Assessment of the Renewable Energy Generation Towards Net-Zero Energy Buildings: A review

Asam Ahmed[1], Tianshu Ge[2], Jinqing Peng[3], Wei-Cheng Yan[4], Boon Tuan Tee[5], Siming You[1]*

1=James Watt School of Engineering, University of Glasgow, Glasgow, UK, G12 8QQ

2=Key Laboratory of Power Mechanical Engineering, Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, MOE, Shanghai, P.R. China

3=College of Civil Engineering, Hunan University, Changsha, Hunan, China

4=School of Chemistry and Chemical Engineering, Jiangsu University, Zhenjiang, Jiangsu, 212013, P. R. China

5=Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

*Corresponding author: Siming.You@glasgow.ac.uk

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ABSTRACT

Decarbonizing the building sector is extremely important to mitigating climate change as the sector contributes 40% of the overall energy consumption and 36% of the total greenhouse gas emissions in the world. Net-zero energy buildings are one of the promising decarbonization attempts due to their potential of decreasing the use of energy and increasing the total share of renewable energy. To achieve a net-zero energy building, it is necessary to decrease the energy demand by applying efficiency enhancement measures and using renewable energy sources. Net-zero energy buildings can be classified into four models (Net-Zero Site Energy buildings, Net-Zero Emissions buildings, Net-Zero Source Energy buildings, and Net-Zero Cost Energy buildings). A variety of technical, financial, and environmental factors should be considered during the decision-making process of net-zero energy building development, justifying the use of multi-criteria decision analysis methods for the design of net-zero energy buildings. This paper also discussed the contributions of renewable energy generation (hydropower, wind energy, solar, heat pumps, and bioenergy) to the development of net-zero energy buildings and reviewed its role in tackling the decarbonization challenge. Cost-benefit analysis and life cycle assessment of building designs were reviewed to shape the priorities of future development. It is important to develop a universal decision instrument for optimum design and operation of net-zero energy buildings.

Keywords: Net-zero energy buildings; Renewable energy; Wind power; Solar; Bioenergy; Heat pump; Hydropower

Word count: 9,895

ABBREVIATIONS

No.	Symbol	Description
1	NZEBs	Net-Zero Energy Buildings
2	GHG	Greenhouse gas

3	MCA	Multi-criteria analysis
4	GSHPs	Ground source heat pumps
5	ASHPs	Air Source Heat Pumps
6	CO	Carbon monoxide
7	H_2	Hydrogen
8	CO_2	Carbon dioxide
9	CH_4	Methane
10	N_2	Nitrogen
11	AD	Anaerobic digestion
12	NPV	Net present value
13	CBA	Cost-benefit analysis
14	IRR	Internal rate of return
15	BCR	Benefit-cost ratio
16	FIT	Feed-In Tariff

1. INTRODUCTION

The building sector is currently facing great challenges concerning energy consumption, decarbonization, and a lack of access to modern energy services (i.e. energy poverty) along with the global pressure of fossil fuel depletion [1]. The sector is a major greenhouse gas (GHG) contributor and energy consumer globally. For example, in the UK, it contributed around 40% of the total carbon footprint in 2014, with 69% of these emissions being attributed to heating [2]. Buildings consume about 40% of the entire energy within the EU [3]. In China, this sector accounted for roughly 28% of the national energy consumption which was expected to increase to 35% by 2020. There is a worldwide urgency for taking stringent measures to enhance building energy efficiency and decarbonize the sector [4].

Renewable energy plays a critical role in tackling the challenges of fossil fuel depletion and climate change and has gained an increasing percentage in the energy mix around the world. For example, approximately 30% of electricity production in the UK between April and June 2017 was provided by renewables [5]. The EU is one of the forerunners in promoting decarbonization and the use of renewable energy as reflected by its target, i.e. 20% GHG emission reduction, 20% increase of renewable energy use, and 20% upsurge in energy effectiveness by 2020 from 1990 levels [3].

The aims of decarbonization as well as increasing renewable energy generation in the building sector, stimulate the development of sustainable buildings or buildings with net-zero energy (NZEB) status. An NZEB is defined as a building or construction that has a zero-net consumption of energy or zero carbon emissions over a set period (Figure 1) [6]. A two-way grid is a grid that can deliver energy to and receive energy from a building. The red arrow in Figure 1 is the energy exported from the building to the grid and is used to indicate either off-site or on-site grid. The green arrow refers to the energy delivered to the building from the grid which could be either off-site or on-site renewable energy.

The concept of NZEB can be used to describe a building with traits such as having equal energy generation to usage, a large reduction in energy demands, and the costs of energy being equal to zero or net-zero GHG emissions [7]. It can also refer to as a building that generates sufficient renewable energy on-site to satisfy its energy requirements [8].

There are several ways in which buildings can achieve net-zero energy, including integrated building design, retrofits, and energy conservation [9]. For example, high-quality insulation is integral in helping achieve net-zero energy by effectively reducing energy demands [10]. The use of underfloor heating in place of radiators can reduce energy consumption, as the water does not need to be heated as much to achieve thermal comfort. Finally, renewable energy (i.e.

wind, solar, geothermal, and bioenergy) generation and use play a central role in fulfilling NZEBs.

