Life Cycle Carbon Footprint Assessment of Power Transmission Equipment

Kaibin Sun[1], Changzheng Shao[1](✉), Yue Sun[2], Chengrong Lin[1], Xin Cheng[3], Weizhan Li[1], Bo Hu[1], and Kaigui Xie[1]

[1] State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, China
cshao@cqu.edu.cn, lwz98cc@163.com, hboy8361@163.com, kaiguixie@vip.163.com

[2] China Yangtze Electric Power Co., Ltd., Yichang 443000, China

[3] State Grid Shanxi Electric Power Company Economic and Technological Research Institute, Taiyuan 030000, China
cxcx1997@163.com

Abstract. The recognition of life cycle carbon footprint (LCCF) of power transmission equipment is of great significance to the de-carbonization of power systems. Based on the technical features of power transmission equipment, the concept of LCCF is proposed in this paper, which includes fixed carbon emissions and variable carbon emissions. Firstly, to evaluate the LCCF of power transmission equipment, the life cycle of transmission equipment is divided into five stages: raw materials, manufacturing and assembly, transportation, operation, and maintenance, decommissioning and scrapping according to the time series, and the carbon emissions in all stages of the life cycle are calculated in combination with various carbon emission factors and quality criteria. Then, based on the concept of equal annual value, a conversion model for carbon footprint is proposed to realize the comprehensive evaluation of LCCF. Finally, the correctness and effectiveness of the proposed method are verified by simulation analysis. The results show that fixed carbon emissions account for a certain proportion of LCCF. To achieve the double carbon goal on schedule, it is necessary to study the LCCF of power transmission equipment and make independent contributions to accelerating the process of de-carbonization.

Keywords: Power transmission equipment · Life cycle · Carbon emissions · Double carbon target

1 Introduction

Since entering the 21st century, climate change has attracted more and more attention. The main cause of climate change is greenhouse gases, in 2014, China's non-carbon greenhouse gas emissions were 2 billion tons of CO_2e, only accounting for 16% of the total greenhouse gas emissions, therefore, low-carbon development is the internal demand of China's sustainable development [1]. Energy activities are the main source of

F. Sun et al. (Eds.): ICEIV 2022, LNEE 1016, pp. 79–91, 2023.
https://doi.org/10.1007/978-981-99-1027-4_9

CO_2 emissions in China, accounting for more than 80% of the total social CO_2 emissions, among which the CO_2 emissions from the power industry account for more than 40% [2]. Therefore, to cope with climate change, the de-carbonization of the power industry becomes necessary.

Facing the urgent need for low-carbon transformation in the power industry, domestic and foreign researchers have carried out a series of research on energy structure optimization and low-carbon optimization technology [3–9]. In terms of energy structure optimization, Ref. [3] analyzes the transformation trend of the electric power discipline research system under the dual carbon goal, and the construction of a new power system with new energy as the main body will be the key to achieve China's carbon peak and carbon neutrality strategic goals. Reference [4] proposed an energy-carbon integrated price method and low-carbon scheduling strategy for multi-energy systems to optimize the energy structure and reduce system carbon emissions. Reference [5] proposed a low-carbon power grid transformation model, which takes into account the aging and decommissioning of coal-fired power stations, the installation of renewable energy power plants, and the expansion of power grids, and optimizes the power structure to provide more economic and low-carbon decisions.

In terms of low-carbon technology optimization, Ref. [6] comprehensively considers energy time-shifting and rapid regulation characteristics of the flexible operation mode of carbon capture power plant, multi-time scale characteristics, and zero carbon emission characteristics of DR resources, to achieve low-carbon economic scheduling of power system. Reference [7] proposed a multi-stage coordinated optimization model that considers carbon capture technology, spinning reserve, and power generation technology to achieve a low-carbon economy. Reference [8] defines the technical and policy targets of low-carbon transformation as a backcasting problem, establishes a bi-level optimization problem, and provides a new perspective for the decarbonization of the power industry. Based on the carbon trading mechanism. Reference [9] proposed a low-carbon economic scheduling method for power systems considering thermal power unit heat storage transformation, which realizes economy and low-carbon.

The above research has studied the energy structure and low-carbon technology in reducing the carbon emissions of power, which can lay a certain theoretical foundation for the de-carbonization of China's power industry. It is worth noting that the above studies mainly consider the direct carbon emissions from the "source side" of the power system while ignoring the carbon emissions existing in the power industry chain [10].

