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Research on Energy Consumption Constitution and Energy Efficiency Strategies of Residential Buildings in China Based on Carbon Neutral Demand

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Abstract: To assist in the implementation of carbon peaking and carbon neutrality in China, due to the contradiction between the increasing energy consumption of residential buildings in China and the higher energy efficiency goals, this paper illustrates that the energy consumption constitution of residential buildings in the whole life cycle and then puts forward comprehensive energy efficiency strategies. With literature and statistical data, the main part of building energy consumption lies in the materialization and use phases, which both will be continually increasing, and divided into energy utilization and waste. By inducing the energy consumption in the use phase, the energy consumption of residential buildings can be further classified into the energy consumption of indoor environments, residential behavior, and public facilities, where the internal factor of continuous increase are all elaborated. Via the analysis of energy waste causes, this paper constructs a model of energy consumption in residential buildings, reveals that the key to energy efficiency in residential buildings lies in scientific decision-making, lifestyle improvement, and appropriate energy efficiency technologies and measures adoption, and points out that promoting building energy efficiency through the whole life cycle of buildings and building activities is needed to achieve carbon compliance and carbon neutrality.

Keywords: residential building; energy use; energy consumption; enclosure structure

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1. Introduction

In 2021, carbon peaking and carbon neutrality were first written into the work reports of the Chinese government. It was clearly claimed that China is striving to achieve carbon peaking by 2030 and carbon neutrality by 2060, which are major strategic decisions made by the Party Central Committee after careful consideration, and are related to the sustainable development of the Chinese nation and the community of human destiny. In such an era, it is of vital significance to investigate building energy consumption and then discuss energy efficiency strategies to prepare for carbon peaking and carbon neutrality.

Since the implementation of the building energy efficiency policy in 1986, China has made remarkable achievements in theoretical research, standard formulation, engineering design and construction, and the development proceeding can be divided into four phases: the exploration phase in China ended in 2020, where the building energy efficiency goal was proposed to be a 30% reduction in building energy consumption based on 1981; the pilot demonstration phase was between 2000 and 2005, with the introduction of a series of energy efficiency standards, norms, and energy efficiency targets of 50%; in the development phase from 2005 to 2015, the energy efficiency target was set to reach 65% on the basis of the previous stage, and after 2005, Beijing, Shanghai, Jiangsu, Zhejiang, and other most provinces have implemented a 75% building energy efficiency target in this promotion phase.

Despite the set energy efficiency goals tending to be higher, the actual energy consumption of residential buildings in China keeps increasing continuously. According to the China Building Energy Consumption Annual Report 2020, issued by the China Association of Building Energy Efficiency [1], from 2005 to 2018, the whole-life energy consumption of buildings nationwide rose from 934 million Tce in 2005 to 2.141 billion Tce in 2018, expanding 2.3 times, with an average annual growth of 6.6%.

In terms of different energy sources' consumption of residential buildings in China, electricity, and gas consumption are both increasing. According to the annual data released by China's National Bureau of Statistics [2] (Table 1), China's per capita domestic energy consumption continued to grow from 2010 to 2019, with an average growth rate of over 5%. As depicted in Figure 1, with the popularization of "coal to gas" and natural gas, the per capita consumption of coal and gas has decreased year by year. After 2017, the consumption of liquefied petroleum gas (LPG) also dropped, while natural gas consumption increased rapidly. Therefore, from the perspective of the energy consumption constitution, the domestic energy consumption of urban residents is mainly electricity and natural gas.

Table 1. Per capita domestic energy consumption of Chinese urban residents between 2011 and 2019.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
Per capita domestic energy consumption (kgce)	294	312	334	344	366	392	412	431	438
Per capita coal consumption (kg)	68	68	68	68	70	68	66	55	47
Per capita electricity consumption (KWh)	418	459	513	523	548	607	650	717	756
Per capita LPG consumption (kg)	11.9	12.1	13.5	15.8	18.5	21.3	23.1	22.4	20.3
Per capita natural gas consumption (m^3)	19.7	21.3	23.7	25	26.1	27.4	30.1	33.4	35.7
Per capita coal gas consumption (m^3)	10.9	10.1	7.9	7.1	5.8	4.5	3.7	3.4	3.3

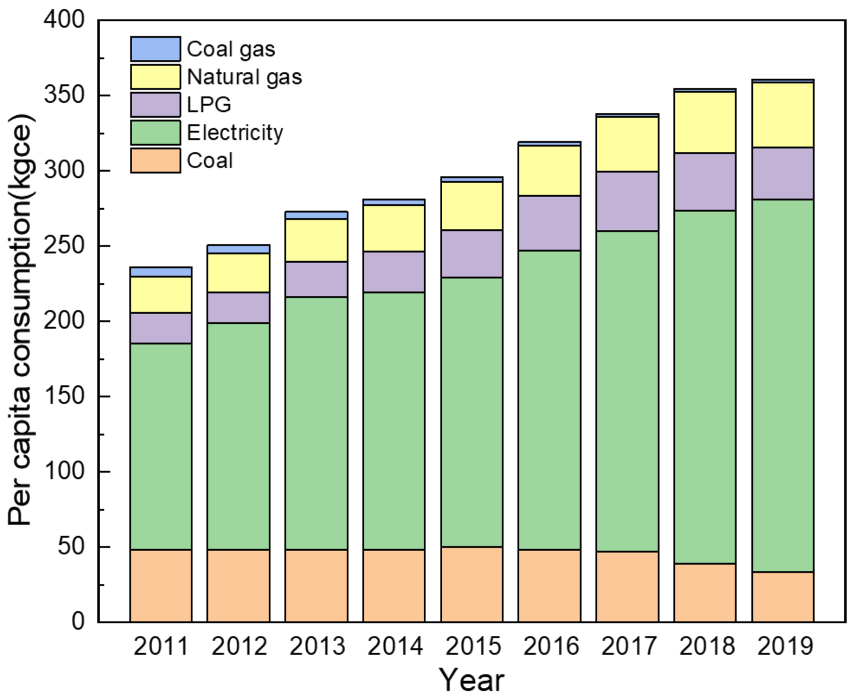

Figure 1. Trend per capita of different energy sources' consumption of Chinese urban residents between 2011 and 2019.

