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Life Cycle Assessment of Carbon Footprint and Mitigation Strategies for Double-Layer Hollow Tents in Western Sichuan Pastoral Regions

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Abstract

As a vital residential structure in the fragile ecosystem of Western Sichuan pastoral regions, tents generate substantial carbon emissions throughout their life cycle, yet lack standardized assessment frameworks. This study addresses this gap by developing a life cycle assessment model tailored for double-layer hollow tents, covering five phases: material production, transportation, construction, operation & maintenance, dismantling and recycling. The model quantifies carbon emissions at each phase and identifies dominant contributors. The results showed that the carbon emissions during the operation and maintenance phase and transportation phase accounted for the highest proportion, accounting for 74.1% and 13.8% of the total emissions, respectively, totaling 87.9%. Through sensitivity analysis, it was found that increasing the steel recovery rate to 85% can reduce carbon emissions during the demolition phase by 4.6%, while replacing traditional diesel transportation with electric trucks can reduce carbon emissions during transportation by 78.3%. By combining solar energy integration and localized material supply strategies, carbon emissions per unit area have been reduced by 46.6%. This study provides a methodological foundation for low-carbon tent design and offers technical support and methodological guidance for carbon emission accounting in the Western Sichuan pastoral area and the Qinghai-Tibet Plateau region.

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1. Introduction

Amidst the escalating urgency of global climate change mitigation, the Western Sichuan Plateau, as a critical terrestrial carbon sink and ecological security barrier in China, has witnessed a continuous increase in the strategic importance of precise carbon emission quantification and decarbonization practices. Given the ecological fragility and unique living environment of the Western Sichuan pastoral regions, detachable dwelling units such as double-layer hollow tents not only adapt to the nomadic lifestyle and production needs of plateau herders but also withstand harsh climatic conditions. Their lifecycle carbon emission management has become a pivotal component in achieving carbon neutrality.[1] Existing carbon emission accounting predominantly relies on general building data from low-altitude regions, failing to accurately reflect the realities of the Western Sichuan Plateau. Consequently, quantifying the carbon footprint of high-altitude detachable dwellings and proposing low-carbon technological strategies have emerged as core challenges for ecological conservation and sustainable development in the region.

In recent years, lifecycle assessment (LCA) has emerged as a cornerstone for quantifying environmental impacts across product lifecycles, with ISO 14040/14044 standards providing robust methodological frameworks. International initiatives

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like the European Building Performance Assessment System (EPBD) and tools developed by the U.S. Green Building Council (USGBC) have advanced green building certifications.[2~5] For high-altitude regions, studies such as Wang Xiaoliang *et al*.[6] have quantified carbon ecological pressures from building energy consumption on the Qinghai-Tibet Plateau, while Yao Fei proposed a carbon-microecological correlation model for tent thermal regulation.[7] Hakan Alıcıfocused on optimizing low-carbon textile production chains for tent materials.[8] However, existing research predominantly targets fixed structures or low-altitude scenarios,[9-11] lacking a specialized LCA model for detachable buildings in plateau environments. This gap hinders the precise adaptation of carbon accounting and decarbonization strategies to the unique climatic and anthropogenic conditions of Western Sichuan.

This study focuses on double-layer hollow tents in the Western Sichuan pastoral area, constructing a lifecycle carbon emission model applicable to plateau regions. Carbon emission intensity is adopted as a cross-comparative metric, with the system boundary encompassing the entire chain from material extraction, construction, transportation, operation, and maintenance to waste recycling. By referencing international and domestic carbon emission databases and integrating plateau-specific field data,[12,13] a traceable carbon accounting system is established to quantify the carbon reduction efficiency of plateau-adapted technologies. This model addresses the theoretical gap in carbon emission quantification for detachable dwellings, providing methodological support for low-carbon tent design and carbon neutrality pathways in the Western Sichuan pastoral region.

2 Life cycle assessment carbon emission accounting for tents

2.1 Selection of research subjects

The Western Sichuan Plateau is located between the Qinghai-Tibet Plateau and the Chengdu Plain, and its unique natural environment and ecosystem hold a significant position nationwide.[14] The region features high altitude, low air pressure, thin air, strong solar radiation, and large diurnal temperature variations, connecting the hinterland of the Qinghai-Tibet Plateau with the Chengdu Plain, and exhibiting significant altitude differences. The local climate is harsh, and natural resources and available materials are scarce. During the Western Zhou Dynasty, pastoralists gradually developed a nomadic way of life adapting to this harsh climate, known as "following water and grass”. [15] In this situation, tents, created as a living form for pastoralists to adapt to nomadic life on the plateau, began to appear and be widely used, continuing to the present day.

