IOP Conf. Series: Earth and Environmental Science **94** (2017) 012166 doi:10.1088/1755-1315/94/1/012166

Comparative study on life cycle environmental impact assessment of copper and aluminium cables

Wei Bao*, Ling Lin, Dan Song, Huiting Guo, Liang Chen, Liang Sun, Mei Liu, Jianhua Chen

China National Institute of Standardization, No. 4, Zhichun Road, Haidian District, Beijing, China

baowei@cnis.gov.cn

Abstract. With the rapid development of industrialization and urbanization in China, domestic demands for copper and aluminium resources increase continuously and the output of copper and aluminium minerals rises steadily. The output of copper in China increased from 0.6 million tons (metal quantity) in 2003 to 1.74 million tons (metal quantity) in 2014, and the output of bauxite increased from 21 million tons in 2006 to 59.21 million tons in 2014. In the meantime, the import of copper and aluminium minerals of China is also on a rise. The import of copper concentrate and bauxite increased from 4.94 million tons and 9.68 million tons in 2006 to 10.08 million tons and 70.75 million tons in 2013 respectively. Copper and aluminium resources are widely applied in fields such as construction, electrical and electronics, machinery manufacturing, and transportation, and serve as important material basis for the national economic and social development of China. Cable industry is a typical industry where copper and aluminium resources are widely used. In this paper, a product assessment model is built from the perspective of product life cycle. Based on CNLCD database, differences in environmental impacts of copper and aluminium cables are analyzed from aspects such as resource acquisition, product production, transportation, utilization, and resource recycling. Furthermore, the advantages and disadvantages of products at different stages with different types of environmental impact are analyzed, so as to provide data support for cable industry in terms of product design and production, etc.

1. Introduction

Currently, the scale of global wire and cable market has exceeded €100 billion, in which Asia, Europe, America, and other regions takes 37%, nearly 30%, 24%, and 9% respectively. The wire and cable industry in China plays an irreplaceable role in the global wire and cable industry, and the output value has overtaken the U.S. and ranked first in the world since 2011.

In 2011, the sales value of China's wire and cable industry exceeded CNY one trillion for the first time and reached CNY 1.1438 trillion, with a growth rate of 28.3% and total profit of CNY 68 billion. Wire and cable industry is only second to the automobile industry in China. The total output value of wire and cable industry of China has exceeded the U.S., making China the first largest wire and cable manufacturing country in the world. The huge market space for cable products owning to the sustained and rapid development of China's economy has made Chinese market a great attraction for the world. After merely decades of reforming and opening-up, the great production capacity of China's wire and cable manufacturing industry has impressed the world greatly. With the constant expanding of industries such as electric power, data communication, urban rail transit, automobile, and shipbuilding in China, demands for wires and cables increase rapidly and great development potential is seen in wire and cable industry.

In cable industry, the "argument over copper and aluminium" has lasted for years. With the steep decline in cable manufacturers' profit rate due to long-term high price of copper, demands for "saving copper with aluminium" or even "replacing copper with aluminium" have ramped up. However, there are different opinions on the feasibility of "saving copper with aluminium". Some have proved the reliability of aluminium cables by taking the cases in Europe and America as examples, while others have indicated the differences between aluminium cables and copper core cables through some supporting materials. As a result, the "argument over copper and aluminium" is not over and the development of aluminium cables stands still [1].

2. Methodology

Life Cycle Assessment (LCA) is a process where the environmental loads associated with a product, process, or activity are evaluated throughout its entire life cycle from raw material collection to product production, transportation, marketing, utilization, re-utilization, maintenance, and final disposal. LCA first identifies and quantifies the consumption of energy and materials and their emission in the environment, then assesses the impacts of such consumption and emission to the environment, and finally identifies and assesses the opportunities to reduce such impacts [2].