Research showed that the proportion of industrial power consumption in China had decreased year by year, from 72.37% in 2014 to 69.16% in 2017 [3]. Conversely, the proportion of residential power consumption showed sustained growth, from 12.73% in

2014 to 13.78% in 2017. From 2014 to 2017, China's industrial electricity consumption grew at an average annual rate of 2.25%, while that of domestic power consumption was 6.61%. According to the regression model, the per capita electricity consumption in China was calculated to be increase to 801.52 kWh and 1414.00 kWh in 2020 and 2030, respectively. Although the fast growth rate reached an average annual growth rate of 6.32%, it was still at a low level. By 2030, China's per capita household electricity consumption will be just equal to that of the European Union, about one-third of that of America, which showed that the per capita electricity consumption in China by 2030 will present a certain distance from its peak value. According to the announcement on the website of the National Energy Administration of China, in 2020, the power consumption of the whole society was 7511 billion kWh, with a year-on-year growth of 3.1%. Among them, the electricity consumption of primary industry was 85.9 billion kWh, up 10.2%. For secondary industry, tertiary industry, and residents, it was 5121.5, 1208.7, and 1094.9 billion kWh, respectively, up 2.5%, 1.9%, and 6.9%, independently year-on-year [4]. Based on these data, the growth rate of domestic electricity consumption in China will remain around 6%.

With the national urban gasification rate increasing steadily in terms of natural gas consumption, the gasification population has risen from 300 million to 500 million. The per capita domestic gas consumption of urban residents has increased to about 130 m^3 during China's 13th Five Year Plan period. By 2020, the consumption of urban gas, industrial fuel, gas power generation, and chemical gas will be 121, 109, 58, and 32 billion m^3, accounting for 38%, 34%, 18%, and 10%, respectively [5]. Compared to 2015, the share of urban gas increased by 5.5%, and additionally, there were significant regional differences in natural gas consumption. According to the Investigation and Research on Gas Consumption Index of Residents in Tianjin [6], the annual average household gas consumption in 2011 was 92.82 m^3, while in 2017, it was 113.20 m^3, where the growth trend was also obvious. Some researchers thought the average consumption of urban households in China had decreased steadily; however, taking the total number of households in the district as the base and ignoring the existence of numerous vacant houses mainly accounted for the bias of the research results. Macroscopically, although the growth trend of natural gas consumption in China has slowed, the growth rate was still high at over 8%. The main driver of natural gas consumption was industry and residential, accounting for 37.9% and 34.3% of the total natural gas consumption, respectively [7]. Compared with foreign countries, in 2017, the per capita gas consumption of residents in China was only 55 m^3, far from 428 m^3 in the United States and 752 m^3 in the United Kingdom [8].

Therefore, the total and unit consumption of energy sources in Chinese residential buildings presented an upward trend [9]. Hence, this paper will start with the constitution of residential buildings energy consumption, constructing a residential buildings energy consumption model with literature and statistical data, to reveal the internal causes of residential buildings energy consumption rising, and then analyze the contradiction between the continuous enhancement of actual energy consumption in residential buildings and the rising energy efficiency goals, finally putting forward targeted energy efficiency strategies and measures.

2. Materials and Methods

2.1. Energy Consumption Constitution of Residential Buildings

Generally speaking, building energy consumption should not only be focused on the operational energy consumption of buildings but also studied from the broad perspective of energy consumption in the whole life cycle.

The broad building energy consumption can be classified into energy consumption in the materialization phase (E_{ma}, including production and transmission of building materials, energy, and equipment), energy consumption in the construction phase (E_{cp}, including project demonstration, design, audit, and construction), energy consumption in the use phase (E_{um}, including use and maintenance), and energy consumption in the demolition phase (E_{dt}, including demolition and harmless disposal). In the recent ten years, the irrational development of the real estate industry in China has been the leading cause of the rapid development in high pollution and energy-consuming industries, such as steel and cement industries, and the emergence of overcapacity. On the one hand, the amount of steel used in construction exceeded 40% of China's steel production; on the other hand, the steel used in construction accounted for 30–50% of carbon emissions in the materialization phase. The China Building Energy Consumption Annual Report 2020 showed that in 2018, the energy consumption of buildings in the whole life cycle was 2.147 billion Tce, accounting for 46.5% of the total national energy consumption. Among them, the energy consumption in the materialization phase was 1.1 billion Tce, making up 51.3% of the energy consumption of buildings in the whole life cycle and 23.8% of the national energy consumption; the energy consumption in the construction phase was 47 million Tce, accounting for 2.2% of buildings' energy consumption in the whole life cycle and 1% of the national energy consumption; energy consumption in the use phase of buildings was 1 billion Tce, occupying 46.6% of the energy consumption of buildings in the whole life cycle and 21.7% of the national energy consumption, that was E_{ma} = 51.3%, E_{cp} = 2.2%, E_{um} = 46.6%.

With the higher building height, better decoration requirements, and more investment in the heat preservation and insulation of the building envelope, the energy consumption in the materialization phase shows an upward trend. The carbon emissions in the materialization phase accounted for 20% to 60% of the carbon emissions of buildings in the whole life cycle, especially in residential buildings and schools, where the proportion exceeded 60% [10]. It is evident that the energy consumption in the materialization phase cannot be ignored for building energy efficiency. Moreover, the energy consumption in the above four phases also varies due to building types and functions, use conditions, climate, economy, and other factors. Therefore, based on other research results, the energy consumption in the four phases of building activities is shown in Figure 2a. A detailed classification of building energy consumption can improve the accuracy of the benchmark values of building energy consumption, and ensure that a high degree of similarity among the compared buildings is a prerequisite for a reasonable evaluation of building energy consumption levels [11]. Thus, scientifically defining the constitution of energy consumption is a significant fundamental work to investigate building energy consumption.

The definition of energy consumption constitution should initiate from the perspective of productivity levels and ecological ethics and analyze energy consumption into two aspects: energy utilization and energy waste. Energy utilization refers to normal and necessary energy consumption in order to meet the needs of production and life. For example, the use of air conditioners and refrigeration in summer is bound to consume electrical energy, but due to the limitations of existing techniques, it is inevitable that the conversion of electrical energy into cold will produce waste. So energy consumption includes two parts: utilization and waste. The utilization, which is the normal part of energy conversion, is necessary, while the waste, that is the consumption of energy in the conversion process, is ineluctable and normal, both belonging to energy consumption.

Energy waste refers to improper use or consumption without restraint. Energy waste in residential buildings is mainly manifested in three forms: the first is waste in lifestyle, which is lack of awareness of energy efficiency and controlled consumption; the second is waste in technical measures, referring to the energy consumption caused by the failure to adopt the necessary techniques and measures to meet the technical standards stipulated by governments; the third is waste in policy decisions, demonstrating the energy consumption caused by unscientific and unreasonable policies and decisions.

