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The Third Solar Decathlon China Buildings for Achieving Carbon Neutrality

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Abstract: This research explored buildings for carbon neutrality to solve the global warming problem in the Third Solar Decathlon China (SDC). The methods were derived from subjective and objective evaluation aspects based on the competition rules. Then, the results of the concepts, technologies, and prospects of 15 buildings were output. The conclusion was summarized after a discussion as follows: (1) Solving global warming through carbon neutrality is widely required and research into this issue is required now. (2) Research methods were determined via five subjective and five objective contests with multiple sub-contests. (3) Fifteen buildings' concepts, technologies, and prospects were determined regarding the carbon neutrality aspect. (4) A good architectural design concept was needed before building for carbon neutrality. (5) This research summarized the current development of architecture concepts and technologies in academia and industry. (6) Thirty-five kinds of active and passive technologies were determined, where PV as an active method and modular assembly as a passive method were the most used in this competition. (7) The technologies used with a low frequency, such as wind turbine, Stirling engine, hydrogen fuel cell, UHPC, PCM, and SST walls technologies, also need further attention. (8) The prospect of carbon neutrality, especially for energy production in residential buildings, may shift people's passive acceptance of carbon neutrality to active energy production. (9) Using ANP to produce the SDC ranking may be considered for more scientific investigations to demonstrate the carbon neutrality effect. (10) The limitations will continue to be researched in the future. Finally, this research aimed to make a contribution to solving the global warming for sustainable development.

Keywords: global warming; carbon neutrality; architectural design; energy use; sustainable development; Solar Decathlon China

1. Introduction

1.1. Background

Global warming has been a global problem for a long time. At least from the 19th century, scientists began to recognize the involvement of carbon dioxide in global warming [1]. From 1950 to 1971, more and more researchers solidified the hypothesis of anthropogenic global warming [2,3]. Although there also exist some queries about man-made global warming, the conclusion that global warming is man-made is generally considered to be common sense given the abundance of research evidence [4]. In 1972, a series of international policies on global warming began to develop. The United Nations Conference on the

Human Environment (UNCHE) in Stockholm roused international concern about global warming [5]. In 1987, Our Common Future was published by the World Commission on Environment and Development (WCED) to define a consensus-based concept of sustainability for global development. The book explained that the amount of carbon dioxide should be reduced, as it leads to global warming [6]. In 1992, the United Nations Conference on Environment and Development (UNCED), also called an Earth Summit, held in Rio de Janeiro, resulted in the Rio Declaration on Environment and Development, as well as Agenda 21, and introduced the Framework Convention on Climate Change (UNFCCC) for achieving sustainable development through specific actions, including carbon reduction [7]. In 1997, the Kyoto Protocol was issued, which was the first quantified legal document under the UNFCCC to promote global energy conservation and emissions reduction for sustainable development [8]. In 2009, the 15th United Nations Climate Change Conference was held in Copenhagen, Denmark, to discuss the global emissions reduction agreement from 2012 to 2020 after the first commitment period under the Kyoto Protocol expired. Unfortunately, at that time, no agreement on a new legal document was reached. A second commitment period was agreed to in 2012 to extend the agreement to 2020 [9]. In 2015, the 21st United Nations Climate Change Conference was held in Paris, France. Negotiations resulted in the adoption of the Paris Agreement, which has governed climate change reduction measures since 2020. The first evaluation based on this quantified legal document will be in 2023. One of the aims is to keep the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels [10]. Therefore, carbon neutrality is more and more important for attenuating global warming to achieve sustainable development.

1.2. Literature Review

Carbon neutrality refers to offsetting the generated carbon dioxide (CO_2) through carbon capture, storage, and conversion within a certain period to achieve “zero emission” of greenhouse gases [11]. This concept was accepted worldwide after the Danish government initiated a competition to find a model for a carbon-neutral community. In the 1990s, Denmark’s Minister for the Environment, Svend Auken, returned from the Kyoto Climate talks enthusiastic about his country reducing its carbon emissions. In 1997, he announced this competition, and the winner was Samsø, which became the world’s first 100% renewable-energy-powered island in 2005 [12–14]. In the same year, Future Forests used the term “carbon neutral” in their business plan and founded a company in London, which was later rebranded as The Carbon Neutral Company [15,16]. In 2006, the New Oxford American Dictionary’s Word of the Year was “Carbon Neutral” [17]. Although such terms alternate between “neutrality” and “neutral”, more and more academic and research institutions use “carbon neutrality” nowadays. In 2018, the glossary in the Intergovernmental Panel on Climate Change (IPCC)’s Working Group Report used “carbon neutrality”, defining it as “net zero CO_2 emissions”, which means that anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period [18].

Regarding carbon neutrality development in China, in 2014, the country proposed its intention to achieve its carbon peak around 2030 [19,20]. In 2020, Chinese President Xi Jinping pledged to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060 at the 75th session of the United Nations General Assembly. This is China’s first long-term climate goal, which requires China to rein in CO_2 and probably other greenhouse gas emissions to net zero [21]. Recently, at the 2021 World Economic Forum, President Xi Jinping advocated for international cooperation on climate change in the context of carbon neutrality to achieve the United Nations 2030 Agenda for Sustainable Development [22]. Based on China’s current national conditions, the goal of carbon neutrality for sustainable development will be achieved mainly from the research and design application of green buildings, smart technologies, healthy living spaces, renewable energy, building materials and structures, urban renewal, rural revitalization, and other aspects. In this research, the Third SDC buildings are researched for carbon neutrality.

1.3. Research Significance

To solve the global warming problem, carbon neutrality needs to be achieved from the international to country levels. This research focused on carbon neutrality through a Third SDC buildings analysis with the aim to contribute to solving the global warming problem. Based on the architecture concepts, technologies, and prospects, this research produced a significant contribution toward achieving carbon neutrality for sustainable development.

2. Research Objects

2.1. The Third SDC Buildings

The Third SDC buildings were constructed in Desheng village, Zhangbei county, Zhangjiakou city, China, in 2021 for an international collegiate science and technology competition for solar-powered buildings. This competition was introduced by the Solar Decathlon (SD) of the United States Department of Energy with the aim to create a fully functional, comfortable, livable, and sustainable living space by freshly integrating clean energy, energy conservation, and environmental protection into the architectural design [23]; this was hailed as the Solar Olympics and the Green Building Expo.

In the Third SDC competition, 15 demonstration buildings were built by 15 teams from 29 universities globally. Information on the 15 buildings and the teams is shown in Table 1. The site construction progress from July to September 2021 is shown in Figure 1, and photos of the building sites are shown in Figure 2.

Table 1. Information regarding the 15 competition buildings and teams.

No.	Teams	Projects	Universities	Countries
1	Y-Team	Y-Project	Xi'an Jiaotong-Liverpool University Zhejiang University/University of Illinois at Urbana-Champaign Institute Thomas Jefferson University	China China USA
2	DUT and Associates	24 × 35 Housing Home	Dalian University of Technology	China
3	HIT and UCB	Modular Sustainable Cube	Harbin Institute of Technology	China
4	DTU-SUDA	Aurora	Technical University of Denmark Soochow University	Denmark China
5	THU	The Steppe Ark	Tsinghua University	China
6	HUI	HUI House	Hefei University of Technology University of Lille	China France
7	SRF	Pixel House	Shenzhen University RMIT University	China Australia
8	CUMT and AGH	T&A House	China University of Mining and Technology AGH University of Science and Technology	China Poland
9	Tianjin U+	R-CELLS	Tianjin University The Oslo School of Architecture and Design Tianjin Chengjian University	China Norway China
10	XJTU+	SMART	Xi'an Jiaotong University	China
11	CCMH	Pitched House	Chongqing University	China
12	BJTU+	BBBC	Beijing Jiaotong University Loughborough University	China UK
13	Solar Ark	Solar Ark 3.0	Southeast University Swiss Federal Institute of Technology Zurich Sanming University	China Switzerland China

Table 1. *Cont.*

No.	Teams	Projects	Universities	Countries
14	Hope Land	Hope Land-Natural Courtyard	Zhejiang Normal University Shenyang Jianzhu University Chemnitz University of Technology	China China Germany
15	Qiju 3.0	Qiju 3.0	Xi'an University of Architecture and Technology Southwest Minzu University	China China

Foundation construction Building assembly Building completion

Figure 1. The Third SDC construction progress.

No. 1: Y-Project

No. 2: 24 × 35 Housing Home

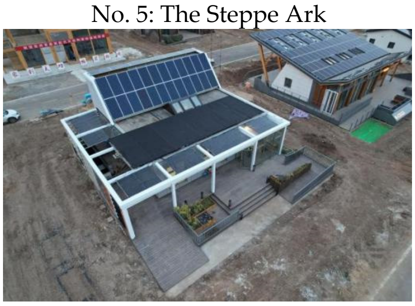
No. 3: Modular Sustainable Cube

No. 4: Aurora

No. 5: The Steppe Ark

No. 6: HUI House

No. 7: Pixel House



No. 8: T&A House

No. 9: R-CELLS

Figure 2. *Cont.*

No. 10: SMART | No. 11: Pitched House | No. 12: BBBC

No. 13: Solar Ark 3.0 | No. 14: Hope Land-Natural Courtyard | No. 15: Qiju 3.0

Figure 2. Buildings site photos.

2.2. Research Framework

The theme of the Third SDC was sustainable development, smart connection, and human health. Even though the theme of each session changes with the times, the Third SDC presented a significant contribution to the attainment of carbon neutrality, both in practice and academia. Thus, this research on carbon neutrality based on the Third SDC buildings aimed to investigate useful ways to avoid global warming to some extent.

