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Economic Impact of Electricity Interruptions: A Case Study Based on Sri Lanka

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Abstract: A power system responsible to supply reasonable level of reliable, qualitative electricity supply to its consumers in an acceptable price. Reasonable level is defined as one balancing the need for power supply and the cost involved. This includes increasing adequacy and security of the system. If the frequency and duration of outages can be reduced, the benefit can be given to consumers. Cost of Unserved Energy is considered as a basic parameter of economic evaluation in the process of increasing the power system reliability. Initial research was conducted before two decades ago and now it is needed to conduct a study of up-to-date on the scope. Thus, research to assess the cost of Unserved Energy for Sri Lanka was conducted and the outcome of the research is presented in this research paper. Consumer survey is chosen as the methodology of the research and it is conducted into three separate electricity consumer categories of domestic, industrial and Commercial. Each category is sub-grouped according to different classifications and separate results have shown for momentary planned and unplanned and non-momentary planned and unplanned interruptions. Finally, the results of each category are averaged into two final values one each for each classification considered.

Keywords: Unserved Energy, Cost of Unserved Energy Consumer Survey, GDP, Electricity Interruptions

1. Introduction

Electricity is important in economic development of a nation and it cannot be overemphasized as the access to reliable electricity increases the productivity and public well-being. As being an island in the Indian Ocean, Sri Lanka having the area of 65,610km^2 in land and sea. It has a tropical climate with two tropical monsoons named as northeast and southwest. It is blessed with many natural resources including gems, mineral sand, graphite, limestone, hydropower, phosphate and clay. With USD 81.32 billion GDP value and USD 3,835 GDP per capita value, Sri Lanka is a middle-income country [1]. Since the end of the three-decade long civil conflict in 2009, Sri Lanka is now focusing on meeting the long term strategic and structural development challenges as it strives to transit to the group of upper middle-income countries. Over 50% of total GDP contain Services and main economic sectors are tourism, tea and rice production, and apparel and gem industries. Biomass or fuel wood, imported petroleum/coal and hydro are the major primary energy supply sources in Sri Lanka. At the end of 2016, 98.7% of the total population had access to electricity from national electricity grid [2] and now it is increased to almost 100%. Now the power industry focus is more to increase the quality and reliability of the power system.

In the agenda of increasing the quality of service minimizing power interruptions take high priority. Since both the interruption durations and frequency are too high in Sri Lanka many investments are to be made in order to improve the situation. In order to justify such investments an assessment of the cost avoided through improved supply continuity becomes vita.

This research focuses the attention of costs incurred due to the interruptions of electricity to customers. Impacts of momentary interruptions (of duration less than 6 seconds) and non-momentary interruptions, separately considered unplanned and planned interruptions. Planned interruptions are pre-announced and imposed in order to carry out maintenance work by the supply authority. Unplanned interruptions are caused due emergency switching or break down without pre-informing to the customers. Forced interruptions of transmission and distribution failures are taken together into this category.

A mathematical model or a function is defined and used for the assessment of Cost of Unserved Energy. Customer Damage Function (CDF) is introduced to identify the economic loss incurred to the consumers because of power outages. CDF quantifies the monetary amount of damage per outage, per kWh of Unserved Energy or per kWh annual consumption of energy. The advantages of this method are low cost, easy to repeat and use of publicly available data. The major disadvantages are no feedback is taken from the customers; all the customer categories are taken together leading to high error margin.

2. Concept of Cost of Unserved Energy

Cost of Unserved Energy is an economic concept that is intended of measurement of willingness of electricity customers to pay to avoid a period of time without power or, conversely, the willingness of electricity customers to accept compensation for a period of time without power. This value is used to make a number of investment and refurbishment decisions on the electrical power system, with the aim of optimizing the reliability of the network.

Further it can be argued that the it is a key economic evaluation parameter used for make decisions in investments to upgrade and refurbish the network of each level of power systems.

In generation planning, Cost of Unserved Energy important to assess whether generation capacity is adequate or not. This planning is targeted to achieve economic growth and minimizing the total losses in the economy resulting from interruptions.

Cost of Unserved Energy is one of the main parameters used in Transmission Planning as well. The economic impact of losing a load or not being able to supply a load needs to be determined before a decision is made in an investment. Cost of Unserved Energy is used in the justification of capital expenditure required to implement a project and the justification is done by The Least Economic Cost (LEC) method [3].

Distribution needs Cost of Unserved Energy for load forecasting, reliability-based planning and investment decisions. In load forecasting process, it requires economic impact measurement disaggregated by substation level and by economic segment. This requirement is fulfilled by Cost of Unserved Energy. Reliability based planning requires Cost of Unserved Energy in a similar way to Generation to support capital breakeven planning. Distribution Planning requires Cost of Unserved Energy for Infrastructure Investment for various alternatives. The Cost of the project to the electricity utility is weighted against the cost impact to customers' energy if the project is not done.

