Design and optimization of zero-energy-consumption based solar energy residential building systems

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Abstract. Energy consumption of residential buildings has grown fast in recent years, thus raising a challenge on zero energy residential building (ZERB) systems, which aim at substantially reducing energy consumption of residential buildings. Thus, how to facilitate ZERB has become a hot but difficult topic. In the paper, we put forward the overall design principle of ZERB based on analysis of the systems’ energy demand. In particular, the architecture for both schematic design and passive technology is optimized and both energy simulation analysis and energy balancing analysis are implemented, followed by committing the selection of high-efficiency appliance and renewable energy sources for ZERB residential building. In addition, Chinese classical residential building has been investigated in the proposed case, in which several critical aspects such as building optimization, passive design, PV panel and HVAC system integrated with solar water heater, Phase change materials, natural ventilation, etc., have been taken into consideration.

1. Introduction
In recent years, energy consumption of residential buildings in China has shown a tendency of substantially increase. The main cause of the above-mentioned tendency lies in the following two aspects: Firstly, with the development of residents’ living standards, customers’ demands for energy consumption are continuously increasing. Secondly, the continuous and rapid growth of newly-built residential buildings in China has given rise to a substantial increase of total amount of residential buildings, thus significantly increasing the total energy consumption. According to the released China Energy Statistical Yearbook in 2015 [1], China’s total residential electricity consumption reached 698.92 billion kWh in 2013, corresponding to 12.4% increment as compared to that in 2012; Considering the ever increasing residential energy consumption, energy-saving techniques have attracted more and more attentions. Compared with the developed countries, the development of energy saving buildings in China is still in its infant stage. Not until 1986 did China promulgate and implement the first regulation referred to as ‘Energy conservation design standard for new heating residential buildings (JGJ26—86)’, aiming at propelling the energy saving of buildings to attain an energy-saving rate of 30%. In 1995, the Ministry of Construction promulgated the second energy saving Standard ‘Energy conservation design standard of new heating residential buildings (JG9 26—95)’, followed by proposing ‘Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone (JGJ134-2001)’ and ‘Design Standard for Energy Efficiency of
residential Buildings in summer-hot and winter-warm zone (JGJ75-2003)' in 2001 and 2003, respectively. In all the above-mentioned standards, the government made compulsory requirements on energy-saving design and raised the requirement on energy-saving rate to 50%. In 2010, such as ‘Design Standard for energy Efficiency of residential Buildings in severe cold and cold zone (JGJ26-2010)’ and ‘Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone (JGJ134-2010)’, which required an energy-saving rate up to 65%, were promulgated in some related areas. Despite all this, there still exists a gap between the standard in the developed countries as England, the U.S., and Germany and that in China.

In 2009, the United States’ government released the report titled ‘US federal zero energy consumption, high-performance green building administrative order’. By 2020, residential buildings may be facilitated a zero net energy-oriented design. By 2030, new residential buildings is to achieve zero energy consumption England, on the other hand, has led the study on ‘zero energy buildings’. In 2006, the England government put forward to establish an environment-friendly future in a conference concerning the sustainable development of residence, zero carbon emissions were achieved by all new buildings by 2019 [2]. Furthermore, European Council for an Energy Efficient Economy has proposed the target of making ‘nearly Zero-Energy residential buildings (ZERBs)’ [3]. Thus, people all over the world are working towards the aspect of ‘zero-energy-consumption’ buildings.

