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Review

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THE USE OF NEW TECHNOLOGIES IN THE CONSTRUCTION AND OPERATION OF PREFABRICATED BUILDINGS WITH ULTRA-LOW ENERGY CONSUMPTION

Abstract. This article provides a brief overview of new technologies developed for use in construction in cold regions of China. These technologies aim to significantly reduce environmental impacts, lower winter heating costs, and create comfortable living spaces during high summer temperatures. Chinese scientists have created ultra-low-energy buildings that are not connected to the central heating system. The following technical solutions are proposed for highly efficient heat conservation in residential spaces during the winter: a prefabricated building structure integrated with a solar heating system; the use of heat accumulators; and the development of a geothermal tunnel ventilation and heating system. To reduce indoor temperatures in the summer, the installation of sun protection systems, as well as thermally insulated roller blinds on doors, windows, and external walls, is proposed. These technological advances have been shown to significantly reduce building operating costs and carbon emissions. The implementation of this integrated technology in the construction of residential buildings in cold climates will enable the commissioning of heating systems without the need for public heating and will reduce carbon emissions over the entire life cycle.

Keywords: ultra-low energy prefabricated buildings, renewable energy, clean energy, district heating

Conflict of interest: the authors declare that there is no conflict of interest.

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ИСПОЛЬЗОВАНИЕ НОВЫХ ТЕХНОЛОГИЙ ПРИ СТРОИТЕЛЬСТВЕ И ЭКСПЛУАТАЦИИ СБОРНЫХ ЗДАНИЙ С УЛЬТРАНИЗКИМ ЭНЕРГОПОТРЕБЛЕНИЕМ

Аннотация. Выполнен краткий обзор новых технологий, разработанных для использования при строительстве в холодных районах Китая с целью значительного снижения вреда, наносимого экологии, а также уменьшения экономических затрат на оплату теплоснабжения в зимний период и создания комфортного температурного режима в жилых помещениях при высоких летних температурах. Китайскими учеными созданы здания со сверхнизким энергопотреблением, которые не подключены к системе центрального коммунального теплоснабжения. Для высокоэффективного сохранения тепла в жилых помещениях в зимний период предлагается применять следующие технические решения: сборная конструкция здания, интегрированная с системой солнечного отопления; использование теплоаккумуляторов; разработка геотермальной туннельной системы вентиляции и отопления. Для снижения температуры в помещениях в летний период предлагается установка солнцезащитных систем здания, а также систем теплоизоляционных рулонных штор на дверь, окна и наружные стены. Установлено, что использование данных технологических разработок приводит к значительному снижению эксплуатационной себестоимости зданий и количества углеродных выбросов. Внедрение комплексной технологии в строительство жилых зданий в холодных климатических условиях обеспечит введение в эксплуатацию отопительных систем без коммунального теплоснабжения и снизит углеродный выброс за полный жизненный цикл.

Ключевые слова: сборные здания с ультранизким энергопотреблением, возобновляемые источники энергии, экологически чистые источники энергии, централизованное отопление

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Introduction. Currently, great importance is placed on the development of technologies that conserve natural resources and minimize environmental impacts from industrial activities. These considerations are also taken into account when developing construction technologies.

In recent years, Chinese scientists have been actively developing construction technologies for the construction of ultra-low-energy prefabricated buildings in cold regions, with the goal of eliminating the need for centralized heating provided by municipal heating networks during the winter. To meet residents' needs for comfort, improve quality of life in cold regions, and reduce utility bills for energy consumption, the researchers propose using renewable energy sources.

The document "Plan for Implementing Carbon Peak in Urban and Rural Construction"[1] (abbreviated as "Feasible Project"), jointly adopted by the Ministry of Housing, Urban and Rural Development of China and the National Development and Reform Commission of China, emphasizes that in order to save energy resources and eliminate the use of municipal central heating, it is necessary to promote the construction of buildings with ultra-low energy consumption.

