Multi-case study on the carbon emissions of the ecological dwellings in cold regions of China over the whole life cycle

Zhixing Luo\textsuperscript{1,2} and Yiqing Lu\textsuperscript{2}

Abstract
This study employed the bottom-up life cycle assessment method, examining the life cycle carbon emissions of three dwellings constructed at different times with different techniques in Yinchuan City, China, i.e. traditional earth brick dwelling (Case 1), brick–straw bale dwelling (Case 2), wood–straw solar energy dwelling (Case 3). The study aimed to find the methods of reducing carbon emissions, so as to slow down the global warming. The results showed that (1) with excellent thermal insulation properties, straw bale was remarkably effective in reducing carbon emissions from heating at the use stage; (2) 15 kWp solar photovoltaic panels contributed to offsetting the carbon emission of the dwelling; (3) straw bales and logs could store the carbon in building envelope, which partly offset the carbon emissions. The findings of this study have proved that ecological building materials and solar photovoltaic system have great potential in reducing carbon emissions of buildings, and can provide a basis for the design and material selection of future dwellings in order to promote the development of green dwellings.

Keywords
Life cycle assessment, carbon emissions, ecological materials, straw bales, solar energy

\textsuperscript{1}State Key Laboratory of Green Building in Western China, Xi’an University of Architecture and Technology, Xi’an, China
\textsuperscript{2}College of Architecture, Xi’an University of Architecture and Technology, Xi’an, China

Corresponding author:
Zhixing Luo, Xi’an University of Architecture and Technology, No. 13 Yanta Road, Xi’an 710055, China.
Email: allexa@qq.com
Introduction

There is an increasing evidence showing that the overconsumption of fossil fuel has led to global warming and the most influential factor is the emission of greenhouse gases (Luo et al., 2016). Construction is one of three major sources of greenhouse gases (Lu and Yang, 2013) and the carbon emissions over a life cycle have aroused wide concern among increasingly more researchers worldwide (WBCSD, 2008). Vernacular dwelling, as the earliest building type that is most closely related to humans and exists in the largest number, is the most sustainable building type (Lu and Yang, 2013). Different from urban buildings, most vernacular dwellings are constructed by residents spontaneously and mainly scattered individually, thereby lacking the use of modern technologies and overall planning and building standards. Since 2000, the completed floor space of Chinese dwellings has been growing at a rate of 0.797–1.026 billion m²/year; these newly built dwellings are mainly designed with reinforced concrete structure and wood–brick structure, which account for 73 and 25%, respectively THUBREC (2016). The growth in total size of dwellings spurs the growth of energy consumption and carbon emissions in two aspects: (1) the manufacturing of considerable non-renewable building materials consumes plenty of energy and (2) the ever-increasing building area results in the large amount of operating energy consumption.

Dwellings play an important role and have great potential in building energy conservation and emission reduction. For example, in 2014, the commercial energy consumption of Chinese dwellings was 0.28 billion tce, accounting for 25% of the total national building energy consumption, among which the electric power was 192.7 GW h. Meanwhile, the rural biomass energy (straw and firewood) consumption amounted to about 0.102 billion tce (Sandanayake et al., 2016). Besides, the change of traditional residential pattern and lifestyle in rural areas has led to the alternation in the way of energy consumption, namely the rapid decline of biomass energy along with the extensive use of commercial energy like coal, liquefied petroleum gas, and electric power, which further results in the carbon emissions growth of dwellings.

Many studies have been carried out on the carbon emissions of buildings and the focuses of these studies can be grouped into the following categories: (1) The carbon emissions from manufacturing of building material. For example, Buchanan and Levine (1999) investigated the global impact of wood as a building material by considering emissions of carbon dioxide to the atmosphere; the study showed that wood buildings require much lower process energy and result in lower carbon emissions than buildings of other materials such as brick, aluminum, steel, and concrete. Sandanayake et al. (2016) developed a model to estimate and compare emissions at foundation construction and demonstrate its application using two case studies, and employed analytical hierarchy process to obtain weighting factors to assess impact categories under global and local perspectives. Kunić (2017) did a quantitative comparison of various thermal insulation materials; the study found that artificial materials can have a desirable carbon footprint reduction in the long run, comparable to other thermal insulation materials. (2) The calculation methods of building carbon emissions, including process-based life cycle inventory analysis (process-LCA), economic input–output LCA (EIO-LCA), and hybrid-LCA. Luo (2016) put forward the process-LCA method of China, and summarized and analyzed 44 factors affecting the carbon footprint of the building from the aspects of planning and design, and mechanical and electrical system. Dixit and
Singh (2018) developed an IO-based hybrid-based embodied energy calculation model by integrating actual energy use data into the latest IO accounts. Zhang and Wang (2016) proposed a hybrid approach that combines the advantages of P-LCA and EIO-LCA. (3) The carbon emissions from different types of buildings (e.g., different structures, materials, and functions). Luo (2016) analyzed and calculated the CO₂ emissions of 78 office buildings in construction materialization stage, and the storeys of the building and the consumption of construction materials are taken as two independent variables to set up a prediction model for CO₂ emissions of office buildings in materialization stage. Yu et al. (2011) found that in comparison with a typical brick-concrete building, the bamboo-structure building requires less energy and emits less carbon dioxide to meet the identical functional requirements. Gong et al. (2012) compared three types of residential buildings with framework structures in Beijing: concrete framework construction (CFC), light-gauge steel framework construction (SFC), and wood framework construction (WFC); the study shows that over the life cycle, the energy consumption of CFC is almost the same as that of SFC, and each of them is approximately 30% higher than that of WFC. (4) The calculation of carbon emissions of buildings at different stages of a life cycle (including building materialization, building operation, and end-of-life). Hong et al. (2015) analyzed GHG emissions during the construction phase of a case study building on the basis of an extended system boundary in the context of China by utilizing detailed onsite process data, and the results showed that indirect emissions accounted for 97% of all GHG emissions. Sandanayake et al. (2018) compared GHG emissions and energy consumptions during timber and concrete building construction; the comparative results of the study indicated that use of timber can reduce embodied emissions as well as transportation emissions during the construction stage. Wang et al. (2018) developed a conceptual framework in this study to facilitate the assessment of carbon emissions over the life cycle of building demolition waste and found that the recycling of metal waste has far higher environmental benefits compared to masonry wastes. (5) Strategies for reducing building carbon emissions (Huisingh et al., 2015; Rogers et al., 2015). Huisingh et al. (2015) believed that we have to radically transform our societal metabolism toward low/no fossil-carbon economies, design and timing of suitable climate policy interventions, such as various carbon taxation/trading schemes. Rogers’s (2015) study showed that it is both practical and economically feasible for a homeowner to reduce their net operational GHG emissions by 80% of the 1990 values by using combinations of micro generation equipment to supply their heat and electricity demands.

