Sustainability Evaluation of the Ecological Footprint of Rural Residential Houses with Difference Martials

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Abstract. The building energy consumption accounts for a significant proportion in the total energy consumption. In the paper, we provided a quantitative evaluation method of house sustainability based on ecological footprint theory. To compare the ecological footprint of different materials houses in the northern urban and rural areas of China with the ecological footprint in the world, four models of different residences with different materials were built to calculate the ecological footprints in whole life cycle. The results show that if we could reduce the ecological footprint of rural houses, the new energy-saving technologies and low-carbon supply systems will be applied in construction and materials with less ecological footprint will be used. Architects could search for much more design methods to reduce the ecological footprint of rural house in whole life cycle.

1. Introduction
In recent years, the global warming caused by carbon emissions produced by human activities has become a hot issue in the field of international academic community and governments. How to achieve carbon emission reduction and the sustainable development of economy and society has become a prominent issue in the development of China's economy. In China, 750 million people live in rural areas and rural residential areas are 24.1 billion square meters, thus the energy consumption of rural house occupies a large proportion of the country's total energy consumption of the building. Hence, reducing the rural residential energy consumption is the key to developing a low-carbon economy. The paper uses the theory of ecological footprint to make quantitative analysis and compare between the northern rural house and multi-layer residential to develop low-carbon building design strategies [1-3].

2. Ecological footprint theory
To calculate the solar density, the equation is, $p_i = \frac{\text{total solar energy value}}{\text{total building land areas}}$.

The calculation formula is:

$$EF_r = \sum_{n=1}^{N} \frac{r_j \cdot \sum_{i=1}^{n} A_i}{r_j \cdot \sum_{i=1}^{n} c_i / p_i}$$

(1)
Among them, $E_{Fr}$ represents the ecological footprint of the consumption in each stage ($ghm^2$); $ef$ represents per capita ecological footprint ($ghm^2/cap$); $r_j$ represents the land equalization factor j ($ghm^2/hm^2$), $A_i$ represents the per capita ecological footprint of the i resource ($ghm^2/cap$); $c_i$ represents the per capita energy consumption of the i resource; $p_j$ is the energy density of building ($sej·hm^{-2}$).

According to the research results, the ecological footprint calculation formula [2-6] of the construction wastes is:

$$E_w = r_w·A_w = r_w·\sum_{n=0}^{S} S_n × 60×0.067×10^{-3}×10^{-4}$$  \hspace{1cm} (2)

Calculate the total ecological footprint of the building wastes in construction and demolition stage ($E_w$) based on equation 2. Therefore, the whole life-cycle ecological footprint ($EF$) is the ecological footprint of the main consumption items ($EF_r$) plus the building wastes produced in the life-cycle ($EF_w$), that is $EF = EF_r + EF_w$ [2, 6-10].

3. Patterns of house with difference materials

3.1. The farm house

Farm house covers an area of 474m$^2$ for two families in Fig. 1. The house is single-floored with the height of 5.2m. One of the families is three-Bay and the main building area is 103m$^2$, the other one is four-Bay with building area of 128m$^2$. The farm house did not use solar, wind, geothermal and other active energy forms and technologies with high initial investment costs, instead it uses fire pit, Kang, firewall, wall insulation, double glazing windows and a series of passive design techniques combined with local traditional customs.

3.2. The fire pit-adobe house

Adobe bricks work as the main material of building envelope structure, fire pit as the main heating system and solar-heating water system as the hot water supply system. This project uses new stove Kang as part of the energy supply system in daily life. Besides, biogas can be used as auxiliary energy for cooking and lighting. The overall running mode of the farm house is in Fig. 2 Adobe walls are thick and regenerative, they absorb solar radiation during the day and release the heat at night when the temperature is low.
3.3. The solar-straw house
Straw bricks are the main wall materials of the solar-straw house. Low-temperature solar radiation heating system works as the main heating system of the house. Other supply system of the house, such as solar-heating water system, stove Kang, and biogas, are the same with fire pit-adobe house. The overall running mode of the solar-straw house is shown in Fig. 3. Daily average radiation of the heating season in Dalian area is about 9536kJ/(m².d), this project has a heating area of 91.4m².