Drawing on innovative developments, patented achievements, and technical know-how, an innovative team from the Hongsheng Institute of Building Sciences in Heilongjiang Province has created a demonstration park of prefabricated, ultra-low-energy buildings, which are proposed for construction in cold regions. All buildings in the park eliminate the need for central heating from the municipal district heating network (the electricity cost for auxiliary heating with electric appliances in winter is approximately one-tenth of the cost of central heating from the municipal district heating network), and are equipped with air conditioning and refrigeration systems for the summer.

The China Society for Construction Engineering Standardization (CECS) has developed relevant industry and local standards (technical codes)[2] for the construction of ultra-low-energy prefabricated structures. These standards offer an effective solution to the challenges associated with long-term dependence on district heating in buildings in colder climates, which requires high and significant increases in energy consumption, leading to increased carbon emissions. Building operating costs and carbon emissions are significantly reduced by using ultra-low-energy building construction technologies that utilize highly efficient heat conservation methods and a prefabricated structure that can incorporate solar heating systems, heat storage units, low-cost clean-energy heating systems, geothermal ventilation and heating systems, building sun protection systems, and thermal-insulating roller blind systems for doors, windows, and exterior walls.

Setting tasks. To significantly reduce environmental impacts and lower heating costs, Chinese scientists have developed ultra-low-energy building designs that are not connected to the central district heating system.

The researchers' goal was to use a comprehensive "passive priority + active optimization + intelligent control" technology to create ultra-low-energy building construction technologies for highly efficient heat conservation. The design utilizes a solar heating system and heat accumulators; a low-cost, zero-emission heating system powered by renewable energy; a geothermal tunnel ventilation and heating system; sun protection systems and thermally insulated roller blind systems for doors, windows, and exterior walls. These buildings utilize heating in winter without the need for district heating, and cooling in summer without air conditioning, reducing operating costs and carbon emissions. This solution to the problem in extremely cold and frigid regions of China and, for example, in arctic climate zones, makes it possible to abandon the use of central municipal heating during the winter period.

Design features of ultra-low energy buildings. To address these challenges, the authors developed a number of design and engineering solutions.

For example, to ensure maximum sunlight duration and intensity, the building's orientation to the south or southwest should be 5–10°, and the distance between buildings should comply with the current national standard GB 50180–2018 "Urban Residential District Planning and Design Standard"[3], ensuring no light is blocked on the winter solstice. Furthermore, the building's shape should be straight, and the distance between two vertical walls should not exceed 12 meters.

Section 4.0.9 of GB 50180 sets out the solar insolation requirements for residential buildings (Table 1).

[1] 城乡建设领域碳达峰实施方案. URL: https://www.gov.cn/zhengce/zhengceku/202207/13/content_5700752.htm (date of access: 15.01.2025).

[2] 聚苯模块保温墙体应用技术规程. URL: https://www.gongbiaoku.com/book/5ez18337k1f (date of access: 15.01.2025) ; 模塑聚苯（EPS）模块外保温工程技术规程. URL: https://www.gongbiaoku.com/book/b0q19850k5n (date of access: 15.01.2025) ; 模塑聚苯模块混凝土剪力墙建筑技术规程 https://www.gongbiaoku.com/mobile/read/fyj19619rx4 (date of access: 15.01.2025) ; 装配式聚苯模块保温系统技术规程. URL: https://csrcare.com/Standard/Show?id=105010 (date of access: 15.01.2025) ; 聚苯模块外墙保温系统应用技术规程 URL: https://std.samr.gov.cn/db/search/stdDBDetailed?id=0EA8236BB0E67B5BE06397BE0A0A2001 (date of access: 15.01.2025) ; 聚苯模块保温系统技术规程 URL https://std.samr.gov.cn/db/search/stdDBDetailed?id=0EA8236BB0E67B5BE06397BE0A0A2001 (date of access: 15.01.2025).