There are two distinct features of LCA which differentiate it from other conventional assessment methods. The first feature is full course. The greatest advantage of LCA is the expanded system boundary and scope of study. Instead of merely assessing the production process that generates waste, it assesses the environmental loads or impacts of a system throughout its entire life cycle. Therefore, the shift of pollution from one life cycle stage to another is avoided effectively. The second feature is comprehensiveness. It considers not only the impacts of waste on environment, but also the comprehensive impacts on environment due to the consumption of resources and energy. Assessing from an overall perspective is a distinct advantage of LCA, and this avoids the transfer of pollution from a process with improved environmental loads to another process in the system that is caused by conventional methods. The steps of LCA are established as per the frameworks in ISO and SETAC. There are four steps in LCA: (1) Definition of objective and scope: the objective and scope of the study and relevant functional units are defined. (2) Life cycle inventory analysis: it's a data collection process for environmental loads of a system based on material and energy balance. Environmental loads include the consumption of resources and energy, and solid, liquid and gas waste. (3) Environmental impact assessment. (4) Interpretation result.

In 1993, SETAC summarized the basic structures of LCA into four synergistic components, i.e., definition of objective and scope, life cycle inventory analysis, impact assessment, and improvement assessment, in its LAC Outline: A Practical Guide. See Figure 1 below.

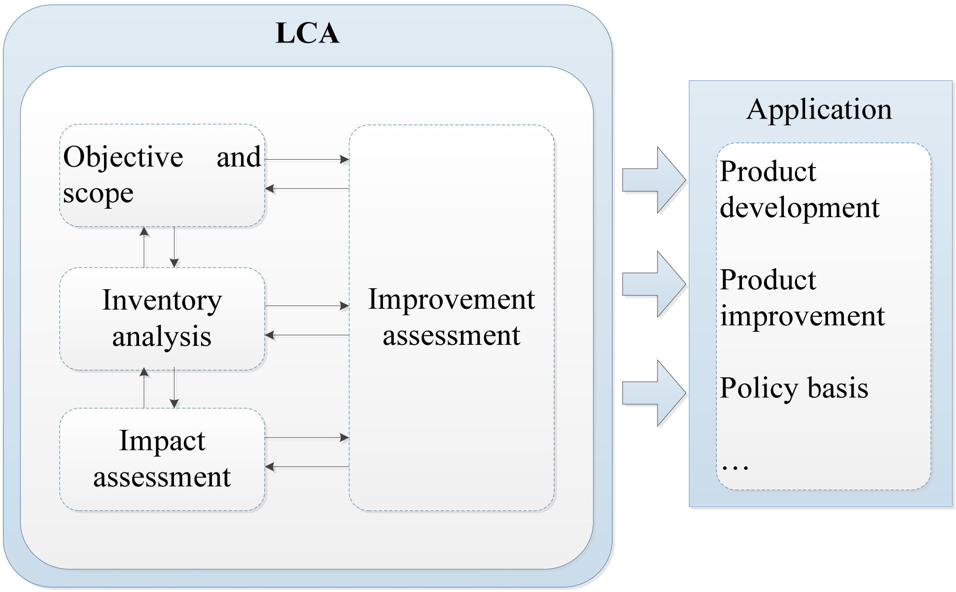

Figure 1. Basic structure of LCA

3. Life Cycle Environmental Impact Assessment on Cables

3.1. Objectives

From the perspective of entire life cycle, every life cycle stage of copper and aluminium cables is reproduced in this paper. Through life cycle inventory analysis, the environmental impacts of copper cables and aluminium cables with the same current-carrying capacity are compared.
Note: In this paper, the maximum DC resistance of cables at 20°C as specified in the *Conductors of Insulated Cables* (GB/T3956-2008) is taken for the calculation of line loss at utilization stage.

3.2. System boundary

In order to reflect the environmental impacts of copper and aluminium cables during their entire life cycles in a more comprehensive way, a comprehensive data collection is carried out at stages such as raw material acquisition, product manufacturing, product utilization, transportation, and disposal of relevant products; calculation and analysis are carried out as per the methods of LCA. See Figure 2 below.

