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RESEARCH ARTICLE

EVALUATION OF THE ENERGY AND ENVIRONMENTAL IMPACTS OF ZERO- ENERGY BUILDINGS (ZEB): LITERATURE REVIEW AND STATE OF THE ART

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ABSTRACT

This study was supported financially by the Afro-German Network of Excellence in Science (AGNES), through the program "AGNES Intra-Africa Mobility Grant for Junior Researchers". Zero-energy buildings (BEZs) are considered an integrated solution for solving the problems of energy saving, reducing the environmental impact of buildings. NZEB might even be possible with electricity generation if enough renewable energy could be used. In addition, various building service systems using renewable energy sources have been widely considered for potential applications in NZEB. All these new features extend the technical limits of conventional energy-efficientbuildings. They also attach a deeper involvement to the sustainable development of building technology and therefore pose a challenge to the performance evaluation work of NZEB. This paper presents a literature review of the evaluation of NZEBs. An overview of NZEB definitions and energy efficiency measures is presented so that the research focus and technological limitations can be clarified for the NZEB assessment. Next, a summary of the commonly used research method, tool and evaluation performance indicator is provided for the methodologypart. This part also includes a discussion on the application of life cycle analysis (LCA) in the NZEB assessment and the role of LCA in promoting a well-defined NZEB. Finally, potential progress in NZEB assessment with possible development trends is highlighted in terms of energy storage, load matching and intelligent network.

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INTRODUCTION

Commercial and residential buildings consume a lot of energy, i.e. almost 40% of primary energy in the United States or Europe, and almost 30% in China (1-3). In order to reduce the dependence of the building on primary energy, a number of studies on energy-saving technologies have been conducted worldwide. Furthermore, the use of renewable energy was considered as reasonable solutions to global warming, air pollution and energy security (4). By integrating renewable and energy-efficient energy technologies into the building, BEZ, an innovative concept of high-performance building, is proposed. By reaching the net zero energy target, energy and environmental problems in the building will be addressed in an aggressive and integrated manner. Numerous initiatives have been presented by many countries, organizations and associations to promote NZEB research and events in recent years. The International Energy Agency (IEA) Solar Heating and Cooling Program (CHS) approved Task 40 (Towards Net Zero Energy Consumption Solar Buildings) in 2008 (5). The objective of this task is to develop a common understanding, a harmonized international definition framework, tools, innovativesolutions and industry guidelines. The NZEB database worldwide is installed as part of the task. The demonstration projects in this database provide realistic experiences in terms of design, operation and testing. A similar database was compiled by the Department of Energy of the United States of America. In addition, the Department of Energy has launched alliances for ZEB and which are authorized by Congress in EISA 2007 (Energy Independence and Security Act of 2007), Net-Zero Energy Commercial Building Initiative supports the goal of net zero energy for all new commercial buildings by 2030 (1). The United States Commission has an energy action plan to achieve a net zero energy for all new residential construction by 2025 and a net zero value for all new commercial construction by 2030 (1).

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In addition, the objectives of the NZEB were also announced by the European Union (EU) in 2009, namely that all EU Member States must ensure that all newly constructed buildings produce as much energy as they consume on site by the end of 2018 (6). Certain similar proposals or promotion plans for NZEB orresidential use of renewable energy are also presented in the United Kingdom, Canada and Japan (7-9). A literature review in this area suggests that most NZEB projects have not presented a comprehensive review of how to assess the energy and environmental impact of NZEB. Not only the definition and technical connotation of the NZEB, but also the evaluation methodology are a lack of summary and clarification. This article will present an overview of the NZEB assessment with its definition, methodology and development status, so that a basic framework for the NZEB assessment can be obtained. Following the "object-methodology-trend" logic for the evaluation, a guided tour through the NZEB literature is presented to provide a new perspective on this topic of interdisciplinary research.

Evaluation object: The main purpose of the NZEB assessment is to quantify the impact of NZEB on energy and the environment. However, the purpose needs to be clarified prior to assessment for two issues:

Definition: It refers to three fundamental considerations: what are the key elements of NZEB definitions? What is the relationship between the key elements? And what key elements of the different definitions can be selected as an indicator of assessment?

The difference in factors in the definition of NZEB would certainly have a direct impact on the evaluation results, although the elements of the definition are limited in a common scope. Thus, a clarification of the definition of NZEB would make the assessment more effective with certain factors of the object.

Energy efficiency measures: There are still uncertain factors in the assessment object. New integration with renewable energy extends the technological frontier of NZEB. Thus, the conventional evaluation framework for the passive-designed building where the Integrated Photovoltaic Building (BIPV) cannot be directly adapted to the BEZ assessment without appropriate updates. As there is no specific description or limitation of the energy efficiency measures used in NZEB, the uncertainty of the assessment work will increase in addition to some of the factors in the definition. Several representative renewable energy technologies, widely used in recent NZEB projects, will be briefly presented with the corresponding assessed content

NZEB Definition

As for the definition of an NZEB, there is so far no consensus on a common expression, which can be satisfied by all participants in this field of research. As mentioned in the ref. (10) depending on the project objectives and the values of the design team and the building owner, the proposed definitions have different weights on the specific descriptions. However, through research, exchange of ideas and discussions over the past few years, a common view has emerged that a widely accepted definition of NZEB should be a definition framework containing different elements, such as: limits, parameters and criteria, etc. In this common framework, various participants may choose elements at different levels to form a specific definition, based on individual considerations on cost, local climate, environmental protection demand or the feasibility of an on-site renewable energy source. In this way, the definition framework that contains different levels of NZEB for different scenarios can be useful for proposing a roadmap or a guideline for countries, regions, associations or design groups based on their specific requests. The basic elements of the NZEB definition and their relationships are illustrated in Fig. 1. The basic elements are the building system, the energy network and the weighting system. In order to make a clear equilibrium calculation for the net zero target, a limit needs to be clarified for the on-site renewable construction system. Within this limit, the building system consumes supplied energy, such as electricity, natural gas, from renewables and on-site energy and returns the energy to the grid when the renewable energy (REP) system generates surplus electricity.

Because of the different design objectives, different weighting systems are chosen to calculate the net energy obtained by the entire building system. For example, building owners generally care about energy costs, so they prefer to choose a weighting system in the cost balance rather than in the energy balance. Finally, weighted demand and supply are compared to check whether the net zero balance can be achieved according to the specific technological solution. This can be considered as the operating mechanism of the core NZEB assessment.

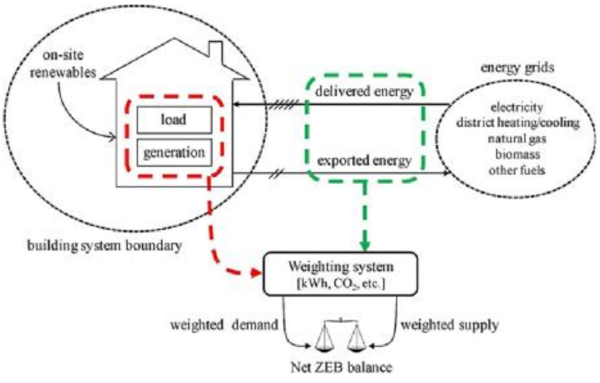

Fig. 1. System structure and basic elements of BEZ (11)

In addition to the basic elements and the operating mechanism, the definition also includes certain parameters, such as: limit, weight, evaluation period. The boundary of the building system is not just the physical boundary and can even be virtual (12). With an extension of the limits of the building's real footprint to the virtual economy's range, more possible options for sourcing REPs will become available. Therefore, the definition changes from narrow to broad. The U.S. Department of Energy presented a comprehensive definition that covers four types of NZEB: ZEB site, ZEB source, ZEB issues and ZEB cost (1). The evolution of these four typical ZEB definitions appears to be in a similar boundary extension trend. The definition of NZEB with the widest boundary, even allows the owner to buy “green electricity” from large-scale renewable power plants. Thus, when the limit is set, the type of REP system, which is on-site or off-site, can be clarified.