Different methodologies are used to Cost of Unserved Energy assessments, including case studies, econometric methods and consumer surveys [4-6]. Case Studies are carried out after significant blackouts which affect large areas and a large number of customers. This study covers direct and indirect costs of interruptions. The advantage of this method is accurate data will be obtained from the customers because customers' minds are fresh with their experiences with the blackout situation. The critical point is blackout situations are not regular. Thus, it is not practical to conduct a case study just after a blackout. The researcher should be ready to conduct a case study if a blackout is reported.

The customer surveys are being the most common and preferred methodology preferred in Cost of Unserved Energy Assessment. Customers are encouraged to report the past experiences in power outages. If sufficient data is unavailable, responses will be taken based on estimations of similar situations of a hypothetical interruption. The advantage of this method is the responses are taken from the customer's side and they are more accurate than the alternative methods.

Econometric Methods use publicly available data such as GDP, electricity sales, tariff to analyze the Cost of Unserved Energy a mathematical model or a function is defined and it is used to assess the Cost of Unserved Energy [7]. Customer Damage Function (CDF) is defined to show the economic loss incurred by the customers due to power outages. Customer Damage Function is defined as monetary amount of damage against per outage, per kWh of Unserved Energy or per kWh annual consumption of energy. The advantages of this method are low cost, easy to repeat, use of publicly available data. The major disadvantages are that no feedback is taken from the customers, and that all the customer categories are taken together leading to a high error margin [4].

Three studies have been conducted throughout the Power Economics history in Sri Lanka in the scope of Cost of Unserved Energy. The very first research has been conducted in 1990 and presented the final results as 57 LKR/kWh for Industrial Sector and 12.31 LKR/kWh for Commercial Sector [8]. Second research has been conducted in 1997, which has given the estimated result of 142.72 LKR/kWh [9]. In 2002, Cost of Unserved Energy of Sri Lanka was estimated for planned and unplanned interruptions as US$ 0.66 and US$ 1.08 per kWh respectively [10].

3. Methodology: Consumer Survey

Consumer survey method is the method which is widely used to assess the Cost of Unserved Energy instead of other different methods and it is chosen for this research too. An assumption is made at the inception that the customer is the best person to assess their own costs based on previous experiences. Consumers are encouraged to report and explain their previous experiences related to the interruptions in electricity supply. If sufficient past data isn't available, consumers are encouraged to estimate their experiences based on an event of hypothetical interruption. The conduct of consumer survey involves six steps as described in A to F sections [8, 11-13].

A. Consumer Categorization

Based on different tariff categories of Ceylon Electricity

Board, consumers are categorized. For this research three main categories are taken as industrial, commercial and domestic. Each category is subdivided according to their electricity consumption.

Industrial sector is sub grouped according to the categorization of Central Bank of Sri Lanka according to their contribution to the national economy [1]. The same categorization with few modifications is used in this survey. The study focuses the sub categories of contributing 2% or above to the national GDP to avoid complexity. The remaining all categories are taken together which has 3.33% contribution to national GDP (Table 1).

Table 1. *Contribution of Different Sub Sectors in Industrial Sector to the National GDP.*

Category	Abbreviation in this paper	GDP (LKR million)	Percentage
Food, tobacco, beverage	Food	697,904	43.69
Apparel, Textile leather industry	Apparel	268,342	16.8
petroleum, Chemical, plastic and plastic	Petroleum	263,843	16.52
Mineral (Non-metallic)	Mineral	38,921	2.44
Metal (Fabricated Metal)	Metal	56,102	3.51
Transport and Machinery Equipment	Transport	56,102	3.51
Plantation -Tea	Tea	88,541	5.54
Plantation - Coconut	Coconut	77,640	4.86
Other	Other	49,875	3.33
Total	Total	1,597,268	100.00

Source: Central Bank of Sri Lanka: Annual Report 2019 [1].

A sample of 270 customers was chosen for the survey which included 50 from each of the first three categories and 20 from the remaining each category. Responses were obtained 100% of the sample.

Commercial sector was grouped into six different categories, keeping to the Central Bank categorization of the Service Sector which is used to obtain the contribution to the GDP from each sub sector (Table 2). A sample of 160 was chosen for the survey with 30 responses of each from first four categories and 20 each from the remaining two categories.

Domestic Sector is grouped in to four sub categories for the survey. It is assumed that all the households in a category are contributing equally for the GDP. Thus, in the final analysis they were weighted according to the population distribution among four sectors as presented in Table 3. Fifty responses from four sub categories were taken for the customer survey covering the Domestic Sector.

Table 2. *GDP contribution of the commercial categories.*

Category	Abbreviation for this paper	GDP (LKR million)	Percentage
Retail Trade- Wholesale	Retail Trade	739,827	40.71
Restaurants and Hotels	Restaurants	25,716	1.41
Communication and Transport	Communication	476,722	26.23
Real Estate, Insurance and Banking	Real Estate	285,751	15.72
Government Sector	Government	213,440	11.74
Private Sector	Private	75,947	4.19
Total	Total	1,817,403	100.00

Source: Central Bank of Sri Lanka: Annual Report 2019 [1].