As one of the main forms of living for herdsmen in western Sichuan, tents have unique regional characteristics. However, most of the existing tents have low indoor temperatures and poor comfort, which affects residents' work efficiency and physical and mental health. Therefore, our team has designed a double-layer hollow tent specifically for the western Sichuan pastoral area based on civilian tents, as shown in Fig. S1. After testing, it has good adaptability to the local climate and the indoor thermal environment has also been significantly improved.[16] The design of double-layered inflatable tent utilizes the air space between the layers to create a greenhouse effect. The heat generated by solar radiation promotes air circulation and increases the indoor temperature, thereby improving indoor comfort.[17] The heat compression brings about air flow, thus raising the indoor temperature to improve indoor comfort. In the design of typical residential unit, the double-layered hollow structure is adopted, forming an air interlayer between the inner and outer tent fabrics. Ventilation openings are designed at the top and bottom of the tent, as shown in Fig. S1.

It measures 4900 mm in length, 4190 mm in width, 3000 mm in height, and 1700 mm in eaves height. The tent base area is 20.53 m^2, and the total built-up area is 48.25 m^2, which can accommodate 5-8 residents.

In the tent's flat design, the rectangular space of the traditional typical dwelling unit is continued, with the central stove as the core, and functional spaces arranged around it.[18] For the traditional typical dwelling unit, the spatial form mainly considers square space, combined with the roof style of traditional ethnic architecture to design a double-sloped roof. The structure uses a frame structure and built through the connection of supporting structures and nodes. The tent material is entirely made of steel structure, and the support steel pipes and connecting heads are all made of high frequency welded pipes. The inner tent fabric is white polyester plain weave satin, and the outer tent fabric is white polyester waterproof canvas.[15] The accessories are standardized, in small quantities, and overall lightweight, with the weight of a single living space equivalent to only 20~40% of a wool tent.[19]

2.2 Definition and selection of carbon emission factors

The definition of carbon emission factor is derived from the emission factor method, which is currently one of the most widely used methods for carbon emission accounting.[20] The energy carbon emission factor refers to the amount of greenhouse gas produced by consuming a unit of energy, and is an important parameter used to characterize the greenhouse

Table 1: Carbon emission factors of major materials.

Material	Unit	Carbon emission factor
Welded straight seam steel pipe	kg	25.3×10^{-1}kg/t
Polyester waterproof canvas	kg	25.7kg/t
Polyester plain weave silk	m^3	4.5×10^{-1}kg/m^3
Animal waste	kg	11.8×10^{-1}kg/t

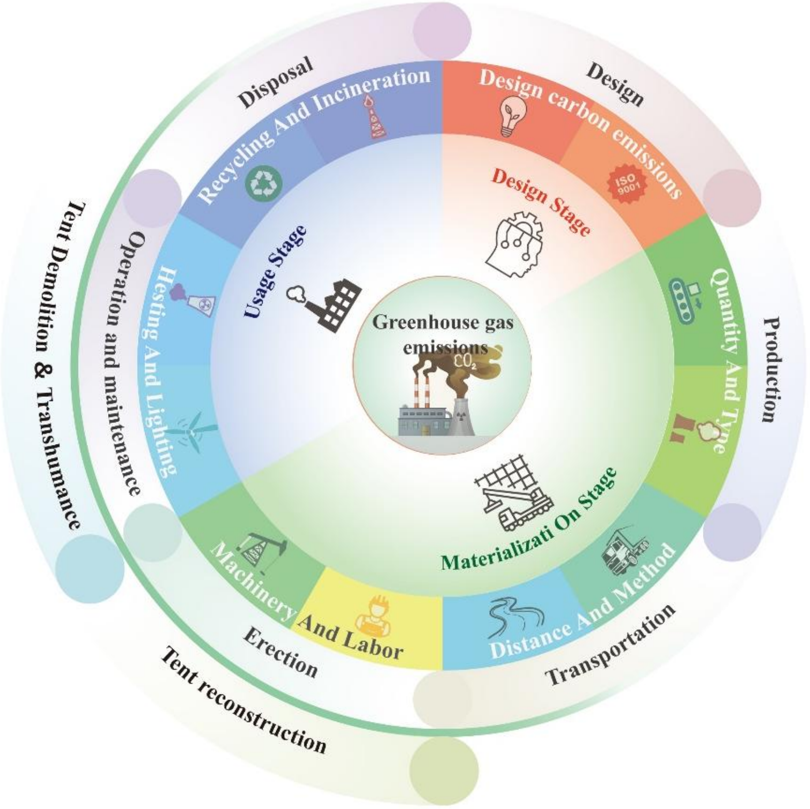

Fig. 2: Tent greenhouse gas emission life cycle assessment boundary diagram.

gas emissions of a certain energy source, as well as the basic data for carbon accounting. The greenhouse gas emissions generated by energy consumption activities are all converted into carbon dioxide equivalent emissions and are expressed in kg per unit using carbon dioxide equivalent and related activity units.