[3] 城市居住区规划设计标准. URL: https://www.chinesestandard.net/PDF/BOOK.aspx/GB50180-2018 (date of access: 15.01.2025).

1. The solar insolation standard for residential buildings is no less than the solar insolation at 2:00 PM on the winter solstice.

2. Before constructing an addition to a building, it should be taken into account that this will not reduce the solar insolation of adjacent residential buildings. An exception is the installation of an external elevator.

3. The solar insolation duration for new residential buildings during the renovation of older areas should not be less than 1 hour during the Dahan season.

Table 1. **Solar insolation requirements for residential buildings (GB 50180–2018, Table 4.0.9)**

Parameter	The climate zone in which the construction is carried out				
	Climate zone I, II, III		Climate zone IV		Climate zone V, VI
Number of permanently residing population in cities, million people	> 50	< 50	> 50	< 50	Unlimited
Days characterizing insolation	January 19–21 (Dahan season, “Great Cold”)			December 21 (winter solstice)	
Duration of insolation, h	> 2	> 3		> 1	
Effective insolation range (true solar time)	from 8:00 a.m. to 4:00 p.m.			from 9:00 a.m. to 3:00 p.m.	
The beginning of insolation	From the lower level of the window sill*				

* The lower level for the window sill should be no less than 0.9 m.

These conditions are necessary to maximize solar energy gain and reduce the building’s heating load.

When designing detached buildings (particularly residential ones), certain conditions should also be taken into account. For example, the usable area of each building should be at least 80 m^2, so medium-sized and large apartments should be the primary focus. A vestibule should be placed at the entrance to each building, especially in colder areas, to create a buffer space between the outdoor and indoor spaces to conserve heat. At least one living room (at least 4.5 m wide) should be located on the sunny side of the house (on the southern side). Tile or stone, which have significant heat storage properties, is recommended for the flooring in the south-facing living room and bedroom. Flexible flooring can be used for the north-facing bedroom.

The design of a south-facing balcony must meet the following requirements:

a) the distance between the horizontal walls of the balcony must be equal to the width of the living room, with no dividing doors to ensure natural convection of cold and hot air, balance the room temperature, and improve indoor air quality;

b) the balcony overhang must be at least 1.6 m, which maximizes the area of light accumulation in the room;

c) the balcony skylight must be located at ceiling level to maximize sunlight penetration into the room and increase the illuminated floor area;

d) a monolithic thermal-insulating roller blind with a thermal resistance of $R \geq 1{,}5$ $(m^2{\cdot}K)/W$ must be in stalled on the inside of the balcony skylight on the south side of the building. Thermal-insulating curtains should also be installed on the inside of balcony windows on other sides of the building to improve (maintain) the thermal regime in this part of the house in winter and to shade the building in summer;

e) place at least 300 mm of planting soil on the balcony floor and install pots of soil on the inside of both walls to absorb solar thermal energy through the skylight and store it in the soil during the day (Figure 1). This is called light accumula-

Figure 1. An example of the placement of soil and plants on a balcony

tion and is calculated using the formula: $Q = C \cdot M(T_2 – T_1)$, where Q is the heat accumulated in the soil, J; C is the specific heat of the soil, J/(kg °C); M is the volume of soil, m^3; T_1, T_2 are the initial and final soil temperatures, respectively, in °C. Based on the calculation formula, it can be concluded that the greater the volume of planting soil, the more thermal energy accumulates during the day and the higher the possibility of maintaining the thermal regime and increasing the temperature in unheated rooms.

These unique solar thermal energy accumulators on south-facing balconies act as renewable active heat sources, used in the design of ultra-low-energy buildings. Furthermore, other natural or non-standard heat accumulators can be used to accumulate solar thermal energy to increase and maintain a comfortable indoor temperature.