Some other important parameters of the definition are metric, weight, period, etc. Metric and weight (also called credit) can work together to convert the supplied energy and output energy into a uniform form, for example, the amount of energy, cost or emission, so that the equilibrium comparison for the net zero energy objective can be performed on a fair platform. In addition, the time period and the types of energy (operational energy, total consumption or intrinsic energy) determine the time scale for comparing objects. For example, the conventional definitions of NZEB are mainly based on the annual energy consumption of the building operation, so that the NZE target generally represents the annual balance of a building connected to the network without taking into account the energy accounting throughout the life cycle (13). On the other hand, an integrated solution that can achieve the annual balance of a building may not be able to meetthe net zero target for each month, or other smaller time scales. Figure 2 shows a case: PV (photovoltaic) solar production capacity increases with an increase in building load.

The lowest curve (A) shows that no more than 28% of the building load can be satisfied on the basis of a net count of 10 min. The adequacy analysis at the monthly level shows a maximum match of 67%, although the annual yield fully balances the annual demand (14). The assessment period should therefore also be clarified in the definition. Since the basic principle of the NZEB definition is a balance between weighted supply and demand, different types of equilibrium can lead directly to different evaluation conclusions. In most cases, only two parameters: the consumption of the building and the production of renewable energy sources RES (RES) are taken into account in the calculation and assessment of net energy. Some discussion of other types of balancing is introduced in Ref. (11,12).

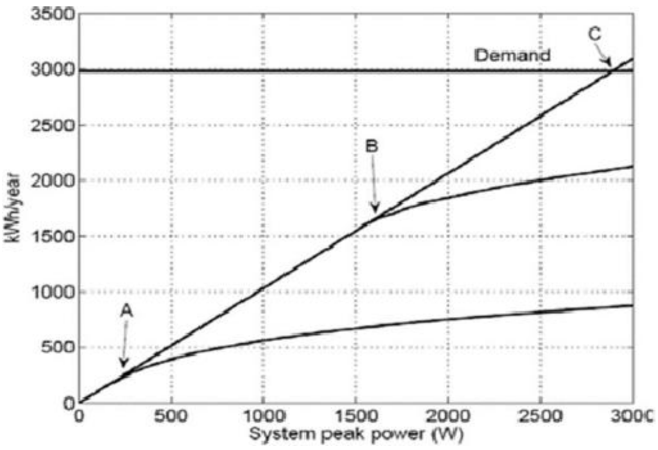

Fig. 2. Impact of the timescale on the results of the evaluation of load matching (14)

$$\boldsymbol{Net\ Energy} = |\boldsymbol{Output}| - |\boldsymbol{Input}| = \sum \boldsymbol{i}\ \boldsymbol{Outputenergy}(\boldsymbol{i}) \times \boldsymbol{weight}(\boldsymbol{i}) - \sum \boldsymbol{i}\ \boldsymbol{Delivered\_energy}(\boldsymbol{i}) \times \boldsymbol{weight}(\boldsymbol{i}) \geq \boldsymbol{0} \quad (1)$$

In addition to the literal definition, NZEB can also be defined as a mathematical equation. Satori et al. discussed the NZEB definition criteria and presented a simplified equation to describe the definition, which is represented by equation (1) (11). The Federation of European Heating and Air Conditioning Associations (REHVA Working Group) also uses a similar mathematical definition (15). As shown in equation (1), these expressions are clear to be understood that the balance between the output energy and the input energy over a period of time must be zero or even positive when the boundary of the building zone is fixed. The setting of the limit, period, weight, etc. is not contained in this equation, as the definition conditions depend on the objectives of the designers and may not be appropriate, limited in a constant form.

The definition can also be presented graphically, as shown in Figure 3. The starting point (reference building) in the weighted demand category represents a building constructed according to the basic energy saving requirements of the local codes. It is used as a basis for comparison only for reference. Thanks to energy efficiency, the energy load has been reduced to a low level, as shown by the points L, D and Lm in the abscissa. These three points represent different types of balancing for load/production balance, input/output generation and monthly net balance (16). Second, enough orderly credit, such as the amount of electricity produced, is provided by renewable sources. In this case, three points of intersection of the supply and demand lines may be on a 45° line that represents different types of equilibrium that can be achieved at different time scales or limits. In addition, various weighted supplies, such as CO2 emissions, equivalent primary energy, may be reported in order on the basis of the energy conversion calculation.

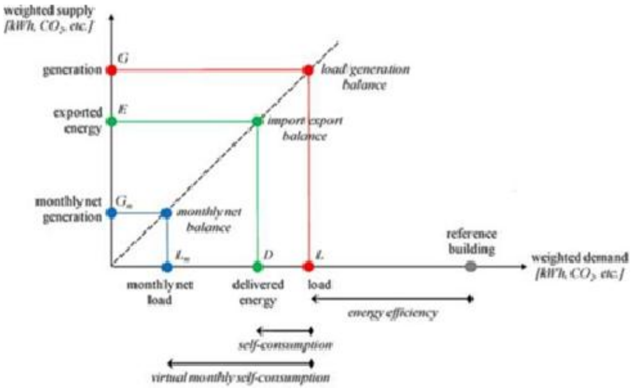

Fig. 3. Graphic expression of NZEB (16)

Figure 4 shows an energy flow diagram (Sankey diagram) of a building that can also be used as a graphic definition for NZEB.

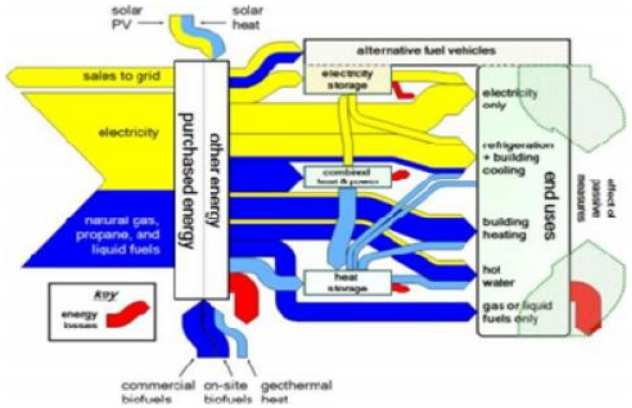

Fig. 4. Energy flow diagram for the building (17)

The square frame on the right side represents end-use charges, including electricity, heating, cooling, etc., while the available energy resources are shown in the square frame on the left side. He showed that various types of energy, such as: electricity, thermal energy, fuel or gas, supply the building system for the end user.

Entries at the top and bottom of the energy source framework are different sources of renewable energy. On the left side of the power source frame, the energy sold to the grid and the energy purchased on the grid can be compared to verify whether the net zero energy target can be achieved after being converted to a uniform metric. In this way, the performance of the entire system, including the building and associated service system, can be quickly assessed by comparing two energy flows. In addition to the D.O.E definitions, REHVA proposes a technical definition of NZEB almost necessary for the implementation of the "recast of the directive on the energy performance of buildings" (15). Hernandez and Kenny discussed similarities and differences in various related definitions and defined a LC-ZEB (zero energy building life cycle) (13). Kilkis introduced a new metric for net ZECBs (zero-carbon buildings) and NZExBs (zero-net buildings) (18). The status and prospects of energy-efficient and net-zero buildings were examined by Voss et al., and the relevant definitions were also discussed in theory (19). Two articles of synthesis present an overview of the definition of ZEB (zero energy buildings) in terms of the study of literature and calculation methodologies (10,12). A coherent framework of the definition, covering five relevant aspects of the limit, weight, balance, pairing characteristics and measurement and verification of the NZEB, is presented in ref (11). Based on the review of elements, parameters, mathematical forms, graphic forms and related studies, it can be summarized that the definition framework may be an appropriate option for promoting NZEB.

It can provide detailed options available for the criteria of various participants, although there is no simplified and internationally accepted definition. Through the definition framework, a basis for legislation and action plans to effectively promote the development of NZEB can also be created. Participants from different organizations, research fields and nations can choose elements from different levels to form a practical definition based on their own capacity, economic level, etc. In addition, it is essential to clarify the definition of NZEB prior to the evaluation work, as a clear definition can provide a direct and simplified guideline for the purpose, the research method, the tool and the evaluation performance indicator.

Energy-efficient measures: Although the occupants of the building are commonly regarded as consumers of energy products, most of the electricity, natural gas, etc., is actually consumed to drive the building service systems (BSS), such as heating systems, air conditioning. Thus, the performance of the BSS becomes an important consideration for the NZEB assessment. Energy efficiency measures applied in the main building body result in energy saving of BSS and improved performance of NZEB.