In recent years, researchers have tried to use ecological building materials, usually logs and bamboo, to build envelopes and have evaluated their performance in energy saving and emission reduction. For instance, Zhen and Zhang (2018), through on-site measurements, determined the energy consuming capability of wooden structure houses in cold regions of China and found that these houses had no obvious thermal defects and had good energy saving performances. Huang et al. (2017) compared the performance of bamboo in constructing envelopes with that of timber. The result displayed that bamboo showed disadvantages in severe cold and cold zones, and advantages in full bamboo/timber constructions in hot and temperate regions. Straw is another commonly used ecological building material, with billion tonnes of harvest each year across the world. Although the construction of straw bale buildings can be traced back to the invention of packer a century ago, the on-site test studies (Ashour et al., 2011; Gallegos-Ortega et al., 2017) and the
successful applications of the straw bales in modern buildings have proved that straw bales have extraordinary heat insulation performance and high adaptability. Straw bales can be used in various ways, such as: (1) to fill walls directly (Gallegos-Ortega et al., 2017); (2) to be compressed into straw–clay building blocks after mixing with clay (González, 2014); (3) to prefabricate straw–brick walls (Shea et al., 2013). From these studies, the three straw solutions investigated have much better thermal performance than fired bricks or concrete blocks.

Some researchers, from the perspective of life cycle, analyzed the differences that lie in the carbon footprints of natural materials and modern industrial materials. Gustavsson et al. (2006) and Gustavsson and Sathre (2006) found that using wood to replace concrete was effective for reducing the carbon emissions of buildings over the whole life cycle. Sandanayake et al. (2018) compared changes in the greenhouse gas emissions between timber buildings and concrete buildings during construction. Sierra-Pérez et al. (2018) evaluated the environmental influences of using cork wood insulation boards as building materials in Barcelona metropolitan area, and the results demonstrated a high potential of retrofit buildings with cork insulation boards from an environmental and economic perspective. A recent study of Lehmann (2013) showed that cross-laminated wood was quite suitable for urban low-carbon multi-story buildings after examining. González (2014) studied two different approaches of manufacturing wall with wheat straw and found the positive role of agricultural products in reducing carbon footprint.

Some studies considered natural plant materials as carbon sinks. Stocchero et al. (2017) introduced the concept of “city equilibrium” and regarded urban wooden buildings as carbon sinks which could balance the carbon emissions in city; they suggested that since trees absorb the carbon in air during growth, wooden products worked as permanent carbon pools. Salazar and Meil (2009) found that wood-intensive houses were able to neutralize the carbon emitted over 34–68 years in Ottawa. Lawrence (2015) explained how plant-based materials contributed to reducing the carbon emission during the materialization of buildings as well as the energy consumption. Although forestry biomass has long been the major carbon pool on the earth, the carbon stored in forests or regenerated forests is limited by the long growth period of trees. In contrast to forest plants, straw, as a byproduct of grain, is a short-growth-period, renewable agricultural product. Unused agricultural wastes can account for 2.5 Gt carbon each year worldwide (Haberl et al., 2007), which is equal to a quarter of the annual CO₂ emission of fossil fuel (Peters et al., 2012). Therefore, straw bale buildings have a great potential for storing CO₂.

Although plenty of studies are on ecological construction, few studies have been conducted on the carbon emission of straw bale buildings over a life cycle through practical cases, particularly when the introduction of new technologies is creating more advanced forms of straw bale buildings. This study, taking three rural dwellings constructed at different times in Yinchuan (two of them were straw bale houses built with different techniques) as examples, based on process-LCA, calculated and analyzed the carbon emissions of the three dwellings over a whole life cycle. The objectives of this study are (1) to compare the differences in carbon emission between different types of ecological dwellings over a whole life cycle, especially the differences in energy consumption and carbon emission during building materialization and operation; (2) to evaluate the contribution of solar energy to reduce building emission in northwest regions of China; (3) to provide reference for the design and material selection for dwellings, considering the local resources, to further promote the development of green dwellings.
Case introduction

Traditional earth brick dwelling (Case 1)

All the traditional earth brick dwellings in Yinchuan (Figure 1) were built by farmers spontaneously during 1950s–1990s. They are generally solitary single-story houses characterized by single function, regular sides, and simple structure. The dwellings, usually with 3–5 rooms lined up and facing the south, have only one room along the depth direction. The shape coefficient of building mostly ranges within 0.7–0.8. The area ratio of southern windows to wall is approximately 25%, and neither the side walls nor the north walls have windows.

The common building envelope is constructed in the following ways: (1) the exterior wall is 350 mm in thickness and is made up of earth bricks; the foot of wall is built on a cobble base with five layers of sintered bricks; the heat transfer coefficient (K value) of the exterior wall is 1.83 W/(m² K); (2) the roof is usually flat; wooden rafters are directly fixed on the load bearing exterior walls with reed mats and hay (whose thicknesses together are no less than 200 mm) covered on them instead of tiles; and the total heat transfer coefficient of roof is 2.04 W/(m² K); (3) the floor, with a cobble base, is leveled by medium-coarse sand and is covered with a layer of solid clay bricks on the surface; the heat transfer coefficient is 1.18 W/(m² K); (4) the front door is a single-leaf inward opening wooden door with a cotton curtain hanging on the outer surface to keep warm in winter; the windows are usually made up of single-layer glasses and wooden frames; the heat transfer coefficient of external windows is 6.5 W/(m² K).

