energijom potrošača i proračun očekivanih šteta potrošača

Izvorni znanstveni članak

Članak predstavlja metodologiju anketiranja o troškovima prekida opskrbe električnom energijom potrošača i rezultate provedene ankete s ciljem određivanja troškova prekida opskrbe potrošača (*CIC*) ovisnih o trajanju prekida. Anketa je provedena u 2004. i 2005. na više od 100 kućanstava uglavnom iz grada Osijeka i drugih urbanih i ruralnih područja u istočnoj Hrvatskoj. Dodatno, anketiran je jedan veliki industrijski potrošač s ciljem usporedbe rezultata različitih tipova potrošača (kupaca). Utvrđene su krivulje štete potrošača i prikazan proračun očekivanih šteta, tj. ukupnih očekivanih troškova prekida opskrbe potrošača u sustavu (*COC*) korištenjem razvijenog Visual Basic algoritma za analizu pouzdanosti opskrbe potrošača.

Ključne riječi: *opskrba električnom energijom, potrošači, troškovi prekida opskrbe, anketa, kućanstva, očekivana šteta*

1 Customers' characteristics and interruption consequences

Karakteristike potrošača i posljedice prekida opskrbe

In order to assess customer power supply interruption costs it is necessary to understand the nature and variety of their consequences on customers and utilities. Figure 1 [1] represents direct economic and social, as well as indirect consequences of utility outages and customer power supply interruptions regarding the possibility to assess their actual value in money. It is important to stress that the direct economic consequences are those easier to assess, but the impact of other (direct social and indirect consequences is certainly not negligible. Therefore any attempt trying to put the value to the customer interruption cost should clearly state the nature of the consequences being assessed.

Customer interruption costs depend mostly on both customer characteristics (ways their activities depend on electricity usage, their size, demography, load curve) and the nature of the interruptions themselves (duration, frequency, energy not served, area and number of customers affected). There are several customer types, usually defined

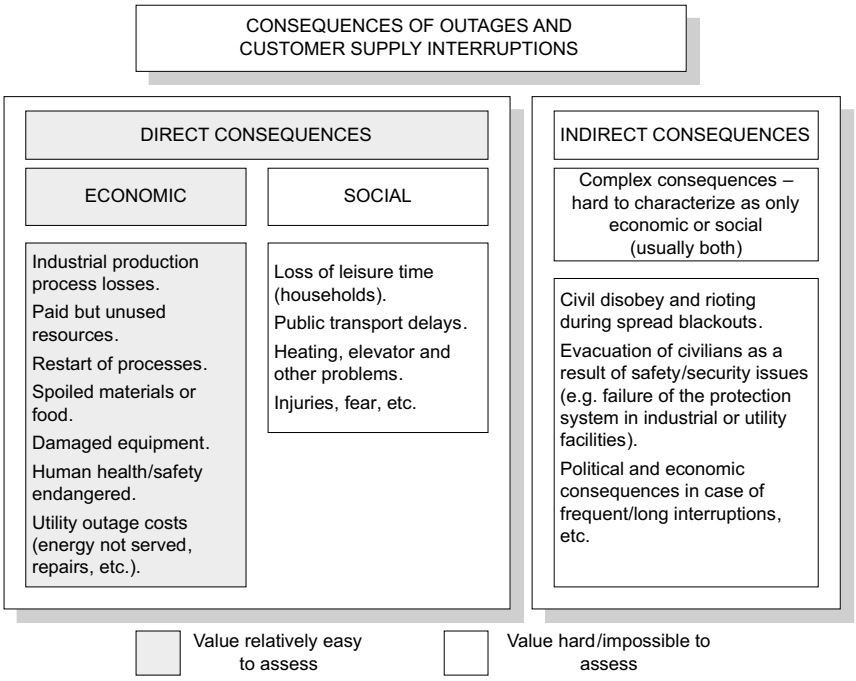

Figure 1 *Consequences of power system outages and customer supply interruption*
Slika 1. *Posljedice zastoja u elektroenergetskom sustavu i prekida opskrbe potrošača*

by their nature of electricity usage as [1]:

- Households
- Agriculture
- Commercial Users (service providers – no direct production)
- Government, Institute and Office Buildings (finance, insurance, education, health, social...)
- Industrial Users (productive process involved)
- Large Users (industrial with consumption over determined value).

Since conducted survey is focused on the largest group of electricity consumers - households it is important to stress that in Croatian tariff system [2] they are defined as so called "consumers on low voltage – households", together with other low-voltage consumers: public lighting and commercial users (up to 1 kV). Other groups in [2] are so called medium (>1 to <110 kV) and high (≥ 110 kV) voltage consumers.