Thus, the energy efficiency measure, which is not defined in the definition, has a direct impact on the realization and evaluation of the NEZB. As shown in Figure 5, NZEB mainly involves three types of energy efficiency measures: Passive design, service system and power generation from RES. A good passive design of the building, which can include optimized orientation, a high-performance thermal insulation envelope, good sealing and well-designed shading for windows, generally reduces the thermal and electrical load of the buildings. In order to achieve the reduced loads, various HVAC systems (heating, ventilation, air conditioning), ECS systems (hot water), lighting systems, etc. are offered. The functional purpose of these systems is to create a comfortable interior environment for the occupants. Inevitably, a variety of energy sources, such as natural gas or electric power, are needed to run BSS. Thus, the Renewable Energy Production System (REP) must be installed to compensate for energy consumption. In this way, an NZEB could be possible with the production of electricity and heat from a renewable energy source, if sufficient energy capacity could be installed. The term "Building Energy System (BES)" generally refers to the combination of BSS and REP, as more and more NZEB choose to use certain integrated systems, such as CCHP biogas (combined cooling, heating and electricity), photovoltaic thermal collector, etc. Renewable energy is used not only for electricity generation, but also for heating, cooling or ECS production S, as a 100% renewable energy solution for sustainable buildings (20). Therefore, a clear distinction between the BSS and the REP system could disappear due to the greater number of forms of RES integration in the NZEB. A new configuration or integration will make BES more compact and more reliable for NZEB. With regard to possible energy efficiency measures for BES, Anderson presented a track map for NZEB in terms of benefit and risk, as shown in Figure 6 (21). Most energy-efficiency measures in the low-risk area have already been commercialized, though building-related integration solutions still require further exploration and demonstration.

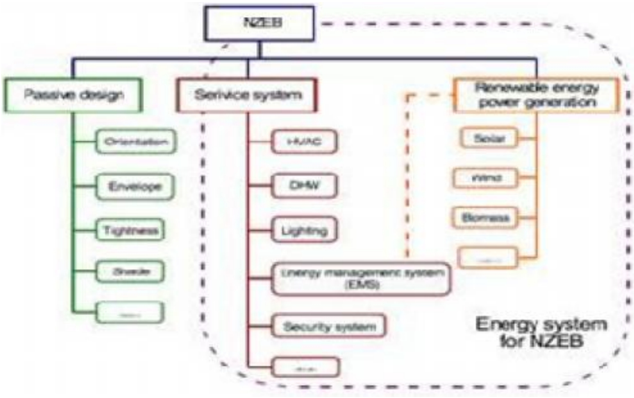

Fig. 5. Design elements for NZEB

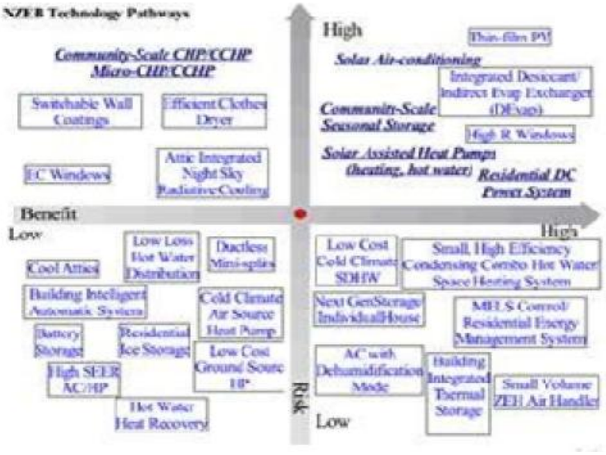

Fig. 6. Possible technologies for NZEB (Ref. source information)

Technologies in the high-risk area, such as: micro-CCHP, solar air conditioning, solar-powered heat pump, etc., which can be classified as BES technology, have been the subject of great research interests by the university and research institute in recent years. As a basic part of traditional HVAC and ECS systems, refrigeration or heat pump systems use the vapor compression cycle to provide thermal power. Although they have been accepted as a type of constant-performance device for HVAC and ECS systems by most of NZEB's existing projects, some of these systems' flaws, such as a high dependence on electricity, a treatment coupled with temperature and humidity, a working fluid that is not very environmentally friendly. , etc., encourage researchers to propose new solutions forbetter building performance.

The recent development of BES is reviewed in Refs. (22, 23), and prospects for the future use of highly efficient energy systems and efficient uses of renewable energy are presented with regard to residential refrigeration, electricity generation and energy storage (24). Compared to conventional HVAC and ECS systems, technologies that integrate the use of renewable energy with BES can further reduce primary energy consumption in NZEB. Some typical energy efficiency measures of the BES, which have been applied in demonstration buildings, arebriefly described below. It should be noted that the technologies that will be discussed in this section include onlyHVAC, ECS and electricity generation in the BES, and are selected on the basis of case studies on regional demonstrations and limited research experiences. Because local climates, energy-saving standards or economic levels, etc. have direct influences on NZEB's technological options, a technological framework with an openness to diversity must be encouraged for more opportunities for sustainable development. In fact, it's almost impossible to present an overview of all the technologies that can be used in NZEB design. The technologies discussed in this section do not include passive energy saving design, lighting, devices and optimization control and relatedadvancements of energy efficiency measures for building envelopes and internal conditions in NZEB can be foundin the ref. (25).

Solar heating: Given the cost, solar heating is the most direct and practical energy-efficient measure to improve the performance of buildings in less developed regions or countries, and is widely reflected in the NZEB design results. Solar thermal use should be based on the integration of solar collectors in the building. The facades of buildings can be solar collectors and thus become multifunctional. In addition, solar collectors canbe used to improve the appearance of the facade when considering their aesthetic compatibility. Currently, sensor installations on south-sloping roofs, south walls, balconies or awnings of buildings are the possible approaches for the integration of SCs in buildings. Since 1980, solar water collectors have grown rapidly worldwide. In some countries, for example in China, the average annual growth rate is as high as 30%. Until 2011, more than 195 million m2 of solar water sensors were commissioned in mainland China, which represented 60% of the global surface area of SC (26). Solar energy has an important role to play in the BES in the development of the solar energy industry in developing countries. The integration of the SC modules in the building facade will be developed and applied, and the technologies for interfacing the integrated solar energy system with the buildings will be studied in depth (27).

Solar sorption cooling: Active solar cooling is a reasonable energy efficiency measure as a conversion from excess solar radiation on the building to cooling power in summer. It can adjust the correlation between the building load and the power capacity of the HVAC system. As a typical active thermal cooling technology, solar sorption cooling offers interesting alternatives to NZEB design with less primary energy consumption. Mature sorption cooling systems available onthe market include a LiBr water absorption cooler and a silica gel adsorption cooler. A heat source of 85°C or more may lead a single-acting LiBr water absorption chiller to operate under conditions of 32°C cooling water temperature and 7°C ice water. The COP (performance coefficient) may reach 0.6 or more. The SC vacuum tube is generally recognized as a better choice than the SC plate for a single-acting LiBr water absorption cooler. The main problem with a single-effect machine is that the operating time depends deeply on the temperature of the hot spring and the cooling water. For example, if the cooling water temperature is above 30°C in summer, hot spring water is required to reach 80°C or more, the normal solar collector cannot meet this demand for 8 hours or more, so the cooling time is limited or cooling performance is affected. As another potential solar-assisted cooling system, the solar adsorption cooling system (silica-water gel) allows operating temperatures to be lower than the absorption system under the same conditions. Thus, the flat collector and the vacuum tube collector can be used to meet the demand of this cooler. Zhai et al. have proven experimentallythat a silica-water gel adsorption cooler can operate for more than 8 hours a day for continuous alternating currentwhen powered by solar water heating. The thermal COP could reach 0,3 when hot water at 60 ° C is used for production (28). The main problem with the solar adsorption cooler is that it needs a large surface of SC because the COP of the entire solar adsorption AC system is low. And a cooling tower and water tank are also needed to maintain a continuous operating state. Thus, the initial cost is higher than the solar-absorbed AC system. For a dual-acting LiBr water absorption cooler, a heat source of 150 °C is required.

This means that normal solar thermal collectors cannot be used for this system, some concentration SCs such as parabolic tank and Fresnel lens are considered as better choices. Recent advances in medium-temperature SCs, in which a special low-emissivity selective coating at 150 °C, showed that vacuum-tube SCs could yield 150 °C with a solar thermal efficiency of more than 40%. This can provide a good match between the SC vacuum tube and the dual-effect absorption cooler.