Table 3. *Sub sectors of the domestic sector.*

Categories	Population million	%
Urban	1.2	5.91
Sub Urban	1.8	8.87
Rural	16.3	80.30
Estates	1.0	4.93
Total	20.3	100.00

Source: Household and Expenditure Survey, Department of Census and Statistics, Sri Lanka [11].

B. Factors to be considered in the survey

Before assessing the cost of power outages, it is essential to examine the impacts to the consumers due to the outage. The impact of an interruption of electricity supply is not same for each customer and it is depending on several factors such as type of the customer (commercial, domestic or industrial), utilization of electricity (ventilation, lighting, motors and drives etc.), interruption duration (momentary, non-momentary), type of day (working day or holiday), time that interruption occurred (night time or day time), availability of standby generators etc. The effects of an interruption occur to the industrial consumers such as production loss, machinery damage, raw material loss etc.

Cost occurs due to the interruption depends on the characteristics of the interruption as well as on the load characteristics of the user. Interruption Characteristics are frequency, duration and occurrence time in the day of interruption. Consumer Characteristics are mainly the type of products or service, type of industrial process, availability of stand by generators, and demand for the product [4].

C. Questionnaire

Separate questionnaires were designed for three customer categories. Questions were formulated to gather information on the cost of electricity interruption to the consumer. The questionnaire included the parts on general information in the installation (Category, Sub Category and Contact information), electricity consumption information based on monthly metering data, financial information such as annual value addition of each industry installation, revenue losses due to momentary and non-momentary interruptions, technical information associated with any backup unit generators installed in the premises and customer's opinion on power system and the amount he is willing to pay for a better quality supply. For convenience in data gathering the information requested was clustered into different categories of losses such as those associated with raw material losses, man power losses, production output losses and costs involved in backup unit generator usage.

D. Pilot Survey

A pilot survey was conducted to check whether the questionnaire is well-formulated. However, the fact that the enumerator meets the interviewee face to face further explanations could be given whenever necessary. The pilot survey confirmed the suitability of the questionnaire and that the meaningful answers can be gathered.

E. Final Survey

The questionnaire in the final survey was posted or handed over to the interviewee in advance. Out of 270 total industrial responses, 145 were taken through face-to-face interviews and 125 through telephone interviews. For the Commercial Sector, 89 responses were taken through personal interviews and 71 through telephone interviews. All 200 responses of Domestic Sector were taken through personal interviews. Information provided was validated using the crosschecking method [12]. As examples, cross checks were done between average electricity bill and average amount of energy, between the capacity of the stand-by generator and the average fuel consumption, and between the generator capacity and average demand.

F. Categorization of interruptions

In order to capture the dependence of the cost on the duration of the interruption, all interruptions are first grouped into momentary and non-momentary categories. Momentary interruptions are those of very short duration of about six seconds. All the other interruptions not counted under the momentary category fall into the non-momentary category. Non-momentary interruptions are further subdivided into six categories based on the duration of the interruption. Each of the six categories are further separated into the categories of planned and unplanned interruptions. Thus, all together there are 12 subcategories of non-momentary interruptions. Interruption duration interval larger than 16 hours takes a negligible probability. Thus, it is not considered in the analysis. The twelve categories and their respective probabilities of occurrence, derived from electricity interruption data records of Ceylon Electricity Board, are given in Table 4.

4. Impacts of Non-momentary Interruptions

A. Averaging the Costs

The first step is to calculate the total interruption cost for a customer using the results obtained with the survey. Total interruption cost for a single customer contains with spoilage value, raw material loss, production loss, labor force loss and cost for backup source. The summation of all the losses is divided by the estimated value of energy consumption of customer during the interruption period if the power supply was available. Equation (1) gives the average Cost of Unserved Energy for the Consumer k denoted by C_{ki} due to an interruption in category i.

$$C_{ki} = \frac{\text{Total cost incurred due to category i interruption}}{\text{Total estimated not served energy within interruption}} \quad (1)$$

If the backup sources are available with sufficient capacity, an assumption is made that no impact has occurred due to the interruption on the gross production and capital summation. Maintenance and running costs presented in LKR/kWh is considered as the Cost of Unserved Energy.

Effects of an interruption have a direct relationship with interruption time duration. Production loss, man power loss, raw material loss is increased with the interruption duration. Thus, it is not justified if all the losses are calculated without taking the difference of interruption duration. Probability of occurrence of category i defined in (2) and given in Table 4 are used for averaging the cost of unserved energy for individual customers.

$$P_i = \frac{\text{No of interruptions in category i within a year}}{\text{Total No of interruptions occured within a year}} \quad (2)$$

The interruption durations are recorded into six-time duration intervals. Thus, this interruption data records are discrete. The mean or expected value of a discrete distribution is the long-run average of occurrences. Averaged Cost of Unserved Energy for the Consumer k denoted by C_k, is obtained by calculating the expected value or in other words summing up the products of C_{ki} and respective P_i. Cost of Unserved Energy for a consumer can be obtained separately for planned and unplanned interruptions. In this case, six-time durations are considered.

$$C_k = \frac{\sum_{i=1}^{r} C_{ki} P_i}{\sum_{i=1}^{r} P_i} \quad (3)$$

In equation (3), r denotes the number of interruption durations (for this case, r = 6).