Traditional dwellings which have simple energy-using ways depend on burning coal or firewood for heating in winter, where the thermal efficiency is below 40%. Many solar energy resources in Yinchuan have not been effectively used in building heating. The single-story dwelling studied in the present study covers an area of 125 m² and lays out in the shape of “L.”

Figure 1. Picture of traditional earth brick dwelling.
**Brick–straw bale dwelling (Case 2)**

The straw bale energy-saving dwelling shown in Figure 2 was built in 2006. Through appropriate constructing technologies, it made the utmost of the abundant local straw resources by using straw bales as external thermal insulation materials to improve the thermal performance of the envelope. Moreover, reasonably designed windows and sunroom are used to collect solar radiation to enhance lighting and ventilation, thereby improving the indoor environmental quality. The covered area of the dwelling is 125 m², including the area of one living room and three bedrooms. In cold months, to keep the rooms warm, kang (a heatable brick bed) is heated by burning coal. The thermal efficiency is about 50%.

The envelope is built in the following ways: (1) the wall (see Figure 3) contains a 240 mm sintered clay brick wall with a layer of asphalt coating on the outer surface; next to the clay brick wall, there is a 250 mm thick straw bale wall which is attached to a stainless wire mesh plastered with cement mortar; the total heat transfer coefficient (K value) of wall is 0.335 W/(m² K); (2) the roof is made up of 100 mm thick reinforced concrete boards covered with a 100 mm thick EPS insulation layer; a cement mortar layer which is no less than 25 mm is used for leveling; modified asphalt membrane is paved on the mortar layer for waterproofing; and the heat transfer coefficient of roof is 0.41 W/(m² K); (3) the floor is tamped with soil; an insulating layer with 300 mm thick coal cinder is paved for 2 m from the internal surface of exterior wall; above the coal cinder layer, there is a 60 mm thick layer of non-reinforced concrete; 20 mm cement mortar layer is built for leveling; the heat transfer coefficient of floor is 0.79 W/(m² K); (4) the windows are double-pane windows with well-sealed single plastic frame for preventing cold air; the heat transfer coefficient of windows is 3.0 W/(m² K).

**Wood–straw solar energy dwelling (Case 3)**

The dwelling of Case 3 shown in Figure 4 was built in 2014. Similarly, it used straw bales as the major materials for wall. In contrast to Case 2, it replaced clay bricks with oriented strand boards (OSBs), thus greatly reducing the dead weight and thicknesses of walls. With a 15 kWp solar energy generating system installed on the roof, it has no heated kang inside;
instead, it has a multi-split heating system driven by electric power. The covered area of the dwelling is 99 m$^2$, including the area of one living room and two bedrooms.

The envelope is built in the following steps: (1) the wall (Figure 5) has a 2.4 m $\times$ 2.4 m $\times$ 2.4 m wooden structure made up of 600 mm $\times$ 600 mm lattices; straw bales are filled in the wooden lattices as thermal insulation materials; the heat transfer coefficient of wall is 0.3 W/(m$^2$ K); (2) the roof is built with 18 mm thick fireproofing OSBs on which 100 mm EPS insulation boards are placed; the heat transfer coefficient is 0.35 W/(m$^2$ K); (3) the floor also has a wooden lattice structure; 200 mm EPS is filled in the lattices for thermal insulation; the heat transfer coefficient is 0.25 W/(m$^2$ K); (4) the windows are thermal insulating aluminum alloy windows with double-pane low-E glasses whose heat transfer coefficient is 1.8 W/(m$^2$ K).

Figure 3. Structural details of straw–brick walls.

Figure 4. Wood–straw solar energy dwelling.
The heat transfer coefficients of the main envelope components of the three dwellings are given in Table 1.

The three cases are different in terms of size, but the functionality is basically the same. In this study, we use “square meter,” which refers as a functional unit. And the total embodied carbon emissions are divided with the total constructed area of each building.

**Climate of Yinchuan City**

The objects of this study, located in Yinchuan City, the Ningxia Hui Autonomous Region of China, are in the cold areas according to the thermal performance partition. Yinchuan has long cold winters and short summers and its annual mean temperature ranges within 5–9°C. The coldest month is January with an average temperature of −14°C and an extreme minimum temperature of −22°C; the hottest month is July with an average temperature of 23.4°C. Yinchuan has a dry and rainless climate and abundant sunshine; thus it is rich in solar energy. With its annual solar radiation amounting to 5711–6069 MJ/(m² a) and annual sunshine duration reaching about 3000 h, Yinchuan comes top in solar energy resources in China (Zhai, 2010). To sum up, Yinchuan City will be suitable for the promotion of straw bales and solar panel technology.

Table 1. Heat transfer coefficients of components of envelope.

| No.   | Exterior wall | Roof | Exterior window | Floor |
|-------|---------------|------|-----------------|-------|
| Case 1| 1.83          | 2.04 | 6.5             | 1.18  |
| Case 2| 0.335         | 0.41 | 3.0             | 0.79  |
| Case 3| 0.3           | 0.35 | 1.8             | 0.25  |
Methods

Method selection

Life cycle assessment is an effective way to evaluate the environmental load of a product’s life cycle. The current methods for carbon emission calculation include EIO-LCA, process-LCA, and hybrid-LCA, among which process-LCA and EIO-LCA are commonly used in analyzing the carbon emission of buildings (Dixit and Singh, 2018). EIO-LCA is a top-down method which calculates the energy consumption and carbon emission based on the amount of money spent on; thus it is able to obtain the data about the carbon emission of all upstream supply chains through calculating the total monetary amount of construction industry spent on energy consumption. When process specific information is not available, input–output approach is an efficient method to estimate environmental impacts (Sandanyake et al., 2016). However, process-LCA is a bottom-up method which can determine the carbon emission of a specific process during construction. Process-based approach requires quality information to develop the assessment model in evaluating environmental impacts. Unit processes corresponding to the main product or process will be modeled for the evaluation. With an overall consideration of the object size and the available data, Process-LCA is used in this study.