Therefore, some scholars began to study the LCCF of the power industry. References [11, 12] adopt the life cycle assessment method, established the Chinese typical wind farm in the stage of construction, operation, and removal of carbon footprint calculation model, through calculation, found that although wind farms use clean energy, in the process of its whole life, make wind turbine consumes a lot of steel and copper, and a large amount of CO_2 emissions and the responsibility for that CO_2 belongs to wind farms. Reference [13] establishes an assessment model for LCCF of EV charging infrastructure, which can realize the mixed de-carbonization of the power grid and further promote the process of net zero emissions. Reference [14] establishes the carbon footprint of the whole process of the integrated community energy system. The above studies have discussed the low-carbon transition based on the concept of LCCF, which has good reference significance. However, there is a lack of research on the LCCF of power transmission equipment.

In view of the above problems, this paper proposes an LCCF assessment and analysis model for typical power transmission equipment. Firstly, according to the time series, the life cycle of power transmission equipment is modeled into five stages: raw materials, manufacturing and assembly, transportation, operation and maintenance, and decommissioning and scrapping. Combined with various carbon emission factors and quality criteria, the carbon emission accounting of each stage of the life cycle is realized. Then, based on the existing characteristics of fixed and variable carbon emissions, combined with the concept of equal annual value, the present value calculation model of carbon emission intensity is proposed to quantify the carbon intensity index of fixed carbon emissions and guide the direction of power system emission reduction. Finally, the correctness and effectiveness of the proposed method are verified by simulation analysis.

2 Life Cycle Carbon Footprint of Power Transmission Equipment Definition and Calculation Process

2.1 Life Cycle Carbon Footprint Definition of Power Transmission Equipment

The power transmission system is an indispensable part of the modern power system, and the function is to transfer the electric energy generated by the generation side to the load side through some power equipment, that is, the bridge between the generation side and the load side, mainly composed of power transformers and transmission lines and other power equipment [10]. Life cycle assessment is an evaluation method used by European and American countries in the 1970s to study the life cycle of industrial products from production to recycling or waste by using the law of conservation of energy and the law of conservation of matter [15]. Carbon footprint refers to the enterprise organization, activities, products, or individuals through transport, food production and consumption, and greenhouse gas emissions caused by all kinds of production processes such as collection, also known as "carbon consumption", usually refers to a kind of new development, for measuring the institutions or individuals for the daily energy consumption and CO_2 emissions to the environment impact indicators [16].

To sum up, the life cycle of power transmission equipment includes five stages: raw materials, manufacturing and assembly, transportation, operation and maintenance, and decommissioning and scrapping. This paper defines its carbon footprint as fixed carbon footprint and variable carbon footprint, as shown in Fig. 1. Fixed carbon footprint refers to the carbon emissions generated by equipment during the raw material, manufacturing and assembly, transportation, and decommissioning and scrapping. The variable carbon footprint represents the carbon emissions generated by the consumption of equipment during the normal operation and maintenance of equipment.

Therefore, the LCCF of power transmission equipment is equal to the sum of fixed carbon footprint and variable carbon footprint, which can be expressed as:

$$\boldsymbol{C}_{\text{total}} = \sum_{i \in \Xi_{\text{fixed}}} \boldsymbol{C}_{\text{fixed},i} + \sum_{j \in \Xi_{\text{variable}}} \boldsymbol{C}_{\text{variable},j} \tag{1}$$

where $\boldsymbol{C}_{\text{total}}$ is the carbon footprint of the whole life cycle; $i \in \Xi_{\text{fixed}}$ represents the set of the fixed carbon footprint of transmission equipment at different stages; $\boldsymbol{C}_{\text{fixed},i}$ is the carbon footprint of stage i of transmission equipment; $j \in \Xi_{\text{var}iable}$ represents the set of the variable carbon footprint of transmission equipment at different stages; $\boldsymbol{C}_{\text{variable},j}$ is the carbon footprint of transmission equipment stage j.

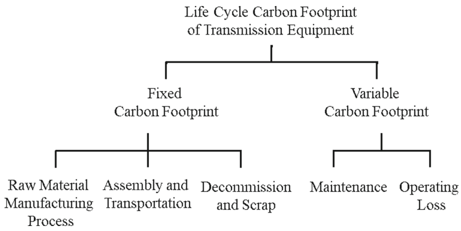

Fig. 1. The diagram of the life cycle carbon footprint of power transmission equipment

2.2 Life Cycle Carbon Footprint Calculation Process of Power Transmission Equipment

The LCCF calculation of transmission equipment includes four steps: selecting functional units, determining system boundaries, collecting data and calculating carbon footprint [13]. The detailed calculation process is shown in Fig. 2.