This article mainly refers to the monitoring reports of the Intergovernmental Pan-el on-Climate Change (IPCC),[5] combined with the International Energy Agency (IEA),[21] the United States Environmental Protection Agency (EPA),[22] the European Commission (EC),[23] and the *China Products Carbon Footprint Factors Database*.[13] Through extensive research on global energy production, conversion, and consumption processes, various energy related carbon emission factors are provided. At the same time, draws on the commonly used high-energy calorific value standards in the *Standard for green performance calculation of civil buildings*.[24] The values are as shown in Table 1.

2.3 Carbon emission accounting unit

Buildings of different scales and sizes have significant variations in energy and material consumption during the materialization phase, directly resulting in a large difference in total carbon emissions, while the lifespan of a tent also affects the accounting results. In order to establish a horizontal comparison between different cases, this article uses carbon emission intensity, which is the average annual carbon emission per unit of building area, as the accounting unit (kg/m^2·a).[25] This can eliminate the influence of tent volume and area, making the accounting results comparable and consistent between cases.

2.4 Tent carbon emissions system boundary

The boundary calculation includes greenhouse gas emissions related to material production and transportation, construction and dismantling, and operational activities.[26] When calculating the carbon emissions of the life cycle of a tent, all activities involving carbon emissions should be included. Through preliminary collection of basic parameters and understanding the current application, the carbon emissions from the dismantling-reconstruction process during the tent's operational phase were added to the calculation. In order to facilitate the analysis of carbon emission sources, it is necessary to simplify and define the system boundary in advance. From the perspective of time boundaries, the carbon emissions of the tent involve various stages from "cradle to grave" throughout its life cycle, as shown in Fig. 2.

3. Life cycle assessment carbon emission accounting model for tents

The carbon emissions accounting of tents is essentially the calculation of the entire process of greenhouse gas emissions from non-existence to existence and then back to non-existence, just like other individual buildings. First, clarify the principles for selecting research objects, and establish a physical model based on this, combining the analysis of survey results with building energy consumption simulation models to construct a geometric model for the carbon emissions calculation throughout the life cycle of the tent.[27,28] Subsequently, the model is validated, and evaluation indicators are proposed.

The total carbon emissions for each stage are summed to obtain the total carbon emissions of the tent's life cycle, and the calculation formula is as Eq. (1):

$$\mathrm{C} = C_{\mathrm{P}} + C_{\mathrm{t}} + C_{\mathrm{e}} + C_{\mathrm{m}} + C_{\mathrm{d}} \tag{1}$$

where *C* is the total carbon emissions of the tent's life cycle (kg); C_{P}, C_{t}, C_{e}, C_{m}, and C_{d} are the carbon emissions generated in the material production stage, material transportation stage, tent construction stage, tent operation and maintenance stage, and tent dismantling and recycling stage, respectively.

3.1 Production stage of tent materials

The carbon emissions during the material production stage include the carbon emissions generated during the extraction, production, and processing of materials. Due to the wide variety of materials, for the convenience of accounting, materials that account for 80% or more of the total quantity in the bill of quantities and 80% or more of the total cost in the bill of costs can be accounted.[29] The carbon emissions during the material production stage (C_{P}) should be calculated according to the Eq. (2):

$$C_{\mathrm{P}} = \sum_{\mathrm{y}=1}^{\mathrm{n}} M_{\mathrm{i}} F_{\mathrm{i}} \tag{2}$$

where *n* represents the total number of material types; *y* represents the tent design life (years); M_i represents the consumption of the *i*-th main material (in this case, the material consumption is the product of the material weight and the material carbon emission factor); F_i represents the carbon emission factor of the *i*-th material.

