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Solar Energy Block-Based Residential Construction for Rural Areas in the West of China

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Abstract: Based on the Great Western Development Strategy and the requirement for sustainable development in the west of China, rural affordable housing, energy conservation, and environmental protection are becoming development standards in the construction field. This paper mainly explores an innovative, sustainable, residential construction method for rural areas in western China, particularly the integration of solar energy technology with modern prefabricated building techniques, formally named solar energy block-based construction. The conscious approach of using volumetric blocks provides superior adaptability and expansibility in integration with a steel structure, thereby reducing the construction time and cost. Allowing a wide variety of configurations and styles in the building layout, this approach can be customized to the end-user's precise location and climate, making rural residential buildings much more flexible and modern. To take advantage of adequate solar energy resource in western China, the blocks are associated with active and passive solar energy technologies, thereby reducing pollution, mitigating global warming, and enhancing sustainability. Therefore, we concluded that solar energy block-based construction could bring significant benefits to the environment, economy, and society. It could also promote sustainable development in the rural regions of western China.

Keywords: block-based construction; solar power; prefabrication; rural housing; sustainable development

1. Introduction

1.1. Research Background

Although China's urban development is moving forward in western regions, there is still an economic gap between the western and eastern regions of China [1], which began with the economic reforms in 1978 and has now reached its highest point. Under the Great Western Development Strategy (GWDS), aimed at boosting the development of the western regions of China and narrowing the gap [2], the Chinese government has been providing increasing financial support and directing investment to western regions, which are expected to benefit from further economic reforms and urbanization [3]. The western region contains 71.4% of mainland China's area, but only 27.04% of its population, and rural population accounts for about 79.21% of the total in the western part of China, as of the end of 2012 [4]. Based on the huge rural population in the west, economic benefits, housing affordability, and energy consumption are the three paramount factors shaping rural development. While the standard of rural living has improved in the western regions, one consequence of urbanization has been a growing demand for the sustainable development of the construction industry [2].

It is widely accepted that China will face a severe shortage of resources during future urbanization [5]. Economic and industrial growth have been accompanied by a growing pressure on

natural resources and environment, which will dominate the developmental difficulties and challenges in the long term. Atmospheric pollution, which was gradually shifting from urban to rural areas [6], is the most pressing of all environmental issues in China. Controlling air pollution is the main task of the forthcoming environmental governance in the western regions of China.

Residents who live in rural areas of China have relied on various fossil fuels for household energy consumption, such as coal and natural gas for cooking and heating. The current situation of domestic energy supply for the residents in rural areas is non-renewable and non-clean resources. More sustainable and green energy supplies, aside from fossil fuels [7], are required to apply to residential construction in response to environmental issues.

There is now a general consensus that it is necessary to apply renewable energy such as solar energy to the residential buildings in rural areas of China. In the west, solar energy has become the center of attention not only by virtue of being clean, safe, and permanent, but also for its abundance. It is calculated that the total solar radiant energy available to the western territory surface would be 9250~5000 MJ/($m^2 \cdot a$), and more important, it can be conveniently and efficiently utilized in the construction industry [8]. Nevertheless, despite these potential benefits of solar energy, the successful and efficient application of solar energy in the construction industry is yet to be realized in western China due to its high cost and the enduring popularity of traditional methods, even though solar energy has been comparatively extensively developed in other industries [9].

1.2. Research Issues

Pushing forward the GWDS, between now and 2020, China needs to encourage more than 100 million residents with a median or low household income in central and western regions to settle down in rural communities and villages near small towns [10]. Therefore, the lack of affordable rural housing continues to be one of the most critical issues facing rural communities in the west. In order to address these problems, accelerating the development of rural housing and innovating construction methods adapted to the western region of China has become a pressing task for architects and civil engineers.

As the significant factor related to environmental damage, traditional building construction wastes a large amount of resources and produces massive dust pollution and building waste. Rural construction should take atmospheric pollution into account by prioritizing clean and renewable energy. In this paper, sustainable residential construction will be explored in terms of energy saving, environmental protection, and comfortable rural living, avoiding the waste of resources and environmental destruction.

1.3. Scope and Objective

Founded on the above discussion, the objective of this research is to explore a sustainable residential construction that reflects the "sustainability" of environmental health, economic viability, and social equity in the development of rural areas in the western regions of China. The aims of the research are to dissect the principles and approaches of innovative solar energy block-based construction to guide residential development in rural areas and to describe the sustainable construction and industrialization technologies used to realize an efficient, low-priced, flexible, non-polluting, and environmentally friendly residential building. As a result, this paper concludes with two schemes for a rural residential building formed of various sets of blocks. We aim to prove their reliability for future practice and improve the welfare and livelihoods of people residing in rural areas.

2. Trends of Rural Residence

Planning and design, together with the resource protection and social structure of buildings and users' needs, impose special limits and requirements on residential building development in rural areas. Rural residential construction is considerably different from metropolitan buildings in China.

It is essential that the trend of rural residence in West China lead to innovative developments in construction methods.

2.1. Resource Conservation and Environmental Friendliness

The energy consumption of rural residential buildings was responsible for more than 65% of total building energy use in China [11]. Especially in the rural areas of the west of China, the economy is underdeveloped and traditional biomass is the dominant fuel used for daily life, representing more than three quarters of rural building energy use in 2005 [12]. In addition, heating and cooking fuel relies mainly on wood and crop straw, which contain low thermal efficiency and release an enormous amount of harmful fog. These are also conducive to serious air pollution and natural resource waste. As the use of energy in rural area converts from traditional biomass to more conventional fossil energy, such as coal and natural gas, the environmental impacts have grown. Therefore, concentrating on rural residential energy saving has great practical significance.

Greenhouse gases and choking smog from fossil fuel combustion emissions have become the foremost factors driving global climate change [13], along with world population growth and the rapid development of the industrial economy. Severe environmental issues including air pollution and resource consumption, which are particularly serious in contemporary China, have become major concerns. The construction of rural residences should be conducive to the sustainable development of rural areas and environmentally friendly.

Taking advantage of renewable energy to enhance the recycle of resources is also paramount for economic and social development. Building a sustainable energy system based on renewable energy has become a crucial way to resolve the problems of energy shortage and environmental safety. Solar energy, which has the advantages of wide distribution, *in situ* acquisition, zero transportation, and less impact on the environment, has been internationally recognized as one of the most competitive new energies of the future. Solar energy is a renewable and clean energy that can be transformed into electric power by means of solar panels that store sun rays. The rich solar energy resources in West China provide a wide application prospect. For all these reasons, it is obligatory to apply solar energy to these rural residential buildings in order to realize sustainable development in the future.

Furthermore, a majority of residential buildings in the western rural areas are made of clay solid brick walls and single-pane glass windows, which increases the energy consumption for thermal insulation and wastes cultivated land resource. Construction waste containing lead, asbestos, or other hazardous substances can be as high as 10% to 15% of the materials and poses an enormous threat to the natural environment [14].

As incomes and living standards grow, rural families demand higher quality housing and lower energy consumption in each home. Therefore, it is necessary to explore more sustainable residential construction methods that include energy efficiency, resource conservation, and environmentally responsible strategies s far as possible, meeting seasonally varying energy needs.

2.2. Short Time and Low Cost

Western China's rapidly growing population is living in rural villages and towns, where most residential construction is inefficient and costly, and many struggle to provide basic living needs. The feature and style of rural residential buildings vary from place to place in the west, but these are simple structures with limited consideration of the time and expenses required during construction and end use [15]. Since considerable variability exists, there is an excellent opportunity to reduce the time and cost.