3 Carbon Footprint Assessment Model of Power Transmission Equipment Based on Life Cycle

According to the LCCF of transmission equipment defined in this paper, this section aims to establish the carbon footprint assessment model of transmission equipment raw material acquisition, manufacturing and assembly, transportation, operation and maintenance, and decommissioning and scrapping to quantify the carbon footprint of each stage. The carbon footprint assessment model of each stage is as follows.

3.1 Raw Material Acquisition Stage

In the stage of raw material acquisition, the carbon footprint mainly includes the energy consumed by equipment in the manufacturing process and the corresponding carbon emission of materials. Assuming that the equipment needs n kinds of materials and consumes m kinds of energy at the stage of raw material acquisition, its carbon footprint can be expressed as:

$$C_{\text{M}} = \sum_{i=1}^{n} M_i \times MEF_i + \sum_{j=1}^{m} E_j \times EF_j \tag{2}$$

where C_{M} represents the carbon footprint of raw material acquisition stage, M_i represents the consumption of class i materials, MEF_i represents the production emission factor of class i materials, E_j represents the consumption of class j energy, EF_j represents the carbon emission factor of class j energy.

It is worth noting that in the raw material acquisition stage, part of the materials can be recycled, so the carbon footprint of the recycled materials should not belong to the equipment raw material acquisition stage. In this paper, the utilization rate of materials is defined as η_{M}, and the carbon footprint of the raw material acquisition stage can be expressed as:

$$C_{\mathrm{M}} = (\sum_{i=1}^{n} M_i \times MEF_i + \sum_{j=1}^{m} E_j \times EF_j)/\eta_{\mathrm{M}} \tag{3}$$

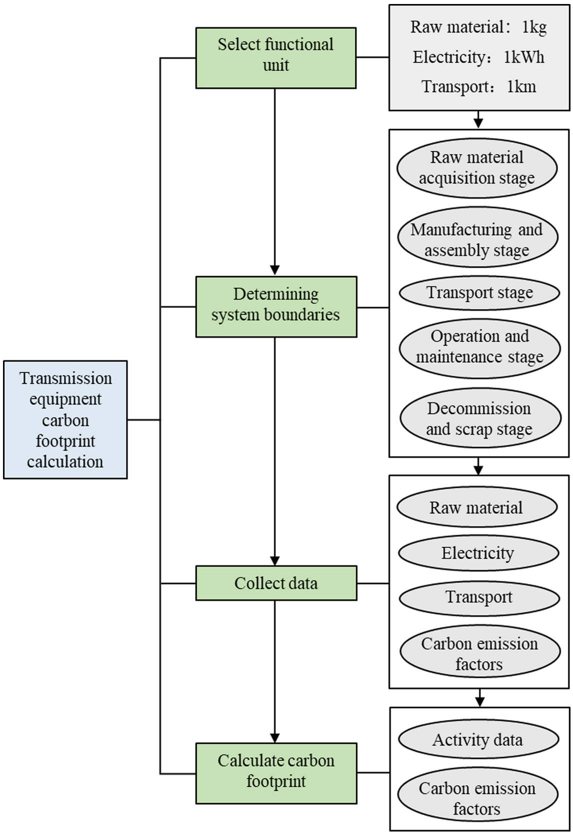

Fig. 2. The calculation procedure for life cycle carbon footprint of power transmission equipment

3.2 Manufacturing and Assembly Stage

In the manufacturing and assembly stage, the carbon footprint mainly refers to the carbon emission corresponding to the energy consumption in the processing link. Assuming that the equipment consumes n kinds of energy in the manufacturing and assembly stage, its carbon footprint can be expressed as:

$$C_P = \sum_{i=1}^{n} E_i \times EF_i \tag{4}$$

where C_P represents the carbon footprint of the manufacturing and assembly stage, E_i represents the consumption of type i energy, and EF_i represents the carbon emission factor of type i energy.