System boundary

The life cycle of the dwellings in the cases of this study is divided into four phases: Phase 1 for material production, Phase 2 for transportation and construction, Phase 3 for building operation, and Phase 4 for the end of life. The materialization stage of building is composed of Phases 1 and 2. The carbon emission sources which are excluded from the system are input manpower, waste disposal after building demolition, and other carbon emission sources like water consumed during construction. The phases of life cycle and system boundary of studied dwellings are shown in Figure 6. As defined in the ISO 14064-1:2012 (2012), greenhouse gases include CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆; during the life cycle of buildings, greenhouse gases mostly are generated by the combustion of fossil fuel either directly or indirectly. In this study, the greenhouse gases are converted into CO₂ emissions, namely kg CO₂e, according to their global-warming potential.
Calculation method of carbon emission

Carbon emission of material production. As the extraction, production, transportation, and assembling of building materials need to input resources and energy, the carbon emission from the manufacturing of building materials ($CE_m$) can be worked out through the equation below

$$CE_m = \sum (1 + \alpha_i) \times m_i \times EF_{m,i}$$

(1)

where $m_i$ is the utilization amount of material $i$ (kg), $EF_{m,i}$ is the carbon emission factor of material $i$ (kg CO$_2$e/unit), and $\alpha_i$ is the wastage rate of building materials at the construction site.

The consumption amounts of the main construction materials of three buildings are presented in Table 2.

| Materials                  | Unit       | Case 1  | Case 2  | Case 3  | Carbon emission factors (kg CO$_2$e/unit) | Data sources               |
|----------------------------|------------|---------|---------|---------|-------------------------------------------|----------------------------|
| Earth bricks               | t          | 135.2   |         | 1.75    |                                          | Christoforou et al. (2016) |
| Sintered clay bricks       | $10^3$ piece | 4.79   | 25.07   | 349     |                                          | Dixit and Singh (2018)    |
| Straw bales                | t          | 3.11    | 2.62    | 5.72    |                                          | Survey                     |
| Glass                      | m$^2$      | 10.80   |         | 12.94   |                                          | Dixit and Singh (2018)    |
| Logs                       | m$^3$      | 6.32    | 5.85    | 12      |                                          | MOHURD (2016)             |
| Sand                       | t          | 11.3    |         | 0.007   |                                          | Yu et al. (2011)          |
| Clay                       | m$^3$      | 6.43    |         | 0       |                                          | –                          |
| Cement mortar              | m$^3$      | 7.08    |         | 184.9   |                                          | Dixit and Singh (2018)    |
| Concrete                   | t          | 22.38   |         | 381.5   |                                          | Wang et al. (2018)        |
| EPS                        | t          | 0.39    | 0.71    | 4205    |                                          | Luo (2016)                |
| Styrene butadiene styrene  | m$^2$      | 264     |         | 0.77    |                                          | Wang et al. (2018)        |
| (SBS)                      |            |         |         |         |                                          |                            |
| Steel bar                  | t          | 2.75    |         | 2310    |                                          | Yu et al. (2011)          |
| Shaped steel               | t          | 7.8     | 1755    |         |                                          | Yu et al. (2011)          |
| Oriented strand boards (OSB)| m$^3$     | 13.4    | 127     |         |                                          | MOHURD (2016)             |
| Wood–plastic composites    | t          | 2.08    |         | 4014    |                                          | Qiang et al. (2014)       |
| (WPCs)                     |            |         |         |         |                                          |                            |
| Wooden windows and doors   | t          | 0.245   |         | 651.31  |                                          | Gong et al. (2012)        |
| Plastic windows            | m$^2$      | 31.4    | 98.4    |         |                                          | Dixit and Singh (2018)    |
| Broken bridge aluminum     | m$^2$      | 16.82   | 79.3    |         |                                          | Dixit and Singh (2018)    |
| windows and doors          |            |         |         |         |                                          |                            |
| Wood doors                 | t          | 0.25    |         | 651.31  |                                          | Gong et al. (2012)        |
| Photovoltaic system        | kWp        | 15      | 2210    |         |                                          | Hou et al. (2016)         |

EPS: expanded polystyrene board.
Carbon emission from transportation. The carbon emitted during transportation \( CE_t \) is calculated through the equation below

\[
CE_t = \sum \left[ \left( \sum_{i=1}^{n} L_{i,j} \times m_i \right) \times EF_{t,j} \right]
\]

where \( L_{i,j} \) is the distance of material \( i \) transported by transport equipment \( j \) (km), and \( EF_{t,j} \) is the carbon emission factor of transport equipment \( j \) (kg CO\(_2\)e/km t), which is determined by the dynamic efficiency of transport equipment and the fuel it uses. The building materials in this study are all transported by highway; the average transport distances of major materials are given in Table 3. The carbon emission factor of highway transportation is 0.168 kg CO\(_2\)e/(t km) (Peng, 2016).

Carbon emission during construction. The carbon emission during on-site construction \( CE_c \) mainly comes from the energy consumed by the mechanical equipment (including fuel equipment and electrical equipment) and can be calculated through the following equation

\[
CE_c = EF_{f,i} \times FM_i + EF_e \times Q_{onsite}
\]

where \( EF_{f,i} \) denotes the carbon emission factor of fossil fuel \( i \) (kg CO\(_2\)e/MJ), \( EF_e \) denotes the carbon emission factor of electric power (kg CO\(_2\)e/kW h), \( FM_i \) is the consumed amount of fuel \( i \) during construction (MJ), and \( Q_{onsite} \) is the electricity amount consumed during construction (kW h).

The major input time of machines and consumed electric power during the construction of the three studied dwellings are presented in Table 4. Yinchuan City is situated in Northwest China the marginal emission factor of Northwestern Power Grid is 1.0935 t CO\(_2\)e/MW h (Christoforou et al., 2016).