2
Methodology for estimation of customer interruption costs

Metodologija za procjenu troškova prekida opskrbe potrošača

Numerous methods have been used for estimation of customer interruption costs, such as [1]:

- Indirect analytical methods
- Blackout reports and studies
- Direct customer survey.

Indirect analytical methods are simple, trying to determine the value of supply service indirectly through: worth of willingness to pay (WTP) for the service (underestimated by consumers), worth of willingness to accept (WTA) the interruptions (overestimated by consumers), deriving interruption costs from national GDP and overall electricity consumption (not related to interruptions but to more or less continuous supply), deriving value of lost leisure time from average incomes (not directly eligible), etc. The problem is that those methods are limited by using the unrealistic assumption and also that they enable only overall/average costs estimation.

Blackout reports are extensive, precise in direct economic and even up to a certain point direct social and indirect interruption consequences estimation but limited only to non-probable widely spread infrequent outages in transmission power system usually not related at all to frequent but limited interruptions in distribution network causing the most problems for most of the customers in the system.

In direct customer surveys customers are surveyed on series of questions regarding their characteristics, energy consumption and most importantly on direct cost estimation of interruptions of different duration, frequency, time of occurrence in case of industrial and commercial users which are usually able to perform the direct cost estimation. For households – the most important fact is their opinion on issues regarding power supply quality and reliability in order to assess also the social and other indirect costs.

The significant limitation of the method is the necessity to conduct the survey on a large number of customers in order to ensure the liability resulting in higher financial and human resource requests compared to other methods. On the other hand, direct customer survey methods can cope with several issues related to customer interruption costs, namely:

- Customer interruption costs being dependable on interruption characteristics (duration, frequency...)
- Customer interruption costs being dependable on customer type (energy usage characteristics)
- Enabling DCE: direct costs estimate eligible for non-domestic customers
- Determining VoLL: value of lost load (supply interruption) applicable to households by willingness to perform preparatory actions (PAM: Preparatory Actions Method), i.e. willingness to invest in supply reliability.

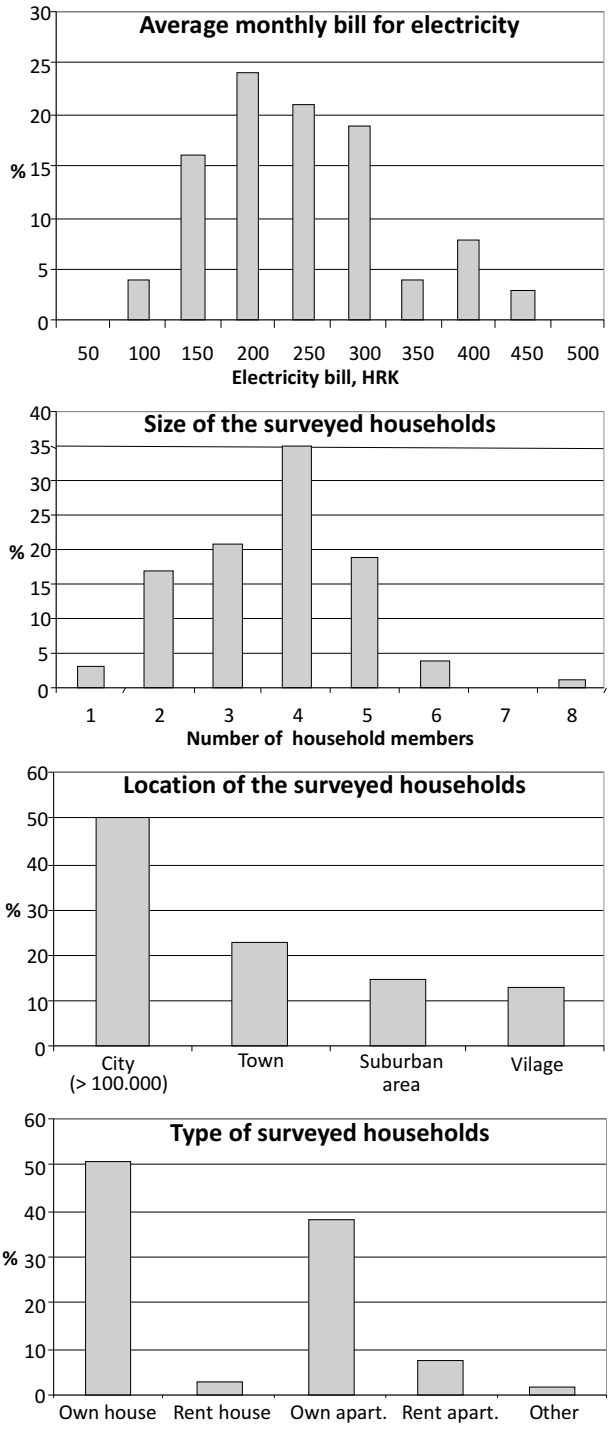

Figure 2 *Surveyed households basic characteristics*
Slika 2. *Osnovne karakteristike anketiranih kućanstava*