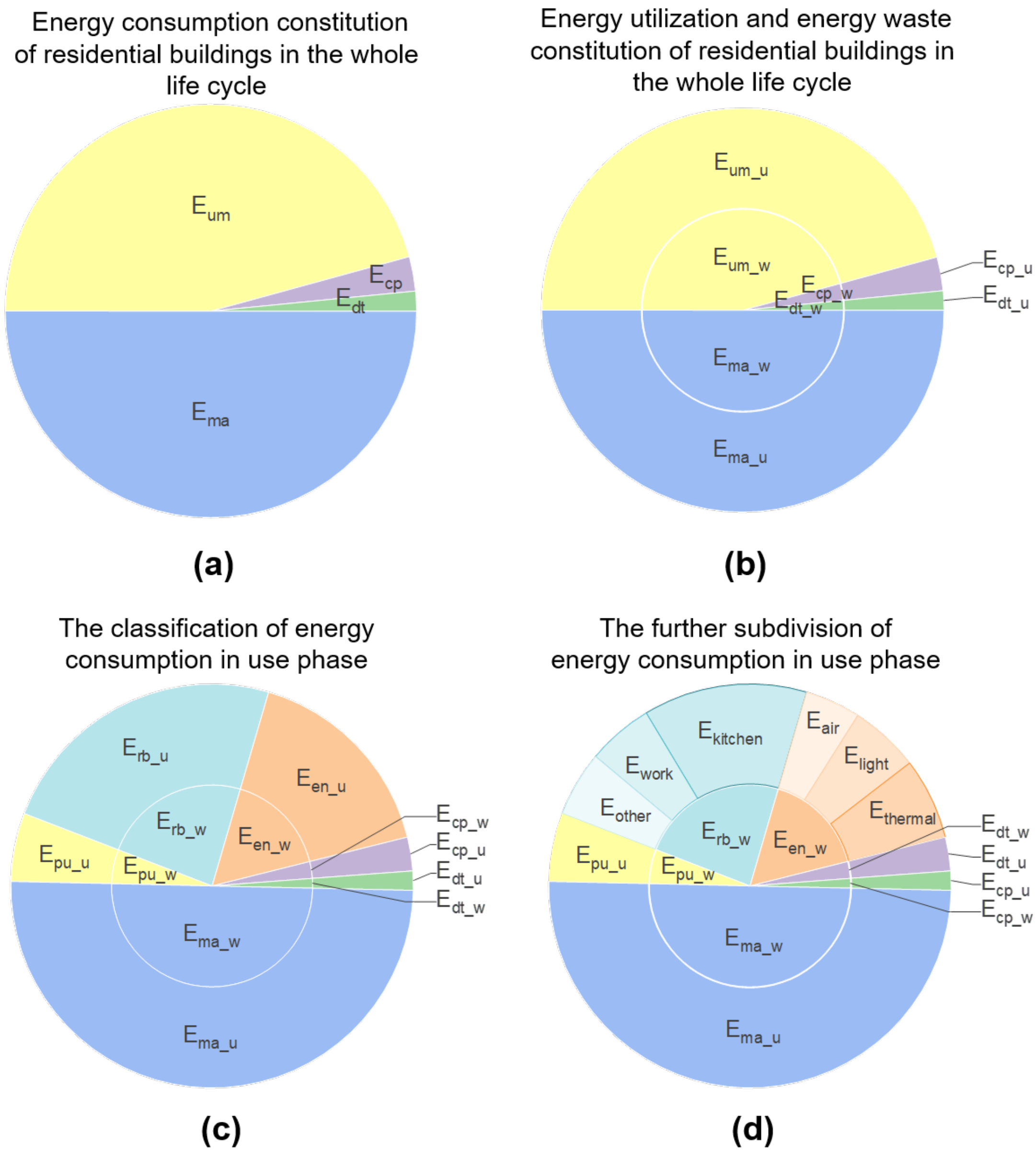

Figure 2. Energy consumption constitution of residential buildings in the whole life cycle. (**a**) Energy consumption constitution of residential buildings in the whole life cycle, where E_{ma} denotes energy consumption in materialization phase; E_{cp} denotes energy consumption in construction phase; E_{um} denotes energy consumption in use phase; E_{um} denotes energy consumption in demolition phase; (**b**) Energy utilization and energy waste constitution of residential buildings in the whole life cycle, where E_{ma_u}, E_{ma_w} denotes energy utilization and waste in materialization phase; E_{cp_u}, E_{cp_w} denotes energy utilization and waste in construction phase; E_{um_u}, E_{um_w} denotes energy utilization and waste in use phase; E_{dt_u}, E_{dt_w} denotes energy utilization and waste in demolition phase; (**c**) The classification of energy consumption in use phase, where E_{pu_u}, E_{pu_w} denotes energy utilization and waste in use phase of public utility; E_{en_u}, E_{en_w} denotes energy utilization and waste in use phase of indoor environment; E_{rb_u}, E_{rb_w} denotes energy utilization and waste in use phase of residential behavior; (**d**) The further subdivision of energy consumption in use phase, where $E_{thermal}$, E_{light} and E_{air} denotes energy consumption of processing, storage and air environment in indoor environment energy utilization; $E_{kitchen}$, E_{work} and E_{other} denotes energy consumption of processing and storage, home-based work and other residential behavior in residential behavior energy utilization.

In the whole life cycle of buildings, there exists energy waste in these four energy consumption phases, as shown in Figure 2b. Based on the above, we can obtain:

$$E_{ma} > E_{um} > E_{cp} > E_{dt} \tag{1}$$

$$E = E_{ma} + E_{cp} + E_{um} + E_{dt} \tag{2}$$

$$E = E_{ma\_u} + E_{ma\_w} + E_{cp\_u} + E_{cp\_w} + E_{um\_u} + E_{um\_w} + E_{dt\_u} + E_{dt\_w} \tag{3}$$

where E denotes the energy consumption of residential buildings in the whole life cycle; E_{ma_u} denotes energy utilization in the materialization phase; E_{ma_w} denotes energy waste in the materialization phase; E_{cp_u} denotes energy utilization in the construction phase; E_{cp_w} denotes energy waste in the construction phase; E_{um_u} denotes energy utilization in the use phase; E_{um_w} denotes energy waste in the use phase; E_{dt_u} denotes energy utilization in the demolition phase; E_{dt_w} denotes energy waste in the demolition phase.2.2. Energy Consumption in the Use Phase and Its Development Trend.

