

Research on the Application of Life Cycle Method in Carbon Emission Accounting of Rural Households

-- Taking the Rural Model in Hebei as an Example Please Center

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Abstract

Against the dual background of China's "dual carbon" goal and the rural revitalization strategy, the low - carbon development of rural areas is a key link in achieving carbon emission reduction across society. This paper integrates the carbon emission accounting method of the Intergovernmental Panel on Climate Change and the life cycle assessment method to construct a nested carbon emission accounting framework of "four stages and three modules" suitable for rural households. Taking rural households in Tangshan City, Hebei Province as the research object, the study found that: the operation and use stage of rural household carbon emissions contributes the vast majority of emissions, followed by the building material production stage. Electricity consumption, embodied carbon in building materials, and emissions from small - scale breeding constitute the three core emission sources. The accounting framework constructed in this paper provides methodological support for the accurate accounting of rural household carbon emissions, and the research conclusions can provide a reference for rural low - carbon development decision - making.

Keywords

Life Cycle Assessment; Rural Households; Carbon Emission Accounting; Rural Areas in Hebei.

1. Introduction

Against the backdrop of intensifying global climate change, China's goals of carbon peak and carbon neutrality require in - depth emission reduction in all fields. Achieving the "dual carbon" goals is not only China's solemn commitment to the international community but also an important way to lead the transformation and upgrading of the economic structure and achieve high - quality development [1]. China has clearly put forward the strategic goals of achieving carbon peak before 2030 and carbon neutrality before 2060. Carbon emission reduction work covers all fields and regions of economic and social development. The achievement of the carbon peak and carbon neutrality goals is inseparable from scientific and rational carbon emission accounting [2]. In this context, rural areas, with their diverse industrial structures, scattered carbon emission sources, and weak statistical data foundation, have become the focus and difficulty of carbon emission accounting and reduction efforts.

Existing research shows that China's carbon emissions mainly come from the power generation sector, and the total carbon emissions of rural households are relatively small. However, from a life - cycle perspective, all stages involved in household energy consumption will generate carbon emissions. Therefore, only accounting for emissions during the household use stage will significantly

underestimate the actual carbon footprint of rural households. Introducing the life - cycle assessment method into rural household carbon emission accounting helps to comprehensively identify emission hotspots and provide a basis for precise emission reduction [3].

Based on this, this paper is based on the actual situation in rural areas, sorts out the existing research results on carbon footprints, clarifies the boundaries and methods for measuring rural carbon footprints, constructs a rural carbon footprint accounting framework, and conducts a case study on rural households in Tangshan City, Hebei Province, providing theoretical support and practical reference for scientifically quantifying rural carbon emissions and formulating rural carbon emission reduction strategies.

2. Research Methods

2.1 Over view of the Life - Cycle Assessment Method

Life - cycle assessment is a standardized tool for systematically evaluating the environmental impacts of products, processes, or services throughout their entire life cycles. In the carbon emission accounting of rural households, the "life cycle" does not refer to the existence cycle of the household itself but to the entire process from material acquisition to final disposal of its physical carriers - residential buildings and major energy - using equipment - while superimposing the daily operating energy consumption of the household.

2.2 Rural Household Carbon Emission Accounting Framework

2.2.1 Calculation Boundary Definition

This study uses individual rural households as the fundamental accounting unit, with a temporal scope of one calendar year and spatial coverage encompassing daily activities within the household residence, adjacent courtyards, and contracted farmland. The accounting methodology adopts life cycle assessment as its framework, employing the emission factor method for quantitative calculation. The basic formula for the emission factor method is: Carbon emissions = Activity level data × Emission factor[4].

Based on the fundamental phase classification of Life Cycle Assessment (LCA), this study divides the life cycle of carbon emissions from rural households into four stages: building material production, construction, operation and use, and demolition and disposal. Among these, the operation and use stage - characterized by its longest duration and highest emission contribution - is further subdivided into three modules: domestic energy consumption, material metabolism, and production activities. This establishes a "four-stages, three-module" accounting framework that maintains the systematic nature of the LCA methodology while accounting for the reality of the close integration between rural production and daily life.

2.2.2 Key Points for Quantifying and Evaluating Carbon Emissions Throughout the Life Cycle of Rural Households

(1) Building materials production phase

The building materials production phase marks the beginning of the life cycle, encompassing the extraction, processing, and manufacturing of the primary materials required for rural residential construction and renovation (such as clay bricks, cement, steel, sand, and gravel). Carbon emissions during this phase primarily stem from the combustion of fossil fuels and electricity consumption in the production process - known as the "implicit carbon" of building materials.