3.2 Material transportation stage

During the transportation process of the tent, carbon emissions are produced by the combustion of fuel in the transportation vehicles. This process mainly includes the carbon emissions from the transportation of materials from the processing plant and equipment storage location to the construction site, as well as the carbon emissions generated from the fuel consumption of material loss and waste transportation during the vehicle transportation process. The transportation distance, transportation vehicles, and fuel selection will all have an impact on the carbon emissions during this stage. The carbon emissions during the material transportation stage (C_{t}) should be calculated using the Eq. (3):

$$C_{\mathrm{t}=} \sum_{\mathrm{y}=1}^{\mathrm{n}} M_{\mathrm{i}} D_{\mathrm{i}} T_{\mathrm{i}} \tag{3}$$

where D_i is the average transportation distance of the *i*-th material (km); T_i is the carbon emission factor per unit weight transportation distance for the *i*-th material transport mode (km·CO_{2eq}/t).

3.3 Tent construction phase

During the design phase of the double-layered inflatable tent, the high difficulty of pastoral mechanical operations and long distances were taken into consideration to the greatest extent. Therefore, mechanical equipment is not required during the construction phase, only direct construction site personnel are needed for assembly. Therefore, the double-layered inflatable tent does not consider the carbon emissions brought about during the construction phase.[30] Based on the pastoral area interviews, it is known that 4-6 adult males are needed during the construction phase. The carbon emissions during the construction phase include three components (Eq. (4)):[13] (1) human respiratory metabolism (1.1 kg CO_2 per labor-day),[5] (2) worker commuting, and (3) tool manufacturing and maintenance.

$$C_{\mathrm{e}} = (1.1R_{\mathrm{i}} + 0.12D_c + 0.8M_t) \times N_{\mathrm{i}} \tag{4}$$

where R_i represents the *i*-th number of total man-days needed for assembly; N_{i} represents the number of times the tent is dismantled and erected for the i-th time within the period of tent usage; D_c represents the commuting distance (km) per working day, M_t represents the tool weight of each component (kg).

3.4 Operation and update phase of the tent

Due to the high altitude and cold environment of the western Sichuan plateau, as well as its unique climate of cold winters and cool summers, local residents can reduce the temperature and create a comfortable environment in the summer simply by opening windows for ventilation.[31] The large temperature difference between day and night requires residents to use yak dung as fuel to heat stoves to increase indoor temperatures during summer nights and throughout winter days. The carbon emissions during the usage phase primarily involve greenhouse gas emissions from energy consumption for heating and lighting, which, given the actual conditions in pastoral areas, can be attributed to the consumption of electricity, heat energy, and animal biomass energy. Therefore, the carbon emissions in the normal usage phase mainly involve calculating the emissions of greenhouse gases caused by the consumption of these three types of energy. The maintenance and updates of carbon emissions accounting mainly include material loss. When calculating, the materials consumed for maintenance and renovation projects during the usage period can be recorded based on existing records of tent maintenance and refurbishment to calculate the types and quantities of materials consumed for maintenance and update phases. The carbon emissions during the tent operation phase (C_{m}) should be calculated according to the Eq. (5):

$$C_{\mathrm{m}} = \sum_{\mathrm{y}=1}^{\mathrm{n}} (E_{\mathrm{i}} EF_{\mathrm{i}}) \cdot \mathrm{y} \tag{5}$$

where E_i denotes the average annual energy consumption of the i-th category of tents; EF_i represents the carbon emission factor of the i-th energy category.

3.5 Dismantling and recycling stage of the tent

When calculating carbon emissions during the dismantling and recycling stages of tents, it mainly includes the default carbon emissions of man-day labor during the dismantling stage, the carbon emissions generated by the energy consumption of waste transportation, and the carbon emissions from the recycling of some recyclable materials. In this case, the carbon emissions generated by the energy consumption of the mechanical equipment used in the tent dismantling process are not considered, only the carbon emissions generated by the on-site personnel dismantling the tent are considered. [32]

In previous statistical examples, construction waste was not detailed categorized, but was directly transported and landfilled for disposal. For this part, only the carbon emissions from the energy consumption of construction waste transportation need to be calculated.[33] The recycling and reuse of waste refer to the process of processing waste into recycled materials, and the greenhouse gas emissions generated in this process are included in the carbon emission calculation.[34] For partially recyclable materials such as steel and waterproof canvas, the energy consumption and emissions in the recycling and reprocessing process should be distinguished from the carbon emission factors of the original materials. Finally, the carbon emissions during the dismantling and recycling stages of the tent can be obtained by subtracting the carbon emissions from transportation energy consumption from the carbon emissions from recyclable parts. The carbon emissions during the dismantling and recycling stages of the tent (C_{d}) should be calculated according to the Eq. (6):

$$C_{\mathrm{d}} = C_{\mathrm{t}} - rC_{\mathrm{p}} + C_{\mathrm{e}} \tag{6}$$

where r represents the material recovery rate.