In recent years, many scholars have carried out the studies on zero energy buildings. For instance, the most of the existing ZEB definitions [4] and roadmap towards net zero and positive-energy buildings [5] have been presented. Furthermore, Shady Attia reveal potential challenges and opportunities for integrating optimization tools, and also assess the gaps and needs for integrating building performance optimization tools in net zero energy buildings (NZEBo) design [6]. Meanwhile, Liping Wang employed simulation method to research zero energy house design in UK [7]. In addition, Ravi S. Srinivasan used a ‘Renewable Energy Balance’ (REB) in environmental building design as a tool to maximize renewable resource use [8] and Ming Jin develop micro grid optimal dispatch with demand response (MOD-DR), which fills in the gap by coordinating both the demand and supply sides [9]. Apart from it, an energy storage system was designed in residential buildings with photovoltaic [10] and PV systems and ground source-heat pumps were found to affect the specific energy demand of buildings [11]. Multi-Attribute Decision Making methods have been used for achieving ZERB [12] and building cluster emulator were also applied in Net-zero energy building clusters [13]. Many scholars have respectively conducted researches on zero-energy-consumption perspectives as concept, calculation, development, application and economic analysis. However, without probing into the systematic design approaches, we have developed the solar energy housing from experimental zero-energy buildings to that of the direction of integrated design of variant aspects.

In this paper, through the analysis on influential factors of ZERB, we probe and investigate the systematic thinking and approaches for the design of zero-energy-consumption solar energy residences. The structure of this paper is as follows: Section 2 describes design method for ZERB by focusing on passive technology and solar systems. In section3, a case is studied on residential building scheme, simulation analysis and energy balance. Section 4 discusses intelligent micro-networks and incremental costs of zero-energy-consumption buildings. Section 5 summarizes five design steps to ZERB.

2. Design method for zero-energy-consumption buildings
A zero-energy building may reduce the energy consumption of a building to the level as low as possible relying on the advanced materials and designs, together with technologies of energy conservation, thus supplementing the needed remaining energy by using renewable energy.

2.1. Energy flow analysis for residential buildings
To achieve a ZERB design, the most important step is to analyse the critical issues such as energy type, flow direction and the other aspects of the building. Figure 1 shows the energy flow diagram of residential energy supplying systems. While the system is divided into energy utilization units at
different ends, energy flow can be further divided into four parts, i.e. inputting, converting, delivering and utilization. The inputting side of energy needs to consume the primary energy, while the generating side of energy is derived from the renewable energy (such as household solar-thermal utilization, photovoltaic power generation and biomass power generation).

![Residential energy flow diagram](image)

**Figure 1.** Residential energy flow diagram.

In the following, ZERB is used to denote the total energy generated through renewable energy in the building that is larger than the total consumption of various purchased energy of the building during the statistical period of one year, but sometimes you may also need energy exchange with the grid to obtain instantaneous balance.

### 2.2. Significant factors influencing energy consumption of residential buildings

Building factors mainly involve shape coefficient, direction of the building and natural ventilation, etc, as well as window-wall ratio and thermal performance parameters of building enclosure. And equipment factors mainly involve system efficiency of air-conditioners. Furthermore, other factors include matching problem between the air-conditioning system and cooling/heating loads of the building, the influence on air-conditioners of heat source inside electrical equipment, and the energy efficiency of household appliances.

As a complex energy system, a ZERB possess direct and indirect influential factors of energy consumption. To improve the entire energy efficiency of the building. The influential factors of energy consumption can be divided into a variety of factors, including outer factors, building factors, equipment factors, habits and other factors. Thus, by finding out the related factors of energy system, corresponding measures will be adopted to both reduce consumption and increase surplus energy.

### 2.3. Design paradigm of ZERB

To design ZERBs, we should adopt integrated methods. Figure 2 shows the design of ZERB relies on systematic ideas, firstly, it is suggested to consider the energy system while designing the buildings, secondly, making the design scheme match the energy system. Thirdly, the building scheme with passive technology optimization as well as advanced energy-saving technology can reduce energy consumption. Fourthly, you could use tools to simulate energy consumption. Fifth, utilization of resources such as solar energy is highly encouraged.
2.3.1. **Passive technology.** When designing ZERB, passive technology may be implemented; the following aspects shall be taken into consideration.