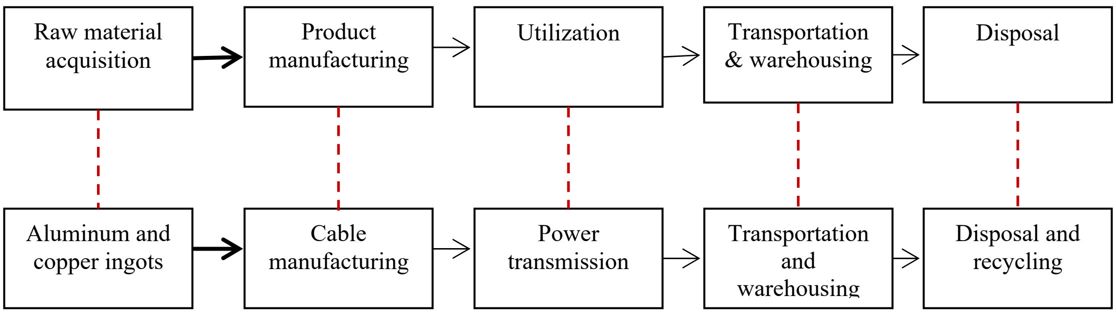

Figure 2. Life cycle of cable products

3.3. Functional unit

As this paper mainly focuses on the life cycle environmental impacts of copper and aluminum cables, the following aspects are considered when functional units are selected.

- Current-carrying capacity
- Insulating and cross-linking materials
- Armoring

- Insulation class

Current-carrying capacity is an important technical indicator in power cable assessment. It refers to the magnitude of current passing through a cable during power transmission. Under thermally stable conditions, the current-carrying capacity of a cable when cable conductor reaches long-term allowable operating temperature is called the long-term allowable current-carrying capacity of the cable. See Table 1 for the allowable current-carrying capacity (A) for direct buried 1-kV XLPE insulated cables as per Table C.0.1-4 of the Code for Design of Cables of Electric Engineering (GB50217-2007).

Table 1. Allowable current-carrying capacity (A) for direct buried 1-3kV XLPE insulated cables [3]

(Equivalent to Table C.0.1-4 of the Code for Design of Cables of Electric Engineering (GB50217-2007))

Number of cores		Three		Single			
Arrangement of single-core cable				Triangular		Horizontal	
Grounding point of metal layer				Single side		Single side	
Material of cable conductor		Aluminum	Copper	Aluminum	Copper	Aluminum	Copper
Section of cable conductor (mm^2)	25	91	117	104	130	113	143
	35	113	143	117	169	134	169
	50	134	169	139	187	160	200
	70	165	208	174	226	195	247
	95	195	247	208	269	230	295
	120	221	282	239	300	261	334
	150	247	321	269	339	295	374
	185	278	356	300	382	330	426
	240	321	408	348	435	378	478
	300	365	469	391	495	430	543
	400			456	574	500	635
	500			517	635	565	713
	630			582	704	635	796
Temperature (℃)		90					
Thermal resistivity of soil (K•m/W)		2.0					
Ambient temperature (℃)		25					

In this paper, two types of cables that have relatively close indicator and the same length (1,000 m) are selected for comparison and analysis (service life is taken as 30 years), i.e., YJHLV82-4×185 (XLPE insulated PVC sheathed aluminium strip armoured aluminium cables, current-carrying capacity: 278A) and YJV224×120 (XLPE insulated steel strip armoured PVC sheathed copper cables, current-carrying capacity: 282A). These two cables have the same insulation class under similar maximum allowable current-carrying capacity and they are armoured and protected by the same cross-linked sheaths [4].

3.4. Types of environmental impact

Types of this LCA-based environmental impact mainly include global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), and energy consumption (EC). CML2001 and EI99 assessment indicator systems are adopted.

3.5. Data collection

Two types of data are involved in this paper. The first type is the production activity data of companies, such as the consumption data of raw materials and energy used for producing 1,000m cables, and the transportation data of companies' transporting products to the clients. The second type is the inventory data of raw materials and energy, such as the input/output data of copper or aluminium during mining, smelting, and processing, etc. The first type of data is sourced from the monitored data of company survey and the second one is sourced from CNLCD and relevant literatures. See the table 2below for the production data of companies.