Carbon emission during building operation. The carbon emission during building operation \( CE_o \), which refers to the carbon emitted by the daily consumption of fossil energy, electricity, and water resources, can be obtained through the equation below

\[
CE_o = EF_{f,i} \times FU_i + EF_e \times Q_{operation} + EF_w \times m_w
\]

where \( FU_i \) is the utilization amount of fuel \( i \) during operation (MJ), \( Q_{operation} \) is the consumed electricity during operation (kW h), \( m_w \) is the amount of water consumed during operation (tonnes), and \( EF_w \) is the carbon emission factor of water (kg CO\(_2\)e/t).

It can be known from ISO 14064-1:2012 (2012) that the default carbon emission factor of lignite is 379.6 kg CO\(_2\)e/MW h.

Table 3. Average transport distances of building materials (km) (Dixit and Singh, 2018).

| Types of building materials | Rolled steel | Mortar | Concrete | Bricks and stones | Glass | Doors and windows | Wood | Sand |
|-----------------------------|--------------|--------|----------|-------------------|-------|-------------------|------|------|
| Distance                    | 60           | 50     | 15       | 25                | 75    | 55                | 35   | 40   |

Energy Exploration & Exploitation 38(5)
Field measurement and computer simulation are two major approaches used for calculating the energy consumption during building operation. Compared with field measurement, computer simulation is able to ensure the consistency of indoor thermal environment parameters and even eliminate the differences resulting from the usage habits of dwellers; thus, it is more suitable for comparative study. The simulation software used for carbon emission research includes Ecotect, Designer’s Simulation Toolkit, IES, Energy-Plus, E-Quest, and Designbuilder (Peng, 2016; Wang et al., 2018).

In this study, Designbuilder V4.6 is used to calculate the energy consumed for heating and cooling as well as the power used for lighting and by electric appliances within the service life of building. All three cases will use the same simulation parameters to improve comparability. The heating temperature in indoor living space (living room and bedrooms) is set at 18°C, the lighting power density is set to 2 W/m², the air exchange rate is 0.5 ac/h, the density of population is 0.03 people/m², and the power density of equipment is 4.1 W/m².

**Carbon emission during building demolition.** The carbon emission during building demolition ($CE_d$) can be estimated by the following equation according to the findings of Wang et al. (2018)

$$CE_d = CE_c \times 90\%$$

(5)

**CO₂ stored in plant fiber.** As mentioned in the “Introduction” section, plant materials capture CO₂ during growth and store it long in buildings. The stored carbon emission ($CE_{storage}$) can

| No. | Types of machines                      | Input time of machines (h) | Electric power consumption (kW h) |
|-----|----------------------------------------|----------------------------|----------------------------------|
| Case 1 | Woodworking circular saw             | 1.1                       | 3.3                              |
|      | Woodworking planer                    | 2.4                       | 8.58                             |
|      | Woodworking tenoning machine          | 2.3                       | 7.76                             |
|      | Woodworking trepanning machine        | 4.2                       | 2.47                             |
|      | Woodworking cutting machine           | 2.7                       | 12.15                            |
|      | Mortar mixer, 200 l                   | 2.5                       | 2.69                             |
| Case 2 | Mortar mixer, 200 l                   | 2.7                       | 2.91                             |
|      | Concrete mixer, 350 l                 | 5.9                       | 47.58                            |
|      | Steel bar cutter                      | 2.0                       | 8.03                             |
|      | Steel bar bender                      | 4.4                       | 7.04                             |
|      | Electroslag welding machine           | 3.3                       | 60.6                             |
|      | Direct-current welding machine, 30 kW | 9.0                       | 27                               |
|      | Electric drill                        | 12.6                      | 5.04                             |
| Case 3 | Electric drill                        | 12.9                      | 5.16                             |
|      | Woodworking circular saw              | 5.2                       | 15.6                             |
|      | Electric hammer, 520 W                | 67.4                      | 35.05                            |
|      | Mast crane, 5 t                       | 8.0                       | 71                               |

Luo and Lu 2009
be worked out through

\[ CE_{storage} = m_{c,i} \times \frac{44}{12} \]  

(6)

where \( m_{c,i} \) denotes the carbon mass contained in building materials (kg).

It should be pointed out that agricultural products capture carbon from the atmosphere, in both the part harvested and in soils. The carbon captured by wood or straw is usually not counted as sequestered from the atmosphere because it might return by degradation. However, carbon captured by soils could be considered as permanent sequestration (González, 2014).

**Carbon emission from whole life cycle.** The total carbon emission over a life cycle (\( CE_{total} \)) can be obtained by the below equation

\[ CE_{total} = CE_m + CE_t + CE_c + CE_o + CE_d - CE_{storage} - CE_{PV} \]  

(7)

where \( CE_{PV} \) refers to the carbon reduced by the PV system, \( CE_{PV} = Q_{PV} \times EF_e \), and \( Q_{PV} \) is the electricity generated by PV system (kW h).

### Results and discussion

**Carbon emissions from building material production**

The carbon emissions of the three dwellings from material manufacturing (excluding carbon storage) are shown in Figure 7. The carbon emissions of Cases 1, 2, and 3 are 29.4, 239.4, and 618.4 kg CO\(_2\)e/m\(^2\), respectively. It can be known from Figures 7 and 8 that (1) earth brick dwelling (Case 1) is the lowest in carbon emission during building material manufacturing as it uses local materials; the sintered clay bricks used to build the foot of wall and to pave floor are the primary carbon source during the material manufacturing phase; (2) in the case of straw bale energy-saving dwelling (Case 2), sintered clay bricks, steel bars, concrete, and plastic windows contributed 89% of the total carbon emission; (3) in Case 3, PV system, shaped steel, and wood–plastic composites (WPCs) are high in carbon emission which contributed 90% of the carbon emission from material production; (4) the contribution rate of straw bales for carbon emission is only 0.1% when they are used as major thermal insulation materials for wall.