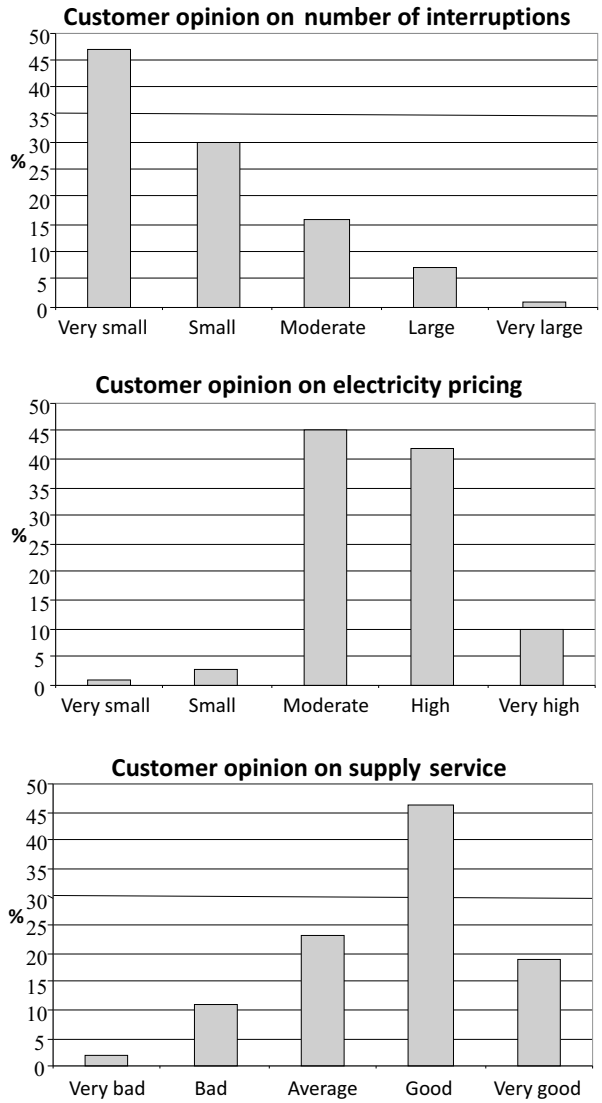

Figure 3 *Customer opinions on supply service and electricity pricing*
Slika 3. *Mišljenje potrošača o usluzi opskrbe i cijeni električne energije*

3
Direct customer survey results
Rezultati izravnog anketiranja potrošača

Considering that no survey on customer interruption has been conducted in Croatia, the authors have benefitted from the experience of the extensive work on customer surveying being reported worldwide [1]. In order to determine the customer supply interruptions in the conducted survey of household customers in Eastern Croatia the Preparatory Actions Method was chosen from [3], but the questionnaire was written and modified by several pilot surveys in order to ensure the eligibility of the method in Croatian electricity market environment. The questionnaire for large industrial user used modified Direct Costs Estimate method from [4] mostly ensuring the power quality standards in Croatia [5] regarding the duration of momentary, short and long interruption (EN 50160) to be presented in the survey. More on conducted survey and questionnaires will be presented in what follows.

3.1
Customer interruption costs for households in Eastern Croatia
Troškovi prekida opskrbe za kućanstva u istočnoj Hrvatskoj

Figure 2 presents the basic information on characteristics of over 100 customers surveyed during 2004 and 2005 [6] mostly from the city of Osijek and other urban and rural areas in Eastern Croatia. Figure 3 presents the surveyed opinions of customers regarding power supply service (as expected generally good/very good) and electricity pricing (as expected generally moderate/high), while Figure 4 presents the results of the survey on customer interruption experience which indicate the significant discrepancy between the average experienced interruption in rural and urban areas. All of this has a significant influence on the willingness to pay (WTP) for the supply reliability and to accept (WTA) the supply unreliability for different users presented in Figure 5.