Design of an ultra-low energy building envelope. According to Fourier's law: $Q = K \cdot F \cdot \Delta T$, where Q is the building's thermal load, W; K is the heat transfer coefficient of the building's enclosing structure, W/(m · K); F is the area of the building's enclosing structure, m^2; $\triangle T$ is the temperature difference between the inside and outside of the building, K. The formula shows that the thermal load is directly proportional to the components on the right-hand side of the equation. After determining the building design scheme, F and ΔT are quantitative values, and only K is variable.

Furthermore, the developed structures must meet the requirements of the current state standards GB 50016–2018 "Code for Fire Protection Design of Buildings"[1] (Article 6.7 "Building Thermal Insulation and Exterior Finishes") and GB 55037–2022 "General Code for Building Fire Protection"[2] (Article 6.6 "Building Thermal Insulation"). To reduce the U-value of the enclosing structure, the authors did not limit themselves to a single type, but used suitable materials and technical means.

As an example, consider a residential building with a height of 3.0 m. The thermal energy consumption for heating 1 m^2 of residential space in winter should not exceed 10 kW h/(m^2 year). To achieve this figure, the enclosing structure must meet the following requirements:

external wall heat transfer coefficient $K \leq 0.15$ W/(m^2 · K);

heat transfer coefficient $K \leq 1.20$ W/(m^2 · K);

structure airtightness class – not lower than 6, door airtightness class – not lower than class 8; airtightness classes must comply with GBT 7106 "Methods for testing airtightness, watertightness, and wind resistance in external doors and windows of buildings";

the heat-transfer coefficient of the external window is $K \leq 0.80$ W/(m^2 · K), the air-tightness class is at least 8;

the heat-transfer coefficient of the roof is $K \leq 0.10$ W/(m^2 · K);

the heat-transfer coefficient on the first floor is $K \leq 0.10$ W/(m^2 · K) if the building has no basement; $K \leq 0.15$ W/(m^2 · K) – when the building has a basement, and the basement roof is the first floor; $K \leq 0.10$ W/(m^2 · K) – when the basement roof is exposed to the air;

the heat-transfer coefficient of the walls between apartments is $K \leq 1.50$ W/(m^2 · K);

the floor of a basement used as a garage with a separate entrance and a depth of at least 4.0 m should not be insulated, although insulation is required on the basement roof. If the basement does not have a separate entrance and is used in conjunction with a vertical ground floor connection, a translucent floor (Figure 2) should be designed in the room with a south-facing ground floor to directly allow light into the basement. A heat accumulator at least 100 mm thick should be installed on the underside of the

Figure 2. Light-permeable floor on the ground floor of a building with ultra-low energy consumption

[1] 建筑设计防火规范. URL: https://www.chinesestandard.net/PDF.aspx/GB50016-2018 (date of access: 15.01.2025).

[2] 建筑防火通用规范. URL: https://www.chinesestandard.net/PDF/English.aspx/GB55037-2022?Redirect (date of access: 15.01.2025).

floor base, allowing direct illumination of the basement through the translucent floor and accumulating heat through daylight;

the enclosing structure of the balcony located on the north side of the building must meet the performance requirements of ultra-low energy buildings in cold regions.

The window area to floor ratio of external north-facing windows should be equal to the lower limit established by the current national standard of the People's Republic of China GB 55016–2021 “Standard for Daylighting Design of Buildings”[1].

According to Article 3.2.1 of this normative document, the determination of the level of solar light acquisition during design should be based on architectural characteristics and operational functions (Table 2).

Table 2. **Values of the natural illumination coefficient under different lighting conditions (GB 55016–2021, Table 3.2.2-1)**

Level of sunlight reception	Lateral natural lighting		Overhead natural lighting	
	standard value of natural illumination coefficient, %	standard value of the coefficient of natural illumination in a room, %	standard value of natural illumination coefficient, %	standard value of the coefficient of natural illumination in a room, %
I	5	750	5	750
II	4	600	3	450
III	3	450	2	300
IV	2	300	1	150
V	1	150	0.5	75

Heating in winter of rooms with low light, low temperature and high humidity. In winter, when light levels are low, temperatures are low, and humidity is high, solar thermal energy accumulators on south-facing balconies (see Figure 1) temporarily lose their ability to heat the space. Therefore, electric heat accumulators equipped with built-in heat-accumulating material should be used (Figure 3).