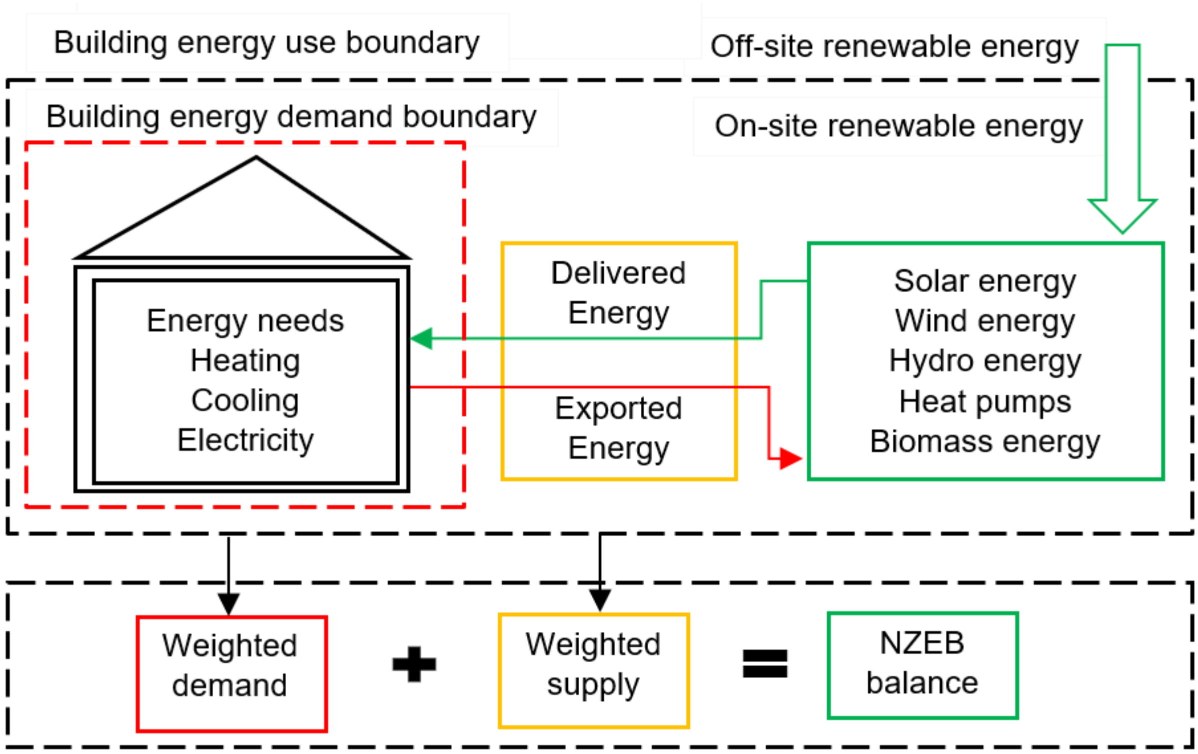

Figure 1. The definition of NZEB.

Extensive studies have been carried out concerning the development of NZEBs with the different types of renewable energy. However, the practical implementation of NZEBs is still in its early stages, particularly for the ones supported by distributed renewable energy supply. There are limited reviews that summarise the development of NZEBs in terms of renewable energy generation and the methods (considering various factors such as economic viability and environmental impacts) of designing NZEBs. Harkouss, and Fardoun reviewed a comprehensive review of NZEB definitions and NZEB designs and their drawbacks. It reviewed the most used electric and thermal renewable energy applications which support NZEBs [11]. Feng, et al. presented features of current NZEB development, reviewed climate-responsive NZEB designs, and analyzed building energy performance and technology options [12]. It is worth noting that, in addition to the concept of NZEB, there is a concept called "net energy" frequently used in the construction industry to account for the difference between the energy consumed by a building and its occupants and systems, and the energy from renewable energy sources. Hernández and Kenny incorporated the "net energy" concept to aid the design of a built environment from a life cycle perspective [13].

There have been few studies reviewing the contributions of renewable energy generation to the development of NZEBs and the techno-economic feasibility and environmental impacts of renewable energy technologies in supporting NZEBs. Specifically, there are rare studies systematically summarising the potential of different types of renewable sources to support NZEBs and the methods that can be used to design NZEBs. This paper will fill these gaps by clarifying the extent to which the use of renewable energy technologies can support NZEBs and their techno-economic and environmental impacts in supporting NZEBs.

The rest of this paper is organized as follows: Section 2 presents the classifications of NZEBs. Section 3 explains the supply options for renewable energy technologies with NZEB. Section 4 explains the methods of cost-benefit analysis and life cycle assessment that are commonly applied to evaluate the performance of renewable energy technologies and development. Section 5 reviews and provides a summary of case studies of NZEB. Section 6 presents the challenges of NZEB development. Section 7 presents a discussion and a summary of the information for renewable energy generation towards NZEB collected in this paper. Section 8 concludes the paper and provides perspectives.

2. NET-ZERO ENERGY BUILDINGS (NZEBs)

2.1 Classification

NZEBs are typically classified into four well-known models based on different modes of energy generation and usage: Net-Zero Site Energy buildings (NZ-site-EB), Net-Zero Emissions buildings (NZ-EB), Net-Zero Source Energy buildings (NZ-source-EB), and Net-

Zero Cost Energy buildings (NZ-cost-EB) [14]. An NZ-site-EB produces a unit of energy for every energy unit consumed on the site itself. The origin of the energy is not considered as it assumes that a unit of energy is equal to that of another, regardless of source. This definition may prevent the identification of cost-saving prospects like peak and off-peak energy tariff rates [15]. An NZ-source-EB produces a unit of energy for every energy unit consumed on the site itself. The energy generation is quantified at the source itself [7]. This definition has an edge over the first one as it considers energy that may be lost or wasted during generation or distribution. However, it also prevents the identification of cost-saving opportunities. NZ-source-EB suggests that some energy produced can be from an off-site source. An NZ-EB defines a building that produces minimally as much emission-free energy as it consumes emission-producing energy [16]. It encourages emissions-producing energy if the same amount of energy is offset by emissions-free energy. For an NZ-cost-EB, the owner of the building has zero utility bills. However, utility providers usually charge certain fees for various reasons such as maintenance. To meet obligations for maintenance and maintain the capacity to meet potential loads, the associated costs may make NZ-cost-EB not achievable. Also, it does not consider the energy production process and is affected by external factors such as variations in fees.

Hierarchical steps have been proposed to develop NZEBs. Firstly, energy use should be reduced by restricting the quantity of loss and heat gain, considering building service systems such as cooling and heating. Secondly, renewable energy technologies can be used to supplement energy supply and to cover part of the energy use that cannot be reduced. Typical renewable energy technologies such as solar thermal, heat pumps, bioenergy, and wind turbines can be considered [17]. It is worth noting that, upon NZEB rating, only the operational energy intended for a building is used while the energy linked to the building's construction (i.e. embodied energy) and commissioning is often ignored [18]. This is mostly due to a lack of data, a preference for traditional construction methods, and the difficulty of quantifying the energy incorporated [19].

2.2 Passive House (PH)

The PH standard has emerged as a key enabler for the NZEB standard. A PH is designed to have an energy demand that is as low as achievable [20]. The PH concept could minimize the energy demand of buildings by enhancing building technology with low energy requirements [21]. It aims to deliver a satisfactory and even superior indoor environment concerning thermal comfort and indoor air quality at the lowest energy cost. The PH standard relies on five major principles: a ventilation system that recovers heat, excellent airtightness, improved thermal insulation, and reduction of thermal bridges [22]. Consequently, when houses are built under the PH standard, the cost normally rises.