The construction time of rural buildings should be minimized. Traditional residential construction in western China wasted a lot of time and effort in handling materials jointing, finishing, and the technology of construction. Additionally, the traditional construction industry has used a delivery system in which all the fragmented materials are delivered from the different suppliers' facilities or warehouses to the construction site [16]. The novelty of the problems generated by urbanization

and technological advances in all processes of construction seems to shorten the work schedule and save time [17]. For single-family or small multi-family houses, construction and interior finishing are expected to be as fast as possible. In view of this situation, in contrast to traditional residential housing forms and practices, the industrialization of the construction industry offers the possibility of accelerating the construction on-site for rural areas.

The construction cost of rural buildings should be controlled. The western regions of China are currently remote and undeveloped areas and the high cost residential construction is too much for locals, especially in rural areas where most local people have medium and lower incomes. On the other hand, in recent decades, the rise in labor costs has threatened the survival of the construction industry [18]. To speed up the urbanization process in the west of China and realize the industrialization of residential construction, costs should be adapted to the regional economic level [19], which would be accepted by the local people generally.

2.3. Diversified Social Structures

Social structure is identified as the patterned social arrangements and relations between different social groups that are emergent from and determinant of the actions of the individuals [20]. The notion of urbanization as the relationship between people and buildings emphasizes the concept that the supply of housing depends on the social structure and related family composition, with different functions, meanings, or purposes. Rural housing needs to be synchronized with the demands of family structure, mode of production, and quality of life, which are constantly changing.

The family structure in the western areas of China has become more and more diverse over time [21,22]. In addition, increased commercial activity produced a high degree of rural family structure ambiguity, especially in western areas, where rural economic growth is fastest.

Overall, changes in family structure not only reflect local social, economic, and cultural changes, but also push forward new demands on rural residential construction. In other words, small-scale family structure means miniaturization of functional space, and diversity of family structure means diversification of functional space. Consequently, one substantial trend of rural residential construction in western China is adaptability, expansibility, and flexibility.

2.4. Traditional Green Building Features

There is a more harmonious relationship between environment and habitat in traditional domestic dwellings than is the case with architecture in Western countries. Traditional residential architecture in western China is characterized by an extreme diversity in forms, techniques, knowledge, and skills in dealing with materials, jointing, finishing, and the technology of construction. The construction tradition is a reflection of the western region's physical, social, and cultural environment, and history. Therefore, it is agreed that indigenous green building technology and recycling materials in the western rural context should be conservative, rooted in deep traditions. Innovative rural construction should derive from rural traditions that directly relate to the local economy and way of life of the people who use them.

3. Features of Solar Energy Block-Based Construction Method

Through the analysis above, to achieve development in western China, a greener, low-cost, and high expansibility architectural concept has become the best choice in rural areas. Innovative construction methods can realize the industrialized production of a block-based construction that can be assembled flexibly to satisfy the different needs of local families. Furthermore, green building technologies such as solar energy, rainwater collection, and recycled building materials have been applied to this block-based construction. It shows great promise in terms of the development of environmental protection and sustainable methods in the rural areas of western China.

3.1. Block-Based Construction

As a sustainable construction method, block-based construction is increasingly being adopted to enhance productivity and alleviate the adverse environmental and social effects of conventional construction activities. In recent decades, the construction technology of steel structures has undergone rapid development in China [23], with steel-framed block structures being adopted into sustainable construction due to the technology maturing and the cost dropping.

Essentially, block-based construction can be subsumed under prefabrication—that is, a manufacturing process that takes place in a specialized facility where various materials are joined together to form a component of the final installation procedure. However, unlike conventional prefabricated construction, which only includes sub-assembled components such as roof trusses, each block of the block-based construction is a complete and individual volumetric unit; this is called block manufacturing or pre-assembly. These blocks, supplied with a set of pipelines and equipment, are always made inside a factory and not considered for on-site production [24]. There is a general consensus that this steel block-based construction method has many inherent superiorities and advantages for local people in rural areas.

First of all, adopting the pre-assembly and prefabrication, the block-based steel construction can greatly shorten the construction cycle and cost, which is beneficial for the environment and people with lower incomes. Compared with traditional on-site residential construction, off-site construction cannot be disturbed by external factors, such as the weather and shipment, during the construction process. Previous research into prefabricated construction indicated that factory production can reduce 83% of construction waste, and 50% or more of the energy consumption [23]. The volumetric blocks are in the factory manufacturing cycle for one to two weeks and only one or two days in the construction site; by contrast, the traditional method of rural residential construction takes at least one year or longer to complete.

Secondly, the sustainable construction method of integration, intensification, and industrialization can achieve an efficient construction process and improve building quality and safety. The steel-framed structure widely used for industrial and civil construction is tougher and more durable than concrete and brick fabric, and has good earthquake resistance and pressure resistance [25]. These functional steel blocks can be controlled and inspected by sophisticated technologies during the production process before being transported to the construction site.

Last but not least, the steel blocks can be freely adjusted and assembled into different forms of houses, allowing a wide variety of configurations and styles in the building layout. Since these assembled dwellings are built in parts, it is convenient for a homeowner to add additional rooms or spaces. This means it is possible to match the diversification of the rural family structure in rural areas of western China. High adaptability, expansibility, and flexibility of block-based construction provide an outstanding opportunity to achieve individual character.

In general, as a sustainable modern construction technology replacing conventional concrete construction, high quality frame blocks save construction time, reduce resources consumption, and satisfy different individual families' demands for building functions. Consequently, block-based construction should spread widely in rural areas.

3.2. Blocks with Solar Energy Technology

In 2011, the International Energy Agency announced that "the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits" [26]. To take advantage of the rich solar energy resources in West China, special blocks equipped with solar energy technology are introduced into the system of block-based construction. The blocks use a range of ever-evolving technologies including solar heating, photovoltaic, and solar thermal energy.

Solar energy is a significant renewable and green source that is broadly characterized as either passive or active depending on the way energy is captured and distributed or converted into solar power [27]. The steel block-based construction combines both passive and active technologies

to moderate the cost, reduce pollution, mitigate global warming, and enhance sustainability, through reliance on an indigenous, inexhaustible, and mostly import-independent energy resource. These benefits and outcomes are universal.

3.3. Integration of Green Technologies

China is facing serious environmental problems and the residential building sector has been required to improve future sustainable development through the integration of a variety of green technologies. These not only include energy efficiency, but also reducing the cost of utility services and maintenance by using recycled building materials and rainwater harvesting.

"Appropriate building elements and materials, which should be durable, sustainable, and easy to maintain, are a significant step of excellent sustainable architectural design" [28]. The choice of residential building material should adjust measures to local conditions, bringing into full play the advantages of limited resources. Straw insulation layer, a rich green material in rural areas, is added to the prefabricated thermal insulation walls of the block enclosure, and has satisfactory insulation properties. The surface of the prefabricated wall is made of environmentally friendly gypsum board, which is light weight, provides insulation, and requires low energy consumption. It is necessary to make use of regional recycled and green materials as much as possible to provide excellent insulation for residences.

Rainwater harvesting technology refers to the accumulation and deposition of rainwater for the purpose of reusing on site, which will provide an independent water supply resolving the shortage of water resources in the western regions of China. Taking the impounding planting roof block with rainwater collection and purification system as an example, a block with a rainwater "collection-purification-reuse" system is installed in the factory. The treated rainwater is stored in a water tank, which is built on the foundation block, and can be reused for gardens, livestock, irrigation, and domestic use. Application of rainwater harvesting in the block-based construction system provides a substantial benefit and sustainable outcomes for both water supply and wastewater subsystems by relieving the pressure of clean water distribution [29].

4. A Long-Term Perspective on Sustainability

Sustainability, as the organizing principle of future development, has many different meanings [30]. In this research related to rural construction, sustainability consists of balancing individual human rights and needs with care for the natural environment [31]. Application of solar energy through a block-based construction method will in the long term promote economic value, neutral environmental impact, human satisfaction, and social equity, thereby achieving the goal of sustainability.