4. Analysis of actual case scenarios for computation

4.1 Carbon emissions during the production stage of tent materials

By searching the bill of quantities, simplifying the conditions based on the accounting method proposed in the previous section, selecting the types of materials that account for 80% of the total material usage as the objects of accounting, ultimately selecting 4 main materials, and conducting tabular calculations as shown in Table 2.

4.2 Carbon emissions during the transportation phase of tent materials

The carbon emission calculation factors for transportation of double-layered hollow tents in the case study primarily consider the carbon emissions from the transportation vehicles from the production site of the raw materials to the construction site. The selected materials and equipment factories are located in Chengdu, Sichuan, and the tent construction site is in the grasslands of the Aba Tibetan and Qiang Autonomous Prefecture, Ruoergai County, in western Sichuan Province. The primary mode of transportation is light truck transporting steel pipes and canvas, with the transportation distances estimated from the factories to the tent construction site. Considering the impact of lower oxygen levels and frequent slopes on high-altitude road conditions, the carbon emission coefficient of diesel trucks has been adjusted to 0.102 kg CO_2/t km.[5,13] According to the principle of grass-livestock balance and the grassland compensation policy in western Sichuan pastoral areas,[17] herders migrate to summer pastures from June to September, and at other times reside at their settlement points in the winter pastures. Settlement grazing takes place at different seasons and times. Based on interviews with herders, the distance between different

Table 2: Carbon emissions from material production process.

Material name	Model specifications	Weight （kg）	Carbon emissions（kg·CO_{2eq}）
Branch pipe	Welded straight seam steel pipe	57	144.21
Connector	Welded straight seam steel pipe	12.2	30.87
External tarpaulin	Polyester waterproof canvas	31	248.00
Inner tarpaulin	Polyester plain weave fabric	5.3	30.21
Rope	IWR/IWS Steel Core Wire Rope	1.6	3.68

Table 3: Carbon emissions during transportation.

Sub-process	Dosage (kg)	Transportation method	Carbon emission factor (kg CO_{2eq}/km)	Distance (km)	Carbon emissions (kg·CO_{2eq})
First transportation	105.5	Light-duty truck	10.2×10^{-2}	325	3502.6
Migration transportation	105.5	Light-duty truck	8.3×10^{-2}	20	1576.2

Note: First transportation refers to the process from the factory to the tent construction site, while migration transportation refers to the nomadic process.

Table 4: Carbon emissions during the construction phase.

Method	Headcount	Carbon emission factor (kg·CO_{2eq}/day)	Annual dismantling frequency	Time utilization （Years）	Carbon emission （kg·CO_{2eq}）
Manual construction	5.0	1.1	6.0	3.0	99.9

Table 5: Carbon emissions during operation phase.

Energy Consumption Type	Annual average energy consumption (kW·h）	Carbon emission factor	Time utilization （years）	Carbon emissions （kg·CO_{2eq}）
Heating	5772.2	5.7×10^{-1}	3.0	26921.7
Lighting	438.0	5.7×10^{-1}	3.0	312.2

migration destinations in the Heihe River Basin is approximately 15-25km. Hence, we can divide the transportation stage into single-way transportation and migration transportation, as shown in detail in Table 3.

4.3 Carbon emissions during the construction phase of tent materials

In this local area, the construction method often involves the on-site construction by family members. According to the research and survey data, it is generally required 4-6 people to build simultaneously. Referring to the "List of Main Materials and Parts in the Industrialized Building Industry Chain and Carbon Emission Calculation Manual",[35] the default carbon emission factor for integrated labor days should be 1.1 kgCO_{2eq}/labor day, worker commuting (average 20 km per person-day via motorcycles), and maintenance of tools such as steel frames and hammers. as shown in Table 4.

4.4 Carbon emissions during tent operation and maintenance phase

The Heihe Pasture is located along the Heihe River in the northwest of Ruoergai County, with an altitude of about 3429.6 meters. The pasture is situated in a cold climate zone with no absolute frost-free period throughout the year. The annual average temperature is approximately 1.5℃, with an annual sunshine duration of about 2390 hours and an annual precipitation of 656 mm. Hence, we can infer that heating is the most critical concern for the pastoralists in western Sichuan.[14] Based on field surveys and interviews, as shown in Fig. S2, we learned that the most crucial heating method in the area is the "fire pit", which involves digging a small pit in the room, building low stone walls around the pit, and using it for heating and cooking. The fuel for the fire pit mainly comes from yak dung and wood. In summer, temperature reduction mainly relies on ventilation, and lighting is mostly provided by fuel cells. Normally, light bulbs are hung in the center of the tent.