Following the introduction of this paper, based on the background of global warming and a literature review of carbon neutrality, the SDC buildings are discussed as research objects.

The research framework discussed in the next section focuses on the analysis methods based on the competition rules, including subjective and objective evaluations. Then, the research results were determined from the Third SDC buildings. The discussion section discusses carbon neutrality in building concepts, technologies, and prospects. Finally, the conclusions are presented.

3. Methods

3.1. Competition Rules

The methods were based on the competition rules. The SD competition had 10 separately scored contest rules (hence the term decathlon), and some contests contained one or more sub-contests [24]. The competition rules of the Third SDC mainly focused on architecture, engineering and construction, energy, communications, market potential, indoor environment, renewable heating and cooling, home life, interactive experience, and energy self-sufficiency aspects. Each contest had a maximum value of 100 points. The final ranking of the SDC was based on 1000 total points. These 10 contests were divided into subjective and objective evaluation methods. The SDC buildings aimed to satisfy the requirements with different methods, especially for carbon neutrality. The Third SDC contests are shown in Table 2.

Table 2. The Third SDC contests.

Contest Name	Available Points	Sub-Contest Name	Available Points	Contest or Sub-Contest Type
Architecture	100	n/a	n/a	Juried
Engineering and construction	100	n/a	n/a	Juried
Energy	100	n/a	n/a	Juried
Communications	100	n/a	n/a	Juried
Market potential	100	n/a	n/a	Juried
Indoor environment	100	Humidity CO_2 level PM2.5 level Lighting	25 25 25 25	Measured/monitored Measured/monitored Measured/monitored Measured/task
Renewable heating and cooling	100	Space Hot water	60 40	Measured/monitored Measured/task
Home life	100	Refrigerator Freezer Clothes washer Clothes drying Dinner party Movie night	15 15 20 20 20 10	Measured/monitored Measured/monitored Measured/task Measured/task Juried/task Juried/task
Interactive experience	100	Media Theme day In the SDC house In the SDC community	25 25 25 25	Measured/task Measured/task Measured/task Measured/task
Energy self-sufficiency	100	Net-zero Off-grid	50 50	Measured/monitored Measured/monitored

3.2. Subjective Evaluation

The subjective evaluation included architecture, engineering and construction, energy, communications, and market potentials aspect. For the architecture aspect, the evaluation mainly focused on the architectural design in terms of the concept, aesthetics, and function. For the engineering and construction aspect, the main focus was on engineering systems that were energy efficient and energy producing, and the construction aspect concerned resource recycling. The energy aspect was primarily judged in terms of energy production, efficiency, management, and safety. For the communications aspect, aside from communication efficiency during teamwork, the new technologies for better communication, such as a VR display and online activities, were also considered. As for the market potential, this contest mainly evaluated the project's potential contribution to the local and regional market with target clients. Subjective evaluation from the human sensation side was based on the quality of the building, construction process, future development, etc.

3.3. Objective Evaluation

The objective evaluation was based on quantitative indicators regarding the indoor environment, renewable heating and cooling, home life, interactive experience, and energy self-sufficiency.

For the indoor environment evaluation, the humidity, CO_2 level, PM2.5 level, and lighting were used for the review. The time-averaged interior humidity was suitable when it was between 40% and 60%. As for the CO_2 level, it was considered better when below 1000 ppm indoors. Moreover, the PM2.5 level needed to be below 35 $\mu g/m^3$. For the lighting, the required illuminations in different function zones are shown in Table 3.

Table 3. Lighting environment evaluation.

Function Zone	Specific Space	Strength of Illumination
Living room	Normal activity	100 lx (0.75 m upper floor)
	Reading and writing	300 lx (0.75 m upper floor)
Bedroom	Normal activity	75 lx (0.75 m upper floor)
	Reading and writing	150 lx (0.75 m upper floor)
Dining room	Normal activity	150 lx (table surface level)
Kitchen	Normal activity	100 lx (0.75 m upper floor)
	Cooking	150 lx (working surface level)
Bathroom	Normal activity	100 lx (0.75 m upper floor)
Walkway	Normal activity	75 lx (0.75 m upper floor)

For the renewable heating and cooling evaluation, each space's dry-bulb temperature needed to be between 22 °C and 25 °C. Furthermore, this also required providing water of at least 40 °C before an average of 500 mL of water had passed through each sink faucet under normal operation.

For the home life evaluation, six aspects were evaluated: refrigerator, freezer, washing clothes, drying clothes, dinner party, and movie night. For the refrigerator evaluation, the time-averaged interior temperature of a minimum 170 L volume between 1 °C and 4 °C was favorable. For the freezer evaluation, a time-averaged interior temperature between −30 °C and −15 °C was required. The freezer volume needed to be a minimum of 57 L. For the washing clothes and drying clothes evaluations, the normal washing machine functions were required to be completed. As for the dinner party and movie night sub-contests, they were quantitative assessments of social activities in the building. Here, we do not go into detail on these two aspects—only building studies related to carbon neutrality were focused on in this research.

For the interactive experience evaluation, the media, theme day, in the SDC house, and in the SDC community aspects comprised the evaluation content. Although all of these used data as quantitative indicators, the aim was to display and publicize buildings in the form of voting. Here, no further concern was given in the main body of the research.

For the energy self-sufficiency evaluation, the net-zero and off-grid were the review contents. For net-zero, all available points were earned at the evaluation period for a net electrical energy balance of at least 0 kWh. For off-grid, each building was required to maintain normal functioning for at least two days (48 h). Normal functioning included a comfortable indoor environment, a fire protection system, living activities, and others.

The Third SDC competition rules included 10 contests with several sub-contests, which were evaluated using five subjective and five objective evaluation methods. Even though the final review of the competition has not yet finished, the designers of each building tried their best to meet the requirements of the competition. In this study, the results based on the aspects of the buildings related to carbon neutrality were researched.

4. Results

4.1. Y-Project

The first project, namely, the Y-Project, used a Y-shaped roof, hence the name "Y". The "Y" also references the Chinese character for "people (人)". The design concept was based on the human living environment and incorporated solar heating, daylight, and agricultural production to achieve carbon neutrality [25]. The structural system used bio-based materials to provide long-term carbon storage, wherein bamboo and straw were joined together to develop a new structural system (Figure 3a). The building envelope used adaptive outer films of ETFE and perovskite photovoltaic (PV) cells, which supplied almost 100% of the building energy. The ETFE membrane mixed the thermal response, natural ventilation, and daylight functions. It could also protect the plant walls during the cold period for carbon neutrality (Figure 3b). The plant walls and natural materials guaranteed better air quality (CO_2 absorption, oxygen release, no VOC emission) (Figure 3c). A greywater reclamation system was selected to recycle and reuse greywater in the household for non-potable purposes. Water from bathtubs, showers, kitchens, and washing machines were treated and reused for toilet-flushing purposes (dual supply) and landscape irrigation, significantly reducing the reliance on water (Figure 3d) [26,27].

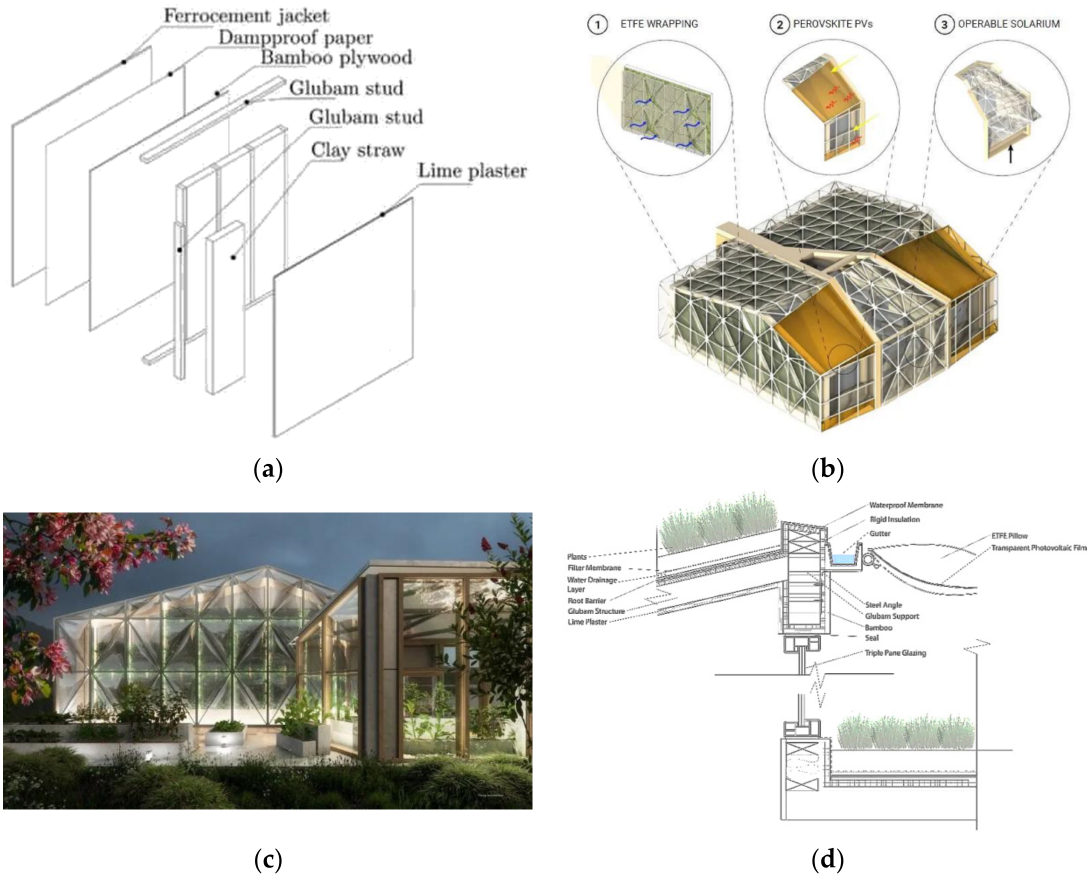
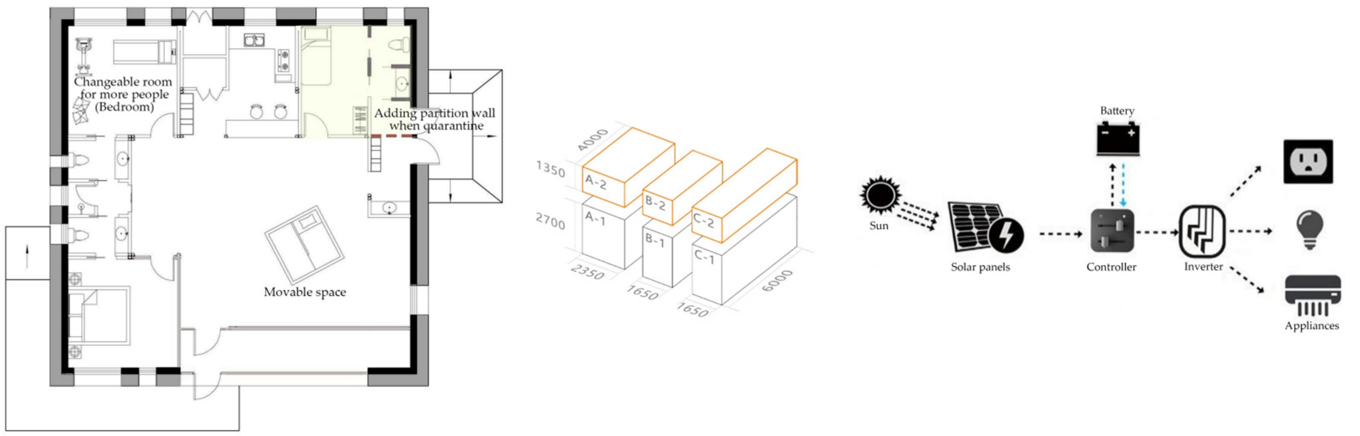