4.1. Whole Lifecycle

The destruction of ecosystems and biophysical resources derives from a series of processes that are initiated by human consumption. This solar energy block-based residential construction method reduces the demand for resources and takes full advantage of renewable resources to bring benefits during its whole lifecycle, including design, construction, operations, and maintenance.

This solar energy block-based residential construction method adheres to the principles of sustainable development, which combines the concepts of environmental protection and resource reservation into an innovative architectural methodology. Paradigms such as high compatibility (symbiotic with design of ecological compensation and ecological adaptation), flexibility and adaptability, reusability, easy upgrade, easy maintenance, and recycling reduce negative human impact and enhance ecosystem services, not only for the construction process but also for the building's whole lifecycle.

4.2. Housing Affordability

Housing affordability is housing deemed affordable to those with a low or median household income. The housing market in rural areas is expanding rapidly, but the lack of affordable housing for low-income families is becoming increasingly prominent. Furthermore, with rising energy costs, affordability of housing is not just dependent on the housing expenditure, but also on the energy expenditure. Accordingly, in western China, the challenge for sustainability is to curb and manage high consumption while reducing the housing expenditure.

Innovative residential construction makes a significant contribution to socioeconomic stability by using industrialization, block strategies, and green technology. On a large scale, promoting the development of the construction industry can promote an economic restructuring in western China. On the small scale, the block is a lower expense including lifecycle cost, manufacture cost, transportation cost, storage cost, *etc.*, so will be practical given the low regional income level. Therefore, the solar energy block-based residential construction method can provide affordable rural residences in the west of China.

4.3. Social Acceptance

As new technologies develop, a primary concern is how the public is going to respond to these innovative applications. Following the sustainable development movement, households' attitudes to sustainable rural living and self-sufficiency, particularly of energy supply, have changed dramatically over the past decade or so. The industrialization method of construction also meets social challenges in that it encompasses urban planning and architecture, local and individual lifestyles, ethical consumerism, and moving towards sustainability.

The solar energy block-based residential construction method provides an opportunity to close the social gap of human wellbeing between the western regions and eastern regions. Moreover, block-based construction has great flexibility to meet the different demands of the rural family structure, which can strengthen relationships and facilitate communication between neighborhoods. The new sustainable residential construction method reduces the individual and collective impact on the environment in favor of a harmonious society through small, inexpensive, and easily achievable steps. There is increasing social recognition of the affordability and environmental benefits of energy-saving construction.

4.4. SWOT Analysis

As an effective and simple planning technique, the SWOT (Strength, Weakness, Opportunity, Threat) analysis method addresses the strategic planning processes that can enable urban development and housing strategy professionals to participate more fully in construction industry improvement [32]. The SWOT approach analyzes strengths, weaknesses, and opportunities as well as threats related to the developmental adaptability of the solar energy block-based construction in rural areas of western China, offering a theoretical basis for this innovative housing strategy. Consequently, these factors can be comprehensively applied in practice by giving full play to the strengths, curbing the weaknesses, seizing the opportunities, and eliminating the threats.

In essence, factors influencing the developmental adaptability of the solar energy block-based construction in western China include both internal influence and external influence [33]. The internal influence refers to the strengths and weaknesses, which are subjective factors that occur during the development of the new sustainable residential construction method. The external impact refers to the opportunities factor and the threats, which are objective factors that influence the development directly (Table 1).

Table 1. SWOT analysis.

Strengths	S1. Industrial production can promote urbanization S2. Solar energy block makes full use of solar energy resource in west China S3. Potential environmental and economic benefits S4. Flexible combination and collocation of blocks adapt to various family structures in rural areas
Weaknesses	W1. High requirements of technique in construction W2. High cost of the solar energy and green technology equipment W3. Uncertainty of the planning and forecasting
Opportunities	O1. Opportunity of development policy for western China, such as GWDS O2. Opportunity for environmental policies O3. Demand to improve living standards for rural residents
Threats	T1. Local governments may lack a rural area's planning T2. Number of local residences to support T3. Competition in the construction market

5. Proposed Solar Energy Block-Based Construction

5.1. System of Block-Based Construction

The proposed block-based construction system is a collection of interacting or interdependent prefabricated volumetric units called modular blocks, forming an integrated whole. Based on the different properties and technologies, there are three main categories of blocks including the solar energy category, the green technology category, and the standard category, in which each of them contains several special purpose-built blocks (Table 2).

Table 2. The system of solar energy block-based construction.

Category	Name of block		Introduction
Solar energy category	Passive solar energy	Greenhouse block	Passively moving heat from the greenhouse block out to the living space by natural convection.
		Solar chimney block	Converting solar radiation into usable heat, causing air movement for ventilating that improves the natural ventilation for the inner rooms.
	Active solar energy	Photovoltaic block	Converting solar energy into electric energy by using photoelectric effect, a compatible system for both grid-connected and off-grid.
		Solar heating block	The conversion of sun radiation into renewable energy for water heating through close-coupled devices of solar thermal collector and storage tank.
Green technology category	Impounding planting roof block		Rainwater collected, used, treated, and reused on-site for homeowners' garden and planting needs.
	Foundation block		The waste recycled materials are turned into a foundation block with underground built-in water tanks
Standard category	Kitchen block		With integral kitchen system
	Bathroom block		With integral bathroom system
	Staircase block		With prefabricated steps and railings; assembled freely into different stores
	Basic-room block		Can be assembled freely into rooms with different size (1800 mm × 3600 mm) with floor heating system

The solar energy category subdivides into the passive solar energy subcategory (greenhouse block, solar chimney block) and the active solar energy subcategory (photovoltaic block, solar heating block) with maturing solar energy facilities and technology on its sloping roof. According to the concepts of

energy efficiency, resource conservation, and environmental protection, sustainable technologies have been utilized in the green technology category, including installing a planting roof block that integrates the rainwater harvesting system and a foundation block that uses the waste recycled materials and installs the water tank underground. Standard blocks act as the basic living spaces and functions for the rural residence such as kitchen, bathroom, staircase, and living room. Each block in the system with a floor heating system matches the construction module of 1800 mm × 3600 mm and thus provides high adaptability, expansibility, and flexibility to assemble various types of rural houses, tailored to residents' wishes.

5.2. Solar Energy Categories

Compared with a traditional prefabricated building, the solar energy block is characterized as the dominant block in the new sustainable residential construction system. It takes full advantage of the regionally abundant solar energy resources and relates to the idea of environmental protection and utilization of renewable resources. The subcategory of passive solar block or active solar block depends on the different intent of design that the blocks capture and distribute solar energy or convert it into solar power.

5.2.1. Greenhouse Block

As a method of isolated solar gain, the greenhouse block incorporates a passive heat distribution system that can improve the thermal and acoustic insulating performance of a residential building. The size of block is 1800 mm × 3600 mm, following the construction modulus with a sloping roof that absorbs solar radiant light and heat more efficiently. All the factory-built components of the greenhouse block are prefabricated. The roof panel is comprised of an electric sun-shading shutter and a glazed ceiling. The main external envelope of the greenhouse block has glazed walls with a sun-shading shutter. In addition, the interior has a thermal mass wall with air vents that close or open to adjust the indoor temperature (Figure 1).