Table 2. Productive data of copper cable and aluminium cable

	Copper cable (YJV224×120)		Aluminium cable (YJHLV82-4×185)	
Consumption of raw materials	Copper	4,124.44	Aluminium pole	1,994.9
	Silane XLPE (kg)	224.67	Silane XLPE	362
	Non-woven fabric (kg)	11.94	Non-woven fabric	16.5
	Galvanized steel strip (kg)	629.7	Aluminium strip	591.4
	PVC sheath material (kg)	528.23	PVC sheath material	896
Consumption of energy	Unit consumption of power (kwh)	3,746.02	Unit consumption of power	1,750
	Unit consumption of water (t)	2.13	Unit consumption of water	3.5
	Consumption of natural gas (NM3)	0	Consumption of natural gas	175
	Unit consumption of diesel (t)	3.4		
	Unit consumption of steam (MJ)	350		
Transportation distance	Truck (km)	600	Truck (km)	600

3.6. Calculation methods for line loss at utilization stage of cable

The main factor for environmental impact of power cables at their utilization stage is the power loss occurred during transmission. See the calculation method provided in Economic Optimization of Power Cable Size (IEC60287-3-2-1995) for the calculation of line loss during transmission. The calculation formula is shown below:

$$P=(I^2_{max}\times R\times L\times Np\times Nc)\times\tau\times T \quad (1)$$

Where,

P— Energy loss during utilization (kwh)

I_{max}— The maximum current of conductor (A)

R— The resistance of conductor (Ω)

L— The length of conductor (m)

N_P— Phase number of conductor in every loop

N_C— Number of loops with the same load

τ— Maximum load loss hour (h)

T— Service life (years)

This calculation is carried out on the background of urban household power consumption with operating voltage of 380V, equipment power factor of 0.85, operating frequency of 50Hz, and operating temperature of 30 ℃. According to the Power Supply and Utilization Technology, the annual maximum power hour (T) is 1,500 hours.

The AC resistance of a conductor is calculated as below [5]

$$R=R'(1+yp+ys)(1+\lambda1+\lambda2) \quad (2)$$

Where:
R—The AC resistance of conductor at the maximum operating temperature (Ω/m)
R'—The DC resistance of conductor at the maximum operating temperature (Ω/m)
ys— Skin effect factor – copper 2.15×10^{-3}
yp— Proximity effect factor - copper 6.46×10^{-3}
λ1— Sheath loss factor -
λ2— Armoring loss factor -

The maximum DC resistance of a conductor is calculated as below:

$$R'=Ro[1+\alpha20(\theta-20)] \quad (3)$$

Where:
R'—The DC resistance at the maximum operating temperature (Ω/km)
R_o— The DC resistance at 20℃ (Ω/km). According to the requirements of Table 2 of *Conductors of Insulated Cables* (GB/T 3956-2008), the maximum DC resistance of 120 copper cable is 0.153 Ω/km.
α_{20}—The temperature coefficient of material at 20℃ under absolute temperature conditions, the value is taken as 3.93×10^{-3}.
θ—The maximum operating temperature (it depends on the type of insulating materials used). The maximum allowable temperature for XLPE is 90℃.

3.7. Inventory analysis

By utilizing the basic data of CNLCD and the modeling and calculation functions of GreenIn, a cable LCA model is built and every available data (including the consumption data of raw materials and energy for cable production and the transportation data of companies) is inputted. The inventory data of raw materials, energy, and transportation is sourced from CNLCD, and some waste recycling data is sourced from literatures [6]. The life cycle inventory data of copper and aluminum cables after calculation is shown in Table 3and 4(For space limit, only main input and output inventories are listed in this paper).

Table 3. Life cycle inventory data of YJV224×120 copper cable

Input / Output	Description	Unit	Value
Input	Copper ingot	kg	4,124.44
Input	Silane XLPE	kg	224.67
Input	Non-woven fabric	kg	11.94
Input	Steel strip	kg	629.70
Input	PVC sheath material	kg	528.23
Input	Diesel	kg	3.40
Input	Steam	kg	350.00
Input	Power (utilization)	kwh	2,116,217.88
Input	Highway transportation	tkm	3,346.45
Output	Nitrogen oxide	kg	9,425.38
Output	Sulfur dioxide	kg	24,136.28
Output	Carbon dioxide	kg	2,265,104.92
Output	Hydrogen fluoride	kg	121.30
Output	Methane	kg	6,175.08
Output	Aluminum (+III)	kg	1.45
Output	Hydrogen chloride	kg	436.78
Output	Lead (+II)	kg	3.25
Output	Arsenic (+V)	kg	1.23
Output	Nitrous oxide	kg	25.31