The service life of the tents in the pastoral area is about 3-5 years, with one-third of the time spent by the herdsmen living in the tents each year. Due to the high transport cost of raw materials, herdsmen generally do not use transported canvas materials for maintenance and instead purchase all the raw materials for renewal after a certain degree of wear and tear, as shown in Table 5.

4.5 Carbon emissions during tent dismantling and recycling phase

The carbon emissions during the dismantling and recycling stages of the tent are calculated by subtracting the recyclable portion of the carbon emissions from the transportation energy consumption carbon emissions. The specific calculation process is as follows Eq. (7):

$$\mathrm{C_d} = \sum_{i+1}^{n} \mathrm{E_{cci}} \times \mathrm{F_i} + \sum_{i=1}^{n} (\mathrm{M_i} \times \mathrm{A_i} \times \mathrm{FM_i}) \tag{7}$$

where n is the number of building materials; E_{cci} is the power consumption of the i-th fuel during the demolition process (kg); $\mathrm{F_i}$ is the carbon emission factor of the i-th fuel (kg $\mathrm{CO_{2eq}}$/kW h); M_i is the consumption of the i-th main material (kg); A_i is the recovery rate of the i-th material; FM_i is the carbon emission factor of the i-th material recovery (kg $\mathrm{CO_{2eq}}$/t).

During this phase, the main components include the tent dismantling process, the transportation of waste materials, and the recycling process. It is worth noting that recyclable materials have brought about a reduction in carbon emissions in this stage. According to relevant literature and planning standards, steel and polyester textile products are recyclable.[8,13] The carbon emissions generated during the material recycling process are shown in Table 6, and the carbon emissions generated during the dismantling and recycling stages are shown in Table 7.

4.6 Results Analysis and Uncertainty analysis

Based on the above accounting results, the life cycle carbon emissions of the double-layer hollow tent can be summarized as 36754.7 kg, and the carbon emissions per unit area is 253.9 kg/m^2. as shown in Table 8, through staged carbon analysis, the following characteristics can be clarified: the main emissions during the operation and maintenance phase account for 74.1% of the total emissions, mainly due to thelong-term dependence on biomass fuels for heating in high-

Table 6: Carbon emission reduction of recyclable construction waste.

Types of waste materials	Recycling rate	Recycling quantity（kg）	Carbon emission reduction（kg·$\mathrm{CO_{2eq}}$）
steels	0.8	70.8	143.3
polyester	0.29×10^{-3}	36.3	0.07

Table 7: Carbon emissions during the dismantling and recycling phase.

Sub-process	Carbon emission（kg·$\mathrm{CO_{2eq}}$）
Tent dismantling	+5.55
Outward transportation of waste materials	+2844.58
Waste material recycling	-143.37

Table 8: Calculation results of carbon emissions per unit area of tents.

Life cycle stages	Carbon emissions（kg·$\mathrm{CO_{2eq}}$）	Carbon emissions per unit area（kg·$\mathrm{CO_{2eq}}$/m^2）
Production	974.2	6.7
Transportation	5078.8	35.1
Erection	99.9	0.7
Operation and maintenance	27234.0	188.2
Dismantling and recycling	3367.9	23.3
Total	36754.7	253.9

Table 9: Estimation of recovery rate interval.

Cenario	Steel Recovery Rate	Polyester Recovery Rate	Dismantling Emissions (kg·$\mathrm{CO_{2eq}}$)	Deviation (vs. Baseline)
Optimal Scenario	85%	0.05%	3,214.5	-4.6%
Baseline Scenario	80%	0.029%	3,367.9	—
Worst Scenario	70%	0.02%	3,589.2	+6.6%

altitude winter. The transportation and disposal stages are the second, accounting for 13.8% and 9.2% respectively, reflecting the shortcomings of insufficient long-distance transportation and material recycling capacity on the plateau, as shown in Fig. 3.