The PH concept aims to achieve clean indoor air, good thermal comfort, and a considerable decrease in the main energy demand, e.g., saving more than 50% of major energy consumption[21]. Based on the PH concept, a building should conform to certain requirements. For example, the demand for space heating energy should not exceed 15 kWh/m^2. The principal energy demand, i.e. the entire energy that domestic applications consume, should not exceed 120 kWh/m^2. Concerning airtightness, a maximum of 0.6 air changes per hour is allowed [23]. Comparatively, the NZEB standard demands that houses must consume on average less than 45 kWh/m^2 per year, including ventilation, fixed lighting, and space heating. The NZEB standard focuses solely on energy consumption, while the PH standard is defined based on the consideration of the indoor environment and quality thermal comfort.

When it comes to defining the sustainability of a building, the materials used in its construction are crucial [24]. Normally, NZEBs do not account for the embodied energy during the construction and production of the materials they use [25]. The energy embedded in the construction of a building includes the energy used in the manufacturing of the materials, their transportation, and the energy required by the machinery during the execution of relevant tasks [26]. According to Chastas et al., the share of embodied energy among the overall energy usage for passive buildings could range from 11 % to 33 % [27].

In some situations, the energy analysis of buildings showed that embodied energy accounted for 50% of all primary energy demand [28]. Ding found that the energy embodied in residential structures ranged from 3.6 to 8.76 GJ/m^2 [29]. Dascalaki et al. measured the embodied energy for a variety of buildings which ranged from 3.2 GJ/m^2 to 7.1 GJ/m^2 on average [30]. Construction energy should be viewed as a tool that can be used to reduce the extraction and exploitation of non-renewable raw materials. Hence, it is desirable to develop a new NZEB rating approach to take into account the variation of embodied energy.

Living Building Challenge is another common approach for designing NZEBs. In this approach, the premise is evaluated based on seven Petals that include place, water, energy, health, materials, equity, as well as beauty. Certification of the framework looks at the actual performance and not anticipated outcomes. As a result, approaches must be operational for at least twelve months before being evaluated [31]. A living building can earn living certification by achieving all imperatives assigned to a typology (renovation or new infrastructure), and Petal certification by satisfying the requirements of at least three Petals. Zero energy certification mandates that projects fulfil 100% of their energy needs with on-site renewables [32].

2.3 Energy Efficiency (EE)

The improvement of EE is critical for the development of NZEBs. The United Nations Development Programme (UNDP) illustrated three ways to decrease the energy consumptions of buildings: (1) Reducing energy demand, (2) Improving ‘technical’ energy efficiency, and (3) Integrating renewable energy sources into a building system in supporting heating, and electricity generation [33].

Effective insulation can reduce buildings' energy requirements by not only preventing the escape of heat during heating months but also stopping unwanted heat from being transferred into the building during cooling months [6]. U-Values serve as an indicator of how effective the building's material is at preventing heat loss. A case study on NZEBs in the UK found the lowest heating loads and total energy consumption were achieved when the external walls had a U-value of 0.1 [34]. In considering which models and concepts of energy efficiency to be applied in buildings, several factors need to be considered including renewable energy supply (e.g., wind energy and solar energy), energy demand reduction (e.g., lighting and heating, ventilation, and air conditioning), and technical energy improvement (e.g., insulation and natural ventilation).

2.4 Active House (AH)

AH is a goal-oriented framework for improving the indoor and outdoor environments (e.g., active shading and switchable roof), as well as the efficient use of energy [35]. AH is creating new opportunities for the built environments. Responding to the issues highlighted in the UN Sustainable Development Goals, AH offers sustainable building solutions which balance energy, environment, and safety while cantering to the needs of a building's users. People are interested in sustainability while also demanding products and services that take their health and well-being into consideration [36]. AH standards have been the subject of scientific investigations, covering daylight design, the sociological perspective of indoor comfort, energy-efficient, and user-focused building design. Lara Anne Hale, for instance, addressed the legitimacy of comfort criteria in the building sector and among policymakers, as well as the importance of user-centric designs of technologies in smart buildings [37].

2.5 Multi-Criteria Analysis-based NZEB Design

MCA is an effective solution to systematically assess uncertainty impacts [38]. MCA housing various assessment criteria (e.g., technical, economic, environmental, and social) are tools that are commonly used for analyzing thermal comfort and energy performance when designing NZEBs [39]. It can be used to evaluate the energy performance of a particular building [40], and the thermal comfort it is offering to occupants [41]. MCA approaches help in evaluating the state of buildings and in comparing them with alternatives such as NZEBs. The comparison permits the best refurbishment approaches to be selected and even procedures that can be used to achieve NZEB requirements. It compares the general performance of different options for determining the best one by evaluating the possible advantages, costs, and hazards [42]. They help people to have a better understanding of how a particular building can operate using different designs [43].

The MCA approach is helpful to guide pre-design and preliminary design stages [44]. The pre-design stage generally involves the selection of the most efficient strategies for conserving energy, while the preliminary design is about choosing a design that is best for the building [45]. In many cases, MCA becomes essential because it determines the sustainability goals of buildings in addition to energy performance goals [46].

In Athens, a study was conducted for comparing several architectural solutions to create additional volumes on existing buildings with the consideration of the NZEB standard. The maximization of comfort conditions for the occupants and minimization of economic impacts were considered. The results highlighted that living space was increased by 22% with an energy-saving and polluting reduction of around 90% [47].

In the Isle of Wight, MCA was applied to determine the procedures of disposal options and wastepaper management. It has been suggested that the best options were gasification and recycling whereas the least preferred options were landfills or exporting to the mainland for incineration [48]. In Turkey, an MCA method was originally utilized for ranking renewable energy supply. The results showed that the priority technologies were hydropower followed by geothermal power [49]. Table 1 summarises existing studies that used MCA to design NZEB.

Table 1. MCA-based NZEB designs.