According to Regulations on Energy Saving for Civil Buildings of China, building energy efficiency is an activity of reducing energy consumption on the premise while guaranteeing building function and indoor thermal environment quality. In view of this definition, traditional building energy efficiency is narrowly defined as energy consumption in the use phase, and it mainly includes environmental energy consumption and functional energy consumption.

According to the Classification and Representation of Building Energy Use Data of China (JG/T 358-2012), building energy consumption is composed of energy consumption by heating, cooling, domestic hot water, cooking, lighting, household/office equipment, elevator, information room, building service equipment, and other specific equipment. However, architecture is a function carrier instead of the function itself and does not require or use energy. Thus, energy consumption is all about people consuming energy directly or indirectly in order to achieve certain needs and purposes [12]. Therefore, the environmental and functional energy consumption, such as heating, cooking, and elevator, can be further summarized into three categories, namely indoor environmental energy consumption (E_{en}), residential behavior energy consumption (E_{rb}), and public utility energy consumption (E_{pu}), as shown in Figures 2c and 3. The first two are the indoor energy consumption of individual households, which can be measured, charged, and managed separately, while the latter is the communal energy consumption of shared households, referring to the energy consumption of common equipment, such as elevators and machine rooms, as well as power line losses.

2.1.1. Energy Consumption of Indoor Environment

Energy consumption of the indoor environment includes the thermal environment, indoor light environment, and air environment energy consumption. This energy consumption is not only closely related to energy equipment but also depends on the external climate, space composition, building shape, and envelop enclosure, where the climate is the most important factor among them.

In heating areas of north China, the average unit energy consumption of buildings is about twice that in other areas, where heating energy consumption accounted for more than 50% of total energy consumption of residential buildings. In the southern region of China, the energy consumption of air conditioners is large, reaching over 30% in some places. In recent years, the growth rate of unit energy consumption in southern China has been significantly higher than that of the northern region, where the energy consumption of air conditioners was on the increase, more significant than that of heating. The total energy consumption of building thermal engineering showed an upward trend [13]. Moreover, with the improvement in living standards, the increase in per capita living area, climate warming, and the rising frequency of extreme climate [14] will further lead to higher thermal environment energy consumption of residential buildings.

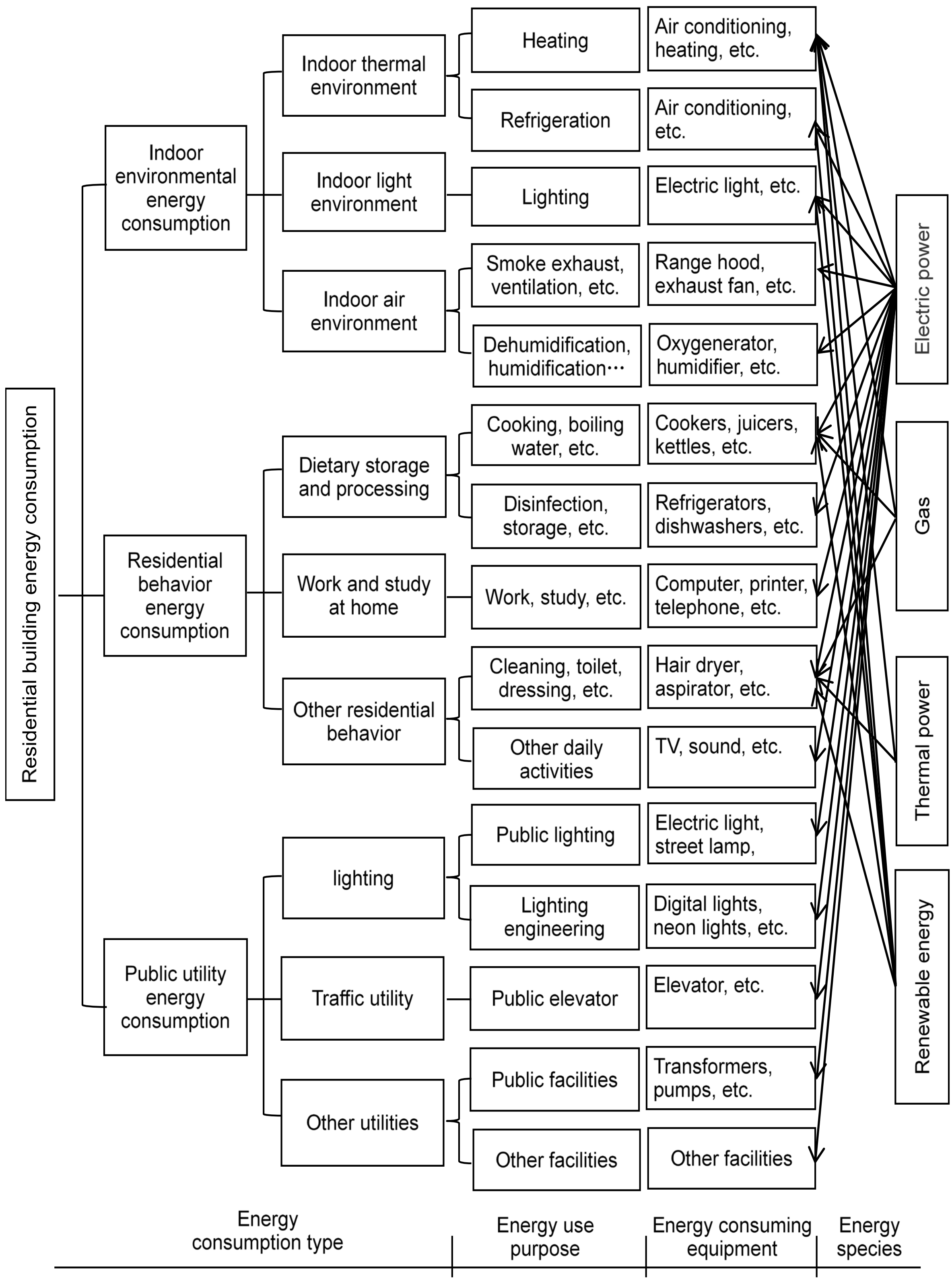

Figure 3. Analysis of the energy consumption of residential buildings in the use phase.