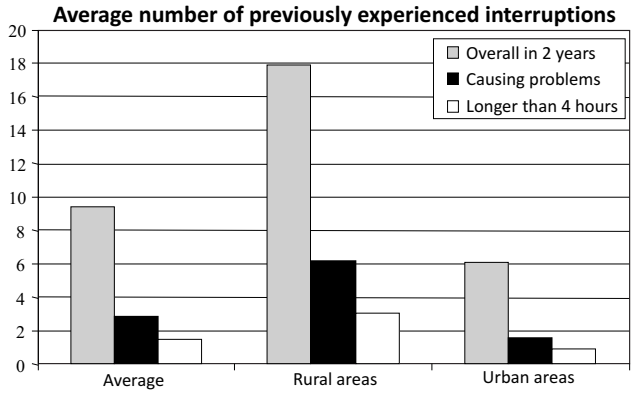

Figure 4 *Customer' previous experiences in supply interruptions*
Slika 4. *Prethodno iskustvo potrošača s prekidima opskrbe*

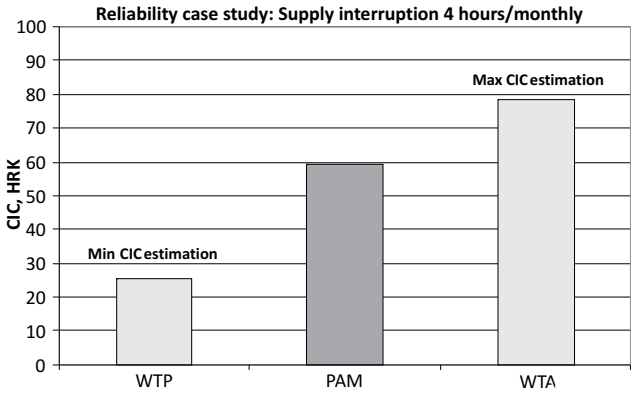

Figure 5 *Customer interruption costs estimated by WTP, PAM and WTA method*
Slika 5. *Troškovi prekida opskrbe potrošača procijenjeni s WTP, PAM i WTA metodom*

Further on, the surveyed customers are mostly concerned (in their own opinion) with problems regarding lightning (old), computer equipment failures (young), kitchen suppliences (women), loosing leisure time (men), while the rioting, accidents and fear are not high on the list of undesired effects of customer interruptions, as well as cleaning which is obviously a postponable action. The survey also indicates that the increased frequency and occurrence of interruptions during leisure time influence positively the customers' willingness to pay (WTP) as well

Table 1 *Average customer interruption costs (CIC) for households in HRK*
Tablica 1. *Srednji troškovi prekida opskrbe potrošača (CIC) za kućanstva u HRK*

Average customer interruption costs	Duration and frequency of supply interruptions					
CIC, HRK	20 min monthly	1 h monthly	2 h monthly	4 h monthly	4 h weekly	1 h daily
WTP	-	-	-	25,35	41,68	58,22
PAM	**0,93**	**4,93**	**15,22**	**59,12**	**170,36**	**-**
WTA	-	-	-	78,46	-	-

as readiness to conduct preparatory avoiding actions (PAM). These are highly important opinions influencing the overall results of the survey and are investigated thoroughly during and after the survey.

As presented earlier and indicated here the preparatory action method (PAM) yields results that are the least influenced by customer age, gender, education and urbanisation level, and is the most appropriate for domestic customers to put the value of interruption cost enabling also the customer interruption costs (CIC) to be defined as a function of interruption duration. Therefore, in prepared questionnaire customers were offered a number of preparatory actions together with expected incurred costs, i.e.:

- Don't do anything – put up with the interruptions
- Purchase candle(s) (1 HRK/hour each)
- Purchase battery/petroleum lamp(s) (5 HRK/hour each)
- Use a cooker on gas/petrol for heating/cooking (12 HRK/hour)
- Rent or purchase small domestic generator (60 HRK/hour) – for basic electricity supply
- Rent or purchase large domestic generator (240 HRK/hour) – for overall electricity supply
- Other activities: name and value them.

Customers usually named additional readiness for purchasing uninterruptible power supply (UPS) in order to prevent damages of highly sophisticated computer and electronic equipment which should be included in future surveys.

The basic results of all used methods in the conducted household survey are presented in form of the average customer interruption costs (CIC) in Table 1.