In addition, it is similar to the raw material acquisition stage, the recycling of materials will offset part of the carbon footprint of the manufacturing and assembly stage, and the utilization rate of materials in this stage is defined as η_P, the carbon footprint of manufacturing and assembly stage can be expressed as:

$$C_P = (\sum_{i=1}^{n} E_i \times EF_i)/\eta_P \tag{5}$$

3.3 Transportation Stage

In the transportation stage, the carbon footprint mainly refers to the carbon emission corresponding to the energy consumed by the transportation means, which is related to the carbon emission coefficient of different transportation modes, the choice of transportation means, and the distance from the manufacturer to the installation point. The carbon footprint can be expressed as follows:

$$C_T = \sum_{i=1}^{n} M_i \times D_i \times EF_i \tag{6}$$

where C_T represents the carbon footprint at the transportation stage, M_i represents the quality of equipment in transportation stage i, D_i represents the transportation distance of transportation stage i, and EF_i represents the carbon emission factor of transportation equipment in transportation stage i by means of transport.

3.4 Operation and Maintenance Stage

In the stage of operation and maintenance, the carbon footprint mainly refers to the energy loss of the equipment during operation and the carbon emission generated by the maintenance of the equipment. Assuming that the service life of the equipment is LT years, its carbon footprint can be expressed as:

$$C_U = (E_1 \times T \times 365 \times LT + E_2)EF \tag{7}$$

where C_U represents the carbon footprint of the operation and maintenance stage, E_1 represents the actual daily power consumption of the equipment in the use stage, T represents the operation time, E_2 represents the power consumption of equipment maintenance, and EF represents the power carbon emission factor.

It should be noted that at this stage, the power carbon emission factor changes dynamically with different operating conditions, namely, the real-time power carbon emission factor. In addition, the electric energy loss and maintenance power consumption of the equipment during operation will also change with the service time of the equipment. Based on this feature, the carbon footprint at this stage is variable.

3.5 Decommissioning and Scrapping Stage

In the decommissioning and scrapping stage, the carbon footprint mainly refers to the carbon emission generated by energy consumption during the dismantling and recycling of equipment or the scrapping process. The stage of carbon footprint and raw materials for the carbon footprint of similar, the difference is that in the retirement and scrap stage, the need to plan for raw materials and equipment after removing material recycle access and manufacturing and assembling stage of the influence of the carbon footprint, so need this stage make up for the part of the carbon footprint, the carbon footprint is retired scrap stage can be expressed as follows:

$$C_R = \sum_{i=1}^{m} E_i \times EF_i - \sum_{j=1}^{n} M_j \times MEF_j \tag{8}$$

where C_R is the carbon footprint at the decommissioning and scrapping stage.

Overall, the LCCF of transmission equipment can be expressed as:

$$\boldsymbol{C}_{\text{total}} = C_M + C_P + C_T + C_U + C_R \tag{9}$$

4 Proposed Conversion Method for Life Cycle Carbon Footprint

Currently, the "average electricity consumption carbon emission factor" widely used at home and abroad cannot perceive the difference in carbon emissions generated by different electricity consumption behaviors in different periods, leading to errors in carbon footprint calculation. With the proposal of dynamic carbon emission factors based on the carbon emission flow theory [17], the temporal and spatial differences of electric carbon emission factors can be effectively perceived, thus providing accurate carbon emission factors for carbon footprint calculation.

It should be emphasized that, according to Section I, the LCCF of transmission equipment includes fixed carbon footprint and variable carbon footprint. The equipment service life span is long, the life cycle of fixed carbon footprint and carbon footprint variable dimension will not in the same time, in order to achieve the LCCF of equipment effectively and accurate assessment needs to be fixed carbon footprint within the life cycle of equipment with variable carbon footprint discount to a reference time. Based on the concept of the time value of finance, the life-cycle carbon footprint conversion method proposed in this paper is as follows.

Assuming that the service life of the equipment is LT years, ir is the discount rate of the annual Carbon footprint, and the carbon footprint conversion factor (CRF) is:

$$CRF = \frac{ir(1+ir)^{LT}}{(1+ir)^{LT}-1} \tag{10}$$

According to the concept of equal annual value, the formula for converting fixed carbon footprint into the same time scale as the variable carbon footprint is as follows.

$$\boldsymbol{C}_{\text{fixed}}^{'} = \frac{CRF \times \boldsymbol{C}_{\text{fixed}}}{8760} \tag{11}$$

where CRF is the carbon footprint conversion coefficient, $\boldsymbol{C}_{\text{fixed}}$ is the fixed carbon footprint in the whole life cycle of transmission equipment, and $\boldsymbol{C}_{\text{fixed}}^{'}$ is the equivalent variable carbon footprint in the whole life cycle.