- **Passive heating.** Through design of various aspects (such as building orientation, surrounding environment setting), the building is capable of utilizing solar energy to the greatest extent for providing heat in winter, whilst mitigating an extremely high temperature in summer days.
- **Passive cooling.** We may store cold capacity generated during the day, while open air-vents at night and release stored cold in structural elements into the air through ventilation at night, thus achieving passive refrigeration in the building.
- **Sun-shading Technology.** Outer sun-shading can be designed either by adopting fixed sun-shading structure or by employing movable sun-shading structure. Besides outer sun-shading, the light guiding and sun-shading system as well as changeable glass can also be utilized.
- **Natural Ventilation.** We properly decide design of the building such as direction of the building, direction, opening and size of windows.

2.3.2. **Scheme optimization.** In this part, we discuss effects on reducing energy consumption from aspects such as windows performance, outer sun-shading, natural ventilation and PCM utilization. Meanwhile, we may select relevant performance parameters and reduce indoor cooling loads and heating loads.

2.3.3. **Equipment selection.** The typical furniture such as cooking equipment, refrigerators, televisions, washing machines and air-conditioners, there also exist other devices such as household entertainment device, ovens, sterilizing cabinets and drying machines etc. Using low-power electrical equipment will have an active effect on saving energy. Efficient air-conditioners or heat pump sets are highly welcome. Currently, the standards of energy efficiency level for household appliances have been established.

2.3.4. **Energy simulation.** Simulation will be performed on energy usage of the building for the whole
year. By adopting comparison demonstration with multi-schemes, we predict formation of energy consumption. Furthermore, simulation software to simulate energy consumption, together with simulation analysis on cooling, heating, ventilation, lighting and other units that consume power in the building.

2.3.5. Solar energy systems. Solar energy is divided into a variety of categories, including photovoltaic, photo-thermal, cooling and thermal utilization, cooling and heating etc, some technology summary you could see table 1. It is necessary to optimize the design of solar energy system on the basis of analysis results of energy balance by combining actual conditions. Furthermore, renewable energy sources can be utilized, with energy be supplied to the greatest extent.

| Category             | Form               | Technical Characteristics                                                                 |
|----------------------|--------------------|------------------------------------------------------------------------------------------|
| Photovoltaic Power   | Different Forms    | Amorphous silicon thin-film solar: Possible to integrate with external walls of the buildings; with about 8% conversion efficiency; Mono-crystalline silicon: With about 18% conversion efficiency of solar energy and high cost. Poly-crystalline silicon: With about 12% conversion efficiency of solar energy and low cost. |
| Generation           |                    |                                                                                          |
| Photo-thermal        | Solar Collector    | Collect solar radiation to heat water by utilizing solar collectors (including natural-circulation-type solar water heaters and forced-circulation-type solar water heating system). |
| Utilization          | System             |                                                                                          |
| Cooling and          | Solar-wall Air     | Waste heat generated from photovoltaic batteries can be collected to heat water and heat in the cavity of the solar wall can be taken away through water circulation. Meanwhile, waste heat of air evacuated from the cavity of the solar wall can also be used. |
| Thermal Utilization  | Collector          |                                                                                          |
|                      | System             |                                                                                          |

Note: PVs efficiency is from product performance information

2.3.6. Energy balance. On the basis of energy simulation, we analyse the system and the form of usable/renewable energy sources in the residential building. Meanwhile, we conduct calculation on energy balance to supplement needed remaining energy. Since solar energy represents the development direction of residential buildings in the future, we will focus on the utilization of solar energy in residential buildings in this paper.

3. Case study
We have built a solar energy residence with an area of no more than 74 m², which applies anti-woo roof structure elements of Chinese classical building. The curve roof can not only maximize PV panels’ power generation efficiency, but also benefit both ventilation and cooling. Meanwhile, the proposed design integrates many passive and active energy-saving technologies. For instance, the external walls and interior surfaces are both made of eco-bamboo, while the walls are fitted with a new high-performance vacuum insulation board and a vacuum and hollow three-layer glass window with high insulation level. In addition, PCM are applied to the surfaces of interior walls to both ease the change of air temperature and increase living comfort. Last but not the least, heat recovery unit or thermal duct is equipped in the back of PV components set to recover heat and ensure high efficiency of power generation, together with solar hot water heaters and heat pump units that are integrated into multi-heat sources equipment systems.