References	Design option	NZEB composition	Criteria considered	Criteria values of optimal options	Major findings
[38]	Design optimization for NZEBs	Performance preference in NZEB system design	Initial cost score, thermal comfort score, and grid stress score	Sizing of the air-conditioning system	• The peak cooling load uncertainty approximately follows a normal distribution. • The renewable system size combination plays an important role in the grid stress
[50]	Early stages of zero-energy building	Using a simulation-based decision support tool	Usability testing	Local benchmarking, building components, comfort conditions	• Aid engineers in increasing the speed and flexibility of assessing thermal comfort and energy performance in early design alternatives.
[51]	A genetic algorithm-based system sizing method	Using the users' multi-criteria performance requirements as part of the design constraints	Energy balance, thermal comfort, and grid independence	60%	• The uncertainties of the NZEB models need to be described better to improve system efficiency.
[52]	Simulation-based multi-criteria optimization of NZEBs	Using building simulation, optimization process, multi-criteria decision making	Wall and roof insulation levels, window glazing type, cooling, and heating setpoints,	Annual thermal loads 6.7% for Beirut and 33.1% for Cedars	• Regardless of the climate, it is essential to minimize a space's thermal load through passive strategies that are ensured by a building envelope with high thermal performance.

		(MCDM), and testing the solution's robustness	and PV system sizing.		
[53]	Multi-criterion NZEB renewable energy system design method	Using Monte Carlo simulations to determine an estimate of the annual energy balance and the grid stress that results from power mismatch	Annual energy balance reliability, the grid stress, and the initial investment	Overall performance 0.78	• The multi-criterion renewable energy system design method improved the overall performance. • The model is effective in optimization of the size of renewable energy systems under uncertainties.
[54]	Net Zero Energy Village	A residential multi-energy system where energy and transport are sectors contemplated simultaneously	Technical, economic, and social analysis	1.0 MW photovoltaic, 5.8 MW wind	• To plan energy systems, the population needs to be involved to speed up the realization of the infrastructure. • A cost-effective and reliable multi-energy system can be developed for a net-zero energy village by integrating volatile energy sources.
[55]	Integrated systems	Through Monte Carlo simulation and statistical analysis (conventional separated design and integrated design)	Initial cost, grid friendliness, and indoor thermal comfort	The initial costs of the air-conditioning, PV, and wind turbine systems were reduced	• When considering system sizing, conventional separated designs should be replaced with an integrated design approach to improve grid economic friendliness.

	by 14.4%, 13.7%, and 11.8% respectively

3. RENEWABLE ENERGY SYSTEMS

3.1 Renewable Energy Supply

Torcellini, Pless, and Deru categorized NZEBs based on the types of renewable energy supply and the configuration of renewable energy use [11]. The first category referred to an on-site supply option that tends to use renewable energy available within the building's footprint. The renewable energy produced was linked to the building, which decreased distribution and transmission losses. The second category referred to an on-site supply option that aimed to make better use of renewable energy resources that are accessible at the building's site boundary. These categories are related to the models (NZ site EB, NZ source EB). The third category referred to an off-site supply alternative that aimed to bring off-site renewable energy resources to the site. The fourth category referred to an off-site supply option that comprised installed renewable energy sources.

An on-site supply option tends to use renewable energy available within a building's footprint. The produced renewable energy is directly used by the building, which decreases distribution and transmission losses. The option also serves to make better use of renewable energy resources that are available at the building's site boundary for local energy production and distribution, as opposed to centralized systems, improving reliability and reducing distribution losses [56]. An off-site supply aims to bring off-site renewable resources to a building site to produce power on-site. Table 2 below summarises the supply options of renewable energy technologies with NZEBs.

Small-scale renewable energy systems, such as solar and wind turbines have been being installed in homes. There are stand-alone systems that allow customers to generate a portion of their energy needs. In the grid-connected mode, the client can either feed excess power back into the grid or store it in storage systems for later use [57]. Specifically, wind turbines are divided into two categories: small-size wind turbines and large wind turbines. Small-size wind turbines are suitable for household and small business applications with a maximum capacity of less than 100KW, whereas large-size wind turbines are utilized for utility power generation in wind farms and are hundreds of times larger than small-size wind turbines [58].

There are three main energy system configurations including distributed energy systems, decentralized energy systems, and centralized energy systems [59]. Centralized energy systems refer to the large-scale energy generation units that deliver energy via a vast distribution network, far from the point of use. Decentralized energy systems refer to the small-scale energy generation units that are used in delivering the energy systems to the local customers. In the decentralized energy systems, the production units that are used could be stand-alone or they could also be connected to other energy systems through the shared resources. The networks and shared resources are used to share the surplus energy. In the case of connections, the systems can become decentralized energy networks that can be connected to the neighborhood systems. A distributed energy system can also be perceived as a small-scale energy generation unit that is near the point of use for the producers. The production units can also be in the form of stand-alone or in some cases can be made to form a network that shares the energy surplus. In the case of a connection in the networks, the energy systems can become locally distributed energy networks linked to nearby similar networks. The integration is perceived as an important step towards developing a smart grid and a reliable communication network is required to manage and control these systems.

Table 2. Supply options for renewable energy technologies with NZEBs [11]

Options	NZEB supply options	Examples
Energy efficiency improvement	Reduce site energy through low-energy building technology.	Insulation, efficient equipment, daylighting.
On-site supply	1. Renewable energy within the building footprint.	PV panels, wind turbines, and ground-mounted solar thermal systems.

	2. Renewable energy within the site.	
Off-site supply	1. Renewable energy off-site produces energy on-site. 2. Purchase off-site renewable energy sources.	Wastes, wood pellets, PV panels, wind turbines.

3.2 Renewable Energy Sources

3.2.1 Hydropower

Hydropower is an important source of electrical energy around the world. It generates one-fifth of global power and is the sole domestic source of electrical generation in several countries (e.g., South Africa, India, and the US) [60]. It was estimated that hydropower provided at least 50% and 90% of national electricity for 63 and 23 countries, respectively [61]. There are two main types of hydropower turbines: reaction and impulse turbines. The level of standing water, "head" and the flow or water volume over time dictate the type of hydropower turbine used for a project. Other influential factors include the cost, turbine efficiency, and the depth of turbine installation [62].

Hydropower turbines are used to convert water pressure into mechanical shaft power which can subsequently be used to power a generator or other machinery. The power generated is determined by the pressure head and the flow rate volume. Modern hydropower turbines can convert up to 90% of energy into electricity; however, this decreases as the size of the turbine increases. The efficiency of micro-hydro systems is typically 60–80% [63].

The intake structure, the forebay, the penstock, and a short canal are the essential components of a hydropower plant [60]. An intake structure at the weir diverts water away from the main river's path and controls the flow of water via the intake. Water is filtered through a forebay to eliminate particulate particles before entering the turbine. In the forebay or the settling tank, the water has been sufficiently slowed to allow particle matter to settle. To safeguard the turbines from destruction, a protection trash rack is usually located close to the forebay. The top of the penstock is required to have a valve that is closable when the turbine is turned down and water emptied for proper maintenance. Water is diverted back to the river via a canal known as the spillway when the valve is closed [63].