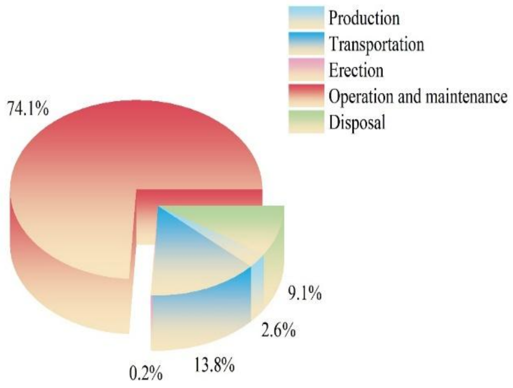

Fig. 3: Proportion of carbon emissions across the life cycle of tents.

This study further quantifies the impact of variability in recovery rates and transportation distances on carbon emission outcomes.

(2) Sensitivity of Recovery Rate

According to the *Chinese Product Life Cycle Greenhouse Gas Emission Factor Database*,[13] the recycling rate ranges and baseline values for recyclable steel and textiles were adjusted.[8] Comparing the scenarios in Table 9, fluctuations in recovery rates result in a difference of ± 6.6% in carbon emissions during the demolition phase.

(2) Variability of Transportation Distance

Based on interviews with herders and the *Research Report on Logistics Carbon Emissions in Plateau Areas*,[36] the range and baseline values of transportation distances were adjusted. Sensitivity analysis in Table 8 shows that a fluctuation of ± 20% in transportation distance can lead to a change of ± 20% in carbon emissions during the transportation phase, as show in Table 10.

Taking into account the combined impact of recovery rate and transportation distance, parameter fluctuations have a significant impact on the expected effectiveness of carbon reduction strategies, and elastic space needs to be reserved in the design.

5. Influencing Factors and Emission Reduction Strategies

By calculating and analyzing the carbon emissions of double-layer hollow tents in the western Sichuan pastoral area, the carbon emission ratios and influencing factors of each stage of their life cycle can be obtained. Based on the comprehensive consideration of the ecological environment and local conditions in the western Sichuan pastoral area, carbon reduction strategies can be proposed from the following aspects.

5.1 Carbon Reduction Strategy During Operation and Maintenance Stage

Maximizing the utilization of locally abundant renewable resources such as solar energy during the operation and maintenance phase enables energy self-sufficiency, substantially reducing reliance on traditional energy sources requiring long-distance transportation.[37] In this study, the pastoral tent integrates 60 flexible solar photovoltaic modules (Fig. 4) with a total power output of 8.4 kW—140 W/m^2 per module covering approximately 60 m^2—combined with a 20 W solar LED (Fig. 5).[38,39] This optimized energy structure reduces the carbon emission contribution of the tent's usage phase from 74.1% to 37.6%.

Table 10: Estimation of transportation distance interval.

Parameter	Transportation Distance (km)	Carbon Emissions (kg·CO_{2eq})	Deviation (vs. Baseline)
Single Trip (Lower)	260	2,845.1	-18.7%
Single Trip (Baseline)	325	3,502.6	—
Single Trip (Upper)	390	4,203.1	+20.0%

Table 11: Sensitivity analysis of different energy sources to carbon emissions.

Scenario	Emission Factor (kg CO_{2eq}/km)	Carbon emissions (kg CO_{2eq})	Reduction vs. Baseline
Baseline (Plain area)	10.2×10-2	5078.8	-
Scenario 1	8.3×10-2	6256.4	+23.2%
Scenario 2	1.8×10-2	1104.3	-78.3%
Scenario 3	5.5×10-2	3372.6	-33.6%

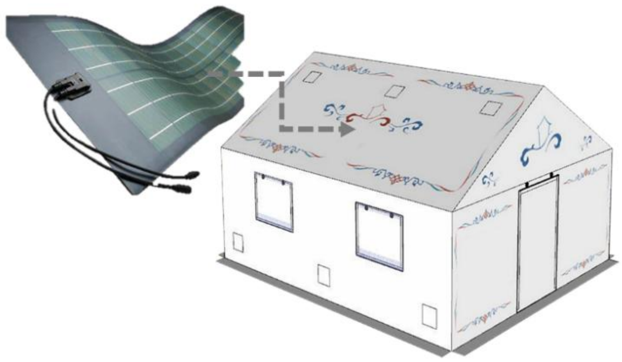

Fig. 4: The use of solar photovoltaic soft panels.