To sum up, the converted value of fixed carbon footprint in the k year is:

$$\boldsymbol{C}_{\text{fixed}}^{''} = \boldsymbol{C}_{\text{fixed}}^{'} \frac{(1+ir)^{k}-1}{ir(1+ir)^{k}} \quad \forall k \in LT \tag{12}$$

5 Case Study

To comprehensively analyze the LCCF of the transmission equipment, transformers and transmission lines in a certain region are selected as research objects in this paper. Besides, to quantify the carbon emissions in each stage of the life cycle, carbon dioxide equivalent (CO_2e) is taken as the evaluation measurement unit.

5.1 Parameter Setting

The transformer is mainly composed of the body, voltage regulating device, protection device, cooling device, and outlet device. The following takes the SZ11-5000/110 transformer as an example to evaluate LCCF [18]. And the service life is 25 years. Transmission lines are mainly composed of wires, towers, insulators, and fittings. The following takes a typical 11 kV transmission line as an example to evaluate LCCF per unit length, which service life is 30 years, and the discount rate is set as 8% [19]. In the decommissioning and scrapping stages, some metal materials can be effectively recycled to compensate for the carbon footprint generated in the raw material acquisition stage. In this paper, it is assumed that 90% aluminum, 70% copper, and 50% steel can be recovered.

Table 1. Carbon emission factors for materials and energy

Material or Energy	Carbon Emission Factor
Copper	6.64 $kgCO_2e/kg$
Aluminum	1.80 $kgCO_2e/kg$
Iron or Steel	1.72 $kgCO_2e/kg$
Magnesium	2.83 $kgCO_2e/kg$
Zinc	3.66 $kgCO_2e/kg$
Ferroalloy	3.60 $kgCO_2e/kg$
Diesel fuel	2.73 $kgCO_2e/L$
Polyethylene	1.6 $kgCO_2e/kg$
Coal	2.46 $kgCO_2e/kg$
Sulfur Hexafluoride	23.9 $kgCO_2e/kg$
Electricity	1.02 $kgCO_2e/kWh$

Table 2. Carbon footprint of each stage of transformer and transmission lines life cycle

Stage	Carbon footprint of transformer ($kgCO_2e$)	Carbon footprint of transmission lines ($kgCO_2e$)
Raw material acquisition	5.61 * 10^5	4.06 * 10^5
Manufacturing and assembly	7.56 * 10^4	1.31 * 10^5
Transportation	5.92 * 10^4	2.91 * 10^4
Operation and maintenance	5.81 * 10^7	8.04 * 10^6
Decommissioning and scrapping	−3.82 * 10^5	−3.21 * 10^5
Total	5.84 * 10^7	8.28 * 10^6

5.2 Numerical Results

To reflect the accuracy of carbon footprint calculation of the life cycle of power transmission equipment, it is necessary to use authoritative carbon emission factors. The carbon emission factors [20] of the main materials and energy in this paper are shown in Table 1.

Table 2 shows the calculation results of the LCCF of the transformer and transmission lines by using the method proposed in this paper, and the carbon footprint distribution diagram of each stage is shown in Fig. 3.

According to the analysis of Table 2 and Fig. 3, in the life cycle of the transformer, the carbon footprint value in the operation and maintenance stage is the largest, which is mainly due to two reasons: one is that sulfur hexafluoride (SF6) will leak from the insulating oil of the transformer, resulting in a large amount of carbon emissions; The

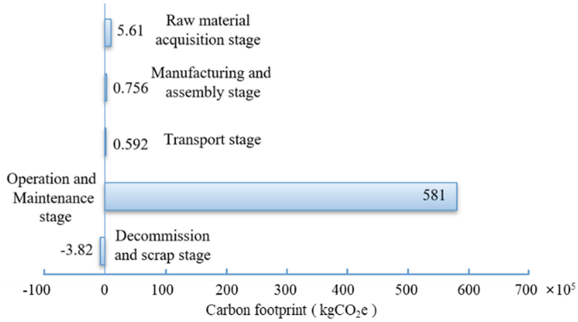

Fig. 3. Carbon footprint distribution diagram of each stage of transformer life cycle

other is that the transformer will cause about 3% power loss during operation, and this part of the carbon footprint is also considerable in the life cycle. In addition, the carbon footprint of raw material acquisition, manufacturing and assembly, transportation, decommissioning and scrapping is 302000 kgCO_2e. At the same time, in order to quantify the carbon intensity index of carbon emissions in the life cycle, the conversion method proposed in this paper is used to convert the carbon footprint to a reference time with the variable carbon footprint. The results are shown in Fig. 4.