**Carbon emission during transportation and construction**

The mass of building materials and the shipment distance determine the carbon emission at transportation stage. As calculated by equation (2), the carbon emissions of Cases 1, 2, and 3 from transportation amount to 10.2, 7, and 3.1 kg CO\(_2\)e/m\(^2\), respectively. The machine input for construction is all driven by electric power as the dwellings are not high. It can be calculated from the data in Table 4 that the electric power consumed in Cases 1, 2, and 3 during construction is 40.4, 172, and 138.7 kW h, respectively; the corresponding carbon emissions obtained by using equation (3), respectively, are 0.32, 1.38, and 1.4 kg CO\(_2\)e/m\(^2\).
Carbon emission from building materialization

Earth brick dwelling (Case 1), the most common type of building in Northwest China, is quite low in carbon emission during building materialization. Its carbon emission only accounts for 1% of the total carbon emission over a life cycle and is 91.9 and 97% lower than those of Cases 2 and 3, respectively. It can be known from Tables 2 and 5 that earth bricks are the mostly used materials for building earth building envelope (135.2 t), accounting for 82.9% of the total mass of envelope (163 t); they contribute to only 10.4% of the carbon emission from material manufacturing (Figure 8(a)). It suggests that earth bricks are low-carbon building materials. Each 1 m³ wall built with sintered clay bricks and cement mortar generates 225 kg CO₂e of greenhouse gases, which is 85.7 times that of the emission for building 1 m³ mud brick wall.

In Case 2, apart from the straw bales used as the major material for the building envelope, plenty of modern industrial building materials are also used. The rebars, concrete, and sintered clay bricks together contribute to 79% of the carbon emission during materialization (Figure 8(b)) and 19% of the total carbon emission over a whole life cycle. Therefore, the carbon emission will be significantly reduced by replacing rebars, concrete, and sintered clay bricks with natural building materials such as logs and straw. For instance, wooden beams, wooden columns, and straw bales are used to replace concrete beams, concrete columns, and sintered clay bricks, respectively.

Although Case 3 used OSBs to build the load-bearing walls and straw bales as wall filling materials, its carbon emission at materialization stage is much higher than those of Case 1 and Case 2. It is easy to see from Figure 8(c) that PV system contributes to 54% of the carbon emission at materialization stage and its carbon emission alone exceeds the materialization carbon emissions of all the materials of Case 3. However, the reduced amount of carbon due to the power generated by the PV system during building operation can offset the amount of carbon from material manufacturing at the earlier state. 22.3% of the carbon emission at the materialization stage is from shaped steel which is easier to be recycled than steel bars and is a relatively green building material. Besides, it is worth mentioning that, WPC, although its raw materials are mostly agriculture and forestry wastes (wood chips and
straw), is a typical energy-intensive material (Qiang et al., 2014) whose unit mass carbon emission exceeds those of all the other building materials except PV system, and thus should be replaced by materials like alkaline copper quaternary-treated lumber whose carbon emission is one-third of that of WPC (Bolin and Smith, 2011).

Table 5. Carbon emission from wall material production of earth brick dwelling.

| Material             | Weight (t) | Mass proportion (%) | Contribution rate of carbon emission (%) |
|----------------------|------------|---------------------|-----------------------------------------|
| Earth bricks         | 135.2      | 82.9                | 10.4                                    |
| Sintered bricks      | 11.9       | 7.3                 | 73.2                                    |

Figure 8. Distribution of carbon emissions from material manufacturing.
Carbon emission during building operation

The energy consumption and carbon emissions in Table 6 are the results obtained when the heating temperature of living space (living room and bedrooms) is set at 18°C. It can be known from Table 4 that straw bales have significant effect in reducing the heating consumption in cold regions. Besides, coal and electric power dominate in the energy consumption of the building. Furthermore, the carbon emission during building operation can be reduced by over 60% when the wall is built with straw bales compared with walls without them.

Carbon emission over a life cycle

Figure 9 shows the carbon emissions of the three studied dwellings over the whole life cycle. The similarity of Cases 1 and 2 lies in that they both have the highest carbon emission during building operation, followed by building materialization. However, the carbon emission of Case 3 at materialization stage is higher than that at operation stage.

The three dwellings differ significantly in the temporal distribution of carbon emission within the 25-year life cycle. Specifically, 99% of the energy consumption and carbon emissions of earth brick dwelling (Case 1) comes from building operation; the carbon emission of straw–brick energy-saving dwelling (Case 2) at the operation stage accounts for 57%; the new straw bale dwelling powered by solar energy (Case 3), although way ahead in the carbon emission from material manufacturing, manages to reach negative carbon emission because its PV system, with the abundant solar energy in Northwest China, can not only generate enough electricity for the dwelling but also send the surplus to electric power grid. The CO₂ stored in Cases 1, 2, and 3 is 48, 81.4, 308.5 kg CO₂e/m², respectively, which account for 16.3, 34, and 49.9% of the carbon emission from building material production.

In addition, as the dwellings are generally characterized by low height, simple construction techniques, short transport distance of building materials, low energy input during construction, and high manpower input, their greenhouse gas emission during construction merely accounts for 0.18–0.51% of the total emissions over a whole life cycle.

Limited by low technology and large heat transfer coefficient of wall, the earth brick dwellings in cold regions are high in heating energy consumption; accordingly, there is great space for improvement. Nevertheless, carbon emissions can be reduced significantly by inputting a small amount of money to, for example, improve the layout, build insulating layer, and/or install new doors and windows. According to the simulated results of Designbuilder, the annual heating coal consumption can be decreased by 28.7–35.6% if 100–200 mm thick straw bales are used as the external insulation materials of wall.

Table 6. Annual energy consumption and carbon emission.

| No. | Area (m²) | Electric power (electric appliance) (kW h) | Electric power (heating) (kW h) | Coal (GJ) | Water (m³) | PV system generated energy (kW h) | Total carbon emission (kg CO₂e/m²) |
|-----|----------|------------------------------------------|---------------------------------|-----------|-----------|---------------------------------|----------------------------------|
| 1   | 125      | 1267.94                                  | –                               | 94.25     | –         | 180a                            | 91.4                             |
| 2   | 132.5    | 1005.13                                  | –                               | 28.93     | –         | 180a                            | 31.4                             |
| 3   | 99       | 976.36                                   | 778.77                          | –         | 180a      | 18,000b                         | 21.6                             |

PV: aThe consumption amount of water is estimated.
bThe energy generated by distributed PV system is from the research of Hou et al. (2016).
However, the connecting methods of straw bales and earth bricks still remain to be further studied. Earth bricks can be directly used to build envelopes in areas less demanding on thermal insulation.