3.1. Initial determination of residential building
We arrange a courtyard in the southwest of the site considering the fact that the special exhibition site
is closed to the river and the limited footprint. First of all, the house is connected with the river. Furthermore, the living spaces indoor surround this courtyard. Secondly, connected with the prevailing wind direction, a courtyard in the southwest of the site is beneficial to improve the outdoor wind environment. In addition, the south-to-north direction of the bedroom’s layout is helpful to get sufficient sunshine, while the living room faces the main landscape in the west.

3.2. Deepening residential building scheme

In the proposed design, we should consider the meteorological conditions as well as the surrounding buildings. In light of the fact that local temperature difference between day and night in the summer is large, and outdoor wind speed and relative humidity is suitable, natural ventilation technology, table 2 is the thermal performance parameter index of the envelope in the case.

| Table 2. Thermal parameter components of building envelope. |
|----------------------------------------------------------|
| **construction** | **Walls** | **Floor** | **Windows** | **Doors** | **Ceiling** |
| Heat transfer coefficient (w/m².K) | 0.2 | 0.25 | 1.0 | 1.2 | 0.12 |

To further optimize the energy systems, the following four cases, i.e. windows performance, external sun-shading, natural ventilation and PCM utilization, are analysed through the simulation.

After considering the way of using three-layer Low-E glass filling argon gas to take place of common double-layer Low-E glass, energy consumption of cooling of sensible heat parts can be saved up to 450 kWh (and that of heating can be saved up to 143 kWh).

We use external sun-shading to prevent solar radiation. The energy consumption of cooling in the summer is capable of decreasing up to 176 kWh after adopting this measure.

PCM are used to both achieve heat storage/release and improve indoor thermal comfort. Heat storage and release of PCM will make cooling (heating) load in the summer (winter) decrease by about 20%, with energy consumption of cooling and heating decreased by 105 kWh and 131 kWh, respectively.

As ventilation of the building in the summer night had been considered in the energy consumption simulation before, the energy-saving is mainly reflected by the fact that the amount of air conditioner energy consumption can be saved up to 57 kWh.

**Figure 3.** Schematic of HVAC system, PV/T system and hot water system for the proposed house.

We combine local meteorological conditions together with resources and select efficient and reasonable energy systems, figure 3 describes air-source heat pump with heat recovery equipment in the summer and recover may waste heat of the condenser to store in the living hot water tank that can be employed for heating in the winter, while outdoor fresh air is pre-cooled and pre-warmed by indoor back-wind through the heat exchangers in summer or winter for reducing fresh air load. Furthermore,
PCM are installed in the floor ventilation tubes so as to not only circulate for accumulation of cold outdoors in the summer night and then make it cycle to release cold quantity indoors in the day, but also circulate and reserve heat by leading hot air around the roof to the tubes in the winter days and make it cycle to release heat indoors. As for cooling load in the summer and heating load in winter, we select air conditioner with the cooling capacity of up to 3.5 kW.

3.2.1. Building envelope. Envelope insulation is critical to the building energy consumption, and building a high-performance envelope constitutes a cost-efficiency strategy. Thus, vacuum insulation panel (VIP) is used in the proposed house by significantly reducing the thickness of the walls and guaranteeing the best thermal effects, because VIPs are 7-10 times than traditional insulation materials in thermal effects. In order to keep envelope insulation at a good condition, insulation materials must be kept dry and thus can be functioning normally. In addition, the products minimize air infiltration and resist to water penetration, whilst allowing moisture to migrate freely and safely into the atmosphere.

