EXPLORATION ON STANDARD FOR QUANTIFYING CARBON FOOTPRINT OF POWER EQUIPMENT - BASED ON LIFE CYCLE ASSESSMENT OF POWER TRANSFORMERS

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Abstract - Chinese State Grid accounts for 40% of the country's total emissions, so quantifying carbon footprint of power equipment is to set a foundation emission reduction of Chinese power companies. Aiming at establishing a standard framework in light of carbon footprint evaluation of power equipment, this paper,taking power transformers' life cycle carbon footprint as the research object, proposes five formulas applicable to each stage of power transformers'life cycle emissions.With a three-dimensional design thinking of "system - data - authentication" and a focus on power transformers, this paper proposes a process and model of carbon footprint calculation of power equipment and conducts a systematic analysis of product carbon footprint by combing orientation evaluation with LCA model. Such a standard aims at helping authorities collect data related to carbon emissions from power equipment so as to provide data support for the subsequent low-carbon design research.

Keywords - Quantifying Carbon Footprint, LCA Model, Orientation Evaluation, Power Transformers' Life Cycle Emission

I. INTRODUCTION

As a new technology used for quantitative analysis of product carbon emission , carbon footprint research has been applied to industries , making great achievements. Take Chinese electricity industry, its greatest sector of carbon emission(up to 40%) for example. Guided by objectives for carbon dioxide peaking and carbon neutrality, extensive research on carbon footprint of power equipment is conducted, setting up a basis for quantifying full life cycle carbon emission from power grid construction, manufacturing, transportation and installation of electric power equipment, and operation and maintenance of such equipment, which further optimizes the asset management system of power equipment, and accelerates a transformation of this industrial chain towards a green and low-carbon one.

On a global scale, scholars have studied product carbon footprint from various perspectives, and actively explored effective ways to reduce the carbon footprint of products. Liu Yun et al. , based on a case study onassessing carbon footprint of a coal-fired power plant in Luliang City, Shanxi Province, has tracked distribution of its carbon footprints in full life cycle .

Ross Ross et al. [2] testified that life-cycle assessment is the most effective and universal technology to support green design and manufacturing. Joyce et al. [3] proposed a heuristic method for carbon footprint of communication products. Dias et al. [4] compared divergences in carbon footprint calculation under different standards, and improved the consistency of calculation results. Zhang et al. [5] proposed a calculation method of carbon footprint ofconnection elements through analytic hierarchy process which makes recursive distribution of their carbon footprint. Venkatesh et al. [6] adopted a process framework and statistical modeling to evaluate uncertainty of fossil fuels'greenhouse gas emission. In order to reduce CO2 emissions and pollutants, Yoshika et al. [7] proposed a calculation method to analyze energy balance and CO2 emissions based on life cycle analysis. Ameta et al. [8] put forward the carbon footprint tolerance analysis method to calculate the carbon footprint of manufacturing and assembly stage, so as to provide decision-making basis for low-carbon product design. Ameta et al. [9] presentedatolerance analysis of carbon footprintcalculation in manufacturing and assembly of power equipment, for further decision-making on low-carbon product design. Ball et al. [10] suggested a transition from lowering carbon emission to utilizing emissions, after studying the model of material -- energy -- waste flow.

With a three-dimensional design thinking of "system - data-authentication" and a focus on power transformers, this paper proposes a process and model of carbon footprint calculation of power equipment and conducts a systematic analysis of carbon footprint in all stages by adopting life-cycle assessment. Based on theories on carbon footprint , the research integrates oriented evaluation with LCA model, laying a preliminary foundation for establishing a standard of quantifying carbon footprint of power grid equipment.

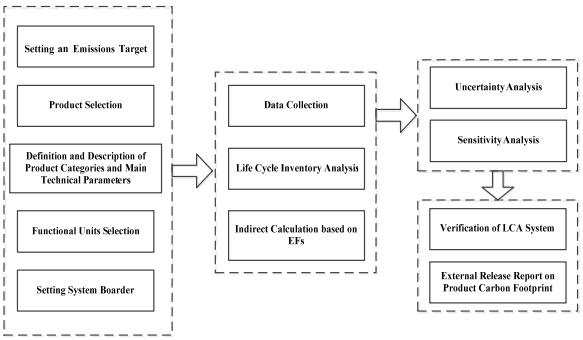
II. RESEARCH METHODS FOR QUANTIFYING PCF

PCF sums up the total greenhouse gas emissions generated over life stages, associated with two types of scopes or boundaries. One scope,namely"cradle to gate", applicable to B2B(business to business) products, measures total emission from raw material mining, product manufacturing, until product leaving

factories. Another scope, “cradle to grave”, is applied to B2C(business to consumer) products, with emission measured from extraction of raw materials to production, distribution, use and terminal disposal of products.