Table 4. Life cycle inventory of YJHLV82-4×185 aluminum cable

Input / Output	Description	Unit	Value
Input	Aluminum pole	kg	1,994.90
Input	Silane XLPE	kg	362.00
Input	Non-woven fabric	kg	16.50
Input	Aluminum strip	kg	591.40
Input	PVC sheath	kg	896.00
Input	Natural gas	m^3	175.00
Input	Power (utilization)	kwh	2,211,531.41
Input	Highway transportation	tkm	2,316.48
Output	Nitrogen oxide	kg	9,858.90
Output	Sulfur dioxide	kg	25,246.43
Output	Carbon dioxide	kg	2,369,288.73
Output	Hydrogen fluoride	kg	126.88
Output	Methane	kg	6,459.10
Output	Hydrogen chloride	kg	456.87
Output	Arsenic (+V)	kg	1.29
Output	Zinc (+II)	kg	8.38
Output	Nitrous oxide	kg	26.47

3.8. Comparison on environmental impact

Due to similar rated current-carrying capacities and production processes, YJHLV82-4×185 aluminum cables and YJV224×120 copper cables are comparable. In order to accurately compare the environmental impacts of these two types of power cables throughout their entire life cycles, comparisons on several types of environmental impact are carried out between aluminum cables and copper cables at different life cycle stages. Table 5 and Figure 3-7. Below are the uniformization results.

Table 5. Comparison on environmental impacts of copper and aluminum cables

Description	YJHLV82-4*185	YJV224*120
CML2001 global warming potential (GWP 100 years) kgco2e	2,558,799.60	2,445,741.86
CML2001 acidification potential (AP) kgso2e	32,976.46	31,609.27
CML2001 eutrophication potential (EP) (kg Phosphate e)	1,379.91	1,323.10
CML2001 human toxicity potential (HTP)(kg DCB e)	1,204,809.58	1,162,351.54
EI99HA energy consumption (MJ)	1,906,362.41	1,822,297.01