3.2.2. HVAC System integrated with solar water heater. A heat pump and a hot water tank are integrated, in which the exhausted heat is used to as an assistant heat source or heat water if insufficient solar radiation is met. For the ventilation side, the needed outdoor air can be delivered based on the required reading data by the CO₂ monitor located in the return section, and thus can be treated after heat exchange with indoor exhaust air. HVAC system includes several critical functionalities, such as air distribution, outdoor unit, indoor unit, heat exchange unit, PCM channels, temperature/humidity sensor, and CO₂ sensor. The characteristic of PCM is elaborated on as follows: Latent heat is 120 kJ/kg, Melting temperature is around 21 °C.

3.2.3. PV/Thermal system. PV panels are installed in a polyline curved roofs in the house. However, most of the solar energy is lost in a heat-emission manner, which otherwise weakens PV performance. Wasted heat produced by PV can be released in summer and collected to heat floor panel in winter, thus establishing a so called 'PV/T system’. Furthermore, the collected heat from PV/T system is used with PCM floor channels to both provide hot air to bedroom and maintain a relative high temperature in winter night.

3.2.4. Solar hot water system. The house uses solar thermal energy to meet almost all hot water demand. On rainy or cloudy days, solar collector cannot meet the demand of providing hot water, while the integrated HVAC heat pump will be operated automatically for heating water. No matter how good the weather is, solar collector with the heat pump can always supply sufficient hot water for the house. Furthermore, temperature stratification is formed in the water tank, thus substantially improving the heating efficiency of solar water system.

3.2.5. Photovoltaic system. PV panels are installed on two south-facing slope roofs as well as the south wall, and its conversion efficiency can be up to 13.4%. PV system consists of several components, including PV Array, Module Supporter, Junction Box, Inverter, and Power Panel. Note that PV installation area corresponds to 60 m² in roofs and 13 m² in a south wall. Thus, the overall capacity is about 10 kW. Using RETScreen software and according to meteorological data etc., we observed that PV systems can generate electricity up to 13362 kWh/a.

Table 3 is the simulation result. From table 3, July being the month with highest energy, while that in the winter days becomes lower. Furthermore, power-generating capacity in every month of the whole solar photovoltaic power generation system can be obtained, which of June is about 1500 kWh. For instance, in June, daily power-generating capacity under normal lighting conditions is about 52 kWh, while that in cloudy days is only 13 kWh. In addition, PV system can produce more energy than consumption, with extra energy flowing into the utility grid.
### Table 3. Annual PV energy production (unit /kWh).

| Month   | Roof 35° inclination slope | 23° inclination slope | 11° inclination slope | 30° inclination slope | Total energy (kWh) |
|---------|---------------------------|-----------------------|-----------------------|-----------------------|-------------------|
| January | 213.72                    | 222.32                | 188.07                | 50.57                 | 674.68            |
| February| 271.08                    | 292.57                | 259.46                | 65.08                 | 888.19            |
| March   | 336.01                    | 378.92                | 354.01                | 82.1                  | 1151.04           |
| April   | 344.54                    | 406.83                | 399.69                | 85.78                 | 1236.84           |
| May     | 363.73                    | 442.62                | 450                   | 91.71                 | 1348.06           |
| June    | 414.05                    | 511.68                | 529.34                | 105.09                | 1560.16           |
| July    | 428.79                    | 526.6                 | 540.87                | 108.57                | 1604.83           |
| August  | 412.6                     | 492.97                | 489.49                | 103.26                | 1498.32           |
| September | 360.87                | 413.98                | 394.05                | 88.79                 | 1257.69           |
| October | 263                       | 290.32                | 264.92                | 63.7                  | 881.94            |
| November| 212.76                    | 224.39                | 193.39                | 50.61                 | 681.15            |
| December| 184.81                    | 190.93                | 160.11                | 43.61                 | 579.46            |
| Total   | 3805.96                   | 4394.13               | 4223.42               | 938.89                | 13362.4           |

#### 3.3. Simulation parameters setting

Parameter settings of energy-consumption are shown in table 4, in which indoor temperature and humidity set points are in strict accordance with the requirements of the competition. It is shown that heat insulation performance of various structures is superior to the same type of products. Furthermore, air conditioning system selects air source heat pump systems with heat recovery device, whose heat recovery efficiency can be up to 70%. When the accumulation of heat of solar collector is insufficient for hot water requirement, the heat quantity recovered will be finally adopted as a supplement. Two aspects are considered when we buy household appliances: Firstly, electrical power consumption is kept as low as possible; secondly, the size of household appliances is kept as small as possible.