After obtaining the cost of unserved energy for each individual in the sample of the corresponding sub category, the summation is averaged for the category to obtain C_s, by weighting the individual values by x_k, the average electricity consumption of the respective consumer, as given in (4).

$$C_s = \frac{\sum_{k=1}^{P} C_k x_k}{\sum_{k=1}^{P} x_k} \quad (4)$$

where, P represents number of consumers included in the sample considered for the survey for the sub category. Two separate values are obtained of C_s for each category corresponding to planned and unplanned interruptions. Considering the contribution made from industry to national economy by each of the industry category industry average C_{In} is derived by weighting the results obtained for each sub category with the contribution percentage to the GDP.

Table 4. *Occurrence probabilities of non-momentary interruption categories.*

	Probability						
Duration (hrs)	**0.001-0.25**	**0.25- 0.75**	**0.75-1.50**	**1.50-3.00**	**3.00-6.00**	**6.00-16.00**	**Total**
Unplanned	0.547	0.104	0.037	0.026	0.011	0.015	0.740
Planned	0.151	0.005	0.008	0.014	0.050	0.032	0.260
Total	0.698	0.109	0.045	0.040	0.061	0.047	1.000

$$C_{In} = \frac{\sum_{S=1}^{N} C_S N_S}{\sum_{S=1}^{N} N_S} \tag{5}$$

Here, N_s is the percentage contribution to the national economy of the category s and N refers to the number of categories (for this case, N=9). Two answers are obtained for planned and unplanned interruptions in this method.

Cost of Unserved Energy for Industry, Commercial and Domestic sectors are weighted according to the GDP contribution of each sector (Table 5) and take the summation to obtain a single value of Cost of Unserved Energy. In this point, it is not straight forward to find the contribution from Domestic Sector to the final GDP. Domestic income is mainly based on salaries and wages. However, those values are already counted in the Industrial and Commercial sectors. Here domestic sector is considered as supply of electricity used for domestic purposes in private residences. It is justified that contribution to the GDP from Domestic sector should be a low value and it should be below 5% of the total GDP. For the calculations the contribution is taken as 3%. To justify this 3% is correct, a sensitivity analyze is done and the calculations are repeated for 0%, 1%, 2%, 4% and 5% as GDP Contribution from domestic sector and check the variation of final results.

Table 5. *GDP contribution from each categories.*

Category	**GDP Contribution (LKR Million)**	**%**
Industrial	1,563,349	18.02
Commercial	1,817,397	20.96
Domestic	260,220	3.00
Not considered to the research	5,033,034	58.02
Total	8,674,000	100.00

Source: Central Bank of Sri Lanka, Annual Report, 2019 [1].

It is essential to obtain one value for planned and unplanned non-momentary interruptions by combining the obtained values together. The corresponding values of planned and unplanned interruptions are multiplied with the probabilities shown in Table 4 and added them together to obtain an average value.

Financial losses should be converted into economic losses and it can be done with a conversion factor of 0.76 which is calculated by the Finance and Planning Ministry of Sri Lanka in 1990s [10].

B. Results for Industrial Sector

The obtained values for costs of unserved energy for non-momentary (planned and unplanned) interruptions are presented in Table 6. The averaged combined cost of unserved energy is presented for each category too. Economic cost is presented within the brackets below each financial cost value. It can be shown that costs are generally high for unplanned interruptions. Heavier the sub sector is more significant is this effect with the exception of non-metallic mineral products sub sector.

Table 6. *Cost of Unserved energy for Industrial Sector Due to Non-momentary Interruptions.*

Industry category	**Financial Cost in LKR/kWh (Economic Cost in LKR/kWh)**		
	Planned	**Unplanned**	**Combined**
Food	97.58 (74.16)	116.42 (88.48)	111.52 (84.76)
Apparel	62.86 (47.78)	325.71 (243.54)	257.37 (195.60)
Petroleum	154.41 (117.35)	512.93 (389.82)	419.71 (318.98)
Mineral	2,772.69 (2,107.24)	2,821.05 (2,144.00)	2,808.48 (2,134.44)
Metal	53.26 (40.48)	216.71 (164.70)	174.21 (132.40)
Transport	308.86 (234.73)	307.88 (233.99)	308.13 (234.18)
Tea	76.70 (58.29)	74.84 (56.88)	75.32 (57.24)
Coconut	50.40 (38.30)	47.51 (36.11)	48.26 (36.68)
Other	406.75 (309.13)	406.35 (308.83)	406.45 (308.90)
Combined	191.93 (145.87)	315.88 (240.07)	257.43 (195.65)

Losses associates with industrial sector can be described as production loss, spoilage, equipment loss, loss of raw materials, man power loss etc. All these losses are occurred with the interruption period. In addition to these effects long time results may occurred in the industrial sector. When a production loss is occurred due to an electricity interruption, expected goals of the industry cannot be achieved. Thus, the demand for the goods and services produced by the industry will be negatively affected. In the comparison of the cost of unserved energy for different sub sectors, mineral industry shows significantly higher values than other sub sectors. Gem, diamond, dement, ceramic industries are considered under the mineral category and those industries are needed a large capacity of electricity to operate their functions in the industry. Thus, it is not viable for them to manage the effects of interruptions with standby generators. Further, these industries stop operating during the interruption periods. Mineral products have a high price and large demand in the market leading to heavy damage due to loss of production. Due to the same reasons, the costs of unserved energy are of very similar magnitude both for planned and unplanned interruptions [12].