Methodologies for carbon footprint calculations are various including input-output method (Input - Output I - O), Life Cycle Assessment (LCA), 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines) [12] [13], and carbon footprint calculator, etc. Among them the most commonly used one is LCA , which has advantages like more accurate evaluation, and ability to adjust accuracy of its range toa specific goal setting.Assessmentstandards of PCF include PAS 2050 : 2008(Specification for the Assessment of Greenhouse Gas Emissions of Goods and Services Over the Life Cycle) and TSQ0010 standard(General Principles for the Assessment and Labeling of Carbon Footprint of Products). Most of the literature now uses PAS2050 and its guidelines to evaluate product carbon footprint.

LCA based on a product life cycle generally includes five stages: creating a product life cycle, determining product boundary, collecting data i.e carbon emission factors, calculating product carbon footprint, and measuring uncertainty. The calculation process is shown in Figure 1.

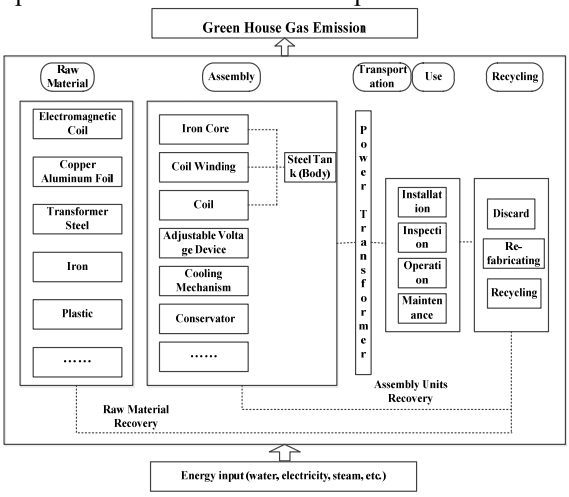


In this paper, evaluation process on PCF covers five stages. In Stage One,a product life cycle diagram is created,coveringall stages a product goes through, involving materials, energy and waste. After determining whether the selected product belongs to B2C or B2B, corresponding life cycle diagrams are created based on stages concerned.In Stage Two, product boundaries are defined as stipulated by the relevant provisions of ISO14025 series standards. When the defined product category boundaries do not apply tothe selected product in assessment, they are supposed to be redefined according to aforementioned standards.In Stage Three, carbon emission factors are collected, encompassing production data and carbon emission factors in the entire life cycle of products.In Stage Four, PCF are calculated on condition that all the items including input, output and waste are taken into calculation formula.In Stage Five, uncertainty is measured. This optional task improves accuracy of calculation and quality of collected data.

III. PCF ASSESSMENT SYSTEM OF POWER TRANSFORMERS

3.1. Assessment Boundary

The system defines PCF accounting boundary of power transformers as is shown in Figure 2. It counts direct and indirect emission of greenhouse gases from entire life cycle stages in raw material collection, production, manufacturing, transporting, installation, operation and maintenance to disposal after use.



3.2. Technical Approach

Research shows that different manufacturers are significantly different in product features and characteristics of production lines, and energy utilization management and etc, so it is partial to adopt a single model to evaluate PCF.The standard to be established in this paper encompasses two parts:orientation evaluation and Life Cycle Assessment(LCA). The former, based on responses made by manufacturing enterprises to questionnaire about their production, disclosesinformation on characteristics of technology , production lines,and energy utilization.The score is calculated according to the weighted value of different items, and thus make a horizontal comparison. The latter(LCA) works out absolute values of carbon footprints of equipment based on its life cycle by combining data collection with modeling calculation. The two evaluation methods complement each other in this research.

3.3. Orientation Evaluation

Questionnaire questions are designed to be objective and answers to them are unique.Meanwhile, the questionnaire is targeted at helping manufacturing enterprises clarifying specific actions of carbon reduction through the options. Questionnaire questions include, but are not limited to, the following options:

Enterprise situations: declaration of low-carbon target on its own or in the name of its group or headquarters ; carbon emissions from its operation or product manufacturing in the past three years voluntarily disclosed to the society or regulatory authorities with proven accounting report by official departments or by the third party; a complete supply chain and carbon emission management system for production.