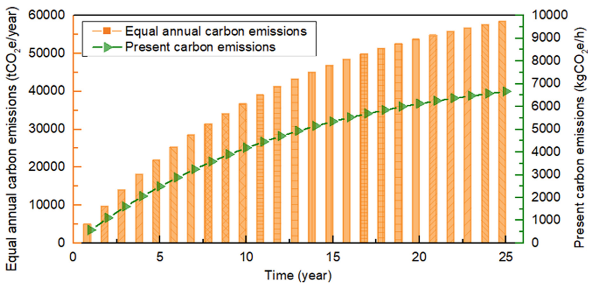

Fig. 4. Schematic diagram of transformer life cycle equivalent carbon footprint

Similarly, the carbon footprint distribution diagram of transmission line at each stage is shown in Fig. 5.

It can be seen from Table 2 and Fig. 5, that in the life cycle of transmission lines, the carbon footprint of the operation and maintenance stage is 8040000 kgCO_2e, accounting for 97.1% of the total carbon footprint. Although the fixed carbon footprint of transmission lines accounts for about 3% of the whole life cycle, which is relatively small, it is very necessary to consider the LCCF to decarbonize the power industry. Similarly, the carbon footprint is converted to the same reference time as the variable carbon footprint by using the conversion method proposed in this paper, and the results are shown in Fig. 6.

By analyzing Figs. 4 and 6, the carbon footprint conversion model proposed in this paper can convert the LCCF of power transmission equipment into the same resolution

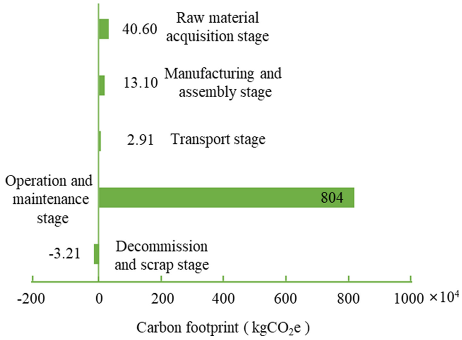

Fig. 5. Carbon footprint distribution diagram of transmission line at each stage of life cycle

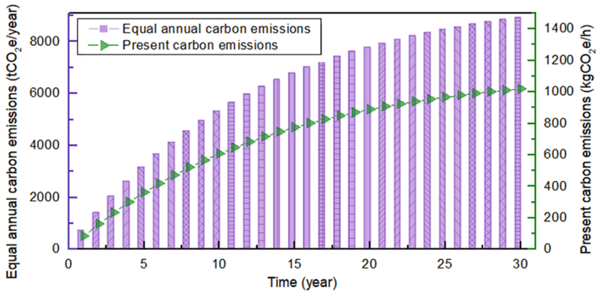

Fig. 6. Schematic diagram of transmission line life cycle equivalent carbon footprint

as the variable carbon footprint, quantify the carbon intensity index of fixed carbon emissions, and realize the comprehensive evaluation of LCCF.

6 Conclusion

This paper presents a model for carbon emission measurement and analysis of power transmission equipment based on the life cycle. The following conclusions are drawn from the analysis of examples:

(1) The carbon footprint of power transmission equipment is generated in five stages of its life cycle, including raw material acquisition, manufacturing and assembly, transportation, operation and maintenance, and decommissioning and scrapping. The method proposed in this paper can calculate the carbon emissions of each stage in the service life cycle and provide a theoretical basis for the LCCF of power transmission equipment.

(2) Based on the carbon footprint conversion model proposed in this paper, the LCCF can be converted into equal annual value and present value carbon emissions, it can realize the comprehensive evaluation of LCCF and provide a more accurate carbon emission model for power transmission equipment.

(3) The carbon footprint calculated in this paper not only reflects the activities related to the equipment and power operation but also quantifies the carbon footprint generated during the production, transportation, and decommissioning of raw materials, which can guide the direction of carbon emission reduction in the power industry and accelerate the de-carburization process.

Acknowledgments. This work was supported by the National Natural Science Foundation of China (52107072), China Postdoctoral Science Foundation (2021M693711), Fundamental Research Funds for the Central Universities (NO.2021CDJQY-037).