Figure 3. Main results of the Y-Project. (**a**) Bio-based structural system. (**b**) ETFE envelope. (**c**) Plant walls. (**d**) Greywater reclamation system.

4.2. 24 × 35 Housing Home

The 24 × 35 Housing Home refers to 24 h-a-day living and 35-year residential life through the changeable design of the space to meet the users' varying functional needs in the full life span of the house to achieve sustainable development, especially carbon neutrality [28]. The architectural design concept combined changeable space for different needs, especially for epidemic patients who do not need to quarantine in a hospital, making the design suitable for low-carbon living to some extent (Figure 4a). The structure adopted a three-stage component assembly strategy, which included the framework, structural insulated panel systems (SIPS), and related decoration. The module size was designed to meet the capacity of a 1AAA 40-foot-high container to facilitate transportation for low-carbon development (Figure 4b). The renewable energy system used the PV effect of solar cell semiconductor material to convert solar radiation into electric energy. Then, the electric energy through the controller charged the battery or supplied the load using the accumulator when the sunlight was insufficient (Figure 4c) [29].



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

Figure 4. Main results of the 24 × 35 Housing Home. (**a**) Flexible space. (**b**) Transportation module. (**c**) Renewable energy system.

4.3. Modular Sustainable Cube

The Modular Sustainable Cube used straw bale modules to build a house to achieve carbon neutrality (Figure 5a). The modular straw bale wall enclosure structure was simplified into five modules and was prefabricated in the factory to avoid unnecessary carbon emissions at the construction site using the Engineering Procurement Construction (EPC) model [30] (Figure 5b). The combination of each module ensured the diversity of architectural space and architectural form. It also focused on energy production through the roof's colorful light-transmitting PV panels to maximize the utilization of natural resources [31] (Figure 5c).

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

Figure 5. Main results of the Modular Sustainable Cube. (**a**) Straw bale modules. (**b**) Prefabricated materials. (**c**) PV panels.

4.4. Aurora

Aurora means dawn, and dawn is a part of the natural cycle of light. This courtyard building focused on human health, with the aim to combine natural resources to achieve low-carbon living. The Aurora's solar roof was an important part of the design. It not only provided energy but also created a feature of the overall environment and architecture. It provided a place for solar panels and supported a zero-energy house (Figure 6a). The building also adopted underfloor heating/cooling to provide more efficient and well-distributed space conditioning. The system consisted of two water tanks and one heat pump, which alternated according to the water condition in the tank and the season (Figure 6b) [32]. The building material comprised bamboo for the structures, external cladding, and interior design. Bamboo is a sustainable and local material that contributes to a low carbon footprint. In this building, cross-laminated bamboo and bamboo sticks were used (Figure 6c). In the construction, mixed reality (MR) technology was used for guiding the roof truss and bamboo brick installation. It was easier to install by direct sight without drawings, which not only decreased the construction difficulty but also saved paper in pursuit of the low carbon demand (Figure 6d).

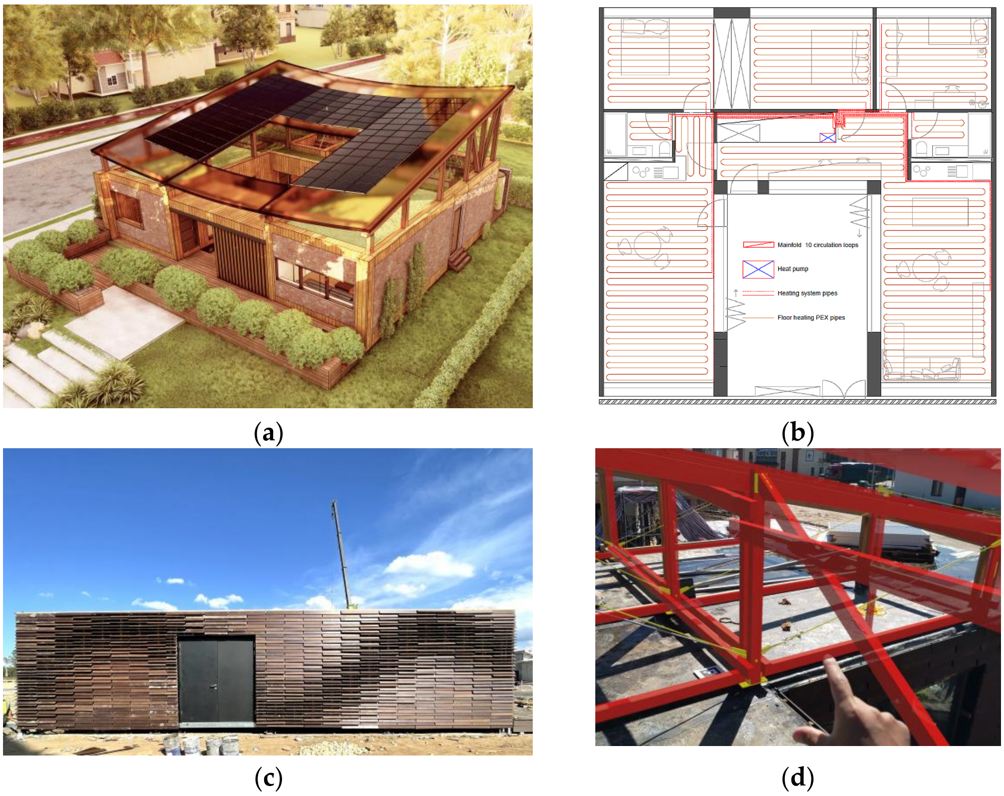


Figure 6. Main results of the Aurora. (**a**) Solar roof. (**b**) Underfloor heating/cooling. (**c**) Bamboo brick wall. (**d**) MR for construction.

4.5. The Steppe Ark

The Steppe Ark focused on the nomadic living characteristics in the competition site of Zhangjiakou city. Zhangjiakou is the connection between agricultural societies in the south and nomadic societies in the north. It is grassland that was once used by nomadic residents to live. This building focused on prefabricated modules, where the designers tried to achieve a shared low-carbon house. It was certified as an active house [33–35]. The Steppe Ark used the modern method of trying to quickly build a new yurt using box structure assembly (Figure 7a). Ten lightweight prefabricated modules were factory-made in advance. The size of the modules was suitable for transportation, and these modules were assembled on site by crane, reducing the carbon footprint during the construction period. For the development use of The Steppe Ark, the sharing concept was also considered, especially for tourism rentals. Shared living not only makes it easy for tourists to experience the nomadic life but is also good for homeowners to earn some money and thus achieve a win-win low-carbon lifestyle (Figure 7b). This building design also fully considered the technologies for carbon neutrality. Indoor light was provided by skylights, side window lighting, and indoor lighting to achieve an energy-saving environment. The air conditioner utilized ground radiation and a convection system to form an efficient and adjustable indoor temperature. Insulated walls used a phase change material (PCM) to passively save energy (Figure 7c). The imitation aluminum PV panels on the roof formed building-integrated PV (BIPV), with a Stirling engine generating renewable energy to offset carbon emissions. The rainwater recycling system ensured the efficient use of water resources (Figure 7d) [36,37].