3.2.2 Wind Energy

Wind turbines convert the kinetic energy of wind into electrical energy [64]. As the airflow from the wind hits the aerofoil blade section of the turbine the lift force is significantly greater than the drag force, causing the blades to turn to produce electricity [65]. The amount of power (P) generated in Watts by a wind turbine is given by the formula:

$$P=\frac{1}{2}C_p\rho Au^3 \qquad (1)$$

where C_P is the coefficient of performance, ρ is the density of air (kg/m^3), A is the swept area of the turbine blades (m^3) and u^3 is the wind velocity (m/s) [66]. The Betz limit defines the theoretical maximum amount of energy that can be extracted from the wind by turbines and is defined as 59.3% [67].

For a standard wind turbine, the pitch bearings connect the rotor hub and the rotor blade and allow the blades to be adjusted so that the maximum amount of energy can be extracted from the wind [68]. Similarly, the yaw bearing is a structure that supports the process of aligning the wind turbine rotors towards the wind. Depending on the size of the turbine this can be an active or a passive system [69]. An active system makes use of a motor to turn the nacelle, whereas a passive system would see a tail fin fitted to the turbine and the nacelle would then be free to move according to the wind direction. Passive systems are generally only used on smaller wind turbines. micro wind turbines are suitable for taller buildings [70].

The main benefit brought about by wind power is low carbon emissions and low fuel requirements [71]. According to estimates by the Global Wind Energy Council (GWEC), wind power could account for 12% of electricity generation worldwide by 2020, which will avoid about 10 billion tonnes of GHG emissions [72]. In the UK, wind energy is an important source of renewable energy, and 15% of electricity in the UK was generated from wind power in 2017 [73]. The total capacity of the installed utility-scale is 82 GW in America alone, meeting 6.2% of terminal demand. In Germany, wind power is an integral part of the electricity market with the installed capacity being 194.53 GW in 2016 [74]. Germany is the country with the largest installed wind power base in Europe, followed by Spain, the UK, and then France. Portugal, Denmark, Poland, Turkey, and Sweden have more than 5 GW of wind installations, and in particular, Denmark has the highest (41%) share of wind energy in its electricity demand [75]. However, the biggest drawback associated with wind energy is the inconsistency of yield [76]. Moreover, a potential issue with distributed wind turbines when located near dwelling houses is shadow flickering for which rotating blades periodically cast a shadow through openings such as windows [77].

3.2.3 Solar Energy

Solar energy can be harnessed through either photovoltaic panels or solar thermal panels. The amount of energy produced is largely dependent on the amount of sunshine incident upon them, which varies enormously across the globe [78]. The energy density of solar radiation at the upper levels of our atmosphere is around 1,368 W/m^2. The energy density at the earth's surface drops to about 1,000 W/m^2 for a surface perpendicular to the sun's rays at sea level on a clear day [79]. The average raw power of sunshine incident on a south-facing roof in the UK is around 110 W/m^2 [80]. The Middle East is located in the so-called 'Sun-Belt' of the earth; thus, it receives numerous terawatts of power from solar radiation. The everyday average solar radiation does differ from one month to another and reaches around 730 W/m^2 during March and drops to about 302 W/m^2 during August [81]. PV energy in Africa is around 470 and 660

TWh [82]. The US has estimated that solar energy potential is capable enough to provide 400 ZWh/y [83].

PV panels generally consist of two thin layers of semiconductor material, such as silicon, sandwiched together. One of the layers is doped with phosphorous to give a negative electrostatic charge, while the other layer will have a dopant such as boron, giving it a positive charge [84]. When light energy hits the cell, electrons are knocked loose from the negatively charged side and are captured by the positively charged side. This flow of electrons is an electric current that can be captured by metal contacts [85]. Efficiencies of PV panels have risen from around 1% conversion up to 46% in recent years [86].

Solar thermal panels differ from PVs in that they use solar energy to heat water, rather than generate electricity [87]. While the energy gained in this way is of a lower grade (can only be used for heating), the solar thermal panels can achieve much higher efficiency than PV panels, with efficiencies of up to 70% [88]. Solar thermal systems can be used with an immersion heater, boiler, or collector. For a typical solar thermal system used for households, flat plate solar collectors are positioned on the roof at an optimum angle for gathering the most amount of solar energy [33]. The water inside the panels is combined with an antifreeze solution to prevent damage from occurring in colder months. The antifreeze solution is heated in the solar collectors and then passed through a heat exchanger to heat the water for the house; the antifreeze solution is kept in a storage tank with an auxiliary heater in case the water temperature is too low [89].

Solar panels are more effective in space cooling when integrated with a thermal-driven air-conditioner. Owing to the availability of a substantial amount of solar energy and lengthy daily sunlight hours, solar-powered cooling systems like thermoelectric cooling systems are considered an intriguing green cooling technology in the Middle East region [90]. The thermoelectric effect, in which refrigeration turns electrical energy generated by photovoltaic cells directly into a temperature gradient, can be used in these systems [91].

A PV system can power thermoelectric cooling systems directly without the use of an alternating current/direct current inverter, thus lowering expenses significantly. Working fluids are not used in thermoelectric cooling systems because there are no mechanical moving parts. Furthermore, these systems are eco-friendly and their GWPs were reported to range from 0.13 to 0.47 $gCO_{2\text{-eq}}$/Wh [90, 92]. Therefore, the combined technologies (e.g., thermoelectric cooling systems and PV) are beneficial for solar energy use and environmental protection, meeting the requirements of NZEBs.

3.2.4 Heat Pumps

3.2.4.1 Ground Source Heat Pumps (GSHPs)

GSHPs serve as a source of thermal energy that can replace a traditional gas boiler [93]. GSHPs make use of the relatively constant temperature of soils, rocks, and water below the surface of the earth to heat spaces and provide hot water for buildings [94]. This is achieved by placing heat-collecting pipes containing water and a small amount of antifreeze (refrigerant solution) in a borehole or shallow trench to extract heat from the borehole. Electrical energy is required to power the pump; however, a typical GSHP will return around three or four times more thermal energy than the electrical energy it consumes [95].