In cold regions like Yinchuan, the carbon emission of Case 3 caused by heating is 89.1 and 62.6% lower than that of Case 1 and Case 2, respectively, during the whole heating period. The reduction may result from the thickened straw bale wall, the insulation treatment to roof and floor, the thermal insulating double-pane windows and doors, and/or the high-thermal-efficiency multi-split heating system driven by electric power. Case 3 has the lowest carbon emission at the operation stage even if the PV system generated power is excluded. The buildings in areas with abundant solar energy are suggested to install PV system so as to reach carbon neutrality. The PV system will generate a large amount of greenhouse gases with the current production technology, which will hopefully be improved with the advancement of manufacturing technology in the future.

**Application prospect of biomass building materials**

It can be known from Figure 9 that with the improvement of technology and equipment efficiency, the carbon emissions of Cases 1, 2, and 3 at the operation stage show a decreasing trend. Case 2 and Case 3 both used straw bales, agricultural waste which can be obtained locally and easily produced and is relatively easy to store carbon. The carbon stored in the straw bales of Case 2 is 81.4 kg CO$_2$e/m$^2$, accounting for 34% of the total carbon emissions at materialization stage; the carbon stored in the straw bales and logs of Case 3 amounts to 308.5 kg CO$_2$e/m$^2$, accounting for 49.7% of the total materialization carbon emission. The inclusion of straw solutions in the cold region will not only lower energy and carbon footprints per m$^2$ of wall, as discussed here, but would also improve operative energy use in buildings. This study suggests that it is beneficial for policy makers to promote straw solutions in cold regions.

**Figure 9.** Carbon emissions at different stages of a life cycle.
Limitations

The limitation of the present study, first, is that the carbon emission of building is related to its renewal frequency; however, the service life of building and the renewal of equipment are hard to determine due to the influences of local economic conditions. For this reason, the service life of building is assumed to be 25 years in this study.

Moreover, the operational energy consumption is the major source of carbon emission in the whole life cycle; yet the greenhouse gas emission during building operation is determined by unpredictable factors like the habits, physical conditions, and ages of users, thus the mean value is obtained by using standard occupancy assumptions.

Conclusions

This study, based on process-LCA, investigated the carbon emissions of three typical dwellings in Yinchuan over the whole life cycle. Among them, one was a traditional local earth brick dwelling and the other two were new straw bale dwellings. The results showed that the carbon emissions over a life cycle were greatly influenced by the design of dwellings. Besides, in cold regions, the largest carbon emission of building was caused by the heating during operation. In this study, it is feasible to promote grass bricks and other biomass materials in cold areas of China. Considering that the vast and sparsely populated Northwest China has a dry and rainless climate and is rich in solar energy resources, and the theoretical electric power generated by the 15 kWp PV system is 18,000 kW h/year, which is able to meet the electricity demand of a typical family, the surplus electricity can be input into the power grid to reach zero-carbon emission of building.

Straw bales and earth bricks are both low-carbon materials for building envelopes, and thus the carbon emitted during their production processes can be ignored. Although they have a small adverse influence on the environment at the early stage due to their simple construction ways, earth brick dwellings are unable to meet the demands on energy saving and comfortable living because they are poor in thermal performance and need a considerable amount of coal to produce. Compared with the combination of sintered clay bricks and straw bales (Case 2), the combination of OSBs and straw bales (Case 3) is an improved method for ecological dwelling construction, which has reduced the use of clay bricks, mortar, and concrete. Furthermore, with the maximum use of wood and straw, the dwelling in Case 3, as a carbon pool, has stored 308.5 kg CO₂e/m² carbon. Therefore, on the premise that the use functions of a building are satisfied, green building materials like straw, wood, and earth bricks should be more widely used and the use of such high-pollution materials like steel bars, concrete, clay bricks, and WPCs should be reduced.

Straw bales used to build envelopes can not only improve the thermal insulation performance of building but also reduce more than 60% of the greenhouse gases emitted during the operation stage. A large amount of agricultural straw is not fully utilized in China every year, which means maximizing the use of straw bales as building materials in construction can store lots of CO₂ in the building. In Ningxia, which is located in a cold region of China, and has a long winter, only 1% of the envelopes of local traditional rural dwellings have insulation layers (Sterner, 2007); it is not sufficient to meet the heating demands merely by enhancing the insulation of envelopes. Therefore, active solar energy techniques are suggested to supplement the heat demands.
Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The research described in this paper was fully funded by Project of Young Science Foundation of National Natural Science Foundation of China (51908441).

ORCID iD

Zhixing Luo https://orcid.org/0000-0003-1546-1902

References

Ashour T, Georg H and Wu W (2011) Performance of straw bale wall: A case of study. Energy and Buildings 43(8): 1960–1967.

Bolin CA and Smith S (2011) Life cycle assessment of ACQ-treated lumber with comparison to wood plastic composite decking. Journal of Cleaner Production 19(6–7): 620–629.

Buchanan AH and Levine SB (1999) Wood-based building materials and atmospheric carbon emissions. Environmental Science & Policy 2(6): 427–437.

Christoforou E, Kyliili A, Fokaides PA, et al. (2016) Cradle to site life cycle assessment (LCA) of adobe bricks. Journal of Cleaner Production 112: 443–452.

Dixit MK and Singh S (2018) Embodied energy analysis of higher education buildings using an input-output-based hybrid method. Energy and Buildings 161: 41–54.

Ferro FS, Silva DAL, Lahr FAR, et al. (2018) Environmental aspects of oriented strand boards production. A Brazilian case study. Journal of Cleaner Production 183: 710–719.

Gallegos-Ortega R, Magaña-Guzmán T, Reyes-López JA, et al. (2017) Thermal behavior of a straw bale building from data obtained in situ. A case in Northwestern México. Building and Environment 124: 336–341.