References

1. Project comprehensive report preparation team: Comprehensive report on China's long-term low-carbon development strategy and transformation path. China Popul. Resour. Environ. **30**, 1–25 (2020). (in Chinese)
2. Global energy Internet development cooperation organization: China's carbon neutral road. China Power Press, Beijing (2021). (in Chinese)
3. Chongqing, K., Ershun, D., Yaowang, L., Ning, Z., Qixin, C., Hongye, G., Peng, W.: "Carbon perspective" of new power system: scientific issues and research framework. Power Syst. Technol. **46**, 821–833 (2022). (in Chinese)
4. Cheng, Y., Zhang, N., Zhang, B., Kang, C., Xi, W., Feng, M.: Low-carbon operation of multiple energy systems based on energy-carbon integrated prices. IEEE Trans. Smart Grid **11**(2), 1307–1318 (2020)
5. Shen, W., Qiu, J., Meng, K., Chen, X., Dong, Z.Y.: Low-carbon electricity network transition considering retirement of aging coal generators. IEEE Trans. Power Syst. **35**(6), 4193–4205 (2020)
6. Yang, C., Guibo, D., Peng, Z., Wuzhi, Z., Yuting, Z., Xinyuan, L.: Multi time scale source load scheduling method of wind power system considering the low-carbon characteristics of carbon capture power plants. Chin. J. Electr. Eng. 1–18 (2022). (in Chinese)
7. Lou, S., Lu, S., Wu, Y., Kirschen, D.S.: Optimizing spinning reserve requirement of power system with carbon capture plants. IEEE Trans. Power Syst. **30**(2), 1056–1063 (2015)
8. Zhuo, Z., Zhang, N., Hou, Q., Du, E., Kang, C.: Backcasting technical and policy targets for constructing low-carbon power systems. IEEE Trans. Power Syst. 1–1 (2022)
9. Yuan, P., Suhua, L., Yue, F., Yaowu, W., Shuhao, L.: Low carbon economic dispatching of power system considering thermal storage transformation of thermal power units. Power Syst. Technol. **44**, 3339–3345 (2022). (in Chinese)
10. Zeng, B., Zhang, J., Yang, X., Wang, J., Dong, J., Zhang, Y.: Integrated planning for transition to low-carbon distribution system with renewable energy generation and demand response. IEEE Trans. Power Syst. **29**(3), 1153–1165 (2014)
11. Ji, S., Chen, B.: LCA-based carbon footprint of a typical wind farm in China. Energy Proc. **88**, 250–256 (2016)
12. Liu, P., Liu, L., Xu, X., Zhao, Y., Niu, J., Zhang, Q.: Carbon footprint and carbon emission intensity of grassland wind farms in Inner Mongolia. J. Clean. Prod. **313**, 127878 (2021)
13. Zhao, E., May, E., Walker, P.D., Surawski, N.C.: Emissions life cycle assessment of charging infrastructures for electric buses. Sustain. Energy Technol. Assess. **48**, 101605 (2021)
14. Bo, H., Kaibin, S., Changzheng, S., Wei, H., Yusheng, Z., Kaigui, X: Carbon perception and optimization method of the integrated community energy system oriented to the whole process carbon footprint. High Volt. Eng. **48**(7), 2495–2504 (2022). (in Chinese)

15. Chau, C.K., Leung, T.M., Ng, W.Y.: A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Appl. Energy **143**, 395–413 (2015)
16. Čuček, L., Klemeš, J.J., Kravanja, Z.: A review of footprint analysis tools for monitoring impacts on sustainability. J. Clean. Prod. **34**, 9–20 (2012)
17. Cheng, Y., Zhang, N., Wang, Y., Yang, J., Kang, C., Xia, Q.: Modeling carbon emission flow in multiple energy systems. IEEE Trans. Smart Grid **10**(4), 3562–3574 (2019)
18. Xingshuang, D., Hongchun, L., Xiaolong, S.: Analysis of the significance of promoting new energy efficiency power transformers to achieve carbon peak and carbon neutrality. Transformer **59**(2), 1–5 (2022)
19. Jones, C.I., McManus, M.C.: Life-cycle assessment of 11kV electrical overhead lines and underground cables. J. Clean. Prod. **18**(14), 1464–1477 (2010)
20. IPCC: 2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventory (2019)