C. Results for Commercial Sector

The obtained values for costs of unserved energy for non-momentary (planned and unplanned) interruptions are presented in Table 7. The averaged combined cost of unserved energy is presented for each category too. Economic cost is presented within the brackets below each financial cost value. It can be shown that costs are generally high for unplanned interruptions.

Table 7. *Cost of Unserved energy for Commercial Sector Due to Non-momentary Interruptions.*

Commercial category	Financial Cost in LKR/kWh (Economical Cost in LKR/kWh)		
	Planned	Unplanned	Combined
Retail Trade	832.09 (632.39)	822.53 (625.12)	825.02 (627.01)
Restaurants	176.68 (134.28)	101.62 (77.23)	121.14 (92.06)
Communication	119.55 (90.86)	122.61 (93.18)	121.81 (92.58)
Real Estate	294.08 (223.50)	336.22 (255.53)	325.26 (247.20)
Government	145.78 (40.48)	141.93 (107.87)	142.93 (108.63)
Private	261.46 (198.71)	330.46 (251.15)	312.52 (237.52)
Combined	453.59 (344.65)	418.19 (317.82)	427.37 (324.80)

In commercial category planned interruptions have higher values than unplanned values of Cost of Unserved Energy. Industries category showed high values to the unplanned category. The reason for this difference is due to the fact that unlike in the industrial category in the Commercial category almost all the effects of interruptions can be managed with backup methods. Customers have given similar data for planned and unplanned interruptions. When the loss is calculated for six interruption durations data obtained through the survey is multiplied with its probability. In Table 4, it is clearly shown that probabilities of unplanned interruptions are lower when the interruption duration increases. In many practical situations, unplanned interruptions are restored by the supply authority within an hour. Thus, it is very rare to obtain an unplanned interruption longer than one hour. For the pre-informed maintenance works planned interruptions take a longer period spanning several hours. Thus, their occurrence probabilities are higher compared to respective un-planned occurrence probabilities. When the Cost of Unserved Energy values are weighted with interruption probability, planned interruptions tend to contribute more than unplanned interruptions due to this reason.

D. Results for Domestic Sector

The electricity consumption patterns of domestic customers deviate from those of industrial and commercial customers. The main difficulty associated with domestic sector is that the activities are not accounted the GDP and most of the activities happen within household and not valued in market. In other terms these activities do not focus with Direct worth (DW) cost estimations. Thus, in the analysis Willing to Pay (WTP) and Willing to Acceptance (WTA) measures are used [13, 14]. Electricity Interruptions may disturb housekeeping activities such as lighting, cooking, washing, air conditioning, entertainment. Electricity customers may face economically measurable or tangible losses such as food spoilage, equipment failures due to momentary interruptions. And immeasurable or intangible losses may present in terms of inconvenience, discomfort and anxiety. Such intangible effects cannot be evaluated in terms of monetary values. Domestic sector has a homogeneous population with respect to the outage costs. In industrial and commercial customer studies show outage costs vary over a vast range. It is noticed that the most critical devices that the residential customers will not be able to use during an outage, are air conditioners followed closely by lighting and less closely by kitchen facilities and washing machines.

In the case of domestic sector, as for GDP calculation, only value addition to the economy is from rental services. However, one will not lose anything in rental services due to power outages. What is lost quality of life and, perhaps, the cost of food in the refrigerator or the cost of a standby generator? This means that the domestic sector will have no serious contribution to Cost of Unserved Energy, making a negative impact on GDP. Anyway, in the final calculations it is assumed that domestic contribution to the GDP is 3%. This 3% is a very rough estimate based on the value additions from domestic sector to the GDP. To justify the answer with 3% contribution GDP from Domestic sector, the calculations are repeated for 1%, 2%, 4% and 5%, as well. The obtained values for costs of unserved energy for non-momentary (planned and unplanned) interruptions are presented in Table 8. The averaged combined cost of unserved energy is presented for each category too. Economic cost is presented within the brackets below each financial cost value. It can be shown that costs are generally high for unplanned interruptions.