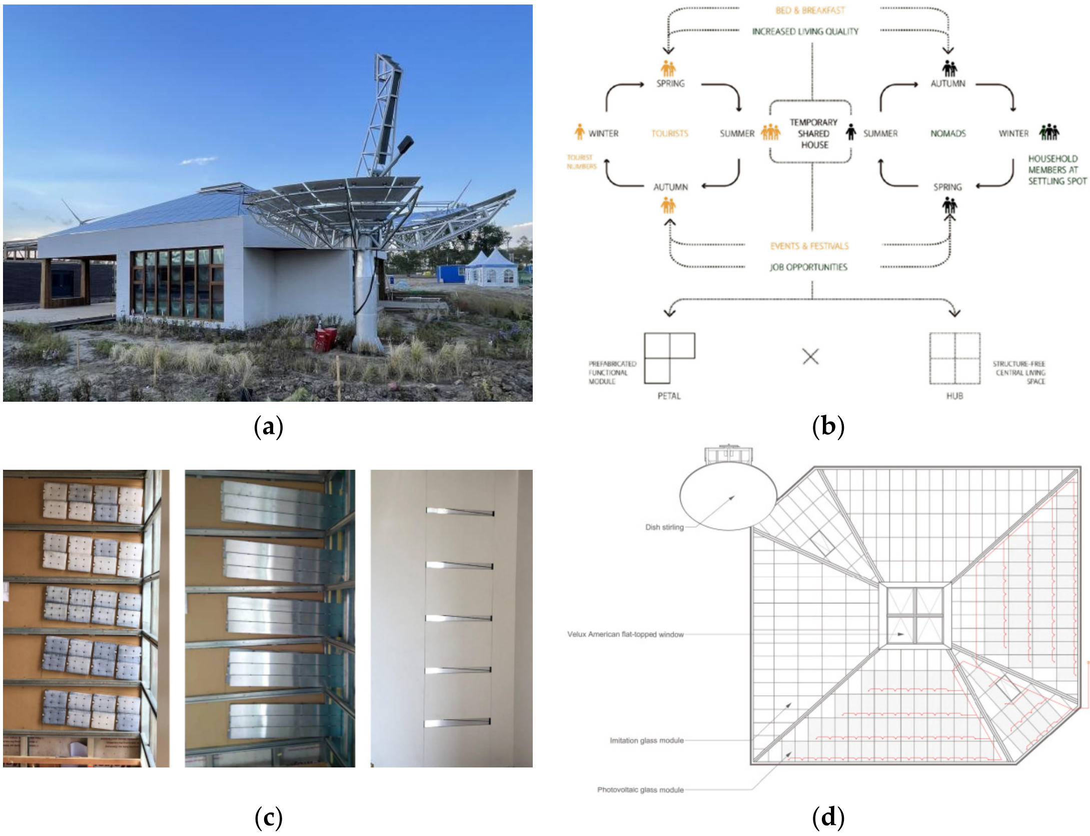


Figure 7. Main results of The Steppe Ark. (**a**) Modern yurt. (**b**) Shared low-carbon life. (**c**) PCM wall. (**d**) PV panels and Stirling engine.

4.6. HUI House

The HUI House was based on Huizhou-style architecture, which is the famous architectural style in China. The building aimed to adopt traditional Huizhou architecture and transform and utilize it in the new era, especially for rural revitalization. The HUI House focused on carbon neutrality by using green building technologies to try to solve the common problems of low quality in traditional Huizhou architecture (Figure 8a). A flexible thin-film solar chip was precisely encapsulated in the glass with highlight transmittance through the laminated packaging process of inner and outer layers. It converted solar energy into electric energy and renewed the traditional tiles with a new aesthetic. With the evaporator installation, the working temperature of the PV cell decreased, which could maintain the photoelectric conversion efficiency (Figure 8b) [38]. A multifunctional supplying system combined the solar-assisted heat pump with power heating and cooling. The heating was not only used for hot water but also for radiant floor heating. The generated electricity also drove the operation of the fresh air equipment to realize fresh air effectively. Moreover, an underground duct system was used to adjust the supply air temperature to form a passive and active carbon neutrality system (Figure 8c) [39]. As for rainwater use, an artificial wetland was planned to be built for rainwater purification using the anaerobic pool, hypoxia regulation, and aerobic pool (Figure 8d) [40].

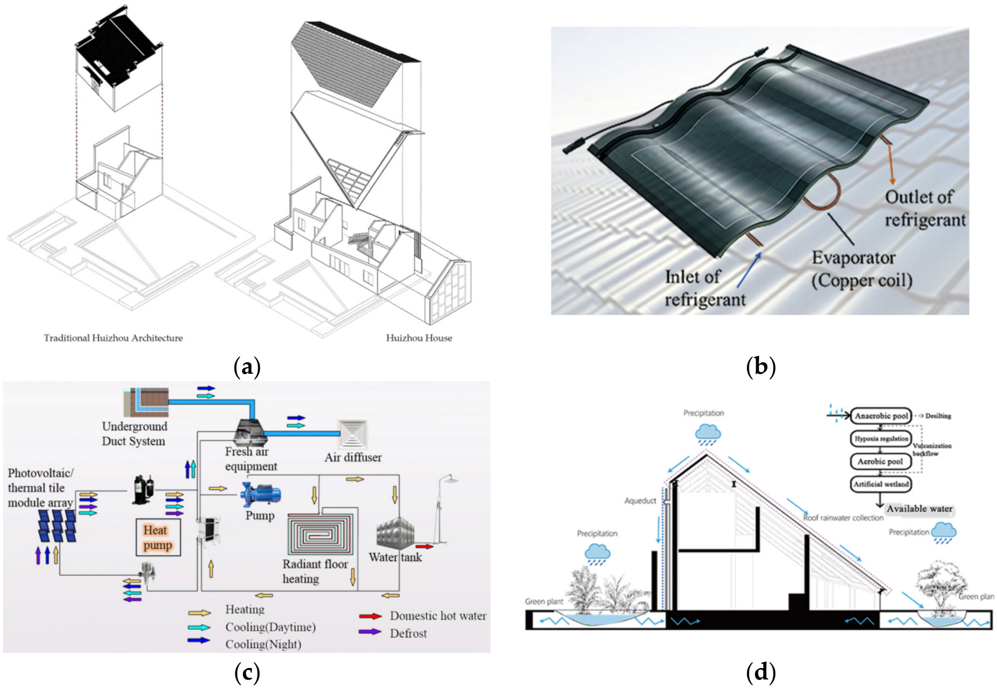


Figure 8. Main results of the HUI House. (**a**) Modern Huizhou architecture. (**b**) Solar chips. (**c**) Multi-functional supplying system. (**d**) Rainwater use system.

4.7. Pixel House

The Pixel House, which was named based on its changeable and flexible spaces, met multiple needs and achieved energy saving and carbon neutrality goals. The indoor movable modules could create multiple spaces for different uses. The functions of this building not only formed various living spaces for various family members with the changeable modules but could also change according to the needs of certain activities. This was beneficial for meeting the changing needs of occupants and reducing carbon emissions to a certain extent (Figure 9a). This building used passive priority and active combination technologies to achieve carbon neutrality. For passive technology, the Trombe wall system was used to save the energy of the thermal environment. The active technology mainly used the BIPV technology on the roof to generate electric energy. Solar bricks and lamps were used in the courtyard. The fence also used PV panels to increase the energy production area (Figure 9b) [41]. The structure of the building was based on prefabricated wooden beams and columns to facilitate quick installation, which decreased the construction carbon emissions, and the wooden material was recyclable and acted as a carbon sink (Figure 9c) [42].

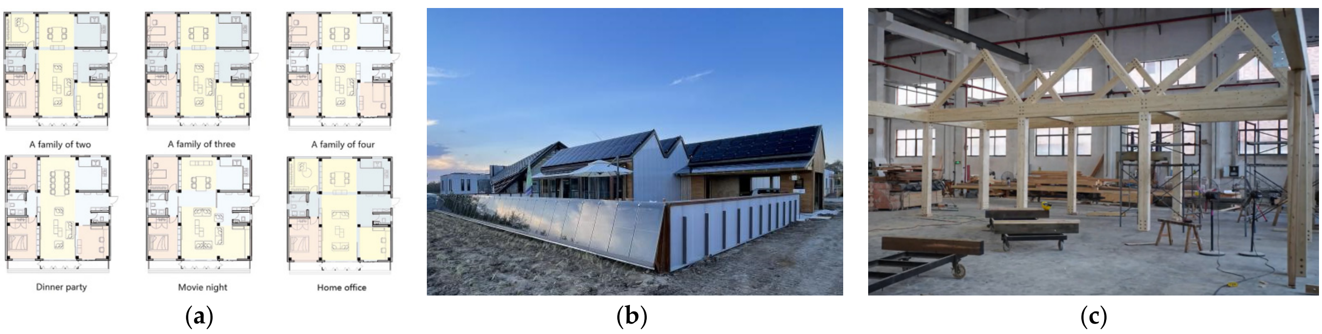


Figure 9. Main results of the Pixel House. (**a**) Changeable modules. (**b**) BIPV and PV fence. (**c**) Prefabricated wooden structure.

4.8. T&A House

The T&A House was named for the participating universities of CUMT and AGH. The building concept, which was based on traditional Chinese quadrangle dwellings, was used with the aim to construct a carbon-neutral, zero-energy house. Considering the prefabricated construction, the building was divided into four kinds of modules and then assembled on site (Figure 10a) [43,44]. Passive technologies were used, including a selective sunlight tunnel (SST) wall, a skylight over the courtyard, a sunroom, and a self-shading corridor. The SST wall used compound parabolic concentrators in the wall to optimize the spotlight effect to adjust the indoor thermal environment, whether in summer or winter (Figure 10b) [45,46]. Active technologies were also considered. The PV components were not only used on the roof but also installed on the western wall to maximize solar energy (Figure 10c). Among all the participants, the ground source heat pump system was used by only this team. This solar system had the role of cooling the roof in the summer and heating the floor in the winter (Figure 10d) [47].