(2) Construction and Building Phase

The construction phase encompasses on-site activities for rural residential buildings from groundbreaking to final acceptance. Emission sources included in this phase comprise: fuel and electricity consumption of construction machinery; indirect emissions from material transportation and on-site waste; and energy consumption for construction workers' daily activities. The CO₂ emissions during rural housing construction CO₂ can be calculated[5].

(3) Operation and Maintenance Phase

The operation and maintenance period refers to the entire operational time frame from the date when rural residential buildings and their ancillary facilities, as well as energy-consuming equipment, pass final acceptance inspection and commence operation until they reach their designed service life. This phase represents the longest duration and generates the highest cumulative emissions throughout a building's life cycle. The demolition and recycling phase encompasses both the structural dismantling and the recovery and disposal of used building materials[6]. This study subdivides this phase into three distinct components for separate accounting: domestic energy consumption, material metabolism, and production activities.

(4) Dismantling and Disposal Phase

The demolition and disposal phase marks the conclusion of a building's life cycle, encompassing the manual or mechanical removal of structures upon reaching their service life, waste sorting and transportation, as well as recycling or final disposal. Currently, rural demolition projects generally lack effective waste sorting and recycling mechanisms, resulting in underutilized carbon offset potential during this stage.

3. Innovative Computing Methods

3.1 Dynamic Equalization Method for the Implicit Carbon in Building Materials

During the construction of rural self-built houses, building materials such as clay bricks, cement, and steel generate substantial carbon emissions during their production phase, known as "embedded carbon." In carbon emission accounting, if all embedded carbon is attributed solely to the construction year, the annual emission figure would be excessively high, failing to reflect the temporal distribution of carbon emissions; whereas using a fixed theoretical lifespan for allocation would underestimate the carbon burden associated with the remaining service life of buildings that have been in use for many years. Therefore, this paper proposes a dynamic allocation method: the embedded carbon of building materials should be allocated based on the actual remaining service life of the buildings, rather than applying a fixed theoretical lifespan. Regarding lifespan, the calculation formula is as follows:

$$E_{annual} = \frac{\sum (M_i \times EF_i)}{L_{remaining}}$$

Represents E_{annual} allocated value of embodied carbon for building materials (kg CO₂e/year); M_i denotes the usage quantity of the building material (blocks, tons, m³); EF_i is the carbon emission factor of the i building material (kg CO₂e); $L_{remaining}$ indicates the remaining service life of the building (years).

In this study, the expected service life of self-built houses in northern rural areas was set at 30 years. The average construction age of the sample houses was 18.6 years, resulting in a remaining service life of 11.4 years. For ease of cross-comparison, the total calculation still employs a fixed annual allocation of 30 years (1,000 kg CO₂e /year). The carbon emission factors were referenced from GB/T 51366–2019 "Standard for Calculation of Carbon Emissions from Buildings" and related research.

3.2 Life Cycle Carbon Emission Calculation Formula

Based on the aforementioned "four-stage, three-module" accounting framework, this study employs the emission factor method to quantify the full life-cycle carbon emissions of rural households. The calculation formulas for carbon emissions at each stage are as follows.

Table 1. Full Life Cycle Calculation Formula

Stage	Item	Formula	Description
Total Life Cycle Emissions	Total	$E_{total} = E_{materials} + E_{construction} + E_{transport} + E_{demolition}$	Sum of four stages
Material Production Stage	Embodied carbon in materials	$E_{materials} = \sum (M_i \times EF_i)$	M_i : material quantity; EF_i : emission factor
	Annual average	$E_{materials,annual} = E_{materials}/L$	L : building service life (30 years)
Construction Stage	Construction emissions	$E_{construction} = E_{machinery} + E_{transport} + E_{labor}$	Includes Machinery fuel, material transport, labor energy
	Annual average	$E_{construction,annual} = E_{construction}/L$	Annualized over 30 years
Operation Stage	Electric heating	$E_{electricheating} = \frac{A \times Q}{COP} \times EF_{electricity} \times R_{electricity}$	A : area; Q : heat load; COP : coefficient of performance; $EF_{electricity}$: grid emission factor; $R_{electricity}$: share of electric heating
	Gas heating	$E_{gasheating} = \frac{A \times Q}{q} \times EF_{gas} \times R_{gas}$	q : natural gas calorific value; EF_{gas} : gas emission factor; R_{gas} : share of gas heating
	Household electricity	$E_{appliances} = AD_{electricity} \times EF_{electricity}$	$AD_{electricity}$: annual electricity consumption
	Cooking energy	$E_{cooking} = AD_{LPG} \times EF_{LPG}$	AD_{LPG} : LPG consumption; EF_{LPG} : LPG emission factor
	Water & waste	$E_{water,waste} = W_{water} \times EF_{water} + W_{water} \times W_{waste} \times EF_{waste}$	W_{water} : water use; W_{waste} : waste amount
	Small-scale livestock	$E_{livestock} = \sum (N_k \times EF_k \times GWP_k)$	N_k : number of livestock; EF_k : emission factor; GWP_k : global warming potential
Demolition Stage	Demolition emissions	$E_{demolition} = E_{machinery} + E_{transport} + E_{disposal} - E_{recycling}$	Includes demolition energy, transport, disposal, minus recycling credits
Simplified Method (Comparison)	Operational energy emissions (commercial energy)	$E_{simplified} = E_{appliances} + E_{electric heating} + E_{gasheating} + EF_{electricity}$	Only commercial energy in operation stage