Table 1 and Figure 5 indicate several conclusions:

- Cost of supply interruptions depends non-linearly on their duration, particularly high increase is found for longer and frequent durations – which are expected with the rise of the customers' willingness to invest in derogated reliability.
- WTP and WTA methods yield respectively the minimal and the maximal value of lost load, due to the fact that customers always underestimate willingness to pay for improving the supply reliability and overestimate (in money terms) the acceptance for the exact opposite derogation of the supply reliability, e.g. for 4-hours interruption once a month.
- It is obvious that the PAM reduces the antagonism of WTP vs. WTA method and is also less influenced by the customers' experience and opinions, therefore is adopted as a principal method for determining the customer damages induced by supply interruptions in chapter 4.

3.2
Customer interruption costs for a single large user in Eastern Croatia
Troškovi prekida opskrbe za pojedinačnog velikog potrošača u istočnoj Hrvatskoj

In 2004 a survey on one large industrial user in Eastern Croatia was performed, using a direct costs estimate (DCE) method due to the fact that such customers are not influenced by subjective opinions and experiences, instead they are usually very familiar with their productive process and electricity usage as well as with cost induced by supply interruptions of different duration and frequency.

The questionnaire was taken from [4] and modified to ensure the power quality standards [5] regarding the interruption duration (EN 50160). It consists of several sections:

- Basic users data: company name and address, function of surveyed customer, main products, number of employees, individual monthly electricity consumption, peak power, power factor.
- Electricity usage data: productive process, UPS existence and usage, own electric energy production (type and size of industrial power plant).
- Customer interruption costs – direct estimate: time necessary for restoration of production after interruption, cost of production interruption, labour extra hours, material and products lost, damaged equipment, additional start-up costs, other (name and value).

Results are presented for two case study scenarios determined by user's electricity usage:

- Case 1: failure of 110 kV network supply resulted in stability of own power plant, all load is lost, production terminated
- Case 2: failure of 110 kV network supply resulted in failure of own power plant, all load is lost, production terminated, start-up of own power plant turbines and generator necessary.

Figure 6 presents the basic results of the survey in form of customer interruption costs in HRK for two case study scenarios.

Customer interruption cost for large industrial user having continuous productive process is driven by lost production that cannot be reproduced, by paid but not used labour hours, damage of equipment (particularly micro-computer control system) and some spoiled materials. This is very prices estimation opposite to one of the domestic users influenced highly by opinions rather than facts.

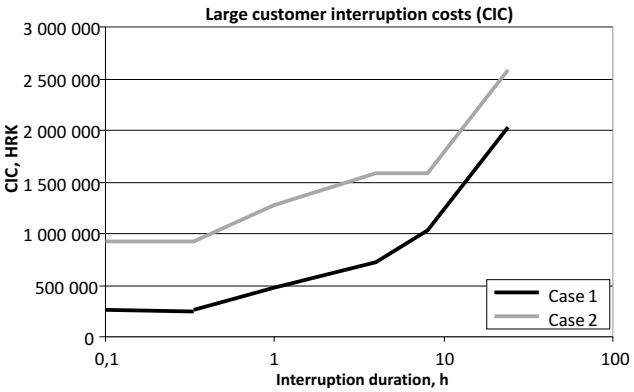

Figure 6 *Customer interruption costs (CIC) for the large user*
Slika 6. *Troškovi prekida opskrbe velikog potrošača (CIC)*

4
Customer damage functions and their application in reliability analysis
Kivulje štete potrošača i njihova primjena u analizama pouzdanosti

4.1
Calculation of customer damage functions
Proračun krivulja šteta potrošača

As can be noticed customer interruption cost in HRK of households (Table 1) and large users (except for the fact that they are both increasingly non-linearly dependable on supply interruption duration) are not comparable. This is due to the fact that the size (peak power and/or energy consumption) is very different for different types of customers. Therefore, in order to conduct the cost-benefit analysis of the estimated costs it is necessary to normalise the customer interruption costs (*CIC*) by energy consumption and/or peak power and obtain so-called customer damage functions *CDF* which can be determined using the following equations:

$$CDF_E(t) = \frac{1}{n}\sum_{i=1}^{n}\frac{CIC_i(t)}{E_i} \text{ or}$$
$$SCDF_E(t) = \frac{1}{n}\sum_{i=1}^{n}\frac{CIC_i(t)}{E_i}. \quad (1)$$

$$CDF_L(t) = \frac{1}{n}\sum_{i=1}^{n}\frac{CIC_i(t)}{L_i} \text{ or}$$
$$SCDF_L(t) = \frac{1}{n}\sum_{i=1}^{n}\frac{CIC_i(t)}{L_i}. \quad (2)$$

where are:
$CDF_E(t)$ - Customer damage function normalised by annual electric energy consumption E_i of customer i depending on interruption duration t, kn/MWh
$SCDF_E(t)$ - Sector customer damage function normalised by annual electric energy consumption where sector represents all customers of the same type (i.e. households, commercial...), kn/kW
$CDF_L(t_{po})$ - Customer damage function normalised by peak load L_i of customer i depending on interruption duration t
$SCDF_L(t_{po})$ - Sector customer damage function normalised by peak load where sector represents all customers of the same type (i.e. households, commercial...)
$CIC_i(t)$ - Interruption costs of customer i depending on interruption duration
n - Number of customers of each sector or load group (could have several sectors).