Light environment energy consumption is referred to as the energy consumption in indoor lighting. From incandescent lamps to fluorescent lamps and LED lamps, the energy saving of lighting lamps has been greatly improved. However, the illuminance design value of residential lighting specified in the standard for lighting design of buildings (GB50034-2004) is not only lower than the standard of developed countries but also divorced from the actual use of current residential buildings [15]. In particular, with the increase in suite area, room numbers, and home-work time in the COVID-19 era, the energy consumption of the light environment will further rise.

The air environment energy consumption is mainly the energy consumption of purification, ventilation, smoke exhaust, humidification, dehumidification, etc. With the enhancement of hygiene and health awareness, various ventilators, range hoods, air purifiers, humidifiers, dehumidifiers, etc., are more universal, which will enhance the air environment energy consumption.

In brief, with the improvement in living standards and higher demand for the indoor environment, the energy consumption of the thermal environment ($E_{thermal}$), the light environment (E_{light}), and air environment (E_{air}) in the indoor environment energy utilization (E_{en_u}) will continue to increase to a certain extent, and we can obtain:

$$E_{en\_u} = E_{thermal} + E_{light} + E_{air} \tag{4}$$

2.1.2. Energy Consumption of Residential Behavior

Residential behavior energy consumption consists of the energy consumption of food processing and storage, the energy consumption of working at home, and energy consumption of other residential behaviors. It was shown that the average annual household electricity consumption in Shanghai was 2016 kWh, the average annual unit building area electricity consumption was 28.2 kWh/m^2, and that of gas consumption was 8.3 m^3/m^2, where the consumption ratio of coal and electricity was 3:7 and the air conditioner energy consumption accounted for 31% of total annual household electricity consumption in 2017 [16]. Seen from both the coal and electricity consumption ratio and gas consumption, the energy consumption of food processing and storage accounted for more than 30% of the household energy consumption in Shanghai. As food processing and storage are basic living needs of residents, their energy consumption should be guaranteed, and this energy consumption will be related to the energy types, equipment energy efficiency, residents' lifestyles, which will further rise with people's dietary requirements and kitchen appliances increasing.

Home-based work means that people work at home without going to the office. Home-based work, shopping, and learning at home are beneficial to alleviate urban traffic pressure, save public resources, increase residents' time-use efficiency, and improve the quality of life. In the post epidemic era, Home-based work in some industries and posts will usher in rapid development. Although this lifestyle can save energy consumption in the workplace and other public resources, it increases the energy consumption of residential buildings to a certain extent, which is not only because working at home tends to increase indoor lighting and heat energy consumption but also due to the use of computers, water dispensers, and other equipment.

For other residential behavior, including rest, study, online shopping, bodybuilding, socializing, and entertainment, the research has shown that the average time of urban residents living at home in China was 17.6 h [14]. Due to the change in production and lifestyle, and the extensive use of computers, mobile phones, the energy consumption of both the indoor environment and other living behavior will boost and currently a variety of electrical appliances have been adopted, which not only improve people's lives and labor efficiency but also increase household energy consumption.

Hence, energy utilization of residential behavior (E_{rb_u}) is made up of food processing and storage energy consumption ($E_{kitchen}$), home-based work energy consumption (E_{work}), and other residential behavior energy consumption (E_{other}), namely:

$$E_{rb\_u} = E_{kitchen} + E_{work} + E_{other} \tag{5}$$

2.1.3. Energy Consumption of the Public Utility

The energy consumption of the public utility is composed of the energy consumption of elevators, access control systems, fire-fighting facilities, water supply, and drainage pumps, as well as lighting in public spaces, outdoor lighting, and community landscapes, and transformer and circuit loss, and this energy consumption is generally shared by households in the form of property and elevator usage fees. As the current residential buildings are mostly high-rise buildings, where the average floor will further increase owing to the shortage of land resources, and the transformation of old communities in China, such as adding elevators, garages, and improving community landscapes, will lead to the rise in the energy consumption of the public utility.

Based on the above, as depicted in Figure 2d, the energy consumption of residential buildings in the use phase E_{um} is the sum of the indoor environment energy consumption E_{en}, residential behavior energy consumption E_{rb}, and public utility energy consumption E_{pu}, namely:

$$E_{um} = E_{en} + E_{rb} + E_{pu} \tag{6}$$

$$E_{um} = E_{en\_u} + E_{en\_w} + E_{rb\_u} + E_{rb\_w} + E_{pu\_u} + E_{pu\_w} \tag{7}$$

$$E_{um\_u} = E_{thermal} + E_{light} + E_{air} + E_{kitchen} + E_{work} + E_{other} + E_{pu\_u} \tag{8}$$

3. Results

3.1. Contradiction between Actual Energy Consumption and Energy Efficiency Goals

The contradiction between the increasing actual energy consumption of residential buildings and the continuous improvement in energy efficiency goals is prominent. Via the above analysis of the energy consumption constitution and energy consumption in the use phase, it is not difficult to see:

First, the energy efficiency target in China refers to the energy efficiency rate, which is

$$\textit{Energy efficiency rate} = (100 - \textit{Design building energy consumption/Benchmark building energy consumption})\% \tag{9}$$

where benchmark building energy consumption denotes the annual HVAC and lighting energy consumption of the same function and size building in China in 1981, and design building energy consumption is the energy consumption value of currently designed buildings. It is well-known that with the limited economic level in the 1980s, electrical equipment, such as refrigerators, televisions, and air conditioners, in most Chinese families was rare, and a frugal lifestyle determined that the energy consumption of residential buildings, which was quite low at that time. With the development of the economy, people's living standards have been greatly improved, and indoor environmental energy consumption, residential behaviors energy consumption, and public facilities energy consumption are all increasing continuously, which leads to the contradiction between the rising total and unit energy consumption of residential buildings and the higher energy efficiency targets, even reaching 75% [17].

Second, in terms of calculation methods, when China began its energy efficiency plan in the 1980s, the energy efficiency goal was determined to be a 30% reduction in energy consumption at each step. Thus, the first step had an energy efficiency rate of 30%, the second step was 50%, the third step was 65%, and the fourth step was 75%. As long as the construction of the enclosure structure conforms to the national specification Design Standard for Energy Efficiency of Public Buildings (gb50189-2005), it is considered to have reached the second step with an energy efficiency rate of 50%, and once the construction of the enclosure structure accords with the national specification Design Standard for Energy Efficiency of Public Buildings (gb50189-2015), it is thought to have reached the third step, with the energy efficiency rate of 65% for public buildings. Similarly, as residential buildings meet the relevant standards, they are considered to have reached the third step energy efficiency target with an energy efficiency rate of 65%. In 2013, Tianjin took the lead in achieving the fourth step of the energy efficiency goal, where the energy consumption is regarded as 25% of the benchmark building energy consumption in the 1980s and achieves an energy efficiency rate of 75% with the residential buildings meeting the Design Standard for Energy Efficiency of Residential Buildings (db29-1-2013). It can be seen that current building energy efficiency goals in China are obtained through comparison, while the energy consumption, energy-saving in studies, and statistical reports issued by authoritative departments are the actual energy consumption calculated through investigation and statistics, which leads to the fact that current building energy efficiency goals cannot reflect the actual building energy consumption.