4. Data Sources and Sample Characteristics

4.1 Research Area and Sample Selection

This study selected Tangshan City in Hebei Province as the research area. The region shares common characteristics with rural areas of the North China Plain: a winter heating period of approximately 115 days and predominantly brick-concrete structures. According to official data from the Tangshan Municipal Housing and Urban-Rural Development Bureau, the city has completed the "dual substitution" initiative (replacing coal with gas and electricity) in rural areas, achieving near-complete coverage of clean heating in plain rural regions. These characteristics endow the area with strong regional representative samples, and the comprehensive implementation of the clean heating policy provides a typical sample of the energy consumption structure in rural households following the phase-out of scattered coal use.

Using a stratified random sampling method, with annual family accounts income, population size, and heating method as stratification criteria, a total of 120 questionnaires were distributed, and 104 valid responses were collected, yielding an effective response rate of 86.7%.

4.2 Data Collection Method

Data collection covers both the winter heating period and non-heating periods. The survey combines household questionnaire surveys, on-site measurements and weighing, and electricity bill collection. The questionnaire is designed around the "Energy-Building-Behavior" framework, recording information such as household composition, floor area, construction year, building material consumption, annual energy consumption, heating methods, and energy usage. Electricity bills are used to aggregate electricity consumption over the past year.

4.3 Basic Sample Characteristics

The basic characteristics of the 104 household samples are shown in Table 1. The average permanent population per household was 3.2 people, with families consisting primarily of 3 to 4 members; the average floor area per household was 112 m², brick-concrete structures accounted for 95%, and the average construction age of the buildings was 18.6 years. Winter The distribution of heating methods is as follows: electric heating in 57 households (54.8%), gas heating in 42 households (40.4%), and biomass heating in 5 households (4.8%). This winter distribution largely aligns with the overall structure of Tangshan City's "Dual Substitution" renovation program.

The activity level data and emission factors used for each emission source are summarized in Table 2. Specifically, the embodied carbon for building materials is averaged over a 30-year lifespan (total embodied carbon: 29,860 kg CO_{2e} /30 years). Electric heating is calculated based on an annual electricity consumption of 2,400 kWh, with a grid emission factor of 0.884 kg CO_{2e} /kWh; electric heating accounts for 54.8% of households. Gas heating is calculated based on an annual gas consumption of 600 m³, with a natural gas emission factor of 2.02 kg CO_{2e} /m³; gas heating accounts for 40.4% of households. Household electricity consumption is calculated as 2,150 kWh/year × 0.884 for the sample households. Cooking energy is calculated as 68 kg of liquefied gas × emission factor 3.02. Small-scale livestock farming is estimated using 2 pigs and 10 chickens, employing the IPCC default emission factors (CH₄: 28; N₂O: 265). Water usage and waste disposal are estimated at 80 liters per person per day and 1 kilogram per person per day, respectively. Construction and building operations emissions are calculated based on an average allocation of 6,000 kgCO_{2e} over 30 years. The calculation formula is detailed in Section 3.

Table 2. Average Annual Carbon Emission Structure and Total Emissions per Rural Household

Life Cycle Stage	Emission source	Emissions (kg CO2e/year)	Proportion (%)
Building materials production phase	Implicit Carbon in Building Materials (Annual Average Distribution)	1,000	16.7
Constructio and Building Phase	Construction machinery and labor	200	3.3
Operation and Maintenance Phase	Electric heating (55% of households)	1,167	19.5
Operation and Maintenance Phase	Gas heating (40% of households)	485	8.1
Operation and Maintenance Phase	Cooking energy (liquefied petroleum gas)	205	3.4
Operation and Maintenance Phase	Appliance electricity consumption	1,900	31.8
Operation and Maintenance Phase	Domestic Water Supply and Waste Management	310	5.2
Operation and Maintenance Phase	Small-scale aquaculture	720	12.0
Total		5,987	100

5. Result and Analysis

5.1 Identification of Core Emission Sources

Based on the contribution ratios of various emission sources, rural household carbon emissions can be categorized into three tiers. At the primary level, electricity consumption accounts for 51.3% of total emissions, making it the largest emission source among rural households. T

his structural characteristic reflects a fundamental transformation in the energy consumption pattern of rural households in Tangshan City: scattered coal use has largely been phased out of residential heating, with electricity becoming the dominant energy source.