The input electrical energy drives a compression/expansion cycle that acts on the refrigerant solution. This cycle extracts heat energy from a low-temperature, high-volume body of water and transfers it to a much smaller volume of water at a higher temperature, which can then be used for heating, such as a refrigerator [96]. Just as a water pump can transfer water from a low elevation to a high elevation, a heat pump can transfer heat from a low-temperature surrounding to a high-temperature surrounding. If a renewable source of electricity is used to power the pump, then the system becomes even more environmentally friendly [97]. In Finland, the use of GSHPs for heating in single-family houses is growing and accounts for 38% of the heat supply (25% of homes are supplied by direct electric heating) [98]. One of the authors' previous studies that aimed at planning renewable energy use in Glasgow found that 3,382 units of 22.5 kW GSHPs were needed for 2020 [99].

3.2.4.2 Air Source Heat Pumps (ASHPs)

ASHPs use heat from the air outside to heat underfloor heating systems, radiators, and water in buildings [100]. The benefits of ASHPs include delivering heat at lower temperatures over extended periods, increasing the overall heating efficiency (especially when combined with other renewable technologies), and eliminating fuel bills in NZEBs when the electricity required for an ASHP is powered by another renewable technology [101].

Two kinds of ASHP systems are available: air-to-air and air-to-water [102]. An air-to-water system dispenses heat through a central wet heating system [103]. Heat pumps perform much better at lower temperatures compared to a standard boiler system. They are thus more appropriate for underfloor heating systems or bigger radiators and can give out heat at lower temperatures 20°C for a long time. Air-to-air systems, in contrast, generate warm air that is circulated by fans to heat a house. Such a system cannot generate hot water. Air-to-water heat pumps may be more suitable for recently constructed buildings [104]. It could be less costly if the heat pump is incorporated as part of the original building process, instead of having to retrofit underfloor heating afterward. An ASHP system can reduce carbon footprint since it utilizes a renewable, natural source of heat – air [105]. ASHPs are easier to install compared to other pumps and they do not need constant maintenance, and they can deliver both hot water and heating. However, they are not perfect systems because ASHPs have much higher emissions than GSHPs. Moreover, ASHPs cannot function very well in cold climate zones because of the problem of frost. Also, ASHPs commonly experience coolant leakage [106].

Heat pumps are receiving increasing attention because of their high performance in terms of efficiency. Many studies confirm that, despite different climatic conditions, heat pumps rate are among the most cost-effective and energy-efficient systems for NZEBs [107]. For instance, in Switzerland, more than 90% of buildings are equipped with heat pumps [108]. In Italy, Germany, France, and Denmark, heat pumps are preferable when it comes to meeting NZEB requirements under minimum future building regulations [109].

3.2.5 Biomass

Bioenergy makes up approximately 9% of the total primary energy supply in the world [110]. In the UK, the electricity generated from bioenergy in 2019 was 8.8 TWh, accounting for 25% of the total consumption of renewable energy [111]. In Denmark and Finland, bioenergy represents more than 15% of electricity production, while for countries like Sweden, Austria, Estonia, Belgium, Italy, and Brazil, biomass-based electricity represents around 6 to 8% of total electricity production [112]. By 2018, the global biofuel capacity was 130 GW, with the EU, China, the US, India, and Japan using 42 GW, 17.8 GW, 16.2 GW, 10.2 GW, and 4.0 GW, respectively [113].

Since NZEBs must have a reliable source of energy to achieve a stable energy supply, biomass tends to be one of the most appropriate renewables as it is not affected by climate conditions the way that wind or solar energy is, and a steady supply can be maintained as long as there is enough feedstock sustaining the system [114]. Also, biomass systems have a simple design and are easier to construct compared to the structures required e.g., for geothermal systems [115].

Presently, bioenergy contributes to a sustainable carbon zero society in line with cultural and economic developments and issues [116]. Energy-efficient green buildings, such as NZEBs, reap more rewards from bioenergy than they do from other sources of renewable energy [117]. Economically, biomass, as a clean source of energy, attracts various tax benefits from the government. A study by D'Agostino and Mazzarella determined that, among all the NZEB alternative sources of energy, biomass is most effective regarding energy supply [118].

Bioenergy could be derived from a variety of feedstocks including industrial residues of food and paper, agricultural by-products, sewage sludge, and woody biomass [119]. The process of bioenergy can be broken down into the steps of cultivating feedstock, processing, and then transporting the energy to the intended point of use [120].

The production cost of bioenergy can be significantly reduced if the feedstock is co-fired with pulverized coal. The gaseous fuels and bio-methane produced from the gasification of feedstock can replace natural gas used for heating households. The electric power generated from biomass can also be used as a source of power and heat in the buildings [121]. There are two main routes for biomass conversion, either biochemical or thermochemical. The thermochemical route mainly encompasses four processes: pyrolysis, gasification, liquefaction, and combustion while the biochemical route encompasses two processes: anaerobic digestion and fermentation [122].

3.2.5.1 Pyrolysis

Pyrolysis involves heating biomass in the absence of oxygen [123]. During the process, the chemical compounds thermally disintegrate into charcoal and combustible gases. It is possible to condense most of these combustible gases into a combustible liquid that is referred to as bio-oil, while the others are permanent gases such as CO_2 and H_2 [124]. The three major products of pyrolysis are bio-oil, biochar, and gas. The respective quantities of these products depend on factors such as the process parameters and the composition of the biomass [125]. Assuming constant conditions, the yield of bio-oil is optimized when the pyrolysis temperature is approximately 500°C and the heating rate is high, at around 1,000°C/s. Under such conditions, the yield of bio-oil can be as high as 60–70 wt%, with 15–25 wt% yields of biochar and 10–15 wt% of syngas. Pyrolysis can be self-sustained, as the reaction of syngas and bio-oil or biochar provides sufficient energy to keep the process going [126].

3.2.5.2 Gasification

Gasification, the process of generating a combustible gas from biomass, is accomplished by burning biomass at high temperatures of 700°C with a limited quantity of oxygen [127]. Table 3 displays the gas compositions of diverse gasification processes [128].

Table 3. Gas compositions of different gasification processes [128]

Gases (%)	Gasifier types		
	Fluidized Bed	Updraft	Downdraft
Carbon monoxide (CO)	14	24	48
Hydrogen (H_2)	9	11	32
Carbon dioxide (CO_2)	20	9	15
Methane (CH_4)	7	3	2
Nitrogen (N_2)	50.0	53.0	3.0

The following are the key stages that happen inside a biomass gasifier [45]:

1. Drying: Biomass typically consists of 10–35% moisture. The moisture becomes steam when it is heated to 100°C.

2. Pyrolysis: As the heating continues after drying, the biomass experiences pyrolysis. The biomass then decomposes.

3. Oxidation: Air is added into the gasifier when the biomass decomposes. During oxidation, charcoal reacts with oxygen in the air to generate CO_2 and heat.