Third, the energy consumption calculation is mainly HVAC and lighting energy consumption, that is, the energy consumption of the thermal and light environments mentioned above. Since it does not include air environment energy consumption, it is slightly less than the indoor environment energy consumption, E_{en}, which is far less than the energy consumption in the use phase, E_{um}. Currently, the energy consumption in the industrialization phase, construction phase, and demolition phase is not included in the building energy efficiency design, resulting in a vast difference between the building energy efficiency goal and actual building energy consumption.

In addition, energy efficiency should reduce energy waste rather than limit energy consumption. In order to improve living standards, normal energy consumption is the objective demand of residents' life and the embodiment of the socialist system superiority, which should not be restricted, but effectively guaranteed. The aforementioned indoor environment energy consumption, residential behavior energy consumption, and public utility energy consumption will continue to increase over a certain period with the development of society, and that inevitably leads to an increase in the total amount of energy consumed in China, which is an important reason for the rise in the energy consumption of residential buildings. The China Building Energy Consumption Annual Report 2020 indicated that the building operation energy consumption increased from 480 million Tce in 2005 to 2.11 billion Tce in 2018, with an average annual growth rate of 5.39%, which further supports the above conclusion.

3.2. Energy Waste and Energy Efficiency Strategies

On the basis of the aforementioned energy utilization, loss, and waste, the energy consumption model constructed in this paper and the energy efficiency strategies of residential buildings are shown in Figure 4.

3.2.1. Energy Waste in Technical Strategies

The technical strategies for energy efficiency in buildings summarize adopting a reasonable energy use mode, applying energy efficiency equipment, and improving the thermal performance of the envelope enclosure, etc. (this paper classifies the energy efficiency content in the planning and design phase into project decision-making). If these energy efficiency techniques and strategies do not reach the local average level, or fail to meet the national and local norms, or there exist technical deficiencies, the resulting energy consumption belongs to a waste of energy.

First, optimize energy consumption mode. Adopting building energy supply, choosing equipment with a reasonable energy consumption mode, and utilizing appropriate renewable energy will be the main content and the focus of energy efficiency. Urban residential buildings in northern heating areas of China have basically realized centralized heating, which can save energy by improving the thermal efficiency of boilers. However, the heat loss of the heating network and energy waste due to poor management is also severe [18]. Many studies manifest that developing efficient domestic gas boilers in some areas which can be heated partly in space and in time, as well as district geothermal and solar heating, should be the future development direction [19]. The energy efficiency of thermal power is low. It not only consumes enormous energy and pollutes seriously but also produces waste in varying degrees among transportation, distribution, and terminal use. Therefore, it is a very uneconomical and environmentally unfriendly secondary energy, and if the energy utilization of cogeneration is not considered, the actual energy utilization in the terminal is only about 25%. Thus, household heating with electricity's total energy conversion efficiency is far less than that of gas, which contributes to energy waste. Solar water heaters have been favored by many households of low-rise and multi-story residential buildings, but they have lost their place in higher high-rise residential buildings. Hence, it can be seen that optimizing the energy consumption mode has outstanding practical significance for building energy efficiency.