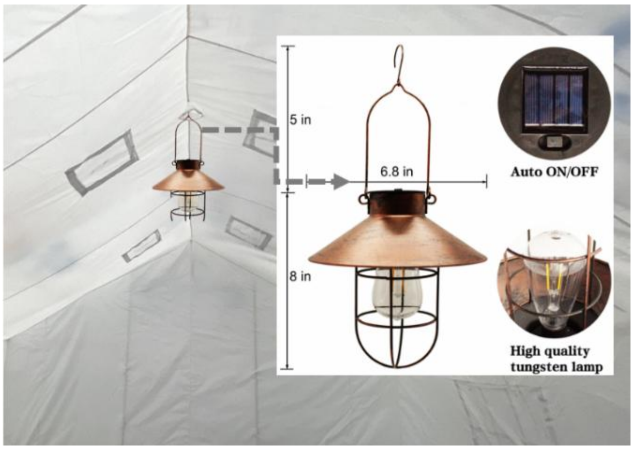

Fig. 5: The use of solar tent lights.

5.2 Carbon reduction strategy during transportation stage

In the material transportation stage, transportation distance, transportation vehicles, and fuel selection all affect the carbon emissions during this stage, but the main influencing factor is the choice of fuel. In order to quantify the emission reduction potential of adopting electric vehicles, this article uses sensitivity analysis to further compare the impact of fuel on the transportation phase, as shown in Table 11. Three scenarios are selected for comparative analysis: Scenario 1: traditional diesel trucks; Scenario 2: Electric trucks; Scenario 3: Hybrid truck.

Results indicate that adopting electric trucks reduces transportation emissions by 78.3%, demonstrating significant potential for carbon mitigation in plateau regions.

5.3 Carbon reduction strategies in other stages

In other stages of the tent's life cycle, such as the design phase and the dismantling and recycling phase, there are also methods to reduce its carbon emissions. For example, in the design phase, fully considering the environmental characteristics of the area where the tent is located, improving the insulation performance of the tent fabric or promoting the use of efficient and durable new insulation materials through reasonable design, strengthening the ventilation inside the tent, reducing the heating energy consumption of the tent, and lowering the carbon emission intensity during operation. During the demolition and recycling phase, the proportion of recyclable materials can be appropriately increased to reduce carbon emissions.

5.4 Carbon reduction analysis of tent life cycle

For the life cycle of tents, using clean energy as a substitute and selecting efficient and durable building materials are usually effective energy-saving and carbon reduction solutions. By comparing the carbon emissions per unit area of tents before and after (Table 12), it can be seen that during the operation and maintenance phase, the use of solar energy helps to reduce the carbon emissions per unit area of tents by 34.1%, while during the transportation phase, the use of electric vehicles can reduce the carbon emissions per unit area of tents by 92.5%. By analyzing the influencing factors and proposing emission reduction strategies, the carbon emissions per unit area of tents can be reduced by 46.6%. To save energy and reduce carbon emissions in high-altitude areas, improve the living environment in high-altitude areas, and provide practical strategies for carbon peak and carbon neutrality.

Table 12: Comparison of carbon emissions per unit area before and after carbon reduction.

Life cycle stages	Carbon emissions per unit area（$kg·CO_{2eq}/m^2$）	Carbon emissions per unit area after carbon reduction（$kg·CO_{2eq}/m^2$）	Carbon reduction ratio per unit area
Production	6.7	6.7	0.01%
Transportation	35.1	2.62	92.5%
Construction	0.7	0.7	0.01%
Operation and maintenance	188.2	124.0	34.1%
Dismantling and recycling	23.3	1.69	92.7%
Total	253.9	135.7	46.6%

6. Conclusion

LCA model reveals that carbon emissions from double-layer hollow tents are predominantly concentrated in the operation and maintenance phase, accounting for 74.1% of the total, primarily due to biomass fuel consumption in the cold plateau environment. The transportation and end-of-life disposal phases contribute 13.8% and 9.1%, respectively, highlighting challenges in long-distance logistics and material recycling capacity in plateau regions. Scenario analysis confirms that integrating solar power generation and clean transportation strategies significantly reduces emissions, achieving a 46.6% reduction in carbon emissions per unit area. Sensitivity analysis further quantifies key parameter impacts: increasing the steel recycling rate from 70% to 85% reduces demolition-phase emissions by 4.6%, shortening transportation distances lowers transport-related emissions by 18.7%, and combined fluctuations in recycling rates and transport distances result in carbon intensity variations between 237.1 and 270.7 kg/m². Future research should prioritize the development of hybrid renewable energy systems and bio-based materials tailored to plateau environments to enhance the robustness of mitigation strategies. Implementing dynamic carbon accounting frameworks and incentivizing localized supply chain development will effectively advance China's 2030 carbon peaking and 2060 carbon neutrality goals.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

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