The second tier includes the embodied carbon in building materials and emissions from small-scale livestock farming. The embodied carbon in building materials increased significantly, despite the overall reduction in total emissions due to the implementation of clean heating policies. Emissions from small-scale livestock farming accounted for 12.0% of the total, primarily originating from intestinal fermentation and manure management processes in livestock and poultry.

The third tier encompasses emission sources such as gas heating and cooking energy, with their contributions being relatively dispersed.

5.2 Result Discussion

The model calculated in this study estimates the average annual carbon emissions per rural household at 5.99 tons of CO₂ equivalent, with electricity consumption accounting for 51.3% of the total emissions-the largest contributor. This structure stands in stark contrast to the traditional rural energy consumption pattern dominated by scattered coal use, reflecting the tangible effectiveness of Tangshan City's "Dual Substitution" clean heating policy.

Notably, the relative contribution of embodied carbon in building materials to total emissions is significantly higher than findings from previous studies that focused solely on operational energy

consumption. This is because rural self-built houses predominantly use high-carbon-emitting materials such as clay bricks, coupled with poor building insulation performance, resulting in a coexistence of "high-carbon construction" and "high-carbon operation." With the advancement of clean heating, with the continuous advancement of policies, operational carbon emissions will continue to decline, and the relative importance of the embodied carbon in building materials will further increase. Therefore, the focus of future rural carbon reduction efforts should gradually shift from "operational energy conservation" to "low-carbon construction."

5.3 Policy Enlightenment

Based on the above findings, the following policy recommendations are proposed:

- (1) Consolidate the achievements in clean heating initiatives. It is recommended to continue implementing operational subsidy policies to ensure affordable energy costs for rural households and prevent the resurgence of scattered coal use.
- (2) Emphasize the carbon sequestration effect of building materials. It is recommended to promote low-carbon building materials such as aerated concrete blocks and thermal insulation mortar in rural dilapidated housing renovation and new rural housing construction, thereby reducing carbon emissions throughout the entire life cycle at the source.
- (3) Establish a management system for emissions from small-scale livestock farming. To address the CH₄ and N₂O emissions generated by livestock farming, the promotion of manure resource utilization technologies (such as biogas projects) can achieve dual benefits of emission reduction and energy recovery.

5.4 Limitations of the Study

The present study has the following limitations:

- (1) The sample is limited to Tangshan City, Hebei Province. The generalization of these conclusions to other rural areas should be conducted prudently in light of local policy contexts.
- (2) Some winter energy consumption data (such as gas usage) rely on respondents' recollections, introducing certain inaccuracies.
- (3) The building material consumption figures are estimated based on standard quotas for typical residences, without accounting for variations in renovation frequency among households, resulting in discrepancies from actual usage.
- (4) During the demolition and disposal phase, due to the current lack of a systematic building material recycling mechanism in rural areas, this study adopts a simplified approach. The carbon offset potential of this phase requires further quantitative assessment in subsequent research.

6. Conclusion

Using rural Hebei as a case study, this paper establishes a nested carbon emission accounting framework based on life cycle assessment methodology, structured in "four stages and three modules." Through empirical research, it elucidates the structural characteristics and key sources of carbon emissions across the entire life cycle of rural households.

The main conclusions are as follows: Rural households contribute the most to carbon emissions during the operational phase, followed by building material production, while construction and demolition phases account for a smaller proportion. Three primary emission sources include electricity consumption, embodied carbon in self-built housing materials, and emissions from small-scale livestock farming. The clean heating policy has significantly reduced operational carbon emissions, yet it has also highlighted the relative importance of embodied carbon in building materials. Future emission reduction strategies should extend beyond "operational energy efficiency" to encompass "low-carbon construction."

Based on the above conclusions, rural households should prioritize consolidating clean heating systems for carbon reduction, promote low-carbon building materials and energy-efficient

renovations of rural housing in the medium term, and establish long-term management systems for livestock emissions and construction waste recycling. The accounting framework developed in this study can serve as a methodological reference for carbon emission calculations in other northern rural regions, though parameters must be adjusted according to local building material types, energy consumption patterns, and policy contexts during implementation.

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