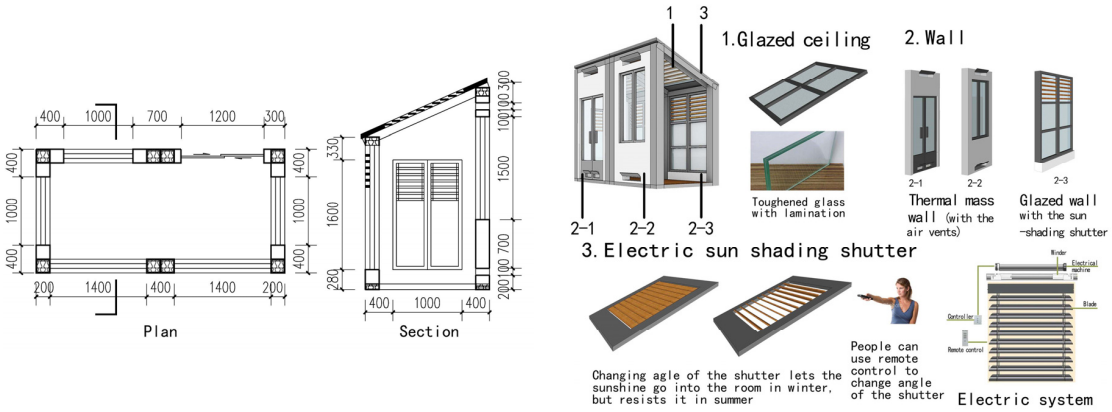


Figure 1. (**a**) Size of greenhouse block; (**b**) components of the greenhouse block.

The best recommendation for rural dwellings house in western regions of China is to place the greenhouse block facing solar path and the other living quarters on the opposite side. The working principle for generating passive solar energy involves utilizing solar energy to passively move heat from the greenhouse block out to the living space by natural convection. In particular, recirculating air flow resulted when the heated air rose and cooler air fell to create pressure differentials that automatically moved excess solar thermal gain without forced convection systems [34].

The passive solar system is essentially composed of an additional space within a living space. In winter, during the daytime, thermal energy is captured from a south-facing greenhouse block and

the heat is circulated by a natural convection flow loop in the cavity between the greenhouse block and the adjacent living block. By contrast, the greenhouse block can be identified as an outstanding insulation or buffer to reduce unwanted heat loss by closing the shading shutter and air vents at night. In summer, the covered electric sun shading devices retrofitted onto the block eliminate all direct solar gain in the daytime, and the down vents are opened to expel hot air by natural convection at night. (Figure 2) Therefore, the greenhouse block is important to achieve thermal comfort for occupants.

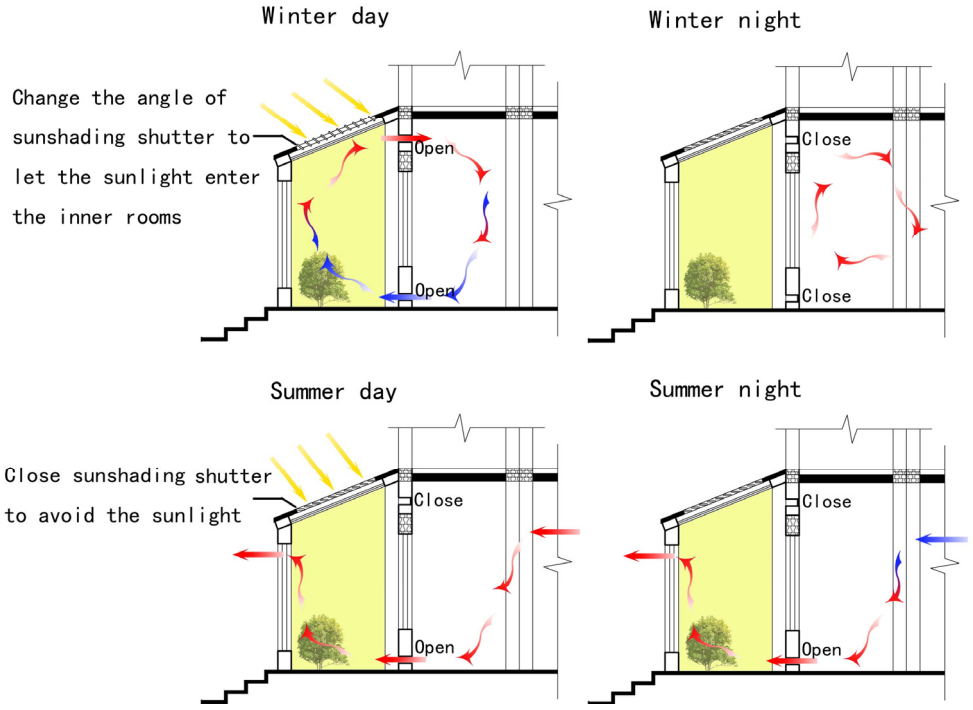


Figure 2. Work flow diagram of greenhouse block.

5.2.2. Solar Chimney Block

Solar chimney technology, a form of passive solar energy utilization, converts solar radiation into usable heat and then causes air movement for ventilating that improves the natural ventilation for the inner rooms. The solar chimney block with size of 3600 mm × 3600 mm is comprised of three key design elements: the solar collector area, the main ventilation shaft, and the inlet and outlet air apertures (Figure 3).

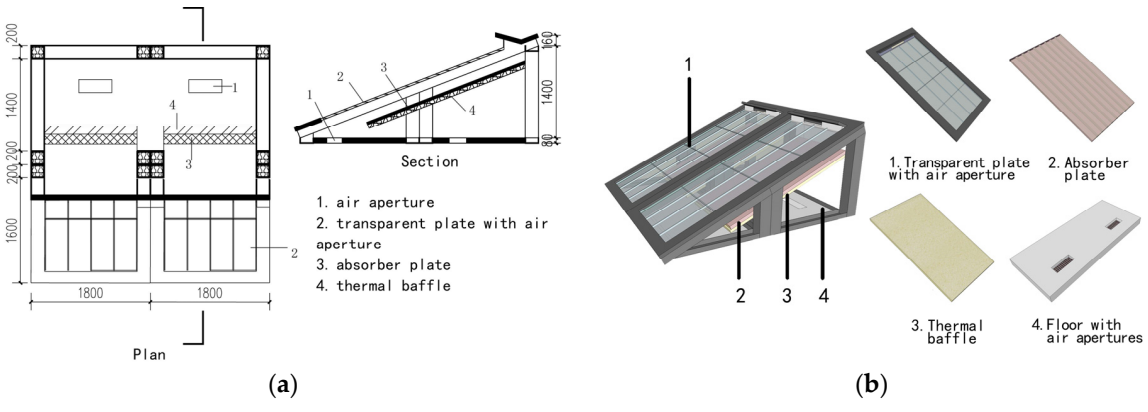


Figure 3. (**a**) Size of solar chimney block; (**b**) components of the chimney block.

The solar chimney block composed of a vertical shaft connecting the interior and exterior can produce a chimney effect to strengthen natural ventilation during summer by absorption of heat from the sun's radiation. Warming the solar collector area enclosed by both transparent glazing sloping roof and radiant ceiling panels, the air inside of the main ventilation shaft is heated, causing an updraft that pulls air through the living space, thereby completing the conversion from heat pressing to wind pressure. In winter, the solar chimney block may be converted into thermal insulation for the building by closing the air apertures (Figure 4).