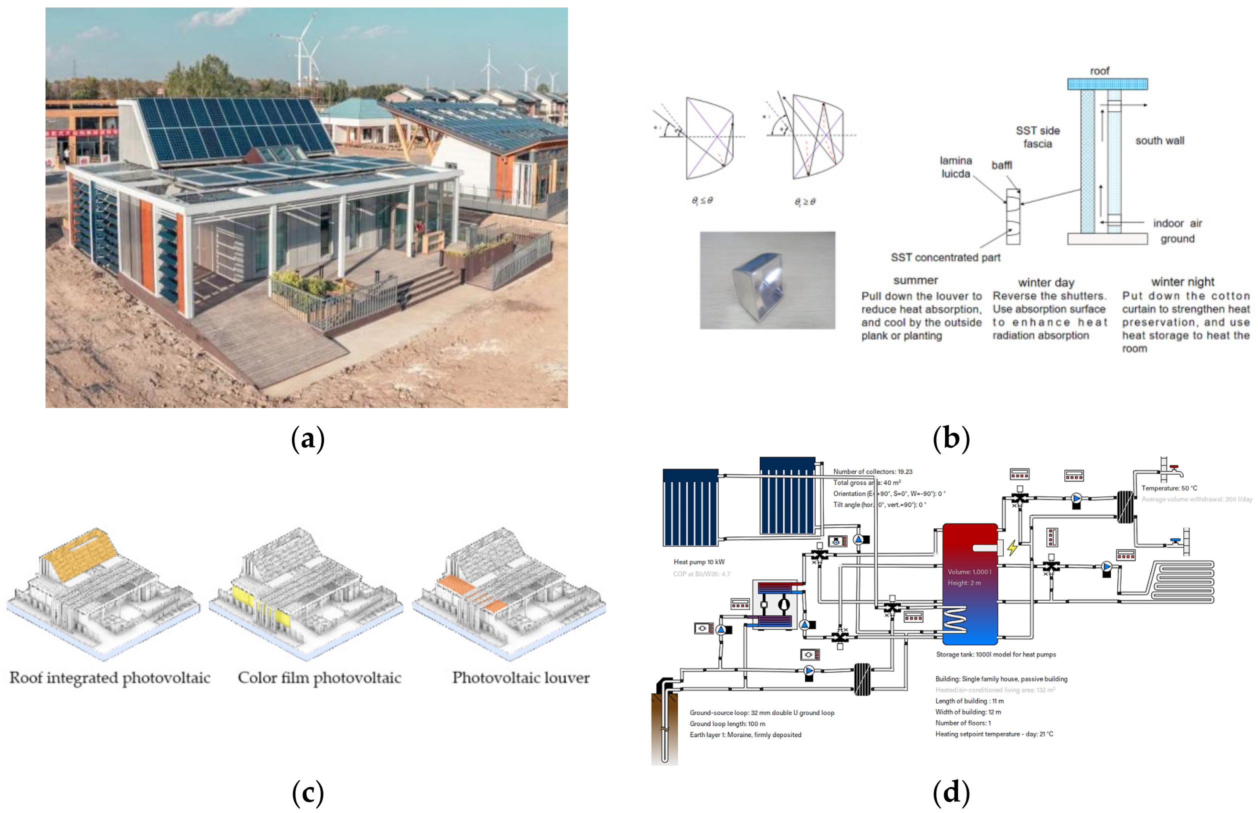
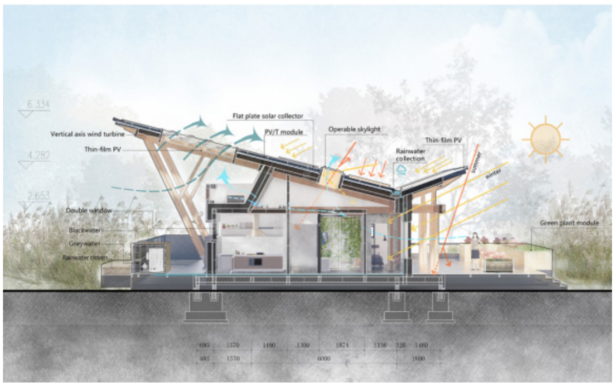


Figure 10. Main results of the T&A House. (**a**) Assembled T&A House. (**b**) SST wall. (**c**) PV used. (**d**) Ground source heat pump system.

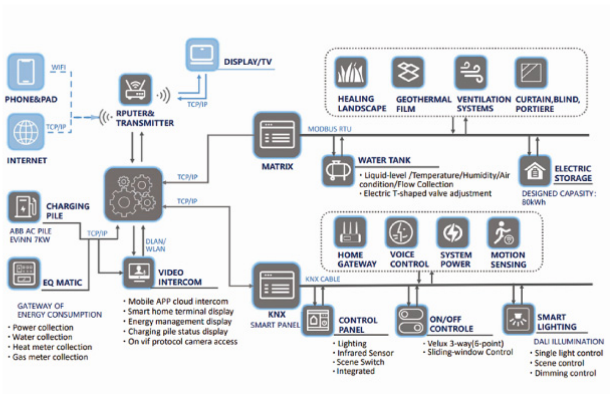
4.9. R-CELLS

R-CELLS stands for renewable, recyclable, reconfigurable, resilient with customization, energy surplus, life cycle, livability, and smart. The designers intended to produce low-carbon and self-organizing cells. This building aimed to achieve a solar house prototype with positive energy, full recycling, smart use, and zero emissions by adopting a close-to-nature design, prefabricated modules, intelligent systems, and energy integration technologies. For a close-to-nature design, positive architectural design methods were considered. The building drew on traditional Chinese architecture, namely, "anti-universal to the sun", to form an asymmetric V-shaped roof for the maximum use of the south-facing natural lighting and to increase the solar gain on the north-sloping roof at the site in northern China. The main building material used was wood, which is recyclable, reconfigurable, and resilient (Figure 11a). For prefabricated modules, five customized modules divided into 15 parts for this building were used to decrease the transportation emissions and the life-cycle emissions based on the users' needs (Figure 11b). For intelligent systems, based on the building information model, the integrated and efficient design model was created in the design phase. The energy management, environmental regulation, smart home scenarios, and voice interactive and smart housekeeper systems were used in the physical building, giving users a comfortable, low-carbon life (Figure 11c). For building energy integration technologies, thin-film PV and solar photovoltaic/thermal (PV/T) modules were installed on the roof. Five vertical axis wind turbines were also used at this windy competition site. The battery stored and supplied power. Photovoltaic, energy storage, direct current, and flexibility load (PEDF) technologies were used in this building. Moreover, the rainwater collection from the roof through grey water treatment formed complementary utilization of multiple energy sources (Figure 11d) [48].



(**a**)

(**b**)



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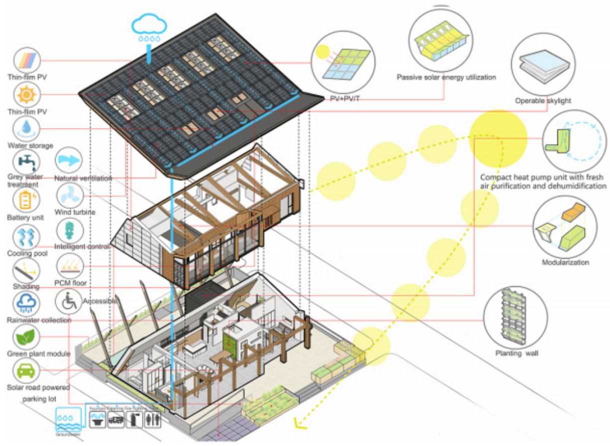
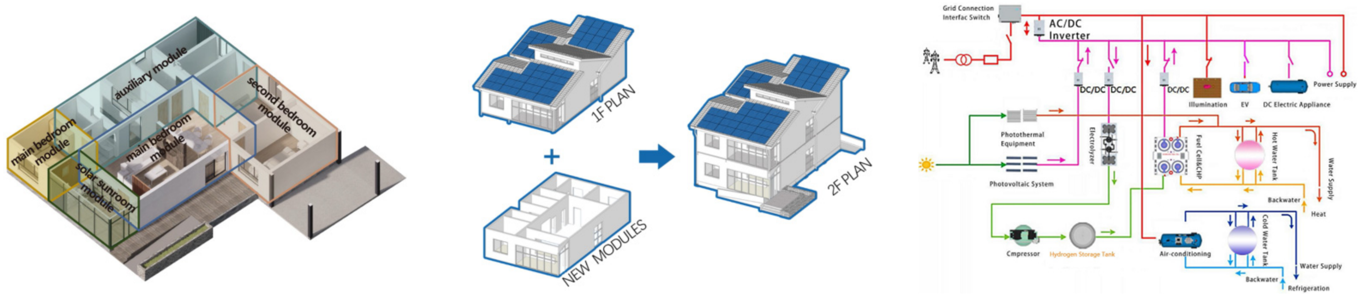


(**d**)

Figure 11. Main results of R-CELLS. (**a**) Close-to-nature design. (**b**) Prefabricated modules. (**c**) Intelligent systems. (**d**) Energy integration technologies.

4.10. SMART

SMART is an acronym for sustainable, modularized, alterable, residential, and technological. The concept was based on the northern China rural building with an aim toward prefabricated assembly with a changeable plan to achieve sustainable development using relevant technologies. This building was divided into five modules for prefabrication in the factory in advance so that the carbon footprint of this building was decreased compared with construction on site (Figure 12a). To make it alterable, the building's designers considered the residents' development so that new modules could be added on the second floor to construct a larger house. It was easier to achieve carbon reduction based on the prefabricated characteristic (Figure 12b). The technologies in this building focused on solar energy and hydrogen fuel cell technology. The BIPV system was used on the roof for solar energy generation. A hydrogen fuel cell was used for electricity production and hot water (Figure 12c). After a certain period, it will achieve carbon neutrality due to the renewable resources that can even be sold to the public grid [49].