Table 2 presents the (sector) customer damage function (*SCDF*) calculated from the survey data for households normalised by both electricity consumption and peak load.

Table 2 *Sector customer damage function (SCDF) for households*
Tablica 2. *Tipska krivulja štete potrošača (SCDF) za kućanstva*

Sector customer damage function SCDF - households	Interruption duration			
	20 min	1 h	2 h	4 h
Normalised by energy consumption, HRK/MWh	0,22	1,12	3,38	12,96
Normalized by peak value, HRK/kW	0,77	3,92	11,88	45,40

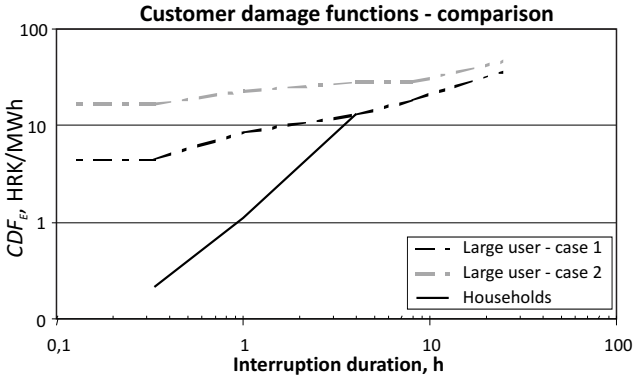

Figure 7 *Comparison of customer damage functions for households and large user*
Slika 7. *Usporedba krivulja šteta potrošača za kućanstva i velikog potrošača*

Figure 7 presents the comparison of *SCDF* for household and *CDF* for a single large user, both normalised by annual energy consumption estimated in survey for household from average electricity bill or indicated directly by large user.

Customer damage functions normalised by annual energy consumption or peak value do not represent the value of energy or power not served used often for reliability calculation, but are used to calculate the overall expected customer outage costs depending on the so-called composite customer damage functions derived from the ratio of energy consumption of each sector or other group of customers at each load node or/and in the distribution or transmission system:

$$CCDF_E(t) = \sum_{j=1}^{m}\left(CDF_{Ej}(t)\cdot\frac{\sum_{i=1}^{n_j}E_{ij}}{\sum_{j=1}^{m}\sum_{i=1}^{n_j}E_{ij}}\right), \text{ HRK/MWh} \quad (3)$$

$$CCDF_L(t) = \sum_{j=1}^{m}\left(CDF_{Lj}(t)\cdot\frac{\sum_{i=1}^{n_j}L_{ij}}{\sum_{j=1}^{m}\sum_{i=1}^{n_j}L_{ij}}\right), \text{ HRK/kW} \quad (4)$$

where are:
$j = 1, \ldots, m$ - Customer group j with m customers (if j consist of single sector customers – $SCDF$ is used instead of CDF in the equation)
$i = 1, \ldots, n_j$ - Customer i from group j with n_j being overall number of customers in group j
$(S)CDF_{Ej}$ - (Sector) Customer damage function for group j
E_{ij}; L_{ij} - Annual consumption and peak load of customer i in group j.

4.2
Probabilistic analysis of expected damages – overall customer outage costs (*COC*)
Vjerojatnosna analiza očekivanih šteta – ukupni troškovi prekida opskrbe potrošača (*COC*)

Composite customer damage functions presented in previous section of the paper present only input data for possible calculation of expected overall damages in the system. In order to calculate those damages the customer outage costs *COC* are introduced [1]:

$$COC_j = \frac{1}{N}\sum_k L_j \cdot CCDF_{Lj}(t_{jk}) \text{ or}$$
$$COC_j = \frac{1}{N}\sum_k E_j \cdot CCDF_{Ej}(t_{jk}), \quad (5)$$

where are:
COC_j - Expected customer outage costs at load node j, HRK/year
$t_{po,ik}$ - Interruption duration at load node j due to the failure k
N - Simulation years.