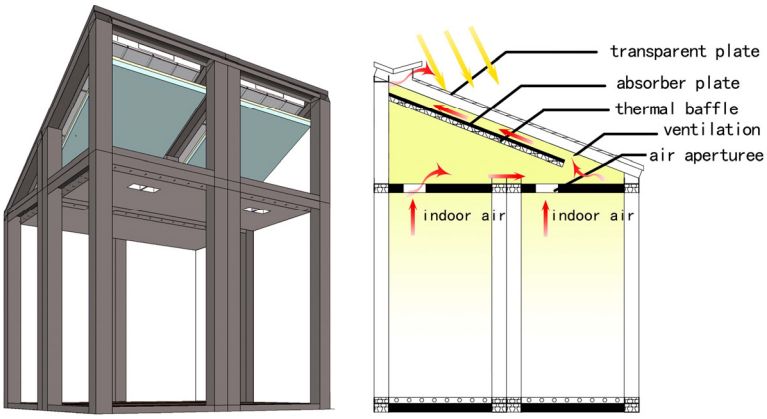
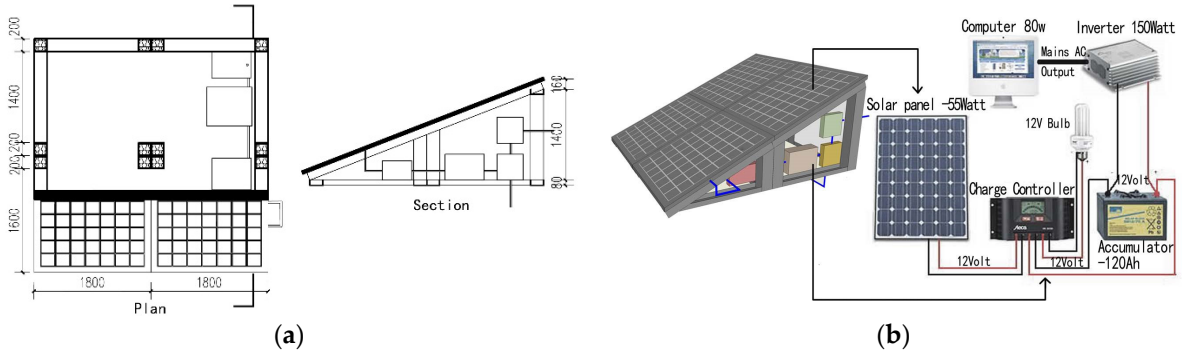


Figure 4. Chimney effect of the solar chimney block.

Thus, the solar chimney block used in solar energy block-based residential construction may benefit natural ventilation and passive cooling strategies of rural residential buildings and reduce air conditioning and mechanical ventilation use.

5.2.3. Photovoltaic Block

Active solar technology, unlike passive solar heating systems, involves the use of mechanical and electrical devices [35]. The photovoltaic block is a form of active solar energy utilization; using solar energy electro-optical technology, it can convert solar energy to electric energy through the photoelectric effect. The size of the block matches the construction modulus of 1800 mm × 3600 mm. The ensemble of photovoltaic block consists of several components, including roof-integrated solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from Direct Current (DC) to utility frequency Alternating Current (AC), and an accumulator to store excess power (Figure 5).



(**a**) (**b**)

Figure 5. (**a**) Size of photovoltaic block; (**b**) components of the solar cell block.

The roof-integrated photovoltaic system is retrofitted with solar panels as part of the roof structure without a mounting system since photovoltaic materials are used to replace conventional roof tiles. The advantage of a roof-integrated photovoltaic system over more conventional non-integrated systems is that reducing the amount spent on building materials and construction labor can offset the initial costs.

According to the results of an investigation [36], a roof-integrated photovoltaic block should have a slope of 35° and be directed south or east, based on the latitude of most western regions. The solar inverter, ensconced in the layer between the roof and the ceiling, is designed to be compatible with both grid-connected and off-grid residences, as the excess AC electricity can be fed into a commercial electrical grid or used by a local off-grid electrical network (Figure 6).

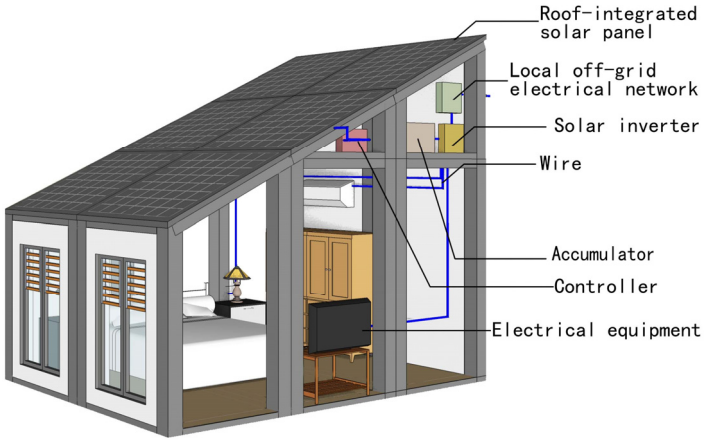


Figure 6. Power transfer of the photovoltaic block.

With the exponential growth of photovoltaic energy, the affordable price of photovoltaic blocks will provide low-income rural residences in the western regions of China with an excellent opportunity to utilize renewable and clean energy.

5.2.4. Solar Heating Block

The basic benefits of active solar energy technology are that controls of electrical devices can be used to maximize the effectiveness of the energy generation system and allow a greater variety of choices for utilizing the energy [37]. The action of a solar heating block is the conversion of sun radiation into renewable energy for water heating through close-coupled devices, a solar thermal collector and a storage tank. The size of the solar heating block is the same as the other standard block with the modulus of 1800 mm × 3600 mm (Figure 7).

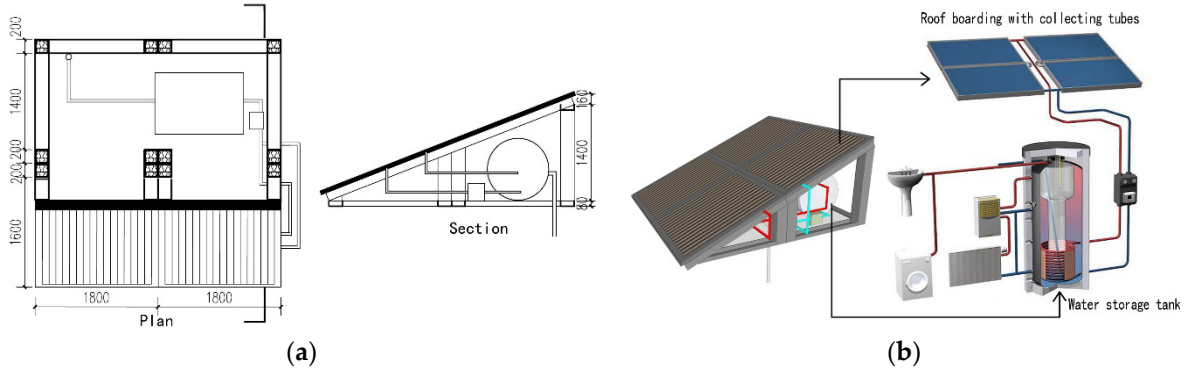


Figure 7. (**a**) Size of solar heating block; (**b**) components of the solar heating block.

The main devices, such as a storage tank, pipes, and a pump, are covered under the solar collector and the hot water circulates between the storage tank and the collectors. The collector is made of a simple glass-topped insulated box with a flat solar absorber made of sheet metal, attached to a set of copper tubes surrounded by an evacuated glass cylinder. The solar heating block can be connected with the bathroom block, the kitchen block, and the other blocks by circulating pipes (Figure 8), which provides hot water for cooking, washing, and bathing as well as a floor radiant heating system.

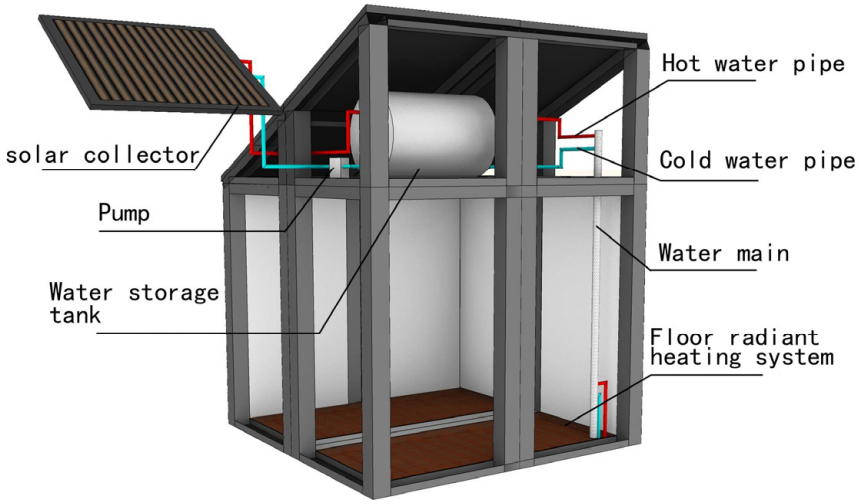


Figure 8. Work flow diagram of solar heating block.