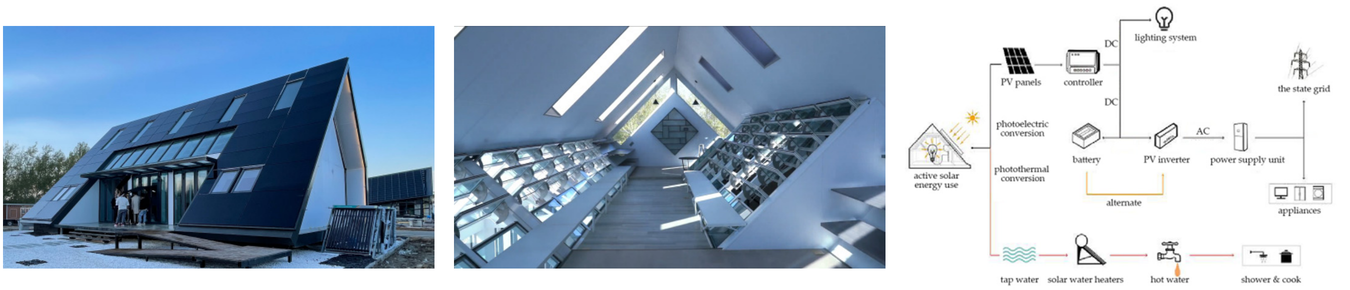


(**a**) (**b**) (**c**)

Figure 12. Main results of SMART. (**a**) Modularized modules. (**b**) Alterable model. (**c**) Energy systems.

4.11. Pitched House

The Pitched House was named for the architectural model, where the roof was inclined at 45 degrees. It aimed to be a multi-function house for living, entertainment, and work to achieve carbon neutrality. The building has two floors to use PV panels on the roof as much as possible. The panels installed on the 45-degree south-sloping roof not only maximized the use of sunlight to achieve carbon neutrality as soon as possible but also formed attractive architectural shapes (Figure 13a). The whole building incorporated a smart energy management system that used the automatic windows on the second floor to regulate indoor temperatures throughout the year (Figure 13b) [50]. Along with photoelectric conversion, photothermal conversion was also used for hot water (Figure 13c) [51].

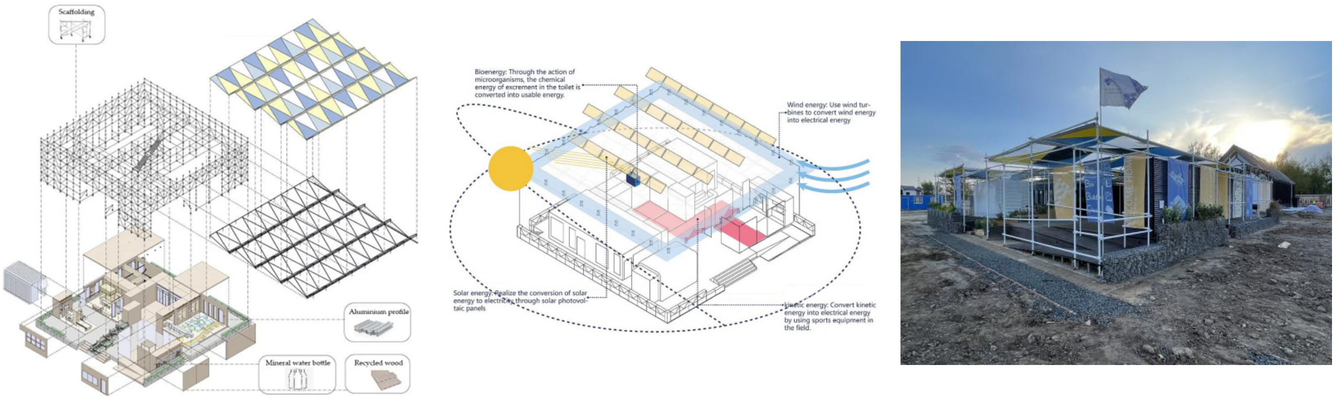


(**a**) (**b**) (**c**)

Figure 13. Main results of the Pitched House. (**a**) PV panels on the roof. (**b**) Automatic windows. (**c**) Energy systems.

4.12. BBBC

BBBC is an acronym for bag, box, building, and cloud. The architecture concept was aimed toward post-disaster reconstruction; therefore, prefabrication and energy self-sufficiency were the most important aspects. Regarding prefabrication, more than 80% of the building design utilized recyclable material, such as aluminum profiles, mineral water bottles, recycled wood, and scaffolding (Figure 14a). The materials can be reused in the future, which is good for decreasing the carbon emissions at the building material level. Concerning energy self-sufficiency, the whole building combined bioenergy, wind energy, solar energy, and kinetic energy to supply electricity for the building (Figure 14b). The building can achieve carbon neutrality and even be carbon negative with time. Overall, this building contributed to carbon neutrality by using prefabricated construction and being lightweight, recyclable, energy-efficient, and so on [52] (Figure 14c).

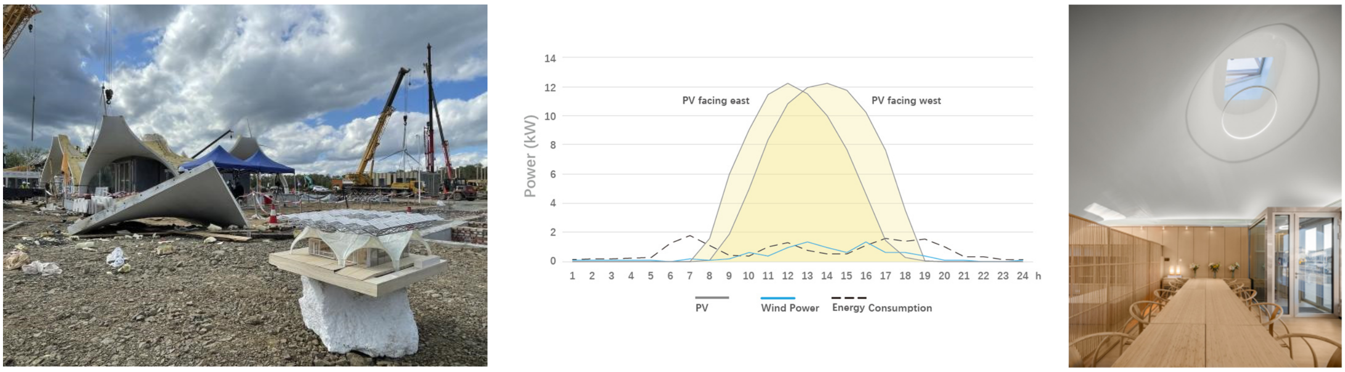


(**a**) (**b**) (**c**)

Figure 14. Main results of the BBBC. (**a**) Recyclable materials. (**b**) Energy self-sufficiency. (**c**) BBBC building.

4.13. Solar Ark 3.0

The Solar Ark 3.0 is the third generation to participate in SDC's architectural works, where it pursued the application of new technology and new energy [53]. The Solar Ark represents the continuous exploration of a better future for human life and environmental sustainability. Ultra-high performance concrete (UHPC) was used by parametric design according to graphic statics to achieve UHPC hyperboloid shells, which were prefabricated in the factory in advance. The whole building consisted of 20 shells, but all the shells were generated using only one mold. This was very helpful for carbon reduction. In addition to applying this high-strength UHPC, it saved nearly two-thirds of the concrete consumption compared with the traditional frame structure under the same building scale (Figure 15a). As for the building energy, 68 solar panels were installed on the building to maximize the use of solar energy. The special feature was that the solar panels were installed in the east–west direction, which could increase the production capacity by 10% compared with the north–south direction when using the same area, and at the same time, adapt to the law of indoor electricity consumption. In addition to solar energy utilization, wind energy was also used in the building to achieve multi-energy complementarity. A vertical wind turbine was installed in the site's northeast corner to generate electricity 24 h a day. An air source heat pump was also used in the building. The total calculated annual electricity generation was 5.2 times the electricity consumption (Figure 15b) [54]. This building could achieve carbon neutrality after 9 years of operation [55]. Passive technologies were also used for carbon reduction. Two skylights on the roof greatly improved the indoor natural lighting and ventilation situation (Figure 15c) [56]. The doors and windows had a thermal conductivity of 1.1 $W/m^2 \cdot K$ and a solar heat gain coefficient of 0.7 to achieve high efficiency and energy savings [57]. Along with the prefabrication, energy complementation, and passive technologies, a variable layout according to the user's needs, rainwater recycling, bamboo furniture, and other aspects were achieved in the building for carbon neutrality.

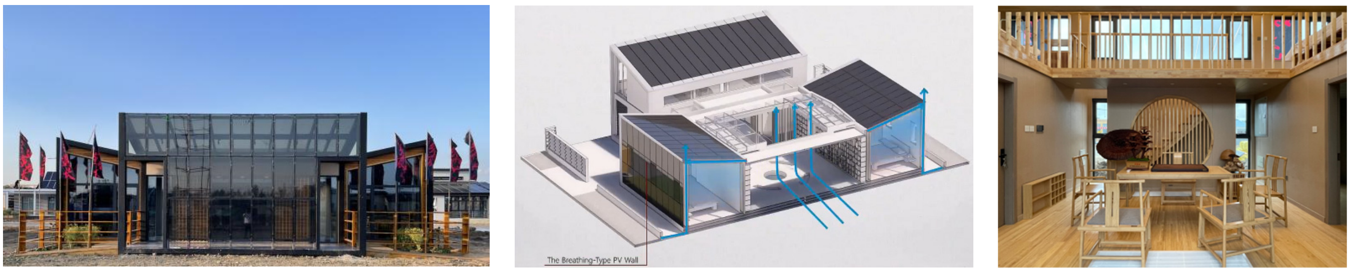


(**a**) (**b**) (**c**)

Figure 15. Main results of the Solar Ark 3.0. (**a**) UHPC prefabrication. (**b**) Energy production and consumption. (**c**) Skylight.