4. Reduction: At high temperatures and as the oxygen supply becomes depleted, CO_2, H_2, and CH_4 are produced.

3.2.5.3 Liquefaction

Liquefaction, which is also known as hydrothermal liquefaction of biomass, is defined as the thermochemical process that converts biomass into liquid fuel by processing it under high temperatures and pressure in a water environment [129]. The typical conditions are 523–647K and 4–22MPa. This temperature is adequate to initiate pyrolysis of the biopolymers, and the pressure is sufficient for maintaining a liquid water processing phase. The duration of the process also has to be long enough to allow the solid biopolymeric structure to break down into liquid components [130]. The basic reaction mechanisms are [131]: depolymerization of biomass, decomposition of biomass monomers, and recombination of reactive fragments.

Since liquefaction is essentially pyrolysis in hot water, the resulting main product is a liquid biocrude. Up to 70% of the carbon is transformed into biocrude, and some lighter products are attained depending on which catalysts are employed [132].

3.2.5.4 Combustion

Direct combustion is the most well-known and most commonly used technology for deriving energy from biomass [133]. In this process, biomass is burnt in extra air to generate heat [134]. There are three main stages involved in the combustion process [135]:

(1) Drying: Biomass inherently contains moisture that has to be removed before combustion occurs. The heat required for drying is provided by radiation emitting from both the flames and the heat stored in the combustion unit.

(2) Pyrolysis: When the temperature of the dry biomass ranges between 200°C and 350°C, the volatile gases are freed. The products are CO_2, CO, CH_4, and high molecular weight compounds like tar that become liquid when cooled. These gases react with oxygen in the air and generate a yellow flame. This is a self-sustaining process, and the heat coming from the burning gases is utilized to dry the fresh fuel to discharge more volatile gases. Oxygen must be provided during this part of the combustion process. When all the volatile substances have been burnt off, char remains.

(3) Oxidation: At approximately 800ºC, the char either burns or oxidizes; oxygen is required both at the fire bed for carbon oxidation and above the fire bed since it reacts with CO to form

CO_2, which is discharged to the atmosphere. Allowing the fuel to remain in the combustor for a longer period allows it to be fully consumed. It is pertinent to point out that all the stages mentioned above can take place at the same time within a fire. It is vital to work towards 100% complete combustion of fuel to prevent wastage and improve the cost efficiency of the combustion process [136].

3.2.5.5 Anaerobic Digestion (AD)

AD is the process whereby organic waste, such as waste or animal food, is disintegrated to generate biogas and bio-fertilizer. This process takes place when there is no oxygen in a sealed container and produces digestate, which can be used as organic manure in farms [137].

The generated biogas can be used to produce heat, electricity, or as a substitute for natural gas [138]. The process is carried out inside enclosed vessels (digesters), whose internal temperatures are maintained between 30 and 55°C [139]. The process takes place in three stages, which are liquefaction or hydrolysis, acetogenesis, and methanogenesis. In the liquefaction process, fermentative bacteria convert complex and insoluble organic matter into monomers. In industrial operations, chemical reagents are used during liquefaction to produce high-quality methane with a shorter digestion time. The second step of AD is acetogenesis, where products of the first reaction are converted to simple organic hydrogen acids and carbon dioxide through the action of acetogenic bacteria such as lactobacillus. The third stage of the reaction is methanogenesis, where methane is produced by the action of methanogens such as methane bacillus [140].

3.2.6.5 Fermentation

Fermentation is an anaerobic biochemical process that breaks down organic compounds such as glucose into value-added products such as ethanol and hydrogen. In a fermentation process, biomass is inoculated with yeast or bacteria, which act on the sugars and yield ethanol and carbon dioxide. To achieve the high product purity required for fuel applications, ethanol can be distilled and dehydrated. The solid residue leftover from the fermentation process can be used as cattle feed to achieve additional environmental benefits. In the case of sugar, the resultant fiber known as bagasse can be used as a fuel in boilers or for further gasification [141].

The fermentation-based hydrogen production can be divided into three categories: first, dark-fermentation, in which no light is used; second, photo-fermentation, in which light is used as a source of energy; and third, a combination of photo- and dark-fermentation [142]. When dealing with fermentation-based hydrogen production, numerous factors should be examined including the types of feedstocks, microorganisms, and technologies (i.e. dark-fermentation, photo-fermentation, and photo- and dark-fermentation) [143]. Refined sugars, raw biomass sources like corn stover, and even wastewater can be used as organic matter for the process. Dark fermentation is a cost-effective and environmentally beneficial method of processing waste biomass. Dark fermentation, with a net energy ratio of 1.9, is thought to be the most promising and well-understood technique of biohydrogen production from biomass [144]. Many anaerobic microbes use hydrogen as a primary energy source. If energy-rich hydrogen molecules are available, such microbes can use the electrons produced by hydrogen oxidation to generate energy. In the absence of external electron acceptors, organisms generate an excess of electrons in metabolic activities as a result of protons being reduced to hydrogen molecules. Hydrogenases are the key enzymes that regulate hydrogen metabolism [145].To improve the performance of dark fermentation (e.g., the yield of hydrogen) different types of bacteria such as *Bacillus amyloliquefaciens* and *Clostridium pasteurianum* have been tested and sophisticated co-culture fermentation techniques were also proposed [146]. Table 4 shows different existing studies that used different renewable energy in the development of NZEBs. Because different renewable energy sources can be used to facilitate NZEB design models, critical parameters such as the location of the building, energy efficiency, and performance should be considered when designing the models and when selecting the renewable source of energy. Building orientation and good installation of insulation facilities also contribute to the efficiency of renewable sources in NZEBs.

Table 4. Renewable energy usage for NZEB development.