Using developed sequential Monte Carlo algorithm in [6] with switching procedure algorithm reported in [7] based on simulation of random numbers and transforming them using the reliability models from [8], taking into account time-dependent failure rate [9] and its distribution [10] for components taking into account advanced failure data collection [11] it is possible to predict the operational history of the system and to evaluate the customer outage costs at each load node and generate the overall system customer outage costs (*SCOC*), where [6]:

$$SCOC = \sum_j COC_j = \frac{1}{N}\sum_j\sum_k L_j \cdot CCDF_{Lj}(t_{jk}), \text{ or} \quad (6)$$

$$SCOC = \sum_j COC_j = \frac{1}{N}\sum_j\sum_k E_j \cdot CCDF_{Ej}(t_{jk}). \quad (7)$$

SCOC, HRK/year

Table 3 represents the calculated system customer outage costs for the distribution case study system presented on Figure 8.

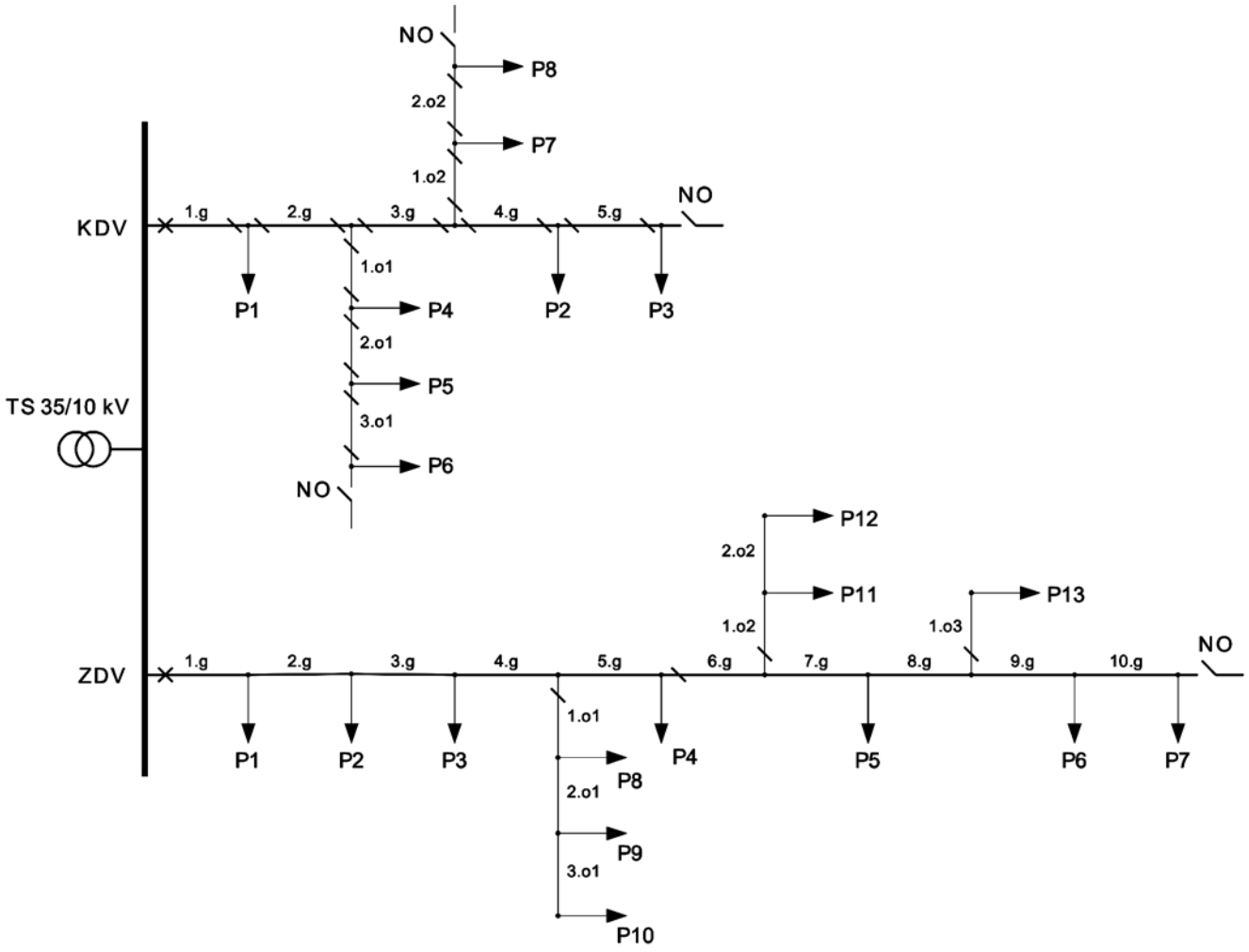

Figure 8 *Distribution case study system for customer outage costs calculation*
Slika 8. *Distributivni test sustav za proračun troškova prekida opskrbe potrošača*