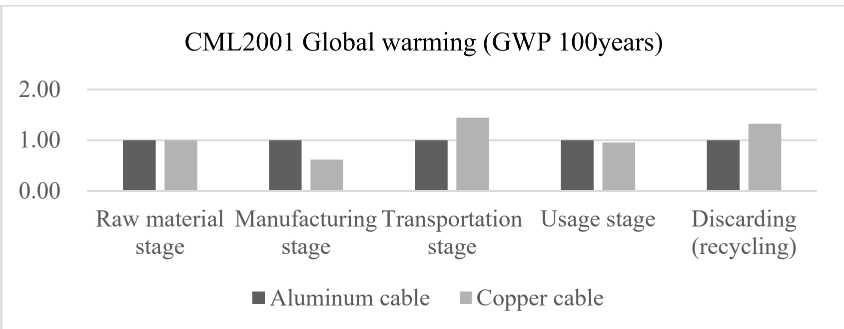

Figure 3. Comparison between aluminum and copper cables on GWP

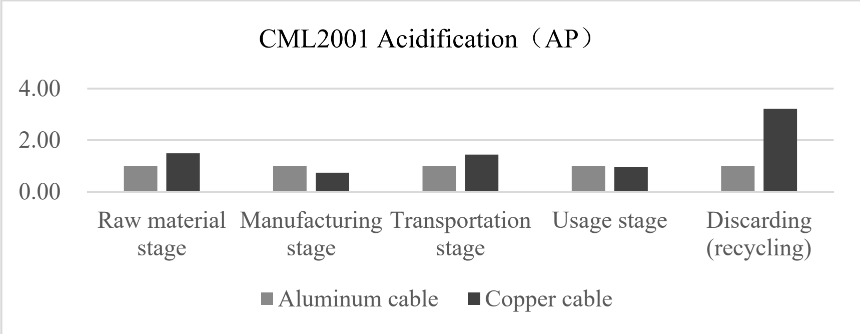

Figure 4. Comparison between aluminum and copper cables on AP

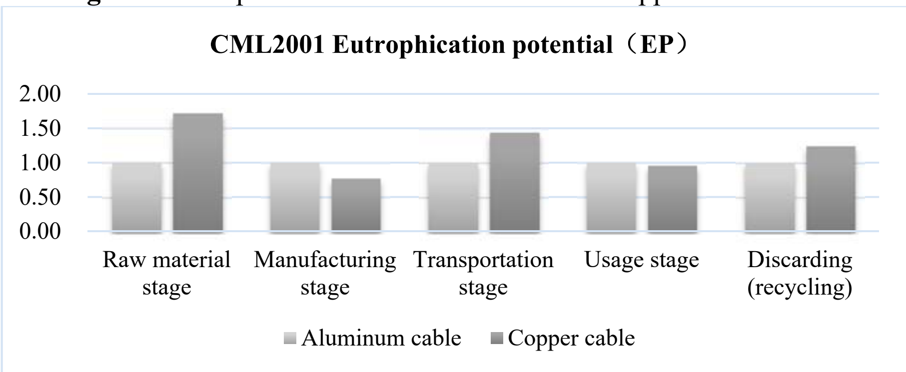

Figure 5. Comparison between aluminum and copper cables on EP

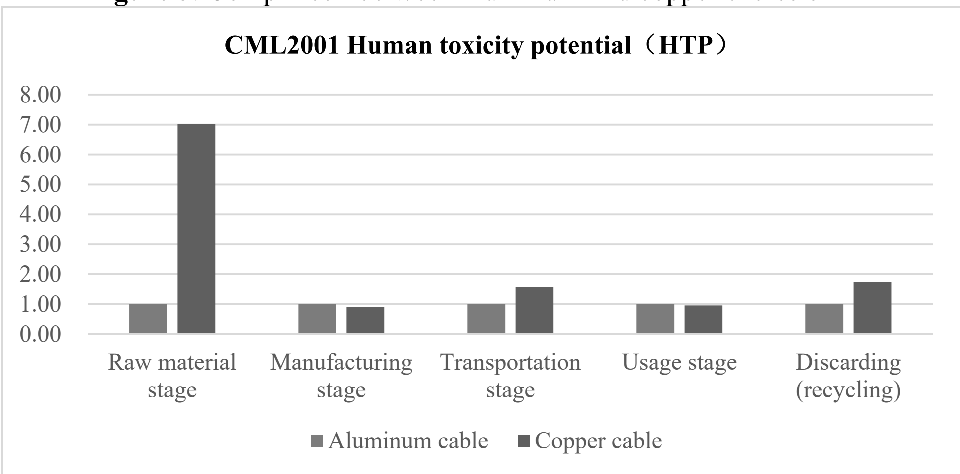

Figure 6. Comparison between aluminum and copper cables on HTP

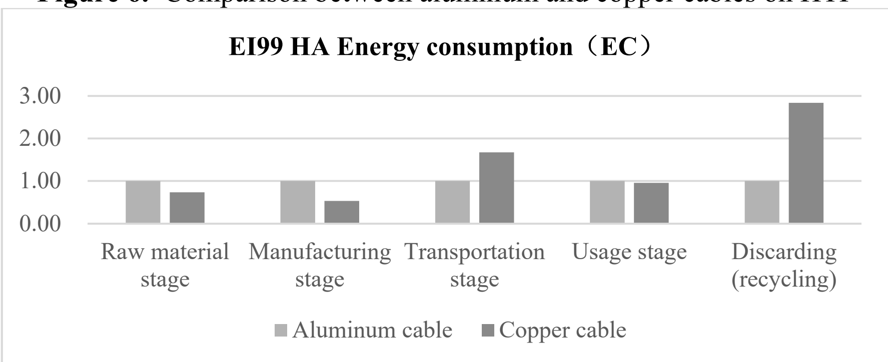

Figure 7. Comparison between aluminum and copper cables on EC

3.9. Description of uncertainty

As the assessment methods of LCA contain both objective and subjective contents, it is not a completely scientific issue. Both the raw data and assessment results of LCA are limited by time and region. Within different scopes of time and region, different environmental inventory data is available. Therefore, the corresponding assessment results are only applicable to a certain time period and region. This is determined by the time and region features of a product system [7].