Table 8. *Cost of unserved energy average for different domestic categories.*

Domestic category	Financial Cost in LKR/kWh (Economic Cost in LKR/kWh)		
	Planned	**Unplanned**	**Combined**
Urban	201.42 (153.08)	201.42 (153.08)	201.42 (153.08)
Sub Urban	159.32 (121.08)	159.32 (121.08)	159.32 (121.08)
Rural	144.57 (109.87)	144.57 (109.87)	144.57 (109.87)
Estates	1,832.43 (1,392.75)	1,832.43 (1,392.75)	1,832.43 (1,392.75)
Combined	232.39 (176.61)	232.39 (176.61)	232.39 (176.61)

Domestic sector results work out to be higher than expected. Rural and Estates have very low electricity consumption values but their Cost of Unserved Energy values are high. Thus, their tariff varies between LKR 50-100 ranges (per month). But when the electricity is unserved, their backup methods are significantly more expensive than the cost of electricity. Let's take an example, when the electricity is unserved they use a candle, coconut oil lamp or kerosene lamps. Price of candle, coconut oil, and kerosene (for one hour) is much higher than the price of electricity for the same purpose (for lighting using electricity). Since their electricity consumption is low, when the unserved energy is normalizing using the Average electricity consumption, the normalized value is increasing. Another reason in the analysis, it was assumed that whole domestic sector has equal weighting factors for the GDP and due to the assumption Cost of Unserved Energy values for Domestic sector was weighted according to the population ratio of the country. In that process values for rural sector was weighted by 0.8 because 80% of the total population is considered as rural.

5. Impacts of Momentary Interruptions

A. *Momentary interruptions: Cost of Unserved Energy Calculation*

The interruption duration is short for momentary interruptions and all the losses are occurred within the short time of the interruption. Thus, another method is needed for the assessment of cost of unserved energy for momentary interruption. The losses happen within a momentary period of several seconds, Cost of Unserved Energy is presented in LKR/kW instead of presenting LKR/kWh. Normalized total cost during a momentary interruption for a consumer is denoted as $C_{k,m}$ and for the corresponding *s* sub category, Cost of Unserved Energy (momentary interruptions) $C_{s,m}$

$$C_{k,m} = \frac{\text{Total Cost due to a momentary interruption (customer k) (LKR)}}{\text{Average Value of Demand of the Customer (kW)}} \quad (6)$$

$$C_{s,m} = \frac{\sum_{k=1}^{p} C_{k,m} d_k}{\sum_{k=1}^{p} d_k} \quad (7)$$

where, p is the number of consumers in the sub sector and d_i is the Average Electricity Demand of Consumer k. Industry average for the Cost of Unserved Energy due to momentary interruptions is calculated by using the same calculation as given in (5).

$$C_{In,m} = \frac{\sum_{s=1}^{N} C_{s,m} N_s}{\sum_{s=1}^{N} N_s} \quad (8)$$

The values of Momentary interruptions are presented also in LKR/kWh to find out whether the final results of non-momentary and momentary interruptions can be combined together. From the results it is seen that such a combination is inappropriate because the results are varying in an unacceptably large range.

B. *Results for Industrial Sector*

Cost of Unserved Energy values for Industrial Sector occurs due to momentary interruptions are presented in Table 9.

Table 9. *Cost of unserved energy due to momentary interruptions - average for different industry categories.*

Industrial category	Cost of Unserved Energy Financial Cost (Economical Cost)	
	LKR/kW	**LKR/kWh**
Food	363.08 (275.94)	237,990.00 (180,872.40)
Textile	38.72 (29.43)	49,605.38 (37,700.09)
Chemical	118.62 (90.15)	78,804.88 (59,891.71)
Mineral	75.20 (57.15)	20,469.53 (15,556.84)
Metal	65.24 (49.58)	616.61 (468.62)
Machinery	4.35 (3.31)	3,111.59 (2,364.82)
Tea	0 (0)	0 (0)
Coconut	0 (0)	0 (0)
Other	0 (0)	0 (0)
Combined	191.46 (145.51)	62,094.21 (47,191.60)

C. *Results for Commercial Sector*

The results for Commercial Sector (due to momentary interruptions) are shown in Table 10.

Table 10. *Cost of unserved energy due to momentary interruptions - average for different commercial categories.*

Commercial categories	Cost of Unserved Energy Financial Cost (Economic Cost)	
	LKR/kW	LKR/kWh
Retail Trade	0.00 (0.00)	0.00 (0.00)
Restaurants	0.00 (0.00)	0.00 (0.00)
Communication	8.65 (6.57)	2,603.45 (1,978.62)
Real Estate	485.59 (369.05)	308,133.40 (234,181.40)
Government	0.00 (0.00)	0.00 (0.00)
Private	0.00 (0.00)	0.00 (0.00)
Combined	78.62 (59.75)	49,130.83 (31,736.80)

D. *Results for Domestic Sector*

The results of Domestic Sector occur (due to momentary interruptions) are shown in Table 11.

Table 11. *Cost of unserved energy average for different domestic categories.*

Domestic category	Momentary (LKR/kW)
Urban	0.00 (0.00)
Sub Urban	0.00 (0.00)
Rural	0.00 (0.00)
Estates	0.00 (0.00)
Combined	0.00 (0.00)

6. Combination of Results and Sensitivity Analysis

To compare the results, the financial and economic cost are presented in LKR/kW and LKR/kWh. As all the losses occur during a very short spell of time presenting in terms of LKR/kWh lead to an unnecessary escalation and thus the alternative approach of presenting in terms of LKR/kW is adopted. Table 12 presents the combination of the results for different categories.