With the progress of solar collection technology and sufficient solar resources, solar heating blocks can be considered an appropriate technology for the rural regions of western China and are used increasingly without a gas or electric booster.

5.3. Green Technology Categories

Aside from solar energy, other green building technologies are also applied to the block-based construction to curb the negative impacts of human construction. In this research, green building technology refers to both the construction and the end-use of buildings that are environmentally friendly and resource conservative throughout their entire lifecycle. The green technology category covers planting roof blocks and foundation blocks.

5.3.1. Planting Roof Blocks

According to the latest results of investigation and assessment, in western China, the current water resources situation involves both water quantity and quality issues, each of which present distinctive challenges for construction [38]. One critical issue of water consumption is that in rural areas of western China, the demands on the supply exceed the natural replenishing ability [39].

The planting roof block not only provides a garden for homeowners, but also increases dependence on water that is collected, used, treated, and reused on-site. The flat roof of the planting roof block is covered with a 15-cm growing medium and a waterproofing membrane for vegetation growth. Under the planting are additional layers including a root barrier and water collecting and irrigation systems (Figure 9).

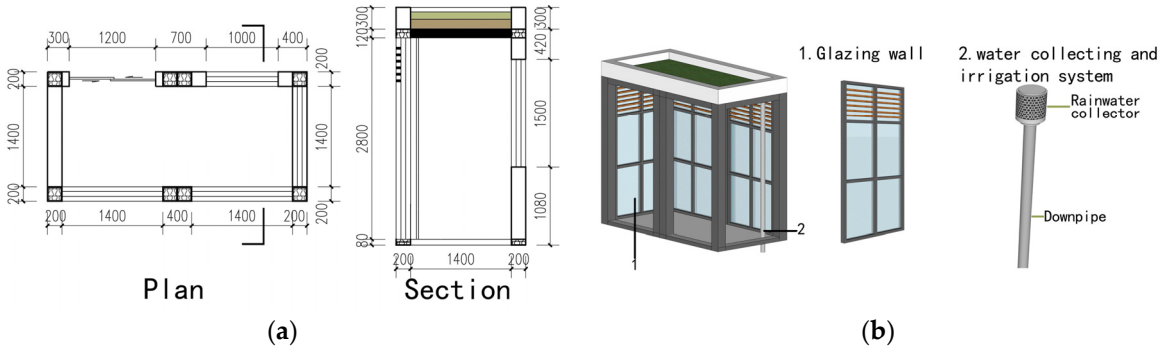


Figure 9. (**a**) Size of impounding planting roof block; (**b**) components of the impounding planting roof block.

The planting roof block works with other sloping roof blocks in combination with gutters and downpipes to capture rainwater and administer water runoff, so that the rooftop rainwater harvesting can supply the household with high-quality drinking water. In addition, the growing medium and plant roots also create a simple rainwater purification system to treat grey water called pre-filtration, and then store it in an underground water tank in the foundation block. Pre-filtration to ensure that the water entering the tank is free of large sediment means that the roughly purified water can be used for livestock, irrigation, car washing, and toilet flushing (Figure 10).

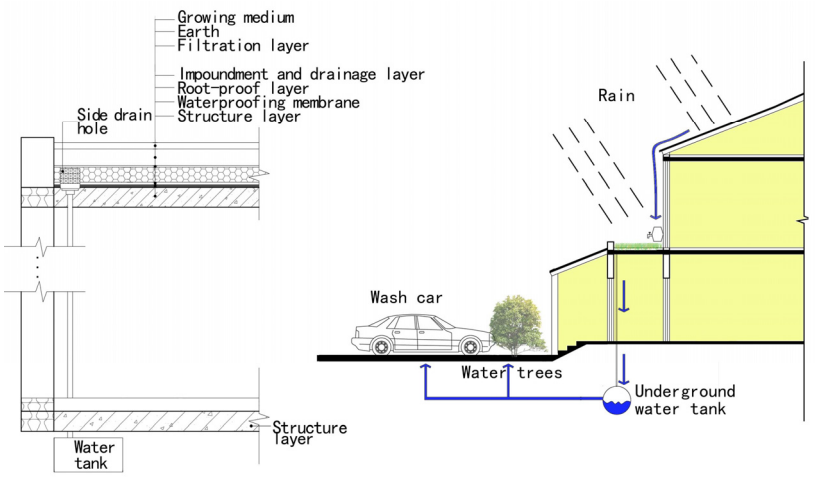


Figure 10. Workflow diagram of planting roof block.

Further uses of the planting roof block include collecting rainwater, treating grey water, providing insulation, protecting wildlife, and creating an aesthetically pleasing garden space. However, the most important function is responding to the lack of water resources in western China.

5.3.2. Foundation Block

Waste recycled materials make a foundation block with underground water tanks, which is the fundamental element of the block-based construction: it connects to the ground and transfers loads from the structure to the ground (Figure 11). At the bottom of the foundation, the soil contains blast furnace ash, which is a byproduct of steel and can be used as anti-freeze soil padding. To keep the above-ground living space comfortable, the foundation block with waterproofing membrane can prevent dampness from seeping through the subsoil. The underground water tank is maintained by adequate rain flow captured by an area of the above-ground block's large sloping roof.

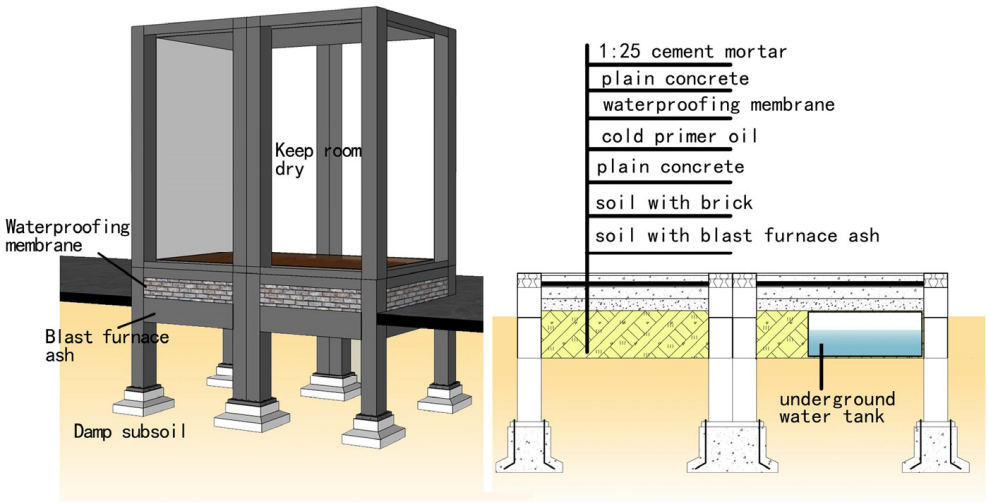


Figure 11. Foundation block.

Compared with conventional waste disposal, using recycled materials in construction prevents the waste of potentially useful materials and reduces the chances of them going to incineration or landfill, which result in air and water pollution. Using a floating draw-off water tank ensures that the water entering the underground tank is clean and keeps the rainwater harvesting system healthy.

5.4. Standard Categories

Standard blocks provide the basic living service facilities for the rural homeowners like kitchen, bathroom, staircase, and living room (Figure 12). The kitchen block with the integral kitchen system and the bathroom block with the integral bathroom system can both be connected with the solar heating block for domestic hot water and an under-floor radiant heating system. The staircase block with prefabricated steps and railings can be assembled with other blocks, providing multiple stories.