The data for this assessment is sourced from company survey data and existing LCA databases at home and abroad. Among these data, the consumption data of raw materials and energy during cable production is sourced from domestic companies with relevant large production scales, mature technologies, and complete management systems, but cannot represent the production data of all domestic manufacturers of aluminium and copper cables. The assessment results of this paper are intended for the studies on LCA assessment methods and environmental impacts only, and the actual data of some companies may deviate, to some extent, from those in this paper.

As the calculations on aluminium and copper cables are all carried out under hypothetical scenarios and there is a slight difference on the current-carrying capacities of the two types of power cables selected for assessment, certain data deviation may exist on resistance and maximum operating temperature during calculation.

4. Conclusions

Contributions to the life cycle environmental impacts of power cables mainly come from the utilization stage of power cables, accounting for over 98% in the contributions of all types of environmental impacts. Taking a service life as 30 years, the calculated power loss at utilization stage is relatively huge. However, power loss also has direct relation to the application scenario of cables. Different application scenarios and service life will influence the calculation results to a great extent.

According to the aforementioned results, reducing power loss during transmission is a major and the most effective and practical method of reducing the life cycle environmental impacts of power cables. Power factor is an important technical and economic indicator of a power supply system. Electrical equipment, while consuming active power, also requires a large amount of reactive power to be transmitted from power source for loading. Power factor reflects the amount of reactive power required by the electrical equipment while consuming a certain amount of active power. The value of power factor has significant impact on the full utilization of the power generation, supply and utilization equipment of power system. Properly increasing power factor can not only give a full play to the production capacities of the power generation, supply and utilization equipment, reduce line loss, and improve voltage quality, but also improve the operating efficiency of the equipment. In addition, line loss can also be reduced by reasonable arranging cross-sections of conductors, adding line loops, installing necessary reactive-load compensation equipment, and taking more effective management measures, so as to reduce the environmental impacts of power cables at their utilization stage.

Furthermore, as for the utilization of recycled raw materials in power cable industry, comparative analysis on the environmental impacts of replacing original materials with recycled metal materials is not carried out in this study because of limited data. Once conditions get mature, the factor of recycled materials can be included in the environmental impact assessment of power cables. For example, the reduction of environmental impacts after replacing original copper with recycled copper can be calculated. In this way, a more comprehensive environmental impact analysis can be conducted on copper cables and aluminium cables.

As for power cable manufacturers, they can, from the perspectives of conductors themselves and production process improvement, further increase metal purity and alloying technology, improve the electrical conductivity of conductors, narrow the gap with developed countries, and reduce reactive power consumption. And they can also reduce the environmental impacts of power cables as much as possible from aspects such as raw material selection, reducing energy consumption in production, shortening transportation distance, and recycling products.

Conflict of Interest
The authors confirm that this article content has no conflicts of interest.

Acknowledgements
This paper is funded by Special Project of Generic Technology Research and Application of National Quality Basis – Research on Typical Generic Technology and Standards Supporting Carbon Emission Trading and Integrated Application Demonstration (No. 2016YFF0204400).

References
[1] Ren L J, Chen S, Zhang J J, Liu L W, Cao L, Yue W C, Wang D, 2010. Uncertainty Analysis in the Inventory of the Life Cycle Assessment. *Journal of Safety and Environment*, (1), 118-121.
[2] Huang C L, Zhang J Q, Shen S T, 2004. Summary of Life Cycle Assessment. *Environmental Technology*, 22(1), 29-32.
[3] *Power Supply and Utilization Technology* 1992. USTC Press.
[4] Zhu Y R, Li X Z, 2001. An Economic Selection of Power Cable Cross Section Area. *East China Electric Power,* 29(5), 4-7
[5] *Plant Power Supply and Exemplifications* 1987, Tongji University Press. [in Chinese]
[6] Jiang J L, Xu J C, Wu Y P, 2006. LCA study of secondary copper. *Journal of Lanzhou University of Technology*, 32(3), 4-6.
[7] Chen W Q, Wan H Y, Wu J N, Shi L, 2009. Life cycle assessment of aluminum and the environmental impacts of aluminum industry. *Light Metals,* (5), 3-10.