Energy utilization: an accepted report or document of purchased green electricity and green certifications on its own or in the name of its group or headquarters; steam for production from high energy consumption industries such as surrounding thermal power plants; secondary heat utilization.

Electrification and digitization: intelligent temperature control device used in vapor phase drying ; automation equipment with key technologies e.g. core stacking; fully automated production of key technologies e.g. core stacking, with comparative advantages;a proportion of over 70% of purely electricity-driven forklift trucks and trailer equipment in production line.

Design and material selection: an industry-leading deployment of advanced environment-friendly and low loss materials, which has comparative advantages in direct or indirect carbon emission reduction; carbon footprint accounting reports onparts of raw materials or modules and assembly line units,issued by the third party.

Supporting information:objects being evaluated(a certain type of equipment) in terms of weight of main raw materials, type and weight of modules and constituent parts;proof of consumption of electricity, natural gas or steam within an accounting period; proof of productivity of a production line or a plant within an accounting period, including equipment model, quantity and capacity.

3.4. LCA Model

Accounting data of power transformers' carbon footprint based on LCA can be roughly divided into three categories:carbon emission factors, material consumed,
and intensity of activities.Inthis research, constantly complemented and updated carbon emission factors are mainly disclosed by authority organizations, commercial databases (CLCD by Sichuan University,CEADs, Ecoinvent, etc.),and informationdisclosed by manufacturers and academies.

IV. EVALUATION OF PCF OF POWER TRANSFORMERS

4.1. Carbon Footprint Assessment of Raw Materials

This evaluation system mainly takes into account five types of raw materials of transformer equipment, namely, transformer oil, silicon steel sheet, steel, insulating paper (board) and electromagnetic wire , which make up more than 98% of the mass of main equipment. If conditions are met, carbon footprints of such components as cooler (oil pump included), blade, fan, switch, casing, oil storage tank, outlet device and etc,-- are calculated by measuring three or more kinds of raw materials which make up the majority of their weight and adding up the sum total. Otherwise, carbon footprints can be estimated according to the empirical value of the total weight of components. In addition, these major raw materials and components generally need to be transported to the production line, and thus incurred carbon footprints can be worked out by calculating the weight of materials or components, the distance traveled and the mode of transportation.
Assuming that there are n types of materials required and m types of energy required, the carbon footprint of raw materials can be calculated as follows:

$$CF_M = \sum_{i=1}^{n} M_i^M \times EF_{M,i}^M + \sum_{i=1}^{n} M_i^M \times L_i \times EF_{T,i}^T \quad (1)$$

In this formula, M_i^M is the consumed amount of Class i materials in the raw; $EF_{M,i}^M$ and $EF_{T,i}^T$ respectively represent carbon emission factors of the production, preparation and transportation of Class I materials ; L_i is the transportation distance.

4.2. Carbon Footprint Assessment of Manufacturing

At present, domestic manufacturers developed uneven levels of monitoring in the production and manufacturing process. Some have realized terminal visualization of the energy use in production lines, whereas others can only provide information on their quarterly electricity usage .

Given the above situation, two calculation models are established for researching manufacturing process: the overall input-output analysis model and apportionment model of production line techniques. From the perspective of system application, the former model should be adopted in the initial stage of power transformer carbon footprint evaluation. With the raise of monitoring levels of manufacturers in production lines and the improvement of relevant mechanisms, the latter model can be gradually promoted and applied on a pilot basis.

1 Overall Input-output Analysis Model The majority of production lines of manufacturers are now centralized, and energy consumption of production lines is not monitored separately. Since only data of total production capacity and overall energy consumption over a period of time are available, the overall input-output analysis model is applicable for the calculation at the present stage.

This model is to allocate consumable production factors such as electric power from the grid, new energy generation (new energy, green electricity, etc.), gas, fuel oil, water, gases and auxiliary materials to the target object according to the number and capacity of equipment. Their carbon footprints are calculated according to the following formula:

$$CF_P = \sum_{i=1}^{n} \alpha_i E_i^P \times EF_{E,i}^P \qquad (2)$$

In this formula, $EF_{E,i}^P$ are emission factors of the I-th element, with values taken based on industry average data . α_i is the magnification coefficient, with a value greater than 1. (values as listed in Table 2) The larger the value of α_i , the higher the uncertainty of measurement.