4.14. Hope Land-Natural Courtyard

In the design of the Hope Land-Natural Courtyard, the architecture concept came from traditional Chinese quadrangle dwellings. Four prefabricated building modules sat around the courtyard (Figure 16a). The building was dedicated to rural revitalization to solve problems such as low energy quality and environmental pollution. The PV panels on the three roofs maximized solar energy. These PV panels were combined with the courtyard to form an air conditioning mechanism. PV panels are not efficient at high temperatures, but the combination with the air layer could effectively reduce the surface temperature of the PV panels and maintain their production performance (Figure 16b) [58]. The interior of the building was mainly made of wood, supplemented by wooden furniture, which could effectively sequester carbon, save energy, and protect the environment (Figure 16c). Furthermore, the smart control system, reclaimed water purification system, indoor greening, and others were also used in this building for carbon neutrality.

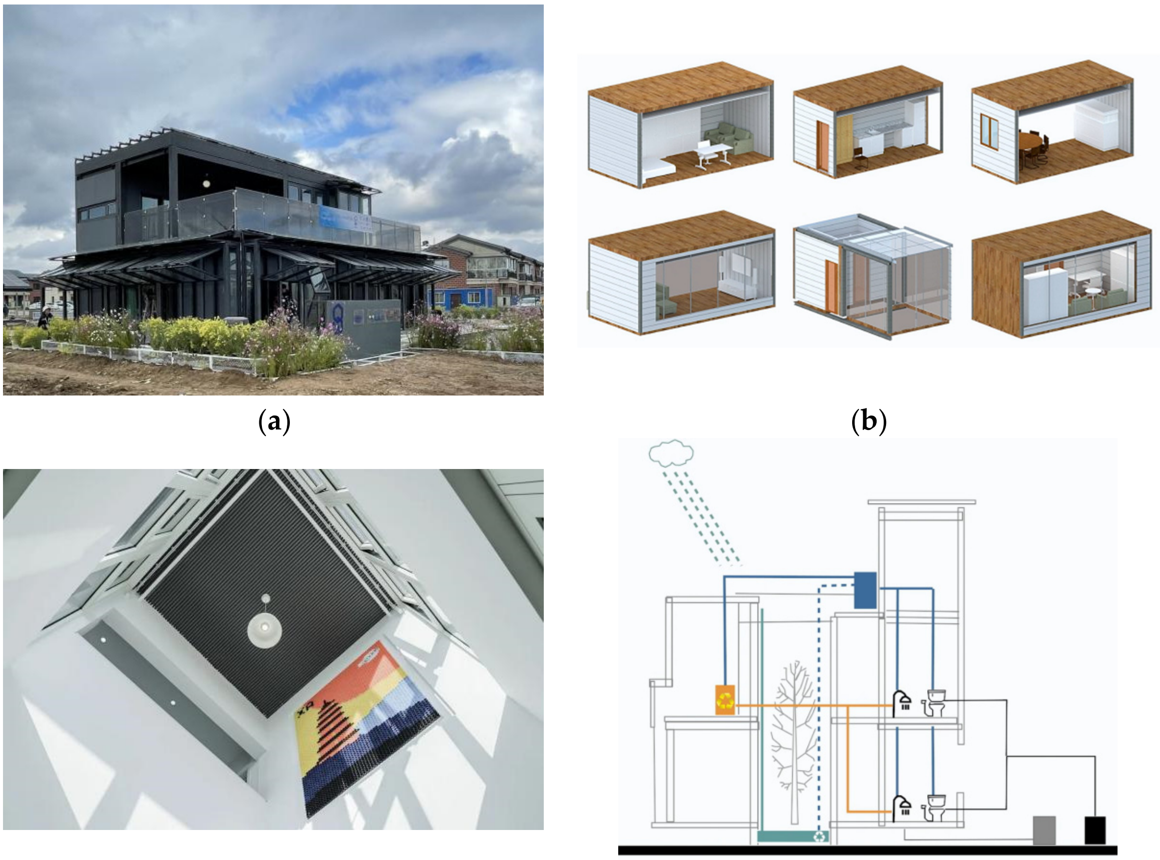


(**a**) (**b**) (**c**)

Figure 16. Main results of the Hope Land-Natural Courtyard. (**a**) Hope Land-Natural Courtyard. (**b**) PV air conditioning mechanism. (**c**) Wood use.

4.15. Qiju 3.0

Qiju 3.0 was the third generation of the Qiju Decathlon building. In some sense, Qiju refers to a good living environment, which was realized through rapid assembly and independent production capacity. This building used C-shaped steel to make the framework of the lightweight and high-strength modules, which could be constructed quickly and reused in the future (Figure 17a). These modules could be freely combined according to the needs of the users, which was conducive to energy saving and environmental protection and could be set on demand without losing the required ductility (Figure 17b). Qiju 3.0 was a two-story residence. In addition to passively adjusting the indoor temperature in a circle of sunrooms on the sunny side, it also supported low-carbon living with effective ventilation, garden planting, and efficient water purification through an indoor atrium (Figure 17c) [59]. Moreover, active technologies, such as BIPV, an air source heat pump, a fresh air system, a radiant pipe, a smart management system, and a water purification system, were also considered for carbon neutrality (Figure 17d) [60].



(**c**) (**d**)

Figure 17. Main results of the Qiju 3.0. (**a**) Prefabricated building. (**b**) Changeable modules. (**c**) Indoor atrium. (**d**) Water purification system.

5. Discussion

5.1. Summary

Starting from the problem of global warming, this research focused on carbon neutrality and aimed to discover a sustainable method to solve this problem. Based on the rules of the Third SDC competition, five subjective and five objective evaluation methods were explained. After analyzing 15 competition buildings in terms of the concepts, technologies, and prospects for carbon neutrality, a summary can be discussed.

Each building had its method of pursuing carbon neutrality. For the architecture concepts, some buildings were more inclined to only focus on the competition theme of sustainable development on a technical level. Some architectural concepts started from practical issues and were committed to rural revitalization, post-disaster reconstruction, grassland features, traditional revival, future development, and more. The competition had a set mission, but each building's solution differed. Architectural design is a complex issue that should consider a building's meaning, technology, future utilization, and more. The concepts are generally devised prior to a building's implementation. With a good concept, the implementation is only a matter of technology.

The technologies used in these buildings are summarized in terms of the different concepts in Table 4. Fifteen buildings started from different architectural design concepts and were then built with multiple technologies for carbon neutrality. Although the design concept may have multiple meanings and the technologies were hard to generalize, from the carbon neutrality aspect, the 15 buildings demonstrated advanced concepts and technologies at home and abroad. This showed the current state of development in architecture, not only in academia but also in the industry [61,62].

Table 4. Main concepts and technologies of the Third SDC buildings for carbon neutrality.

No.	Projects	Main Concepts	Main Technologies for Carbon Neutrality
1	Y-Team	"Y" for human	PV, bamboo material, ETFE, plant wall, greywater reclamation system
2	24 × 35 Housing Home	24 h-a-day living and 35-year residential life	PV, changeable space, assembly modular, SIPS
3	Modular Sustainable Cube	Straw modular modern house	PV, straw brick, assembly modular, EPC
4	Aurora	Solar courtyard building	PV, heating/cooling radiation system, bamboo material, MR
5	The Steppe Ark	Steppe modern yurt	PV, assembly modular, sharing living, skylight, heating/cooling radiation system, PCM, Stirling engine, rainwater recycling system
6	HUI House	Modern Huizhou building	PV, heating/cooling radiation system, rainwater recycling system
7	Pixel House	Changeable modular building	PV, changeable space, assembly modular, Trombe wall, solar bricks and lamps, wood structure
8	T&A House	Modern quadrangle dwelling	PV, assembly modular, SST wall, skylight, sun room, ground source heat pump system, self-shading
9	R-CELLS	Low-carbon and self-organizing cells	PV, assembly modular, self-shading, wood structure, smart system, wind turbine, PEDF, greywater reclamation system
10	SMART	Changeable rural residential	PV, assembly modular, changeable space, hydrogen fuel cell
11	Pitched House	Multi-function house	PV, assembly modular, changeable space, smart system, automatic windows, solar water heater
12	BBBC	Post-disaster reconstruction	PV, assembly modular, rainwater recycling system
13	Solar Ark 3.0	UHPC modular building	PV, UHPC material, wind turbine, air source heat pump, skylight, changeable space, assembly modular
14	Hope Land-Natural Courtyard	Modern quadrangle dwelling	PV, assembly modular, wood furniture, smart system, air layer
15	Qiju 3.0	Assembly modular building	PV, assembly modular, C-shaped steel, changeable space, sun room, plant wall, rainwater recycling system, air source heat pump

For further discussion, these technologies could be divided into active technology and passive technology. There were at least 35 kinds of technologies used in this competition. Based on statistical frequency analysis, a Sankey diagram was generated for the technology ratios (TRs) in Figure 18. This showed the frequency of use of the technologies in these 15 buildings. PV (100%) and modular assembly (80%) were the most used technologies for pursuing carbon neutrality. Almost every building examined here actively used solar energy to achieve carbon neutrality and combined prefabrication in a passive way to reduce carbon. Thus, to achieve carbon neutrality to solve global warming, using PV panels to generate electricity and fabricating the building modules in a factory in advance represented a consensus in this advanced competition [63].