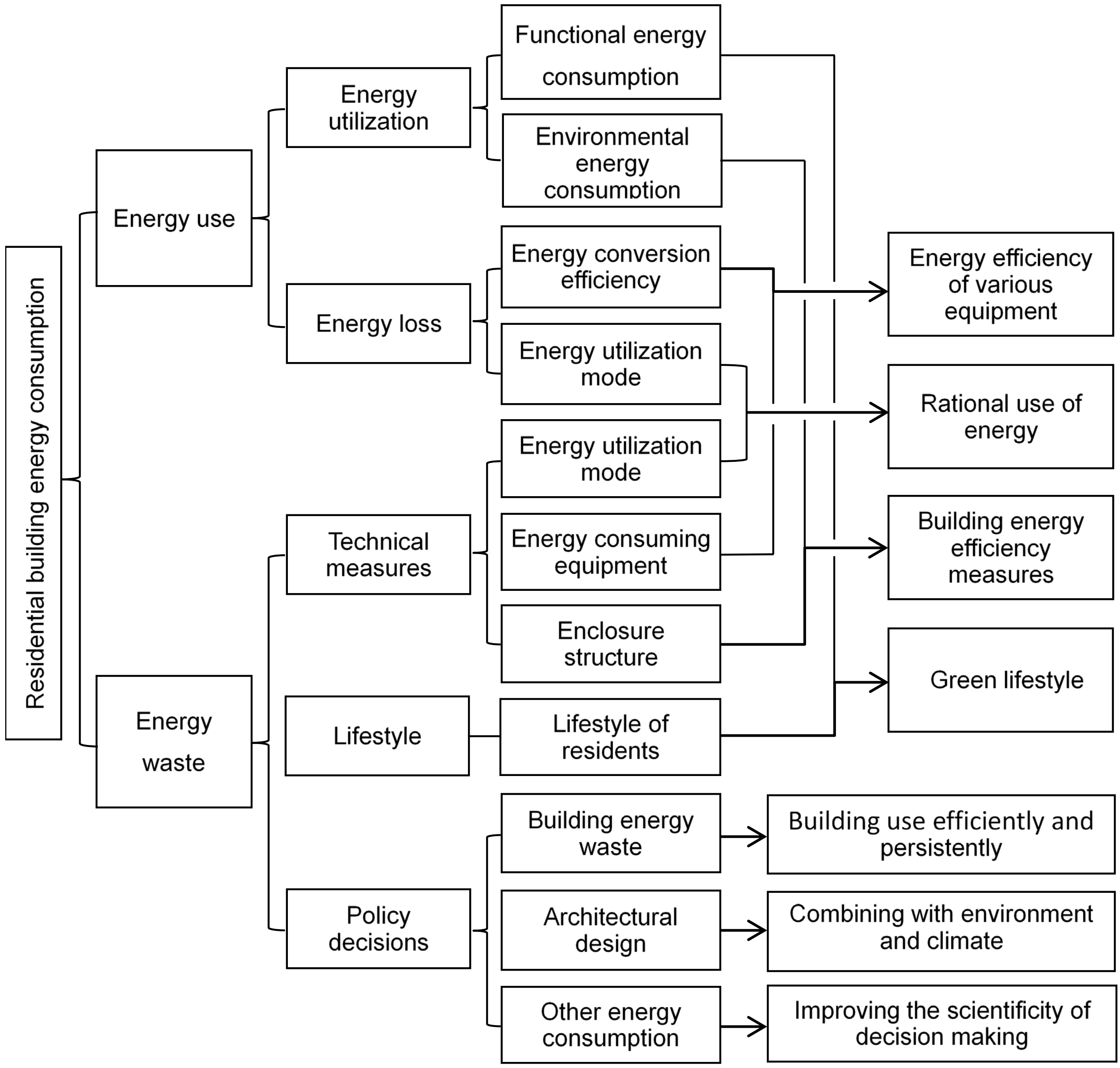

Figure 4. Residential buildings' energy consumption model and energy efficiency strategies.

Additionally, the essence of energy efficiency is to reduce the use of petrochemical energy. The rational utilization of solar energy, geothermal energy, wind energy, and biomass energy has an essential effect on energy efficiency. Furthermore, the staggered peak energy use and energy storage power stations are also vital for building energy efficiency. They are also crucial to replacing traditional air-conditioner heating with domestic boiler heating and substituting centralized heating for distributed heating. Plenty of studies on the optimization of the energy consumption mode have been carried out, and many projects of new energy sources have also been applied in construction, such as ultra-low energy consumption buildings, low energy consumption buildings, low-carbon buildings, etc. Nevertheless, due to the techniques requiring further improvement, immature products, and relatively high cost, the application of new energy in residential buildings is very limited. Hence, the optimization of the energy use mode is the key to the technical strategies for energy efficiency in buildings. The energy efficiency amount of optimizing the energy use mode (ΔE_{em}) is the sum of energy use of non-fossil energy and energy saving after energy use optimization.

Second, apply energy efficiency equipment. Building energy consumption is essentially the energy consumption of energy-using equipment, so the energy efficiency amount of using efficiency equipment (ΔE_{eq}) is the sum of the energy savings of various equipment after taking energy efficiency measures. The application of energy-saving equipment is also one of the keys to building energy efficiency, which requires the development and technical support of relevant industries. Taking water purification equipment as an example, the terminal water supply system developed by the author can not only replace the water purifier with high energy consumption, promote the upgrading of the traditional pipeline purified water supply system to save water resources greatly, but also does not consume electric energy, thus the energy-saving effect is very prominent [20]. In addition, the promotion and application of energy-saving lamps, cookers, variable frequency motors, and air conditioners, etc., have played an important role in building energy efficiency in China but still need improvement.

Third, improve the thermal performance of the envelop enclosure. The energy efficiency amount of the enclosure structure (ΔE_{es}) is numerically the difference in energy loss of the enclosure structure before and after taking thermal insulation measures. Traditional building energy efficiency mainly emphasizes heat preservation and enclosure structure heat insulation, and fruitful theoretical and technical studies have been carried out, so a significant number of new materials and techniques have also been vigorously promoted in practical projects. However, some insulation structures are unscientific, as well as having potential safety hazards, which is exemplified by the peeling of exterior wall insulation layers, and some thermal insulation approaches have serious technical defects, whose actual effect is relatively limited.

The research of Zhang et al., showed that in the passive influencing factors of high-rise residential buildings, the weight of the enclosure structure accounted for 90.69%, which was the most important decisive factor, and the proportion of the external wall structure was 44.66% [21]. In the National Natural Science Foundation Project "Research on the assembly transformation of existing building exterior wall in Yangtze River Delta", the author put forward the technical scheme of assembly, integration, serialization, systematization, and light-weighting in view of the common building defects, such as cracking and peeling of facades in China. Among them, integration referred to the integration of the finish layer, insulation layer, bearing layer (mainly bearing horizontal load and self-weight load), and even solar energy utilization components, etc., to constitute an integrated panel system with the characteristics of self-insulation, self-load-bearing, and free of finish. Based on a complete understanding of the mechanism of the load, climate, and other factors acting on the exterior wall, systematization means to solve the problems of production, transportation, installation, economy, and environmental protection in the transformation of external walls by means of materials and structures. The system meets the energy efficiency and safety needs and enhances the beauty of exterior walls. It improves the service life and quality of exterior walls to avoid common building diseases, such as the vicious circle of bad and repair. It achieves the same life as the exterior wall and the building. Obviously, it has vital practical significance for the energy efficiency and safety of the enclosure structure.

In a word, in terms of technical strategies, the building combined with climate design, scientific building structure adoption, energy utilization improvement, HVAC system optimization, suitable renewable energy usage, and energy-saving equipment selection not only has a long way to go for energy efficiency and emission reduction but also has great potential that directly affects the energy efficiency amount in building operation (ΔE_{tm}):

$$\Delta E_{tm} = \Delta E_{em} + \Delta E_{eq} + \Delta E_{es} \quad (10)$$

3.2.2. Energy Waste in Lifestyle

According to the aforementioned, building energy consumption mainly occurs in the phases of materialization and use, and the main battlefield of energy efficiency in residential buildings lies in the daily life of residents. In terms of energy consumption in the indoor environment, human environmental adaptability has great flexibility. For example, cold in winter and hot in summer are natural phenomena adapted by humans. Adjusting the room temperature lower in winter and higher in summer does not have much impact on comfort, but the energy-saving effect is highly significant. If the temperature of a 1.5 p air conditioner is set to rise by one degree Celsius, and the air conditioner runs continuously for 24 h, the average power consumption can be reduced by about 4.5 degrees. Academician Jiang Yi's studies have long indicated that regardless of whether it is a residential or office building, the vast difference in energy consumption in the same type of building does not stem from whether the advanced technology is adopted for building energy efficiency, but more determined by the different indoor environment and the lifestyle of users [22].

In terms of the energy consumption of residential behaviors, keeping early hours is not only conducive to the body but can also reduce the energy consumption of lighting and other equipment. Behaviors, such as turning off the lights, hot water taps, avoiding cooking too long, etc., will reduce the energy consumption of residential behavior and is conducive to home safety.