Seeing that each carbon emission factor fluctuates with time and regional factors, and its dispersion varies in size,the magnification coefficient αi is used to weight each type of data after scaling, which, in theory, can reduce the influence of differential data confidence levels on result validity.Meanwhile, when the magnification coefficient is used incorrecting theoretical errorscaused by two accounting models, enterprises are encouraged to voluntarilydisclose more detailed data in accordance with the latter model.

2 Apportionment Model of Production Line Techniques

In case real-time monitoring of fineness of particles is realized in separate workshops and production lines and meanwhile data is verifiable, carbon footprints can be calculated according to apportionment modelof production line techniques,, as is shown in the following formula:

$$CF_P = \sum_{i=1}^{n} E_i^P \times EF_{E,i}^P + \sum_{j=1}^{m} G_j^P \times GWP_j^P \qquad (3)$$

In this formula, E_i^P represents consumption of the i-th energy at manufacturing and assembly stage, and $EF_{E,i}^P$ represents emission factors of the I-th energy production. G_j^P is the direct emissions of greenhouse gases in the J-th case, and GWP_j^P is the global warming potential of the J-th greenhouse gas.

Take a coil workshop for example. Apportionment is to allocate consumed electricity, water, oxygen, natural gas and air drying by production lines to each single equipment per unit time according to weighted mass of electromagnetic wires.Likewise, consumption of insulation production line is apportioned to the accounting object according to quantity of insulation parts; consumption of fuel tank production line is apportioned according to steel plate weight, and experiment consumption is apportioned according to to equipment capacity.

3.Carbon Footprint Assessment of Transportation

Transportation occurs when power transformers are moved from manufacturers to assembly sites, and carbon footprints in this process can be calculated based on transformer weight, transportation distance and modes of transportation.

4.Carbon Footprint Assessment of Operation &Maintenance

Operation and maintenance of power transformers covers a long time span and involves chance factors. This evaluation system mainly considers:

(1) In practice, indirect emissions caused by power loss during equipment operation can be estimated according to the average load rate and equipment loss parameters ; (2) Direct and indirect greenhouse gas emissions can be caused by transportation in the case of equipment maintenance, overhaul, and return to factory (due to differentiated parts). In practice, such emissions are estimated referring to past failure rates of this type of product (or the same type of product of the manufacturer) .

The following formula is applied to calculating carbon footprints of equipment operation and maintenance.

$$CF_R = \left(\int_{t_1}^{t_2} \left(\frac{I(t)}{I_0} \right)^2 P_L + P_E \right) (t_2 - t_1) \times EF_{ep} + \beta_i \times F_i \qquad (4)$$

In this formula, $I(t)$ represents a load curve, and I_0 a rated current of equipment, taking A as the unit; P_L represents rated load loss, and P_E rated no-load loss, taking kW as the unit. EF_{ep} represents a carbon emission factor of regional electric energy. F_i is past failure rate of products of this model (or productsin the same category by the manufacturer); β_i is a carbon footprint factor, adjustable according to the devicetype .

4.3. Carbon Footprint Assessment of Decommissioning and Disposal of Power Transformers

At present, decommissioning and disposal of power transformers in China is mainly commissioned to qualified enterprises by power grid companies. The proportion of metal recyclingin power transformers is high while organic insulating materials such as insulating board are difficult to recycle.

In view of difficulty in obtaining detailed data of material recovery after equipment is decommissioned, this system takes the ratio of real-time material recovery price to purchase price during the evaluation as the material recovery ratio, and calculates carbon footprints of equipment decommissioning and disposal according to the following formula:

$$CF_P = -\sum_{i=1}^{n} \gamma_i M_i^M \times EF_{M,i}^M + \sum_{i=1}^{n} V_j^R \times EF_{E,j}^R \quad (5)$$

In this formula, M_M^i is the weight of Class i materials, and γ_i is the ratio of real-time recovery price and purchase price of Class i materials. V_j^R is the consumption of J-type energy in the recovery and disposal stage, and $EF_{E,j}^R$ is the carbon emission factor of the J-type energy in the recovery and disposal stage. Considering the actual proportion of the latter part and the complexity of operation, it is recommended to ignore the latter part.

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