Compared to other heating technologies, using an electric heat accumulator offers advantages such as ease of installation, high efficiency and energy savings, safety and reliability, fully automatic control, and maintenance-free operation.

Other important advantages of heat storage devices as a source of room temperature maintenance are worth mentioning.

First, energy savings. In Harbin, during the cold season, heating using the centralized municipal heating network lasts 180 days, starting on October 20th each year and ending on April 20th of the following year. This heating period can be divided into three 60-day periods: early winter, late winter, and spring.

a *b*

Figure 3. Operating scheme (*a*) and installation of an electric heat accumulator in the room (*b*)

[1] 建筑环境通用规范. URL: https://www.chinesestandard.net/PDF/English.aspx/GB55016-2021?Redirect (date of access: 15.01.2025).

For ease of management and to reduce unnecessary energy consumption, early winter is also divided into three periods: slightly cold, cold, and very cold. During the slightly cold and cold periods, a comfortable room temperature is maintained using a solar thermal energy harvesting device. During the very cold season, residents can decide to activate an electric heat storage device for heating based on the previous day's weather. Off-peak periods for the municipal electric network are from 10:00 PM to 5:00 AM each day. During the very cold period, the time required to connect to the electric current is typically 2 to 2.5 hours.

During the 60 days of late winter, the time required to connect to the electric current for indoor heating is typically 3 to 5 hours. The late winter phase (60 days) also has three periods: very cold, cold, and slightly cold. During these periods, the electric current is used to maintain the temperature, as in early winter.

The three periods of early spring (60 days total) – extreme cold, moderate cooling, and micro-cold – are characterized by the use of electric heating to generate additional heat in buildings, as in early winter. Overall, using inexpensive, clean energy for heating not only fully embodies behavioral energy conservation but also ensures that people can regulate the temperature in their buildings as they wish. It's worth noting that by using different heat sources during different periods, people can independently set their own comfortable indoor temperature.

Secondly, reducing heating costs. In Harbin, the winter district heating fee for the municipal heating network (or so-called heating fee) is 38.32 yuan/m² for residential buildings and 43.30 yuan/m² for non-residential buildings. According to monitoring data over the past three years, in ultra-low-energy buildings, the cost of heating with electricity was approximately 4 yuan/m², or approximately 1/10th of the district heating fee for the municipal heating network.

Another way to conserve and save heat is to install a fresh air supply line along the outer perimeter of the building's foundation and the inside of the basement's outer wall from an underground ground source. The fresh air temperature in the supply system varies depending on external sources (in particular, the temperature of the soil, the basement, etc.).

As a rule, an exhaust fan (noise level ≤ 30 dB) is installed in the kitchen. Each block of the building should have a separate, insulated, and sealed fresh air intake vent. A sealed, insulated tunnel ventilation system should be designed for each entrance, ensuring fresh air flow into the rooms from the tunnel ventilation. A check valve should be installed at the inlet end of the ventilation system. All ventilation openings should be located on the north side of the building and terminated with rain caps.

Fresh air intake vents and ventilation controls should also be installed in each room. A wind indicator panel should be placed at the top of the vent. A dynamic temperature indicator meter should be installed at the main fresh air intake. The number of fresh air intake vents in each room is individually designed based on the area used and the number of permanent residents.

Building sun protection system. When operating ultra-low-energy buildings, sun protection, which is necessary during hot periods, must also be considered (for example, in Harbin, from July to August, maximum outdoor temperatures can reach 30 °C and above).

Two shading methods are used in the design. *The first method* is protection from the outside of the building: installation of sun-protection curtains and awnings (Figure 4, *a*, *b*), planting tall broad-leaved trees on the southern side of the building, etc. *The second method* is sun-protection covering inside the building: installation of sun-protection curtains on the inner side of the southern light orientation to prevent daylight (Figure 4, *c*).