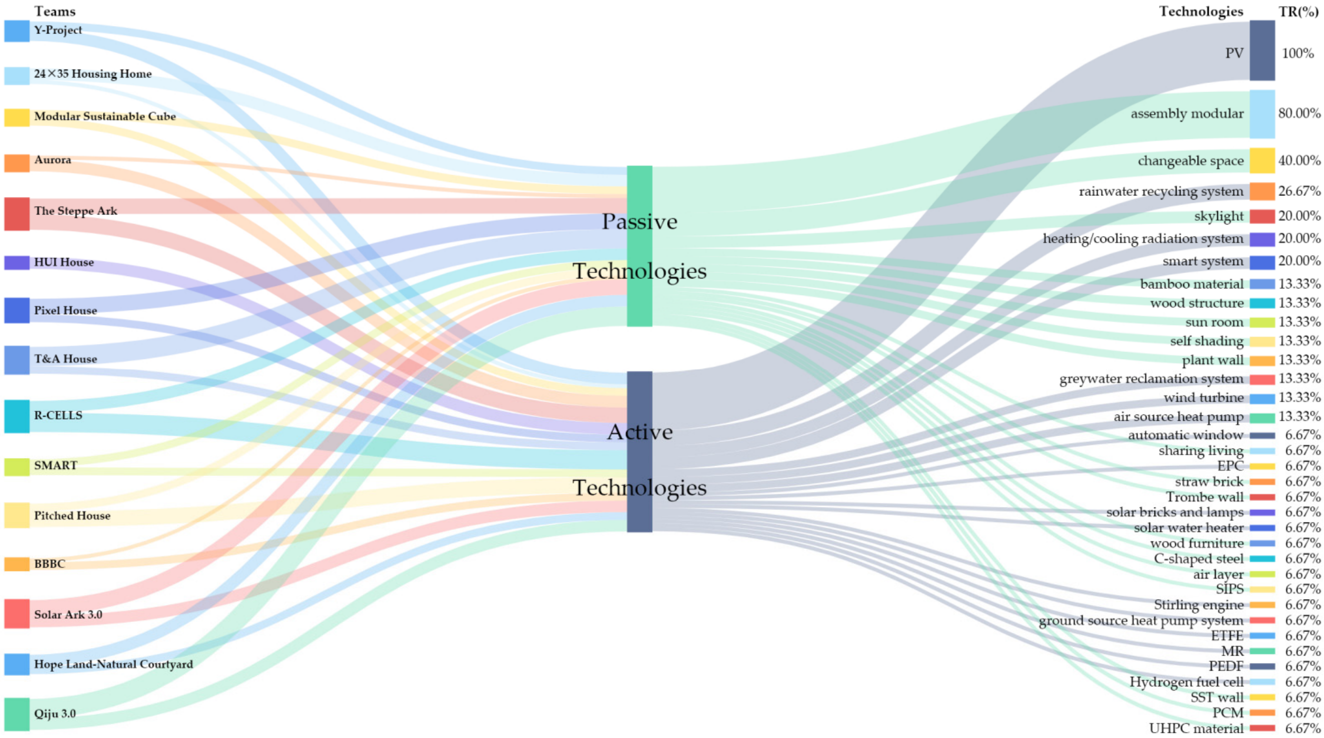


Figure 18. Summary of carbon neutrality technologies in the Third SDC.

Except for the PV technology used in these buildings, wind turbine, air source heat pump, Stirling engine, ground source heat pump system, and hydrogen fuel cell technologies were also used for clean energy generation and consumption. More attention should be paid to these active technologies. As for the passive technologies, the low frequency of use does not mean they are unimportant. In contrast, they may be innovative, cutting-edge technologies [64]. An example was the UHPC, which saved more concrete for better quality; this material may thus be produced more to reduce costs and promote applications to achieve carbon reduction for sustainable development. Additionally, PCM and SST walls were also advanced passive technologies that were used [24].

5.2. Critical Thinking

From the participating buildings of the Third SDC, in striving to meet a carbon-neutral target, some prospects were concluded. Architecture is an ancient subject that has pursued aesthetics for a long time. Nowadays, beginning with modernist architecture, architecture is more focused on technology. Given the issue of global warming, the entire industry has recently started to focus on carbon neutrality. In practice, however, this idea has not taken root in the hearts of all people, but residential buildings could generate power with the above-discussed technologies. From then on, a building can convert input into output, and can not only be energy self-sufficient but can even sell the surplus energy generated from solar, wind, water, and other sources to the public and achieve a carbon-negative status [65]. Residential buildings are the largest building type in the world. Importantly, this will effectively increase individuals' motivation to reduce carbon. Finally, the global warming problem will be proactively solved by everyone [66,67].

Moreover, due to COVID-19, the final review of SDC cannot start yet; thus, objective data are lacking. However, analytic network process (ANP) analysis could be used to simulate the ranking to compare with the present methods [68]. Here, only three projects were chosen for ranking due to the enormous calculation load. The names of these three projects have been hidden to avoid any conflicts. Based on these buildings' technology applications, 17 different technologies were counted. From the design concepts, implementation technologies, and application scenarios, three clusters were established to determine the priorities of these projects. The Super Decisions software showed that the ideals of Project C scored 1, which was better than Project B (0.85) and Project A (0.75), which meant that Project C was the best one of these three (Figure 19). This part of the research was just for showing the method of ANP that may be applied for SDC ranking based on the present ranking rules of 1000 points in total without violating the 10 contests of the SDC. In fact, different contests or sub-contests should be affected by each other with multiple weights. More scientific results lead to better carbon neutrality demonstrations.

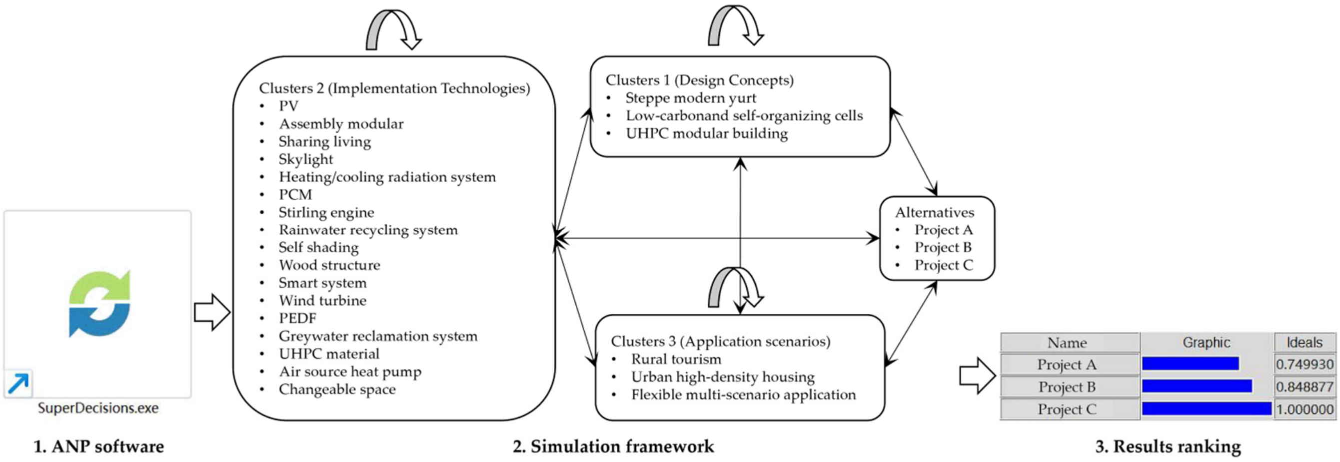


Figure 19. Critical thinking of the ANP ranking method.

5.3. Limitations

However, this research did not focus on the competition ranking but tried to analyze the individual buildings to reach universal conclusions regarding carbon neutrality for solving the problem of global warming. Moreover, with the development of the competition, this research may not be comprehensive. This research only represented the views of the authors. More research on overcoming issues and developing prospects will be done in the future.

6. Conclusions

This study researched buildings that participated in the Third SDC competition to find methods to achieve carbon neutrality to overcome global warming challenges. Some certain contributions were achieved. (1) The global warming background and literature review on carbon neutrality were analyzed. Solving global warming through carbon neutrality is widely required and research in this area needs to be done now. (2) Based on the competition rules, the methods of five subjective and five objective contests with several sub-contests were determined. (3) The results of 15 buildings in terms of the concepts, technologies, and prospects of carbon neutrality were determined. (4) Regarding the aspect of the architectural concepts, a good concept for carbon neutrality to achieve sustainable development was important and prior. (5) A summary of the Third SDC buildings' concepts and technologies was analyzed. This showed the advanced development of architecture in academia and industry worldwide. (6) Thirty-five kinds of active and passive technologies used in this competition were determined. A total of 100% of the designs used the active technology PV and 80% used the passive technology modular assembly, which provided a consensus for carbon neutrality in this competition. (7) As for the technologies used with a low frequency in the Third SDC, this does not mean that they are unimportant. The wind turbine, air source heat pump, Stirling engine, ground source heat pump system, and hydrogen fuel cell technologies used in an active way and UHPC, PCM, and SST used in a passive way should have more attention paid to them. (8) For the prospects of realizing carbon neutrality, energy-producing buildings, especially residential buildings, may shift people's passive acceptance of carbon neutrality to active energy production to achieve a carbon-negative status. (9) The ranking method of SDC could consider ANP due to the interaction of contests and sub-contests to obtain more scientific results without violating the 10 contests of the SDC and offer better carbon neutrality demonstrations. (10) The limitations of this research will be considered and overcome in future research.

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