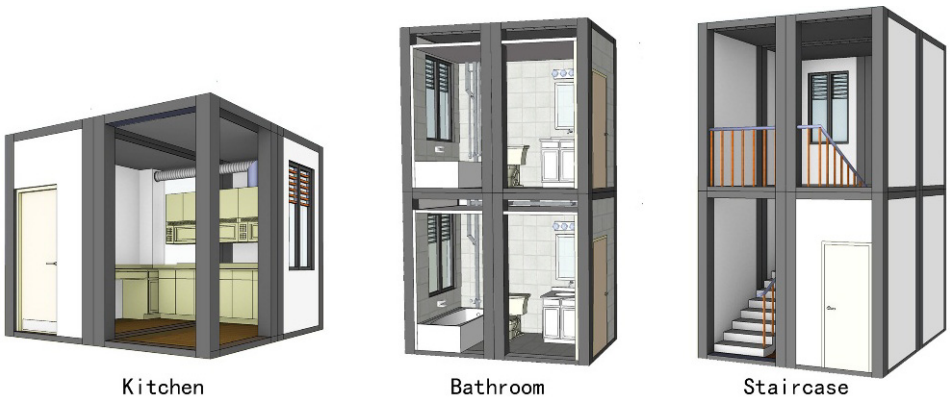


Figure 12. Standard blocks.

The basic room block can be assembled flexibly to create rooms with different sizes and functions. The construction modulus 1800 mm × 3600 mm of the basic block is convenient and seamless to connect with other blocks or itself. For instance, two basic blocks assembled with the size of 3600 mm × 3600 mm can be a study or dining room, and three basic blocks can be assembled as the living room or bedroom with a size of 3600 mm × 5400 mm (Figure 13).

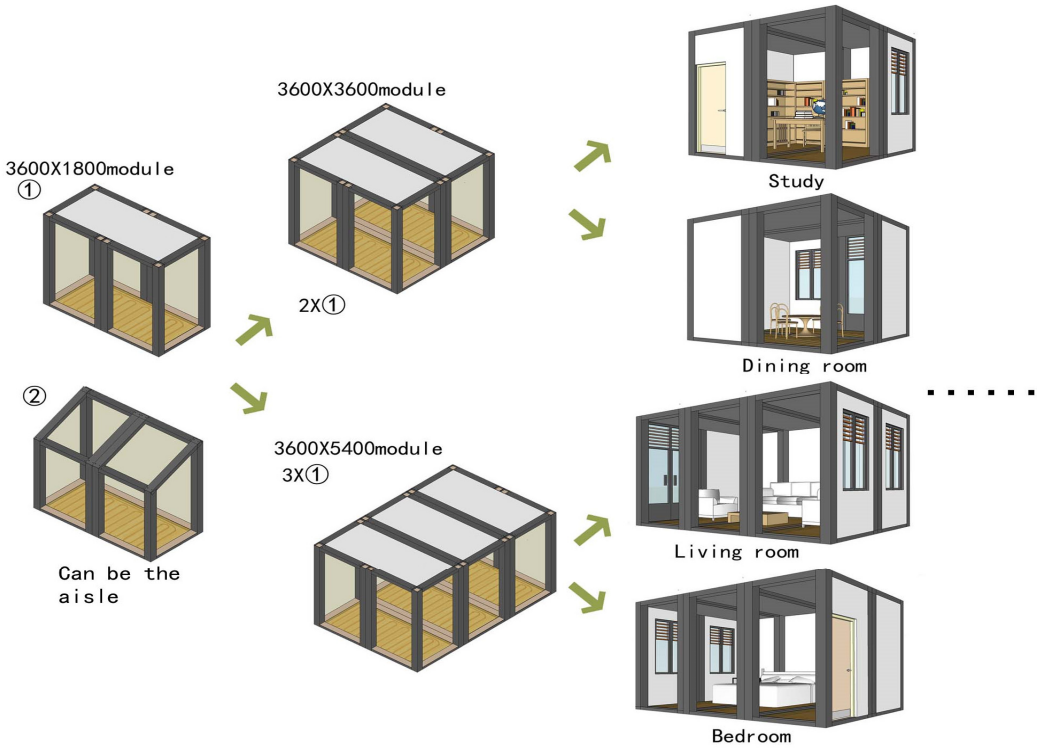


Figure 13. Assembled blocks.

6. Assembly and Prefabrication

In comparison with the more conventional construction practice of transporting all the fragmented materials such as bricks, timber, cement, sand, steel, *etc.* to the construction site, the solar energy block-based residential construction is the architectural practice of assembling individual volumetric units in a factory, and transporting complete individual blocks to the construction site where all assembly is carried out by crane and bolted in the shortest time possible. Accordingly, the process of block-based construction involves the design and manufacture of blocks, usually off-site, and installation on-site to form the permanent building.

6.1. Process of Prefabrication

Block-based construction in rural residential buildings is the assembling of prefabricated steel sections to form structures. Components are prefabricated in their entirety inside a huge, climate-controlled factory on assembly lines. The components of all blocks can be divided into two classes: construction components and device components. The construction components are used for the structure, enclosure, and finish of blocks, such as steel columns, steel beams, floors, insulation walls, and so on [40]. The device components that are used as the server and maintenance of the residential building include a photovoltaic panel, water heating collector, water tank, and so on.

Since there is a relatively abundant steel supply in western China, the block frame can be made of steel with qualities of high strength, good plasticity, and toughness. All of the prefabricated components attempt to use the energy, material, and water recycling system that is conducive to the sustainable development of rural areas [41] (Figure 14). Prefabricated components need to be assembled as the volumetric blocks in the factory. Welding between steel beams and steel columns with high strength and good toughness, which is helpful for earthquake resistance, can form the steel frame of the block. Thus, the basic block unit has built-in quality control.

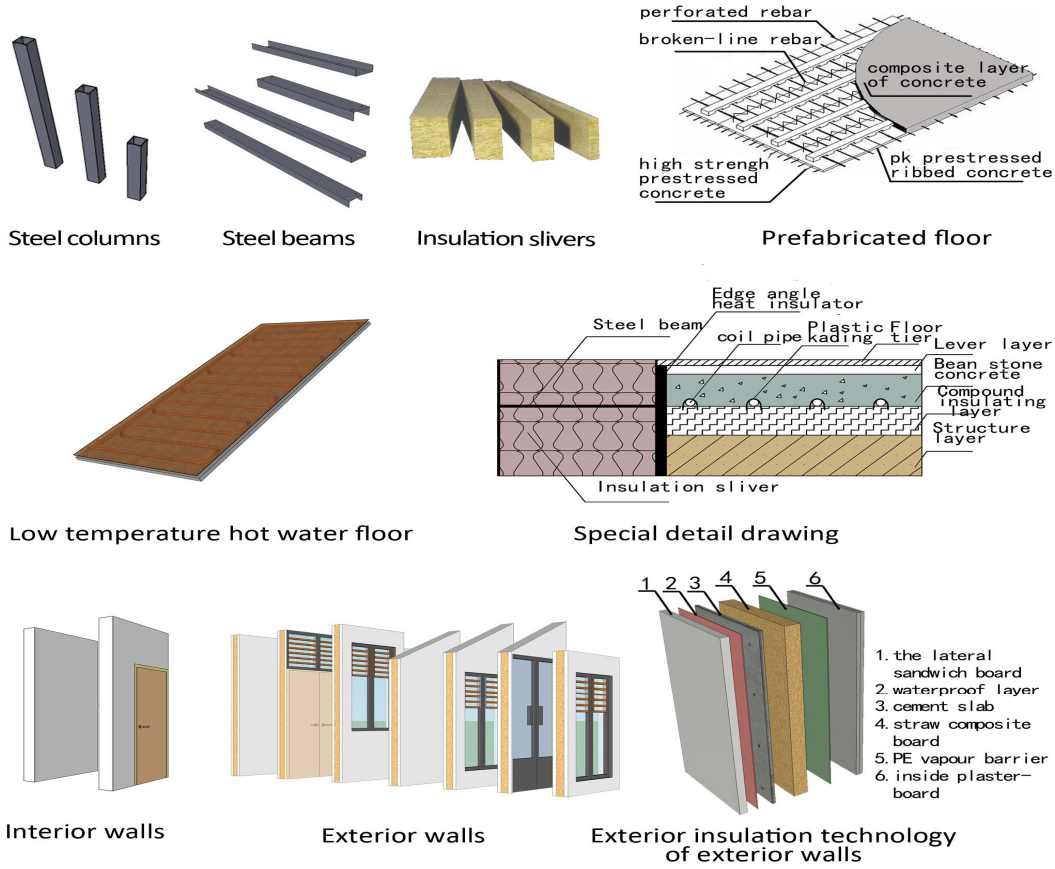


Figure 14. Prefabricated components.