Independent temperature and humidity control: In some regions, a combination of high temperature and high humidity remains a challenge for conventional air conditioning, which tends to be temperature-oriented rather than humid. Thus, if latent heat and sensitive heat for cooling can be treated independently, energy savings and interior comfort can be achieved simultaneously. For example, an autonomous liquid dehumidification air conditioning system and dehumidification by solar- powered rotary desiccator have been implemented. Some hybrid energy systems for buildings that use desiccation dehumidification technology as an important component were reported (29,30). Solar thermal energy is considered a reasonable heat source for the regeneration process and performance will be changed if the periodic availabilityof solar energy can be overcome by certain approaches, such as high desiccant energy storage capacity or a suitable energy storage system. A typical case concerning the prototype of a solar-powered liquid desiccation system for cooling, dehumidificationand air conditioning was presented (31). The system uses a 120 L LiCl solution and 1000 L hot water to store energy. Its average dehumidification capacity is 16 kW and uses 20 m2 SCs. When solar energy is not available, the system can continue to operate continuously for 4 hours. The thermal COP based on heat acquired by SC is about 0.8. The absolute humidity level of the air is reduced from 16 g/kg dry air to 8 g/kg dry air during a typicalAugust day.

LiCl, silica gel and molecular sieve are three commonly used materials in the dehydrating wheel, the temperature range of these materials is 60w 120 °C, 80w 150 °C and 160 °C, respectively. Therefore, a solid cooling system using LiCl and silica gel as wheel materials can use a flat plate collector and a vacuum tube collector to provide regenerative heat. A typical solar dehydrant wheel cooling system was mentioned (32). A seminar room in a public building in Freiburg, Germany, was served by a solar-powered wheel cooling system. A solar air collector was used as the only heat source with an area of 100 m2. The adopted silica gel rotor is designed for an air flow of 10200 m^3/h.

Renewable heat pump: Heat pumps can make good use of various renewable energies or residual heat from the energy supply of buildings (33). Most NZEB demonstration projects choose a Geothermal Heat Pump (GSHP) as the core device of the HVAC system because of its high efficiency. However, the feasibility of applying GSHP should be considered deliberately on the basis of local conditions of temperature and soil character. In some regions, the application of GSHP may require a good match between condensation heat released to the soil in summer and evaporation heat absorbed by the soil in winter. Thus, the GSHP system is partly a form of inter-seasonal thermal storage. Energy efficiency can be increased by 30% more than an air heat pump, and the most important thing is that the GSHP can operate effectively in cold winter.
In some areas where the air is not very cold in winter and very hot in summer, the air heat pump may be more reasonable, particularly for small-scale applications. In recent years, some factors, such as: instability, mismatch between the summer and winter load of the building, protection of water bodies, etc., limit the development of solar thermal, geothermal, underground heat pumps. For example, some demonstration projects did not use a renewable energy heat pump as a stand-alone HVAC system, but used it as a assisted component throughout the energy system. For example, a solar-assisted geothermal heat pump system was applied in a greenhouse and a residence (34,35). A hybrid energy system containing SC, an absorption chiller and a heat pump was reported: the operating results showed that the cooler COP wasapproximately 0.8 and the cooling efficiency of the entire system was 0.2 to 0.3 (36). A hybrid system containinga heat pump can overcome some of the flaws of an independent heat pump system for the demand of individual buildings, but it costs more than a conventional HVAC system.

Electricity generation system: NZEB needs renewable energy generation to offset the energy consumed. While some NZEB definitions allow green electricity to be purchased, most NZEBs have recently created a global trend to use more self-generating energy from the onsite generation system. Research efforts on individual PV cells in recent years have led to progress in improving efficiency, for example, the effectiveness of single-crystal Si cell tests has already been greater than 25% (37). At the same time, cost reduction makes photovoltaic panels a common choice for the on- site power system in NZEB. Compared to PV solar, the production of electricity from solar thermal sources, suchas parabolic augers and Fresnel linear collectors, have no competitive price at the current stage (38). In addition, there are several other options available for REP systems, such as: onsite wind turbine, wind farm, biomass/biogas CHP and even hybrid electric system.

The CCHP system, which simultaneously generates electric and thermal energy from a single fuel source, has proven to be an interesting solution for increasing the total efficiency of an ESA and reducing CO2 emissions. Various HVC technologies, such as: the heat pump, adsorption cooler and desiccation cooling system may be considered in conjunction with a cogeneration system to constitute an integrated energy system for construction as demonstration projects (39-42). Due to its technical complexity and its high cost of purchase and maintenance, it is not so competitive recently in the residential construction sectors, but it is certainly an attractive developmentdirection for NZEB.

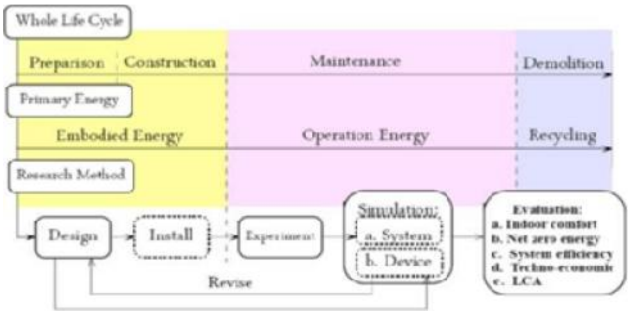

Fig. 7. Data flow diagram for evaluation

With the development of the commercialization of water coolers with small cooling capacities, it can be expected that new market segments for CCHP in the independent (or so-called autonomous) energy system of the public building and even of the residential building will open up. CCHP was considered a good option for cascading energy use for commercial buildings or district areas, a good CCHP design should be combined with appropriate integrated energy users, so even a cooling tower might not be needed. In addition to electric energy, the hydrogen fuel cell is another important source of energy for future buildings, particularly those powered by RES (43,44). Faced with restrictions on environmental emissions and oil depletion, future NZEBs will likely use hydrogen as a substitute for fossil fuels, although large-scale application still requireslong-term research.

With the development of these energy efficiency measures, a building can produce energy to compensate for the energy consumed, or even have a net energy production. To reduce costs, excess energy can be returned to the public power grid when the local grid allows it. At the same time, some NZEBs may still have to be connected to the grid in the short and medium term and consume electricity from traditional power plants when renewable energy generation cannot meet the building's load. Thus, the traditional power grid is faced with a challenge in terms of fluctuating power voltage, transformer overload and inadequate load at neighborhood level.

An intelligent network or intelligent energy flow will be needed in the near future. In addition, the benefits of energy efficiency measures integrated with renewable energy in the NZEB can be categorized as energy saving, cost or emission reduction, etc., and all these benefits must be quantified for assessment. This implied that a set of methodology is required for a standard evaluation process after a clarification of the objects assessed.

METHODOLOGY

The NZEB evaluation methodology discussed in this paper includes the search method, the tool and the performance indicator. Some key parameters of existing assessment systems for the high efficiency building, the green building or the low energy building, for example, the thermal conductivity value of the envelope, the building load, the COP of HVAC devices, are commonly adopted in the assessment system for NZEB. However, the performance indicators of the conventional evaluation have some shortcomings and are not suitable for NZEB evaluation. For example, the NZEB assessment does not focus solely on the amount of energy consumed or even on the balance objective, as a poorly designed building could even achieve the net zero energy target per year simply by oversizing the REP system. In addition, a building, which meets the NZEB definition, but cannot create a comfortable interior space, will lose its meaning as an ideal development model of the conventional building. Thus, a compromise between cost and interior comfort must be found in the content of the assessment. In addition, the assessment of the indoor comfort level and the LCA (life cycle analysis) are of great importance for the NZEB assessment in addition to the conventional energy balance analysis.