### Table 4. Module input.

| Location       | Climate file | Type               |
|----------------|--------------|--------------------|
| Set point      | Air Temperature (°C) 23-25 | Air Relative Humidity (%RH) 45-55 | Air Condition space 54 | Floor area (M²) 54 | space volume (M³) 63 |
| HVAC System    | Equipment    | Cop Fan Efficiency | HRV Efficiency | DHW Solar sourced/heat pump recovery |
| Air sourced heap pump | 3.5          | 70%                | 70%                | Solar sourced/heat pump recovery |
| Occupant       | medium level 4 people | Lighting w/m² 3    |                     |

Additional, we choose four cases’ (see table 5, in which we adopt different kinds of measures) to simulate, Four cases’ simulation results are given by figure 4, figure 4 tells us when we adopt Case4
will be reduce energy consumption by 40% compared with the original design.

| Items                               | Original design | Case 1 | Case 2 | Case 3 | Case 4 |
|-------------------------------------|-----------------|--------|--------|--------|--------|
| Use low-E triple skin glazing       | No              | Yes    | Yes    | Yes    | Yes    |
| Add External sun-shading            | No              | No     | Yes    | Yes    | Yes    |
| Add PCM (floor, ceiling)            | No              | No     | No     | Yes    | Yes    |
| Add Natural Ventilation             | No              | No     | No     | No     | Yes    |

Note: Conditioned space area is 54 m². There are 4 people in the Bamboo House. We keep the temperature to be 23-25°C and humidity to be about 55%RH.

3.4. Energy Balance

Annual power-generating capacity of PV panels is 13362 kWh (see table 3), while annual electricity demand is only 5289 kWh. The power-generating capacity of PV system is 2.5 times as high as that of annual theoretical electricity consumption, and power-generating capacity of every month is higher than electricity demand of the corresponding month. Although, the total energy generated is larger than the total consumption of various purchased energy of the building during the statistical period of one year, here is one point to explain, when the solar energy can’t meet with the demand instantaneously, it is necessary to obtain energy from the grid.

4. Discussion

This paper focuses on the design steps of ZERB systems. However, intelligent micro-networks and incremental costs shall be taken into account when we design.

The ZERB in the future is an autonomous system with capabilities of self-control, self-protection and self-management, which can operate not only parallel with the external power grid but also alone. It is regarded as an important part of the intelligent power grid, which has been proposed recently to encourage local balancing of energy. It’s also helpful to relate the design of ZERB to the design of zero-energy community, which will encourage local balancing of energy [9]. Furthermore, It should also consider the latest development in IoT-enabled smart controls, Jin M develops Virtual Occupancy Sensing which you could use smart meters to indicate your presence in order to improve energy efficiency [14,15].

Nowadays, costs of renewable energy are still higher than conventional power, therefore, we need consider cost control objectives as much as possible. So when we design renewable energy, we should match necessary loads and make incremental cost of ZERB minimum. As for economic analysis of ZERB, Jarek Kurnitski studied cost optimal and nearly zero energy performance calculations for
residential buildings for nearly ZERB’s [16].

5. Conclusion
This paper shows that ZERB can be achieved from three aspects: Firstly, it is capable of reducing energy consumption at the terminals. Secondly, it can improve energy efficiency. Thirdly, it increases the generated energy at the side of renewable energy. More important, this paper shows us that ZERB design should consider the following five aspects: (1) Optimization of building schematic design. (2) Optimization of passive building design. (3) Energy Simulation. (4) Utilization of renewable energy sources. (5) Energy balancing analysis.

Future work is to develop ZERB technology, which include intelligent micro-networks and costs of zero-energy-consumption.

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