Table 12. *Combined cost of unserved energy for different categories.*

category	Financial Cost in LKR/kWh (Economical Cost in LKR/kWh)			Momentary (LKR/kW)
	Planned	Unplanned	Combined	
Industrial	191.93 (145.87)	315.88 (240.07)	257.43 (195.65)	78.62 (59.75)
Commercial	453.49 (344.65)	418.19 (317.82)	427.37 (324.80)	191.46 (145.51)
Domestic	232.39 (176.61)	232.39 (176.61)	232.39 (176.61)	0.00 (0.00)
Combined	137.33 (104.37)	152.76 (116.10)	143.92 (109.38)	51.73 (39.26)

In the Table 12, contribution to the National GDP from Industrial, Commercial and Domestic sectors are taken as presented in Table 5. After that a sensitivity analysis is done as mentioned in section 4. D (Table 13).

Momentary interruptions will not be considered here because no harm is recorded in the survey with momentary interruptions in the Domestic Sector. Thus, only the non-momentary interruptions are considered for the sensitivity analysis.

Table 13. *Sensitivity analysis for the different gdp percentages of domestic sector.*

GDP %	Financial Cost in LKR/kWh (Economical Cost in LKR/kWh)		
	Planned	Unplanned	Combined
0	130.36 (99.07)	145.79 (110.80)	136.95 (104.08)
1	132.68 (100.84)	148.11 (112.56)	139.27 (105.85)
2	135.01 (102.61)	150.44 (114.33)	141.60 (107.62)
3	137.33 (104.37)	152.76 (116.10)	143.92 (109.38)
4	139.65 (106.13)	155.08 (117.86)	146.26 (111.14)
5	141.98 (107.90)	157.41 (119.63)	148.57 (112.91)

7. Variation Patterns of Cost of Unserved Energy Verses Duration of Interruption

When analyzing the characteristics of Cost of Unserved Energy variation with interruption duration, all the categories and sub categories have shown a similar variation pattern for planned and unplanned interruptions. These patterns are similar for all the sub categories with differences in magnitudes. Since all the sub categories have shown similar variation patterns, one from each category is presented in this paper. To examine the variation patterns of Industrial Sector, duration dependent variation of Cost of Unserved Energy for the Industrial sub category of Food, Beverages and Tobacco products is presented in Figure 1. All nine sub sectors of Industrial Sector show a similar pattern of variation with different magnitudes.

In the process of examining the duration dependent Cost of Unserved Energy for Commercial Sector, the characteristics are similar to those in the Industrial Sector. Other six categories are showing a single variation. On behalf of six commercial categories, the results of Wholesale and Retail Trade sub category is presented in Figure 2. Figure 3 presents the characteristics of Domestic sector. This sector is similar with Industrial and Domestic sectors.

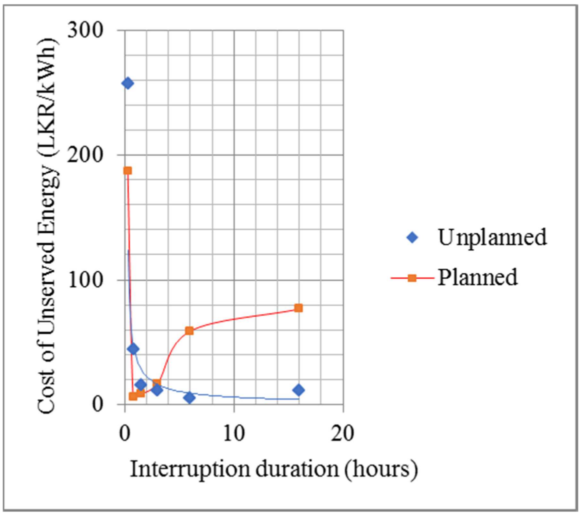

Figure 1. *A sample to Industrial Sector - Cost of Unserved Energy versus interruption duration (for Food, Beverages and Tobacco Products).*

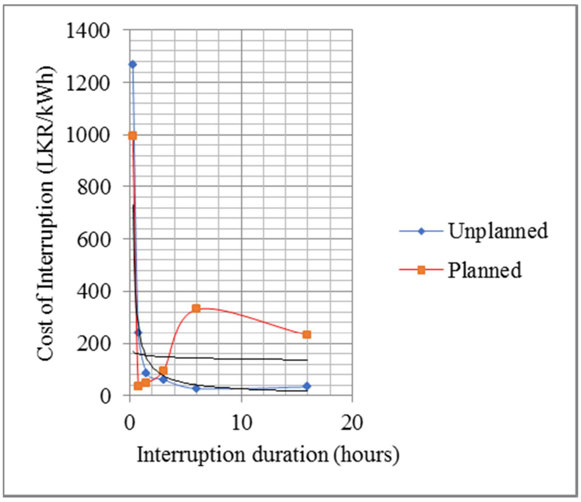

Figure 2. *A sample to Commercial Sector - Cost of Unserved Energy versus interruption duration (for Retail trade and wholesale) [15].*