Search Method: A typical assessment process has been shown in Figure 7 along with the research methods involved. The whole life cycle of the building can be divided into 4 processes, including: preparation (manufacturing and transportation), construction, commissioning, maintenance and demolition. The primary energy consumed during the whole life cycle includes: embodied energy, operating energy and recycling energy. In order to evaluate the performance of a NZEB, performance data from experiments and/or simulations are required. The joint research work follows the same process: the design results are first validated by simulation, and the operational performance pair between the building and the energy system can be predicted. After that, the performance parameters and component curves in BES can be obtained through commissioning (for a commercial or residential building) or experiments (for a test building). The performance data, especially those obtained from steady-state or semi-steady-state tests, are then programmed into a system simulation module so that the annual system performance of dynamic operation can be recorded hourly for evaluation. Finally, evaluation is commonly performed in terms of indoor comfort, system efficiency, net-zero energy balance, techno-economic study, and life cycle analysis (LCA). Research methods common in building performance research, such as experimentation and simulation, can be considered as preparatory work for the evaluation. The completion of an evaluation process is highly dependent on available performance data, such as the power consumption of the NZEB. Thus, an accurate performance analysis can be considered as a meaningful preparation for the evaluation, while the evaluation can also be accepted as a more in-depth analysis from a specific perspective. As mentioned, the main research methods in most studies are experiment and simulation. Generally, experiment can directly provide performance data on NZEB through meter and sensor measurement, but experiment cannot be easily repeated under the same exact conditions of the external environment, especially for the on-site testing of demonstration houses. Therefore, simulation is widely applied as an assisted method to obtain enough performance data, for a whole year (8760 h) or even a lifetime. The simulation model of NZEB with the energy system, which is verified by the actual measured data of the experiment under certain specific climatic conditions, is preferred to use. At the same time, the verified simulation model can be applied in various case studies for more climates, occupancy conditions and economic scenarios.

Tools: A number of simulation tools have been developed for building and energy system in recent years. The functions of simulation tools summarized can cover passive design, active design of energy efficiency measures, and ERP system integration of different types of buildings now (45,46). However, unlike conventional building design, NZEB design focuses more on optimization or trade-off between various design elements. Thus, an ideal evaluation tool should integrate the optimization algorithm into the conventional transient energy consumption calculation. Some simulation software and modules, such as Genopt (47) and TRNOPT (48), can be used to solve some optimization problems in the NZEB design via built-in algorithms. With the support tools, the perfectibility of NZEB designs can be evaluated from an optimized base case. Another feature of the NZEB assessment is a life-cycle sustainability judgment, which can be reflected in the aspects of cost (affordable NZEB), net energy (positive building) and environmental protection (zero carbon building). Thus, a database, which contains all life cycle information on building and system materials, and/or an assessment tool that can perform an assessment calculation for the entire life cycle, is needed for the NZEB assessment and design. Typical environmental assessment tools for buildings, e.g. ATHENA (49), have been introduced in terms of software function and research object (50). Regarding the development of the ideal tool, a discussion on the needs and trends of simulation and design tools for the building and HVAC system was conducted in Ref (51). A detailed review of the literature on BPO (Building Performance Optimization) in NZEB, which includes the concept, history and algorithms of BPO was conducted (52).

Performance Indicator: The performance indicators applied in the evaluation include not only an energy balance factor for definition identification, but also include indoor comfort, economic and environmental influence factor.

Since the evaluation of economic and environmental indicators usually involves the entire life cycle of the building, the application of LCA is also discussed and summarized in the following section 3.4 along with the corresponding improvement ofthe NZEB definition.

Indoor comfort: Indoor comfort can be considered a prerequisite indicator for NZEB evaluation, because as a high performance model for building development, NZEB must provide an ideal space that has a high level of indoor environmental quality and resulting user comfort. Several comfort and energy efficiency recommendations for the NZEB have been presented in comparison to various standards (53). The PMV (predicted average vote) or similar models have already been widely recognized as a comfort assessment tool or index for indoor space comfort. These indicators have also been incorporated into the calculation and output of some transient simulation tools, such as TRNSYS (54), IES (55) and Design Builder (56), as well as CFD (Computational Fluid Dynamics) software for indoor air field simulation, e.g. Airpak (57). Alternatively, the Givoni bio-climatic building diagram can be considered as another typical tool, which is developed based on the comfort zones defined in ASHRAE 55 (58). Some case studies, which use the bioclimatic diagram in the assessment of indoor comfort, have an obvious characteristic of intuition and easy understanding (59,60). In addition to thermal comfort, visual comfort and IAQ (indoor air quality) are also important indicators of quality of life in NZEB (53).

Energy balance: Energy balance is a central concept in the definition of NZEB and therefore EBA (energy balance analysis) is a basic application for NZEB assessment, as the annual energy consumption of a building must be compensated by electricity generation from RES to meet the definitional demand. A case study graphically explains the EBA process in Ref (19). Once the annual distributions of energy demand and solar PV production are obtained via the calculation, the excess power during summer and shortage during winter in NZEB are accounted for as well as the grid power. The demand is met by the supply of on-site solar PV production and grid power; at the same time, the total amount of electricity production is at least equal to the total amount of the remaining demand supplied by the grid. In this case, a NZEB can be confirmed by EBA based on the basic definition in the framework. In addition to the net value, the NSB (net sustainable building) status coefficient, which is a relative ratio, has been proposed by Bojic to demonstrate an equilibrium relationship in NZEB (61).

Life Cycle Analysis: LCA is not a performance indicator, but a research method used for quantitative evaluation of materials used, energy flows and environmental impacts of products. It has been widely applied in the building industry, because it can not only provide a more complete and reasonable analysis on energy and environment. It can impact the product over the entire life cycle, but also be used to determine key design priorities and quantitatively inform sustainable design decision making for various buildings (62). For a building, the LCA assessment process, which is defined by the ISO (International Organization for Standardization), generally consists of four steps: definition of purpose and scope, life cycle inventory, impact analysis, and interpretation (63).

As for the LCA system boundary for buildings, it generally includes the manufacturing (preparation and construction), use (maintenance, servicing, and component replacement), and demolition stages, as shown in Figure 7. Compared to the ABE, which focuses only on the consumption of buildings during their operation, the energy consumptions for the manufacturing and demolition stages are included in the assessment so that the analysis can be performed for a more reasonable and real time period and the entire life cycle. Thus, both embodied energy and energy for demolition are added into the analysis system boundary, in addition to operating energy. Embodied energy here refers to the energy used during the manufacturing phase of the building, while demolition energy is the energy required to demolish the building and transport the waste to landfills and/or recycling plants (63). Once the purpose and scope of the analysis is identified, the inventory analysis and a life cycle impact analysis can be performed. Typical LCA performance indicators are CO2, methane and nitrous oxide emissions, etc., initial and operating costs, etc. (64). The results evaluated in these available performance indicators can be obtained by life cycle interpretation.

LCA definitely poses a higher level challenge for BEZ design, as the definition of BEZ is expanded to include embodied energy of the building and appliances as well as annual energy consumption. Thus, the energy embodied in its constituent materials and systems becomes a significant concern and cannot be ignored in the design, although case analysis in the literature has shown that it only takes up 15-20% of the life cycle energy consumption of buildings (63,64,66). Thus, the full life cycle scale BEZ (LC NZEB) should be redefined as suggested above: LC-ZEB is where the primary energy used in the building in operation plus the energy incorporated in its constituent materials and systems, including generator energy, over the life of the building is equal to or less than the energy produced by its RES in the building over their lifetime (13). A mathematical equation of the definition of LC NZEB in Ref (13) is updated in equation (2).

$$\boldsymbol{Annualized\ Life\ Cycle\ Net\ Energy} = |\boldsymbol{Output}| - |\boldsymbol{Input}| - \boldsymbol{Embodied\ Energy} =$$

$$\boldsymbol{NetOperationEnergy} - \boldsymbol{EmbodiedEnergy} = \sum \boldsymbol{i}\ \boldsymbol{Outputenergy}(\boldsymbol{i}) \times$$

$$\boldsymbol{weight}(\boldsymbol{i}) - \sum \boldsymbol{i}\ \boldsymbol{Deliveredenergy}(\boldsymbol{i}) \times \boldsymbol{weight}(\boldsymbol{i}) - \sum \boldsymbol{i}\ \boldsymbol{AnnualisedEmbodiedEnergy}(\boldsymbol{i}) \times \boldsymbol{weight}(\boldsymbol{i}) \geq \boldsymbol{0} \qquad (2)$$

The graphical definition of NZEB is also updated and shown in Figure 8 based on ref (13). The abscissa represents the AEE (annualized embodied energy) which is a conversion value of the total embodied energy. The embodied energy data for building materials and BES in NZEB is presented in kWh of primary energy per year for the lifetime and is referred to as AEE. The ordinate is the net operational energy which is actually the net energy in EBA (Equation (1)).