3.4. Multi-layer residence
The multi-layer residence chosen in this article located in Liaohua chemical industrial park of Liaoyang city, it is 6-layered with total land area of 5250m² and construction area of 5613.54 m², 20.44m in height, concrete structure, 11.84m in depth and 74.4m in length. Its energy saving rate is 65% and the measures are external thermal insulation system, double glazing and other conventional energy-saving methods, seen in Fig.4.
4. Sustainability assessment

4.1. Comparison of the farm house and multi-layer residence

Figure 4. Standard layer of the multi-layer residence

Figure 5. Comparison of the Wafangdian farm house and the multi-layer residence

Figure 6. Comparison of ecological footprint per capita of the farm house and the multi-layer residence
Fig. 5 is a comparison of the ecological footprint of the farm house and the multi-layer residence, both are sustainable. The ecological footprint index is 60% of the multi-layer residence, and 53% of the farm house, which shows that the multi-layer residence is more sustainable than the Farm house. It can be seen from Fig. 6 that the ecological carrying capacity per capita of multi-layer residence is much less than that of the Farm house, the reason is that the construction land area per capita in rural areas is far bigger than urban areas. The ecological footprint per capita is 0.004 ghm$^2$/cap of the multi-layer residence, and 0.010 ghm$^2$/cap of the Farm house, which illustrates that the load on the environment caused by multi-layer residence is much smaller than the Farm house.

4.2 Comparison of different houses
In order to further analyse the sustainability of the two modes of housing (Fig. 7), it can be seen from the figure that the ecological footprint per capita of the fire pit-adobe house is the lowest and its ecological footprint index is the highest, so it is the most sustainable. The per capita ecological footprint of the solar-straw house is more than that of the multi-layer residence, the ecological footprint index is 60%, which is lower than 68% of the multi-layer residence, so the multi-layer residence is more sustainable in only construction stage. The ecological footprint indexes of the solar-straw house and the fire pit-adobe house are higher than that of the farm house, which implies that their sustainability are significantly superior than the Farm house.

![Figure 7. Comparison of the ecological footprint per capita of different housing (in construction stage)](image)

The solar-heating system installed in the solar-straw house increased the cost of the whole house and the ecological footprint in construction stage. But the energy consumption will be reduced in operation stage, the house almost doesn’t need external energy. Meanwhile, the main building materials are straw, which will not produce construction waste in demolition stage. That is to say, the ecological footprint of construction stage should be compared to the total ecological footprint of the other stages. From Fig. 8, we can see that the per capita ecological footprint of the solar-straw house is slightly larger than that of the multi-layer residence in construction, operation and demolition stage and significantly less than that of the Farm house. The ecological footprint index of the solar-straw house is the same as the multi-layer residence, which indicates that the sustainability of the solar-straw house is the same as the multi-layer residence. It has been greatly improved compared to ordinary houses. From the perspective of the whole life cycle, the sustainability of the solar-straw house is obviously better than the common house. So it is worth of wider application.
5. Conclusion

From the view of sustainability, we have built four ecological footprint models of different houses in northern China based on ecological footprint theory and did a series of quantitative analysis. By comparing the different type houses we find that the multi-layer residence is more sustainable than the farm house in Wafangdian, it is in the state of ecological surplus and its per capita ecological footprint is far less than the Wafangdian farm house. The fire pit-adobe house is the most sustainable in construction stage, and its ecological footprint index is the highest. The per capita ecological footprints of solar-straw house and multi-layer residence are similar in construction, operation and demolition stage, which is less than Wafangdian farm house. The ecological footprint proportion of Wafangdian farm house in construction stage is the highest of whole life cycle. And electricity is the main energy consumption item in operation stage. Also, we can found that the choice of building materials is the core factor to reduce the ecological footprint in demolition stage, and the more efforts in design stage can effectively reduce the total ecological footprint in other stages. So we can reduce the total ecological footprint by reducing the ecological footprint in construction stage and operation stage effectively. Therefore, the most important thing is to choose the materials with less ecological footprint or use prefabricated materials in construction stage, and use energy-saving technologies such as concentrated warmth and gas systems in operation stage. Besides that, the energy-saving measures of rural houses such as fire pit, stove Kang and solar-heating hot water system are worth spreading in the northern areas.

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