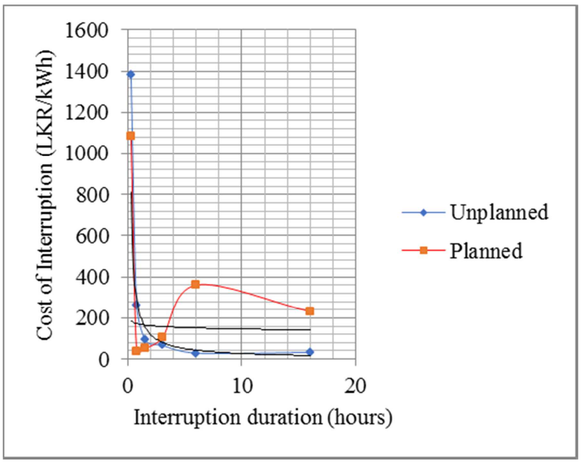

Figure 3. *A sample to Domestic Sector - Cost of Unserved Energy versus interruption duration (for Urban Sector).*

It is observed the characteristics of Cost of Unserved Energy which is dependent on interruption duration is based on three components of start-up cost, loss production cost and shut down cost. The shutdown cost occurs once per interruption and is distributed over the duration of interruption and takes a value inversely proportional to the duration as shown in figure 4. The cost per kWh of lost production is constant over time as shown in figure 5, while the startup cost usually increases with the duration to reach a saturation after about five hours as shown in figure 6. It should be noted that Figures 4, 5 and 6 show the pattern of variation of Shutdown, lost production and Startup Costs; They are not shown the actual magnitudes of the values obtained [15, 16].

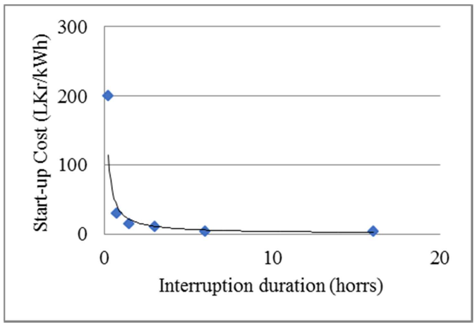

Figure 4. *Startup cost versus duration.*

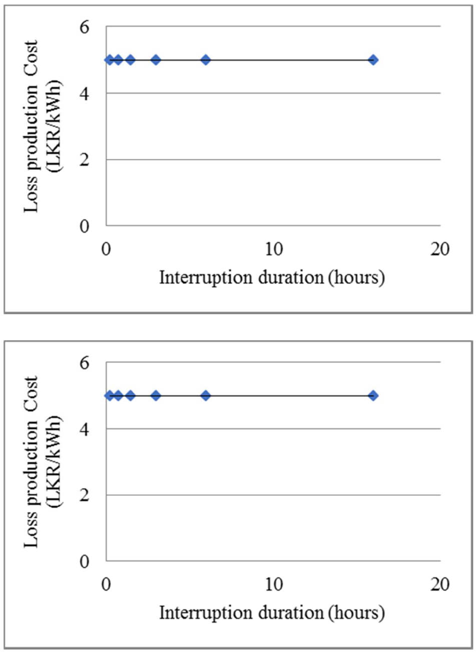

Figure 5. *Cost of lost production versus interruption duration.*

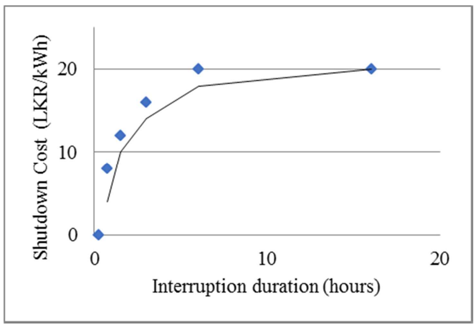

Figure 6. *Shutdown Cost versus interruption duration.*

8. Conclusion

Assessment of Cost of Energy is not an easy task because interruptions are not making periodic or regular patterns. Thus, it is a challenge to present an accurate value using practical methodologies. Among different methodologies, survey method is preferred in most cases to achieve the objects of the research. The results of the survey were given a particular accuracy because response rate of the survey was achieved to 100%. It is clear that the utility needs to take steps to improve its supply reliability in order to retain consumers and to justify the existence of a centralized generation facility.

Cost of Unserved Energy values are calculated in the research through the consumer survey method. Cost of Unserved Energy values for each category were combined to obtain final value. Survey was conducted into different sub categories to obtain the results for each sub category. Variation patterns of Cost of Unserved Energy versus Interruption duration characteristics were examined and were able to present them in this paper.

The estimations obtained in this research can be utilized for power system planning. Final output can be used to make economic decisions related with power system. The results are presented for separate sub sectors while averaging the final value. The indices produced based on this value can be utilized in a wide range of management decisions throughout the utility and not limited to the utility.

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