Based on the basic steel frame, the device components mentioned above can be installed in the unit block. For example, the various mechanical and electrical devices of active solar technology are attached to the sloping roof block to form the solar energy block. In addition, the standard block, sanitary ware, kitchen utensils, appliances, water pipes, and wires are installed within the block in advance.

6.2. Options of Assembly

Completed prefabricated blocks are transported to the residential building site and assembled by a crane; the time needed for on-site assembly is several days or several weeks. Thanks to the easy connections and hermetic sealing [42], the entire process of the block-based construction at the site is efficient, fast, and pollution-free.

The block-based construction allows a wide variety of configurations and styles in the building layout depending on different family structures. Finished buildings are essentially indistinguishable from typical site-built structures. There are only two examples below:

Scheme one is a townhouse for the typical family of parents with one child or an older couple. The families can enjoy their own courtyard and have a peaceful life (Figure 15). It is assembled by:

- Solar energy category: 2 greenhouse blocks, 1 solar chimney block, 2 photovoltaic blocks, 2 solar heating blocks
- Green technology category: 1 planting roof block, 19 foundation blocks
- Standard category: 23 basic room blocks, 2 bathroom blocks, 1 kitchen block, 1 staircase block.

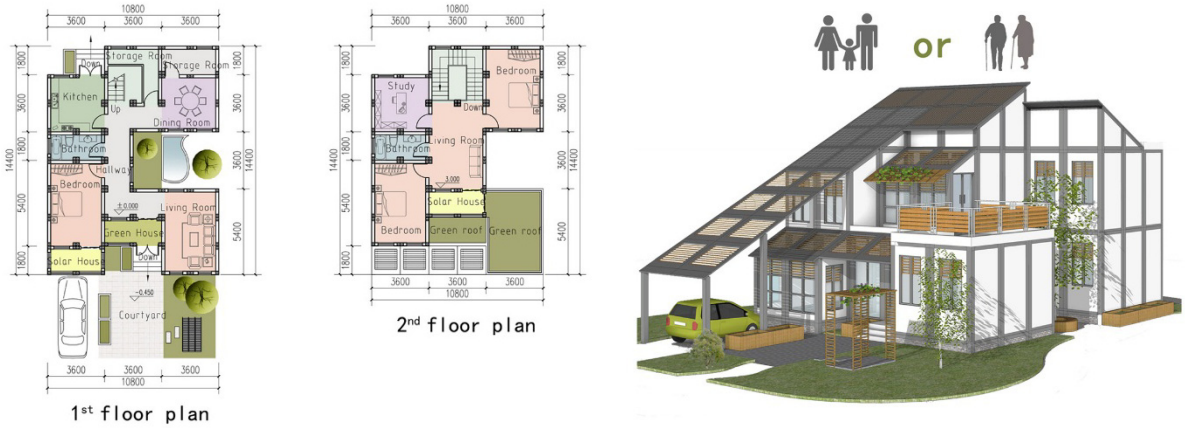


Figure 15. Scheme 1 of the solar energy block-based construction method.

Scheme two is a detached house with two shared courtyards and one shared balcony that it is suitable for three generations under one roof or two related families (Figure 16). The two families can share one courtyard. It is assembled from:

- Solar energy category: 1 greenhouse block, 4 solar chimney blocks, 2 photovoltaic blocks, 4 solar heating blocks
- Green technology category: 2 planting roof blocks, 33 foundation blocks
- Standard category: 41 basic room blocks, 4 bathroom blocks, 2 kitchen blocks, 2 staircase blocks.

Figure 16. Scheme 2 of the solar energy block-based construction method.

So the finite block types can be assembled into infinite residences to match the demands of different families in rural areas of western China.

7. Discussion and Conclusions

Environmental degradation, climate change, overconsumption, and population growth will increase pressures on anthropic activities and behaviors, especially in construction. For a long time, the traditional method of construction has not only wasted a huge amount of resources but also caused serious pollution and other environmental problems. The intention of sustainable architectural design and construction is to "eliminate the negative environmental impact completely through skillful, sensitive design" [43]. Rural residences, which are becoming increasingly popular in the architecture and construction industry in China, represent a significant opportunity for improved energy efficiency, reduced emissions, resource conservation, and improvement of local development.

The research mainly explored the innovative sustainable residential construction method, formally named solar energy block-based construction. It is the integration of solar energy technology with modern prefabricated building techniques. The conscious approach of using flexible blocks or modules provides high adaptability and expansibility, enhancing the rural architectural design concept. Allowing a wide variety of configurations and styles in the building layout means it can be customized to the end-user's specific location and climate, making rural residential buildings much more flexible and innovative than before.

Through reliance on an indigenous, inexhaustible, and mostly import-independent solar energy resource, block-based residential construction integrating passive and active technologies moderates costs, reduces resource consumption, mitigates global warming, promotes environmental responsibility, and enhances sustainability. In addition, s high-performance residential building is not just energy efficient, but also attractive, functional, water-efficient, and resilient to wind, seismic forces, and moisture penetration. Therefore, green building technologies, such as renewable materials and solar energy, are integrated and incorporated into the blocks, so as to achieve the outcomes of environmental friendliness, social equality, and economic growth.

It must be emphasized that the building construction method should comply with the trend of regional economic and social development. In essential, the block-based construction illustrated a housing strategy that will change the orientation of the housing process from construction to manufacturing to installation. There is now a general consensus that this relatively cheap and fast construction method is becoming popular in the rural regions of western China. Delivering well-designed and mass-produced buildings will become a mainstream concept. The block-based residential construction method provides an opportunity to meet this demand.

Nevertheless, innovative construction may have some limitations and problems; the aim of future work on block-based construction is to do further research on these points.

- Leaks can form at joints in prefabricated components or blocks. As prefabricated construction is becoming more popular in China, the weakness of the joints will be solved with the rapidly developing assembly and material technology.
- Transportation costs, initial cost of active solar energy, and green technology equipment cost may be higher for voluminous prefabricated sections than for the materials of which they are made. Correlational research will draw support from construction economics from the viewpoint of the building's lifecycle and public policy.
- Larger groups of buildings with the same type of prefabricated elements tend to look drab and monotonous. This problem involves the fields of architecture and urban design and may lead to new architectural styles or movements differentiating from modernism and futurism.

In brief, the solar energy block-based construction exhibits many of the inherent advantages of sustainable construction technology including, but not limited to, saved time and cost, reduced construction waste, improved quality control, conserved resources, increased adaptability, and flexibility; given these advantages, it will soon be widely spread in rural areas of western China.

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Abbreviations

GWDS	Great Western Development Strategy
SWOT	Strength, Weakness, Opportunity, Threat

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