The 45° line represents an equilibrium line on which the net zero life-cycle energy goal can be achieved. For conventional buildings, the annualized embodied energy must be greater than zero, but the net operational energy can be negative, zero, or positive, which depends on the installed RPC (renewable energy capacity). As technology develops, the distance between building state points and the life cycle balance line decreases. An optimized REP capacity can bring the building state point closer to the LCA balance line. On the contrary, an oversized REP capacity will increase the annualized embodied energy, so that the distance to the equilibrium target becomes longer, although more net operational energy can be gained. The LCA data transfer process for NZEB begins with data collection. Sufficient information from the building owner, design group, and manufacturer must be collected first so that a database of embodied energy and component lifetimes can be established.

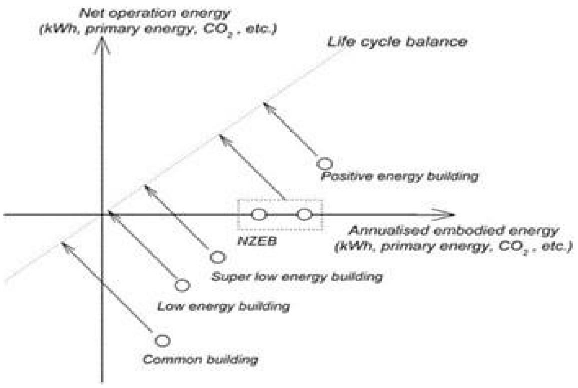

Fig. 8. Graphic definition of the LC BEZ

The embodied energy of each material, system, or product will be calculated for the life cycle of the building under certain reasonable assumptions or limits, e.g., transportation energy to the building site may be ignored in some LCA cases. At the same time, the operational energy consumed by the building and appliances, and the energy production from RES can be obtained by simulation and/or experiment. In this case, the annualized life cycle energy can be calculated and some results expressed in other evaluation indicators can also be obtained by various transfer factors.

A literature review on the life cycle energy consumption of buildings was conducted for conventional and low energy buildings, resulting in a total of 60 cases in different climates (66). A linear relationship between operating energy and total energy across all cases is revealed in the study as well as in some worthy experiments. A similarreview work on life cycle energy analysis is presented by Ramesh et al. The number of cases in this reference increases to 73 in 13 countries (65). The case analysis showed that the life cycle energy consumption of buildingsdepends on operating energy (80-90%) and embodied energy (10-20%). It also pointed out that low energy buildings perform better than zero energy buildings in the life cycle context, based on existing data. He demonstrated that if the assessment is updated from EBA to LCA, some existing NZEB cases may not show satisfactory sustainability performance. Another critical review of the life cycle analysis of buildings in terms of energy consumption and GHG (greenhouse gas) emission shows that the operation phase alone contributes more than 50% to the GHG emissions of buildings (63).

As for energy consumption, building operation takes 80-85% of the total amount and is the largest energy consumer. The life cycle economic design of NZEB has been discussed in ref (67) in terms of life cycle cost and payback period. A case study presented in this paper shows that a low- rise building can benefit from the application of the proposed methodology at the beginning of the NZEB design. The results of this review work show that operating energy consumption accounts for the largest proportion of total NZEB consumption. Thus, research on the building service and REP system, especially on the integrated BES, is of great importance for the design, application, and evaluation of NZEB. In addition, the complexity of the integrated BES can certainly extend the NZEB functionality and improve its performance, but may increase the total initial cost and be negative for LC NZEB.

Development trend: Regarding the development trend of NZEB and related technologies, several researches have proposed roadmapsfor different climates or countries. A global perspective on the possible energy consumption and CO2 emission trajectories of local residential buildings was presented by the Irish Sustainable Energy Authority (SEAI) (68). The roadmap towards a 90% reduction in residential CO2 emissions by 2050 and defines 5 improved scenarios interms of policy, measures, technology and knowledge. Energy efficiency retrofits, renewable energy deployment, low-carbon technologies, and decarbonization of the power grid are the main measures in the roadmap. For NZEB in India, Kappor et al. presented a strategic roadmap with goals, barriers, and recommendations for strategy in the building sector through 2030 (69). Solar application in passive design, water heating, photovoltaics, and high- efficiency AC are suggested technologies in this report, along with energy-saving lighting technologies. The challenges and opportunities for NZECB (net zero energy commercial buildings) in the United States were examined through codes and standards by Ames (70). In addition, natural gas application and measurement technologies are discussed in refs. (71, 72), respectively, with respect to the roadmap and case study towards NZEB. The topic of the roadmap to NZEB development was contained in ref. (73), but that paper was more about the methodology. A technology development roadmap for zero and positive energy smart buildings (NZEB / PEB), and in particular the essential ingredients of the future integration technology, was present in Ref. (74).

In order to achieve a necessary match between production and consumption in NZEB under dynamic real-time conditions, the authors suggested applying intelligent PCS (predictive control schemes), which are based on just accurate enough simulation models and supported by easy installation, commission monitoring and networking schemes. With a rapid development of NZEB, the improvement of the design concept and the specific technology will make an evaluation more difficult. Based on a literature search and our experiences with BES, three considerations should be taken seriously for the evaluation and design of NZEB in the future. First, at the current stage, various options for integrating ERP and traditional electric power into BES should be considered in building design for a transition from a conventional energy-saving building to NZEB. Second, in the short to medium term, the highest priority for BES design should be an integrated BES that can achieve a reasonable balance between annual consumption and RES generation via a central control system. In this way, NZEB's dependence on primary energy would be reduced through the optimized operation of the BES. However, a 100% self-sufficient NZEB without connection to the national grid, which is an ideal model for the future NZEB, is definitely a challenge for the BESdesign of the current stage. Thus, energy storage technology becomes necessary and essential to the goal of self- sufficiency in the medium term. The co-application of RES and conventional assisted energy resource in a building can realize NZEB without energy storage in the current stage, while the smart grid can also eliminate the individual energy storage unit with its intelligence capacity adjustment in the future. Based on the existing work and our considerations on possible advancement of NZEB and consequent promotion in evaluation research, several main development trends of NZEB, which are beyond the scope of most existing demonstration NZEB, are briefly presented.

It should be noted that the technologies summarized in this section are not similar to the specific technologies discussed in Section 2.2: (1) they have not been applied on a large scale or even in demonstration projects; or (2) they are more like a package design concept or integration technology platform, e.g., smart grid, so they cannot be easily classified into a specific type of technology; or (3) little evaluation research can be found in these areas, e.g., load matching and grid interaction. These energy efficient measures or design concepts are options available to further motivate the potential of renewable energy and energy efficiency in NZEB and thus put forth a higher requirement for NZEB evaluation. Developing new evaluation indicators, standard evaluation processes, dynamic online evaluation system for new trends is a continuous progress.

Energy Storage: The most important feature of NZEBs is the power or heat input advantage of RES. However, the output performance of renewable source utilization devices, such as solar PV or air conditioning system, is usually unstable without auxiliary energy sources. Thus, energy storage plays an important role in improving the total efficiency of BES. The instability between energy supply and demand, or peak and off-peak consumption of electricity can be addressed by energy storage facilities, whether it is electrical storage or thermal storage. There are three types of conventional storage batteries widely used today: lead-acid batteries, nickel-based batteries and lithium-based batteries. The indicators evaluated for these typical batteries are energy and power density. The ranges of these two indicators for various batteries are shown in Figure 9. Figure 9 (a) shows a development trend of various batteries in energy density that has been proven by current data. For example, the value of energy density by weight was predicted to reach 170 Wh / kg in 2005 for the LieIon battery, while the peak value in a hook- shaped area was already above 180 Wh / kg for the LieIon battery, as shown in Fig. 9 (b).