Therefore, the green lifestyle composed of good energy efficiency awareness, habits, and behaviors can greatly increase the energy efficiency of lifestyle (ΔE_{lf}). The research results in this area have been abundant, but current publicity and promotion efforts are still insufficient.

3.2.3. Energy Waste in Policy Decisions

At the macro level, the energy waste caused by unscientific and unreasonable policies and management in construction activities is even more incalculable; among them, the energy consumption caused by the vast number of vacant houses is most severe. In 2020, vacant houses in China numbered about 10 billion m^2, consuming about 600 million T of steel and 2 billion T of cement, 1.3 billion tons of standard coal, and 5 billion tons of CO_2. Moreover, more vacant houses will affect the energy consumption and livability of the occupants due to the envelop enclosure with no thermal insulation measures, such as floors and partitions, whose thermal conductivity coefficient is large and heat storage coefficient is high. Thus, the heating and cooling capacity of occupants' rooms will be exhausted by the transition to the upstairs and downstairs through these enclosures. In addition, short-lived buildings and luxury buildings are also the blind spots of current building energy efficiency in China.

There is only one earth, thus energy efficiency and emission reduction in China should be implemented from the perspective of the overall environment and resources. For example, currently, the average building energy consumption per unit area in Jilin Province is 45.8 kg of standard coal/(per square meter per year), which is about four times that of Yunnan Province [23], which indicates that the same project location in Yunnan obviously has an energy consumption advantage. Therefore, local governments policies, such as moderately controlling the total population in severe cold regions, formulating scientific industry standards and norms, scientifically making decisions on the location of major projects, reducing vacant houses, improving the service life of buildings, building long-term livable houses for individual families, and promoting the healthy development of the real estate industry, are of far-reaching significance to the macroscopic building energy efficiency in China.

At the meso level, the rational determination of project location, construction scale, planning layout, monomer scheme, energy consumption mode, and energy efficiency target are all crucial links affecting building energy consumption. First, the design combined with climate and environment should be the primary principle of building energy efficiency. Considering the future climate conditions, the reduction in air conditioner energy consumption is a key strategy of building energy efficiency in China. At the same time, the mass construction of large-depth, small dwelling-size apartments is not conducive to indoor lighting, ventilation, air exchange, and heat dissipation, and also not conducive to livability and decreasing the environmental energy consumption in households [24]. In the author's architectural education experience, we often said that architecture is not a flower in the greenhouse, but it is necessary to accept the baptism of climate all the time. This requires that the building should be designed with the climate in mind, and appropriate and efficient energy-saving and human-friendly strategies should be taken implemented for characteristics such as temperature, precipitation, airflow, and solar radiation in the project selection, site planning, general layout, monomer scheme, and structural design.

Additionally, in the planning phase, it is necessary to reasonably determine the construction scale, building shape, building orientation, sunshine spacing, site wind environment, etc. In the monomer design, the space composition, building facade, external wall doors and windows should be seriously considered to save land, energy, water, and materials. Although from textbook to design specifications, the existing studies on these aspects have been abundant, few are implemented. For example, China's glass curtain wall in the south and north area was not well combined with climate conditions. Once the apartment type is not suitable for occupation, it will promote an increase in housing improvement demand and lead to more housing vacancies. Large condominiums will enhance the energy consumption in the materialization and use phases.

At the micro-level, the selection of efficient and long-lived insulation materials, the adoption of scientific construction schemes and energy efficiency equipment, the careful design of construction drawings, the strict construction according to the drawings, and the elimination of discrepancies between design drawings and construction drawings, and the avoidance of anti-energy efficiency phenomenon are the guarantees of achieving an energy efficiency standard [25]. The review of construction drawings has long been implemented in all parts of China. With the strict implementation of the Green Building Evaluation Standard, it is relatively easy to implement energy efficiency work at the micro-level.

In short, although the energy efficiency (ΔE_{pd}) generated by scientific decision-making is difficult to calculate, if the energy waste caused by policies and decision-making cannot be effectively controlled, other energy efficiency strategies in the construction field will play a limited role or even increase the cost. The energy efficiency significance of the macro level is greater than that of the meso level and even more significant than that of the micro-level.

4. Discussion

1. In order to achieve the goal of carbon peaking and carbon neutrality, it is not enough to just focus on building energy consumption in a narrow sense. It is necessary to evaluate building energy consumption over the whole building life cycle. The energy consumption in the materialization phase is about half of the total building energy consumption, where the energy efficiency by consumption reduction in the production of building materials and equipment, the application of low-energy building materials, and the saving of materials have great impacts. Although the energy consumption of the construction process and demolition treatment accounts for a small proportion, it also has crucial energy efficiency significance. Significantly, the resource utilization of construction waste has a dual significance to energy efficiency and environmental protection in building demolition treatment.
2. Energy consumption and energy waste in the whole life cycle of buildings exist, where normal energy consumption should be guaranteed while building energy efficiency is the reduction in all kinds of energy waste. The energy consumption in

the operation phase includes the energy consumption of the indoor environment, residential behaviors, and public facilities, which will all continue to increase over a certain period and range.

3. Generally speaking, building energy efficiency should be promoted from three aspects: technical strategies, lifestyle, and policy decision-making. In terms of energy efficiency in technical strategies, enclosure structure, energy consumption mode, as well as energy-consuming equipment, all need to be improved to save energy. Although it is difficult to calculate the energy efficiency (ΔE_{lf}) in lifestyle and energy efficiency (ΔE_{pd}) from scientific decision-making, the energy consumption is also within the boundary of building energy consumption and has important practical significance for China to achieve the goal of carbon peak and carbon neutrality. Therefore, further research is urgently needed.
4. The energy efficiency target is calculated based on the benchmark building energy consumption (E_e). Even if it increases from 65% to 75%, this not only fails to reflect the actual energy efficiency level of residential buildings but also contradicts the actual energy consumption of residential buildings, including increasing residential electricity and natural gas consumption. Thus, the current standards related to building energy efficiency still need to be improved.

5. Patents

1. A window screen based on electrostatic adsorption and photocatalyst, Chinese invention patent, ZL201510769642.2;
2. A Mercerized photocatalyst emulsion paint and its production process, Chinese invention patent, ZL201510766822.5;
3. A kind of Water purification process and water purification equipment, Chinese invention patent, ZL201410376716.1;
4. An intelligent multi-purpose anti-theft window, Chinese invention patent, ZL201310229192.9;
5. A composite foam glass exterior wall panel with self-thermal insulation and non-decoration features, Chinese invention patent, ZL201310325951.1.

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