Gong X, Nie Z, Wang Z, et al. (2012) Life cycle energy consumption and carbon dioxide emission of residential building designs in Beijing: A comparative study. Journal of Industrial Ecology 16(4): 576–587.

González AD (2014) Energy and carbon embodied in straw and clay wall blocks produced locally in the Andean Patagonia. Energy and Buildings 70: 15–22.

Gustavsson L, Pingoud K and Sathre R (2006) Carbon dioxide balance of wood substitution: Comparing concrete-and wood-framed buildings. Mitigation and Adaptation Strategies for Global Change 11(3): 667–691.

Gustavsson L and Sathre R (2006) Variability in energy and carbon dioxide balances of wood and concrete building materials. Building and Environment 41(7): 940–951.

Haberl H, Erb KH, Krausmann F, et al. (2007) Quantifying and mapping the human appropriation of net primary production in Earth’s terrestrial ecosystems. Proceedings of the National Academy of Sciences of the United States of America 104(31): 12942–12947.

Hong J, Shen GQ, Feng Y, et al. (2015) Greenhouse gas emissions during the construction phase of a building: A case study in China. Journal of Cleaner Production 103: 249–259.

Hou G, Sun H, Jiang Z, et al. (2016) Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. Applied Energy 164: 882–890.

Huang Z, Sun Y and Musso F (2017) Assessment of bamboo application in building envelope by comparison with reference timber. Construction and Building Materials 156: 844–860.
Huisingh D, Zhang Z, Moore JC, et al. (2015) Recent advances in carbon emissions reduction: Policies, technologies, monitoring, assessment and modeling. *Journal of Cleaner Production* 103: 1–12.

ISO 14064-1:2012 (2012) *Greenhouse Gases – Part 1: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals*.

Kunić R (2017) Carbon footprint of thermal insulation materials in building envelopes. *Energy Efficiency* 10(6): 1511–1528.

Lawrence M (2015) Reducing the environmental impact of construction by using renewable materials. *Journal of Renewable Materials* 3(3): 163–174.

Lehmann S (2013) Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions. *Sustainable Cities and Society* 6: 57–67.

Lu Y and Yang G (2013) *Chinese Vernacular Dwellings*. Guangzhou: South China University of Technology Press.

Luo Z (2016) *Study on calculation method of building life cycle CO₂ emission and emission reduction strategies*. PhD Thesis, Xi’an University of Architecture and Technology, China.

Luo Z, Yang L and Liu J (2016) Embodied carbon emissions of office building: A case study of China’s 78 office buildings. *Building and Environment* 95: 365–371.

MOHURD GB50176-2016 (2016) Code for thermal design of civil building.

Peng C (2016) Calculation of a building’s life cycle carbon emissions based on Ecotect and building information modeling. *Journal of Cleaner Production* 112: 453–465.

Peters GP, Marland G, Le Quéré C, et al. (2012) Rapid growth in CO₂ emissions after the 2008–2009 global financial crisis. *Nature Climate Change* 2(1): 2–4.

Qiang T, Yu D, Zhang A, et al. (2014) Life cycle assessment on polylactide-based wood plastic composites toughened with polyhydroxyalkanoates. *Journal of Cleaner Production* 66: 139–145.

Rogers JG, Cooper SJG, O’Grady A, et al. (2015) The 20% house – An integrated assessment of options for reducing net carbon emissions from existing UK houses. *Applied Energy* 138: 108–120.

Salazar J and Meil J (2009) Prospects for carbon-neutral housing: The influence of greater wood use on the carbon footprint of a single-family residence. *Journal of Cleaner Production* 17(17): 1563–1571.

Sandanayake M, Lokuge W, Zhang G, et al. (2018) Greenhouse gas emissions during timber and concrete building construction – A scenario based comparative case study. *Sustainable Cities and Society* 38: 91–97.

Sandanayake M, Zhang G and Setunge S (2016) Environmental emissions at foundation construction stage of buildings – Two case studies. *Building and Environment* 95: 189–198.

Shea A, Wall K and Walker P (2013) Evaluation of the thermal performance of an innovative prefabricated natural plant fibre building system. *Building Services Engineering Research and Technology* 34(4): 369–380.

Sierra-Pérez J, García-Pérez S, Blanc S, et al. (2018) The use of forest-based materials for the efficient energy of cities: Environmental and economic implications of cork as insulation material. *Sustainable Cities and Society* 37: 628–636.

Sterner T (2007) Fuel taxes: An important instrument for climate policy. *Energy Policy* 35(6): 3194–3202.

Stocchero A, Seadon JK, Falshaw R, et al. (2017) Urban equilibrium for sustainable cities and the contribution of timber buildings to balance urban carbon emissions: A New Zealand case study. *Journal of Cleaner Production* 143: 1001–1010.

THUBREC (2016) *2016 Annual Report on China Building Energy Efficiency*. Beijing: China Architecture & Building Press.

Wang J, Wu H, Duan H, et al. (2018) Combining life cycle assessment and building information modelling to account for carbon emission of building demolition waste: A case study. *Journal of Cleaner Production* 172: 3154–3166.
WBCSD (World Business Council for Sustainable Development) (2008) Energy efficiency in buildings: Facts and trends. Available at: http://www.wbcsd.org/pages/edocument/edocumentdetails.aspx?id=13559 (accessed 5 August 2013).

Yu D, Tan H and Ruan Y (2011) A future bamboo-structure residential building prototype in China: Life cycle assessment of energy use and carbon emission. *Energy and Buildings* 43(10): 2638–2646.

Zhai L (2010) *Study of building adaptability and technology of dwelling in north-western China*. MPH Thesis, Xi’an University of Architecture and Technology, China (in Chinese).

Zhang X and Wang F (2016) Assessment of embodied carbon emissions for building construction in China: Comparative case studies using alternative methods. *Energy and Buildings* 130: 330–340.

Zhen M and Zhang B (2018) Energy performance of a light wood-timber structured house in the severely cold region of China. *Sustainability* 10(5): 1501.