Lead acid batteries have been used for residential solar PV systems for many years and may still be the best choice for this application in NZEB due to their low maintenance requirements and low cost. Lithium and NiMH (nickel metal hydride) batteries are commonly used in mobile communication devices or laptops due to their high storage energy density and C-rate (discharge capacity) (Figure 9 (b)). They are more expensive at the current stage, and can also be used in electric vehicle or small energy storage devices. The lifetime of lead-acid batteries used in solar photovoltaic systems is usually less than 5 years (77), although it is rarely used, because the acid in the battery wears out the internal components. Thus, electricity storage devices will be the most expensive component of the REP system in a NZEB over the life cycle due to maintenance and replacement costs. In addition, possible and expected barriers of electrochemical energy storage devices, e.g., consumption of non-renewable resources or poor battery management, are discussed in Ref. (78), as well as an ideal renewable battery for a sustainable future. Common thermal energy storage methods are sensible thermal energy storage and latent thermal energy storage using PCM (phase change material) or thermochemical energy storage. The technology classification, energy density of thermal energy storage are both shown in Figure 10. Sensible heat storage, such as water tank, has already been widely applied in the SC loop of direct heating systems, DHW systems or even sorption cooling system. The main disadvantage of sensible heat storage, such as the water curve shown in Figure 10, is an unstable operating temperature (about 28 to 100 °C) and low energy storage density. Latent heat storage means that thermal energy is stored by changing the phase of the PCM. The phase change is achieved by absorbing a large amount of heat at a constant temperature. Compared with the sensible heat storage method, it can provide higher energy storage density and more stable operating temperature. The most promising application in buildings of this energy storage method is integration with envelopes, such as PCM floors or walls; it is presented in Ref. (80). It can improve the thermal capacity and inertia of the whole building body and thus smooth the fluctuation of external weather conditions to indoor comfort. However, the supercooling and performance attenuation of PCM can have a negative effect on its stability and high heat storage capacity and at the same time limit the large-scale application in buildings. Through sorption and thermochemical energy conversion, thermal energy is stored chemically. The energy storage density depends mainly on the amount of material, the endothermic heat of the chemical reaction and the degree of conversion of the reaction. Although this process has a higher energy storage density, it generally has disadvantages for a suitable material, as it requires the material to have the characteristics of a completely reversible chemical reaction and an appropriate reaction temperature for different heat sources.

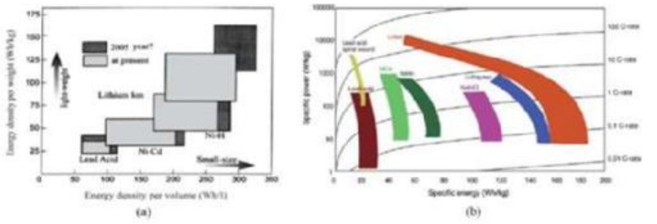

Fig. 9. battery performance: (a) energy density (75); (b) power density (76). (* C-rate is commonly used to describe the battery's discharge capacity)

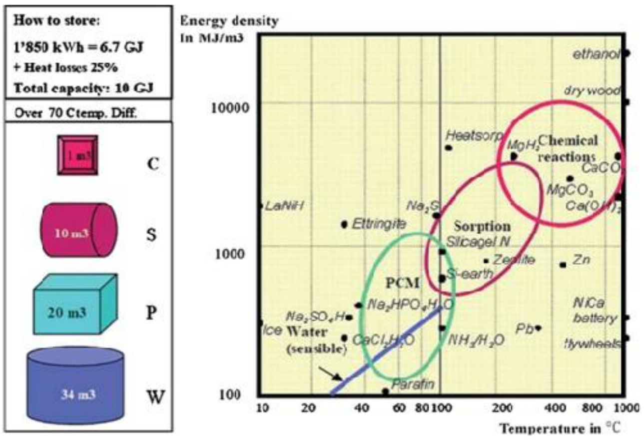

Fig. 10. Energy density of thermal storage technologies (79)

Thus, fewer applications concerning this technology can be found in the building section, also considering the cost factor. As for the possible applications in NZEB, thermal storage can be easily put into practice with regard to the initial and maintenance cost. For example, heavy solid materials have already been widely used in the building envelope for enhanced heating as a passive design strategy.

Their operating temperatures cover a wide range, but the specific thermal capacities are generally lower than those of water or CFM. Another typical application of a solid material is a rock bed, which is typically used in conjunction with a solar air collector. The heat stored during the day is relived at night for assisted heating. Thermal storages based on these materials offer advantages such as cheap and environmentally friendly, although the energy storage density is lower. In addition, various PCMs have been developed and then commercialized as thermal storage materials for cooling, heating, thermal comfort, domestic hot water and thermal source in buildings, as shown in Figure 11. Since heat storage and distribution occurs over a fairly narrow temperature range, PCMs are well suited for applications in small temperature ranges.

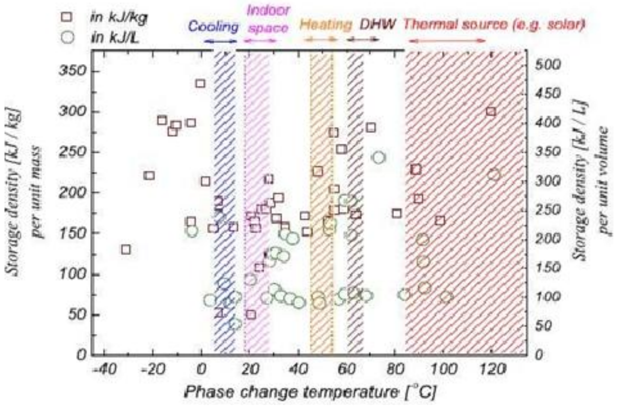

Fig. 11. Storage densities of typical commercial PCMs (original data points are from reference (81))

For example, they can be integrated not only as a passive system for indoor comfort (18 to 26 °C), but also in an active system for chilled water supply (7 °C to 15 °C) or DHW (60 to 65 °C). The heat density values of typical commercial PCMs in Figure 11 show that the average value is about 224 kJ / kg. For BES integrated with RES, e.g. solar AC, thermal storage can stabilize the fluctuation of the solar source to provide a continuously supplied source for solar heating, cooling or DHW production. Feasible PCMs for NZEB are kerosene, lamellar water eutectics, and salt hydrates and their mixtures. In the short term, thermal storage strategies in passive design will be widely applied in NZEB for performance improvement, with respect to its acceptable cost. The temperature of the thermal storage is close to the indoor temperature (18 to 30 °C). In the medium term, with the development of BES with REP, the thermal storage system for possible heating and DHW applications and electricity storage for REP will be integrated into the existing building service system for regular and quality service in HVAC, DHW supply and power supply. The thermal storage temperature reaches a range of 45 to 65 °C. In the long run, with decreasing cost of PCM materials, etc., large-scale practical applications of energy storage will appear in NZEB, for example, cooling energy storage for solar air conditioner, high-temperature energy storage with concentrated SC or exhaust heat from CCHP. The temperature range of thermal storage will be extended to a wider band. The design capacity of the energy storage will depend not only on the demand on the end-user side, but also on the supply on the source side with the potential amount of renewable energy input. The characteristics of the local climate, the building envelope that decides the dynamic nature of the load, are critical factors for the design scheme of the energy storage and the specific function of the energy storage, e.g. assisted heating at night.

Load Matching and Grid Interaction: Although the goal of net zero energy based on the annual balance is chosen as the main evaluation indicator for most NZEBs, a comparison of three NZEB case studies shows that the balance cannot be achieved if the evaluation is performed on a shorter time scale, such as a monthly, daily, or hourly period, and not an annual period (14). Thus, most NZEBs cannot fully achieve self-sufficiency on an off-grid status (energy self-sufficient building) at the current stage and still need a two-way connection via smart meters with the central grid. In order to evaluate the performance of NZEB at different time scales, two indicators, namely load matching and grid interaction, are developed to study the coupled performance between the grid, REP and building. A ratio of building demand coverage by renewable energy supply is commonly used to evaluate the performance of load matching. It can be improved in two ways: by matching demand to generation, also called DSM (demand side management), and by matching generation to demand (82). However, load matching only focuses on the relationship between demand and supply within the NZEB footprint. It cannot be used to describe the interaction between NZEB and the grid.

In general, this type of interaction is assumed to be an ideal state because the public power grid is considered to be unlimited energy storage. The quality and amount of BEZ power output also depends on the performance of the local grid, which means that the utility infrastructure cannot be considered as an ideal and fast-response storage without considering the details, such as voltage, and transmission characteristics. Thus, the concept of grid interaction must be quantified and can be expressed as a ratio of the net grid metering over a given period to the maximum net grid metering in an annual cycle. It is commonly used to describe the average grid stress using the standard deviation of the grid interaction over a one-year period (14). Lund et al. defined a factor, called the mismatch compensation factor, to quantify the imbalance between generation and consumption at the building level (83). In addition to indicators, technology development to address both of these issues is also underway. The ideal BES not only minimizes the energy consumed, but also "reshapes" the dynamic load, e.g., via operation and control- optimization of HVAC or energy storage system, etc., (74). By addressing the matching problem in these solutions, the dynamic difference between load and generation does not become a major obstacle to NZEB. Therefore, the goal of "reshaping" technologies is to achieve dynamic matching between building load and NZEB power supply, and less dependence on additional grid power.