Energy-efficient reconstruction of existing buildings. To reduce energy consumption, existing buildings should be retrofitted according to technological requirements. However, several conditions must be considered.

1. The orientation and shape of the building being renovated must comply with the requirements for ultra-low-energy buildings.

2. When converting an existing building to a very low-energy building, a solar thermal storage unit capable of fully absorbing solar thermal energy should be installed on the sunny side of the building. Inside, potting soil should be used on balconies, and household items that are good heat carriers should be used indoors.

a

b

c

Figure 4. Examples of the use of external (*a*, *b*) and internal (*c*) building sun protection systems

3. The surface of the skylight, consisting of lightweight steel structures and glass curtain walls, adjoins the southern exterior wall of the building, forming a solar thermal energy collector. The surface heat transfer coefficient of the skylight is $K \leq 2.0$ W/(m^2 · K), the illumination angle is from 43° to 47°, the upper surface must be covered with sun protection roller blinds and thermal insulating roller blinds that meet regulatory requirements ($R \geq 1.5$ (m^2 · K)/W) and are height-adjustable (thermal insulating roller blinds can also be located on the lower surface of the skylight).

4. The foundation depth must be no less than the standard freezing depth multiplied by 0.7. The soil on the balcony, floors, walls, and furniture in living spaces must meet technical requirements. The underground surface must be covered with a thermal insulation layer with a heat transfer coefficient of $K \geq 0.15$ W/(m^2 · K). The heating method in the room must correspond to the illumination, humidity, and temperature levels at which the building is used. It is also necessary to install a ventilation system, open-light windows on the south wall of the building, and a fan in the upper part of the open-light window.

Monitoring energy consumption dynamics. As an example, we will consider an ultra-low-energy administrative building. A heat accumulator is used to collect thermal energy, and electrical equipment serves as the primary energy source for maintaining the building's heat. In winter, the building maintains a temperature of approximately 18–24 °C. To accurately track the relationship between temperature and energy consumption, a system for collecting and monitoring temperature dynamics in rooms was installed. Sensors were installed on each floor and in the main room to track not only temperature changes but also other indicators, particularly environmental ones.

Figure 5 shows the data (temperature, PM2.5 content, carbon dioxide concentration, humidity, total volatile organic compounds, and formaldehyde) collected by the dynamic data collection and monitoring system on various dates. The resulting data is used to analyze the building's performance.

a *b*

Figure 5. Information received by the data collection and monitoring system on January 8, 2023 (*a*) and January 2, 2024 (*b*)

By monitoring changes in indoor environmental parameters in ultra-low-energy buildings during 2023–2024, the accuracy of the dynamics and operational reliability of the developed thermal energy collection system were established.

Conclusion. The economic and environmental benefits of using the technologies described in this article for the construction of prefabricated ultra-low-energy buildings in extremely cold regions of China are studied. Specifically, there is no need to connect such buildings to the district heating network during the winter or use air conditioners for cooling during the summer. The construction of ultra-low-energy buildings seamlessly combines prefabricated construction with new highly efficient heat conservation and cooling technologies, significantly reducing the building's operating costs and carbon emissions.

The use of the technologies described in this article yields significant economic benefits. By eliminating the need for connection to the district heating network, the cost of the entire construction cycle (including initial investment and operating costs) is significantly reduced compared to the traditional model. At the same time, environmental issues associated with carbon emissions and the extraction of fossil fuels used in thermal energy production are addressed. Furthermore, increasing energy self-sufficiency reduces consumers' dependence on district heating and increases the resilience of the energy system.

The described new construction technologies make it possible to eliminate the need for centralized public heating in ultra-low-energy buildings located in extremely cold regions of China and are promising for the design of energy-efficient construction and optimization of the energy system in similar climate zones.