Table 3 *System customer outage costs (SCOC) – case study distribution system*
Tablica 3. *Troškovi prekida opskrbe svih potrošača u sustavu (SCOC) – distributivni test sustav*

Overall (expected) annual *SCOC* = 1 108 242,54 HRK/year							
Expected customer outage costs of KDV (cable urban feeder): COC_{KDV} = 106 289,10 HRK/year							
P1 total	P2 total	P3 total	P4 total	P5 total	P6 total	P7 total	P8 total
12 327,41	12 828,16	13 380,72	13 478,56	14 018,53	13 845,62	13 079,21	13 320,88
Expected customer outage costs of *ZDV* (overhead line rural feeder): COC_{ZDV} = 1 001 953,44 HRK/year							
P1 total	P2 total	P3 total	P4 total	P5 total	P6 total	P7 total	
74 025,78	74 615,39	74 595,90	74 749,53	57 863,51	57 990,18	57 299,28	
P8 total	P9 total	P10 total	P11 total	P12 total	P13 total		
110 908,36	110 482,86	111 119,64	67 635,58	68 218,36	62 449,07		

5
Conclusion
Zaključak

A survey on over 100 households has been performed and the results of the survey in form of customer interruption costs (*CIC*) and customer damage functions (*CDF*) have been derived. This is the first ever survey on supply interruption costs in Croatia and this paper presents a significant contribution particularly having in mind the incoming electricity market in Croatia. By knowing (system) customer outage costs (*SCOC*) calculated from customer damage functions it is possible to perform the probabilistic cost-benefit analysis and planning for many different investments scenarios. Probabilistic planning in open electricity market environment has an overwhelming impact due to the fact that deterministic planning procedures are not focused on minimization of costs / maximization of the benefits of investments in reliability of the system which is in a very base of the market competition.

6
References
Literatura

[1] CIGRE Task Force 38.06.01.: *Methods To Consider Customer Interruption Costs in Power System Analysis* // CIGRE, Paris, France, August, 2001.
[2] Vlada Republike Hrvatske: *Tarifni sustav za usluge elektroenergetskih djelatnosti koje se obavljaju kao javne usluge* // Narodne novine, broj 101/2002.
[3] Kariuki, K. K.; Allan, R. N. *Assessment of Customer Outage Costs Due to Service Interruptions. Residential Sector* // Proceedings IEE – Generation, Transmission, Distribution, 1996, 143 part C, pp. 163-170.
[4] Dialynas, E. N. *Assessment of Power Interruption Costs for the Industrial and Commercial Customers in Greece* // Final Report, Athens, Greece, May 1999.
[5] CENELEC, European Comittee for Electrotechnical Standardization: *European Standard EN 50160*, English Version // November, 1994.
[6] Šljivac, D. Probabilistic Cost Analysis of Electric Energy Supply Interruptions // PhD thesis, Faculty of Electrical Engineering and Computing, Zagreb, Croatia, June, 2005.
[7] Šljivac, D.; Nikolovski, S.; Kovač, Z. Distribution Network Restoration Using Sequential Monte Carlo Approach // Proceedings of the 9th International Conference on Probabilistic Methods Applied to Power Systems, Stockholm, Sweden, 2006.
[8] Mikuličić, V.; Šimić, Z. Electric Power System Reliability, Availability and Risk Models // Kigen, Zagreb, 2008.
[9] Vrbanić, I.; Šimić, Z.; Šljivac, D. Prediction of the time-dependent failure rate for normally operating components taking into account the operational history // Kerntechnik, 73, 4(2008), pp. 190-196.
[10] Brown, R. E. *Electric Power Distribution Reliability* // Marcel Dekker, New York, 2002.
[11] Stojkov, M.; Komen, V.; Šljivac, D. Improved Procedures of Distribution Power Network Failure Data Collection for Supply Availability Index Evaluation // Strojarstvo, 51, 2(2009), pp. 127-138.

Authors' addresses:
Adrese autora:

Doc. dr. sc. Damir Šljivac, Associate Professor
Faculty of Electrical Engineering
Josip Juraj Strossmayer University of Osijek

Doc. dr. sc. Zdenko Šimić, Associate Professor
Faculty of Electrical Engineering and Computing
University of Zagreb

Doc. dr. sc. Marinko Stojkov, Associate Professor
Faculty of Mechanical Engineering in Slavonski Brod
Josip Juraj Strossmayer University of Osijek