DSM is a feasible technology solution for adjusting the building load. DSM, also known as LSM (load side management), is defined as an integration technology solution for planning, implementing, and monitoring building utility activities based on load variation. It can influence the customer's energy usage in a way that produces desired changes in the load shape, i.e., changes in the time pattern and magnitude of the system load (84). DSM generally includes six broad categories of load shape objectives: peak clipping, valley filling, load transfer, strategic conservation, strategic load growth, and flexible load shape. With DSM, building energy consumption can be reduced and thus the cost of service for utilities can be lower. Due to on-site REP, NZEB's generalized DSM contains optimized control of renewable energy generation in addition to the conventional definition range, as shown in Figure 12 (a). Through dynamic tracking, monitoring and storage technologies, etc., a more stable supply from on-site generation can be provided to NZEB throughout the year. Rather than attempting to match power generation to consumer demand, the DSM philosophy takes steps to vary load to match available power (85). By applying appropriate DSM technologies, it is possible to reduce the need for new installed intermittent power to meet renewable energy penetration targets.

By HMES (home energy management system), DSM and REP optimization control can be integrated into a standard platform that has a uniform communication and power protocol. On the other hand, occupants, who are also customers of energy products, will be able to join energy programs aimed at optimizing their energy consumption behavior and, finally, achieving efficient management of the local power grid. Thus, the functions of the ideal HEMS (home energy management system) in NZEB can be summarized as follows:

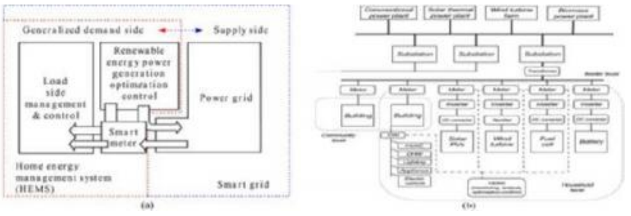

Fig. 12. Power solution for NZEB: (a) HEMS & smart grid; (b) Smart grid

- Integration into on-site or local distribution networks of various energy sources, such as: solar PV, wind, biomass/gas turbine, fuel cell, battery farm;
- Reduction of peak load and additional grid input, and matching of load to on-site power supply, thereby reducing operation and maintenance costs;
- Stability of the distribution system, reduction of power supply interruptions, operation and maintenance costs of the system (86);
- Extend the operational life cycle of appliances, battery, lighting and renewable energy system, create acomfortable and energy efficient style for occupants.

Smart grid: In addition to the load side, the power side in Figure 12 (a) typically contains power generation, power transmission, power distribution, and control system. Some bottlenecks regarding the interaction of power bundles in NZEBs, such as: transient fluctuation of net power, transformer overload (e.g., on-site power generation cannot be consumed instantly via the grid by neighboring buildings), and distribution of many PWR systems, still need to be solved at the feeder or district level. The smart grid is seen as an integration solution to intelligently realize two-way communication or interaction between the BES and national grids. The term "smart" implies that the grid not only inherits the advantages of the traditional infrastructure system, but also has enough intelligence to realize advanced management goals and functionalities.

For a smart grid connected to NZEB, electricity can be generated by a variety of small-scale power conversion units (typically 1 kW to 1 MW), which can be located very close to the end user. Three broad classes of energy sources for NZEB can be identified: on-site REP (solar PV, small-scale solar power, biomass HVDC, wind turbines), on-site generation and backup (small generator, fuel cell, UPS (uninterruptible power supply), batteries), and bulk (conventional power plant, solar thermal plant, wind turbine, or solar PV farm). Figure 12 (b) shows a diagram of the smart grid connection structure. Demand and distributed generation are directly connected at the individual or community level, so that the bulk generation distribution system, small-scale on-site PWR generations, local storage systems, and relevant end-use devices, can be operated autonomously and they are all integrated into a grid structure. Therefore, updated smart meters, monitoring system, and communication protocols are needed to facilitate the "plugging" of local subsystem hardware and software into the national infrastructure. It is expected that NZEB can certainly benefit from a smart grid in terms of reducing the primary energy and carbon emission factors of the grid, as well as the operating costs (11).

Conclusion

In this article, global initiatives and policies, definitions of NZEB are reviewed as well as development trends. Several promising and mature energy efficiency measures for NZEB, such as a solar heating system, solar cooling system, renewable source heat pump, and power generation system, are briefly presented. In addition, the evaluation indicator and relevant research methodology are discussed. The possible application of LCA is also discussed in the NZEB evaluation. Some conclusions are drawn as follows:

- A widely accepted NZEB definition should be a framework with different levels of boundary, metric, criteria, credit, etc. Based on local climate, living customs, and economic factors, it may be best to set definitions at different levels. Within a framework, so that specific roadmaps that demonstrate various progress toward NZEB can be accepted by more participants. However, the difference in NZEB definitions would certainly have a direct impact on the evaluation results, although the definitional elements are limited in a common scope. Thus, clarifying the definition of NZEB can make the evaluation more effective with a clear purpose.
- The energy efficiency measure, which is not limited in the definition, has a direct impact on the evaluation of NZEB performance. The energy system can become a priority on how to further improve NZEB performance because passive building design is already a mature technology in commercial applications and can be achieved in a standardized process by the simulation software. NZEB's energy system, such as HVAC, domestic hot water, and on-site power generation system, could be more efficient with the help of renewable energy.
- A clear distinction between the BSS and REP system may disappear due to the greater number of RES options available to NZEB. Several representative BES highlighted with renewables, such as solar heating, have already been widely applied in NZEB demonstration

projects. A new configuration or integration can make BES more compact and reliable. The benefit of BES integrated with renewables in NZEB, which can be transferred to energysavings, cost reduction, and emission reduction, needs to be quantified for evaluation. Thus, not only the NZEB performance, but also the conversion factors must be obtained. This implies that a standard calculation process and corresponding indicators are needed for NZEB evaluation. Thanks to recent advances in simulation tools and the evaluation system, these new obstacles can be overcome.

- Experimental and simulated building and BES studies are the primary preparatory work for the evaluation, as validated performance results refer to the accuracy of the evaluation. Compared to conventional building design, NZEB integration design generally pays more attention to performance optimization, energy balance, and trade-offs between different design elements. Thus, the primary content of the evaluation work would also be adjusted. For example, indoor comfort and energy balance are typical performance indicators used in the NZEB assessment given its basic definition. In addition, a possible application of LCA in NZEB will make the assessment more comprehensive, as a sustainability assessment result can be obtained in terms of cost control, carbon reduction, environmental impact and even climate change. However, the application of LCA in NZEB assessment makes an inevitable update in the NZEB definition and associated assessment methodology. More work on these research directions is needed so that a more comprehensive assessment framework can be established with the development of assessment tools, indicators, etc.
- The research work is focused on three areas: energy storage, load balancing and grid interaction, smart grid, can further improve the sustainable development of NZEB. These are actually integration concepts for various technologies and make the evaluation more complicated. Further research, such as the development of a new evaluation indicator for load adequacy and grid interaction, standard evaluation processes for different definitions, a dynamic online evaluation system for real-time performance of the two-way connection between NZEB and thesmart grid, are needed. A connection to the national grid, which is an ideal model for the future NZEB, is highly dependent on the integration of renewable energy and energy storage in the short and medium term, while a smart grid will eliminate the individual energy storage unit with its intelligence capacity adjustment in the future. Such possible advances in NZEB and the resulting promotions will pose a new challenge to the existing evaluation system.

Symbols

AC air-conditioning
BES building energy system BSS building service system
CCHP combined cooling, heating and power COP coefficient of performance
DHW domestic hot water
DSM demand side management EBA energy balance analysis
GSHP ground source heat pump
HEMS home energy management system HVAC heating, ventilation, air-conditioning LCA life cycle assessment
LSM load side management NZEB net zero energy building
PCM phase change material PV photovoltaic
REP renewable energy power RES renewable energy source
SC solar collector
ZEB zero energy building

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