Reference	NZEB design	Renewable sources	Critical parameters	Major findings
[147]	On-site or off-site renewable energy supply NZEB	Photovoltaic, micro combined heat and power, off-site windmill, purchase of green energy from the 100% renewable utility grid	Energy efficiency	• Energy efficiency should be the priority to design a cost-optimal NZEB with an on-site renewable energy supply. • It is more cost-effective to invest in renewable energy technologies than energy efficiency.
[148]	Renewable energy balance in environmental building design	All possible renewable sources	Maximizing the use of renewable resources	• Renewable energy balance can be used in environmental building designs to achieve higher levels of sustainability.
[149]	Solar energy for NZEBs	Solar thermal and PV	The total efficiency of the power source and the usage of space	• Using high-efficiency PV modules in construction helps to achieve an almost zero energy balance depending on the boundary conditions as well as the building's energy system design.
[150]	A classification system based on renewable energy supply options	Renewable sources on-site, off-site	Energy efficiency	• A classification system can be developed to distinguish NZEBs based on the source of renewable energy as well as the building's utilization.

[151]	Net-zero energy (NZE) low-rise residential building	Solar energy	Energy performances	• The building orientation has little influence on the energy performance of the systems year-round. • The NZEB design can potentially be utilized in all new and old buildings to ensure low carbon production.
[152]	The impact of photovoltaic and solar thermal on net NZEBs	Solar energy	Percentage of energy provision	• Solar energy can provide more than 76% of the energy demands in NZEBs.
[53]	Multi-criterion NZEB renewable energy system	Conventional renewable energy sources	Annual energy balance reliability, the grid stress, and the initial investment	• NZEB's renewable energy proposal enhances the overall performance by 44% when compared with conventional methods.
[153]	Building-integrated solar renewable energy systems for zero energy buildings	Solar energy	Energy saving	• To meet thermal needs in buildings, using renewable energy with energy-saving measures like installing good insulation will be efficient.

3.2.6 Energy from Solid Waste

Bioenergy-based NZEBs have the additional benefit of facilitating the development of sustainable waste management practices. The amount of waste being sent to landfills has been a cause for concern in recent years [154]. The EU has set a target to restrict the amount of landfilled biodegradable municipal waste to 35% of the 1995 baseline level by 2020 [155]. Generating bioenergy from waste through the technologies mentioned above is a promising solution for tackling the challenges of sustainable waste pile-up and renewable energy production [127]. A study conducted by the Sustainable Development Commission Scotland found that 3.9% of Scotland's total heat demand could be provided through the energy from waste [156]. Up to 300kg of CO_2 could be saved for every tonne of solid waste that is treated [157]. This is because when solid waste is treated, biogenic carbon is excluded. By selling the by-products, waste-treatment systems that generate biomass have a 68% to 98% chance of profitability. Finally, in each of the towns used in the study, bioenergy systems were able to meet 20–23% of the town's electricity demands and 4–5% of heat demands [158].

Using municipal solid wastes as the main source of renewable technology for NZEBs would enhance the sustainability of the system at the community level [159]. In other words, dwellers would participate in providing sources for the system, and the energy suppliers would, in turn, produce power to sustain the buildings [160]. The amount of waste and its composition are vital factors for estimating energy potential. Municipal solid waste is broadly classified into organic and inorganic compounds. The major chemical compositions of some typical wastes in the UK are listed in Table 5.

Table 5. Waste characteristics (UK) [161]

Composition	wt %	Moisture %	Carbon %	Hydrogen %	Oxygen %	Higher heating value kJ/kg
Paper and card	15.9	6.25	45.94	6.35	38.55	17445

Plastic film	4.5	11.31	44.77	6.08	32.45	33727
Dense plastic	9.2	7.5	73.81	11.90	4.83	33727
Textiles	4.3	7.04	47.64	6.30	35.46	8000
Combustibles	13.1	15.88	45.35	5.51	32.45	19771
Glass	5.5	2.25	0.50	0.10	0.40	151.19
Food/kitchen waste	3.3	66.38	44.77	6.08	32.45	19771
Garden waste	31.5	55.16	43.62	5.55	33.92	16282
Other organics	2.6	66.38	44.77	6.08	32.45	19771
Metal	1.1	5.50	4.50	0.60	4.30	1954
Hazardous items	4.1	13.00	0.50	0.10	0.40	12000
Electrical items	0.9	14.11	0.50	0.10	0.40	-
Fines	1.5	14.49	26.30	3.00	2.00	-
Non-combustibles	2.6	0.50	0.50	1.00	4.00	-

Biomass generates around ten times less CO_2 per MWh when compared to traditional fuels [162]. However, the utilization of biomass in urban areas might contribute to a city's fine-particle pollution [163]. The main advantages and disadvantages of biomass versus fossil fuels are summarised in Table 6.

Table 6. Advantages and disadvantages of biomass [164, 165].

Advantages	Disadvantages
• Biomass is a renewable energy source. • Non-edible biomass can be used. • • Climate change benefits from CO_2 -neutral conversion. • Biomass contains less ash, C, FC, N, S, Si, and most trace elements than fossil fuels. • The supply for producing biofuels, sorbents, fertilizers, and other materials is abundant and inexpensive.	• Fuel uses may compete with edible biomass production. • • There is a lack of global control over the production of biofuels and the certification of their origins. • Biomass has a high moisture content. • Biomass has a low energy density. • Some technical problems occur during thermochemical processing, such as slagging and

- Biomass consumption helps to reduce biomass residues and waste.
- Ash aids in capturing and storing toxic components.
- Biomass costs are lower than fossil fuels.
- Biomass can be converted into many fuel chemicals.

corrosion.

- The investment cost is high.
- Biofuels often need to be combined with small amounts of fossil fuels to make them more effective.

3.2.7 Energy Storage

Energy storage can always be essential when handling self-consumption and excess energy can be stored and used when there is a deficiency. Therefore, monetary benefits are realized when using these systems. Energy storage can be used in the generation of income. Energy storage can further be used to generate income by leveraging changes in energy prices; power is purchased during times of low demand and price and exported to the grid when the energy demand and market price are high [166].

When there is an extra renewable generation, energy can be stored in the form of heat, potential energy, chemical energy, etc., and discharged when renewable generation is deficient. To accommodate demand, short-term and seasonal storage might be used. Building owners must evaluate if the benefits of a storage system outweigh the higher initial cost and complexity of the system [167]. NZEBs can use a variety of energy storage methods. Specifically, excess power can be stored in batteries and transformed into thermal energy, or chemical energy [168]. Heat can be stored directly as thermal energy, turned into electricity and stored in batteries, or converted into chemical energy [169].

Battery energy storage systems have been widely regarded as one of the most viable solutions, with various advantages such as rapid reaction, long-term power delivery, and less dependence on the grid [170]. In particular, battery storage can store and release energy at high frequencies, and offer frequency and voltage stability, making it an efficient tool for improving renewable energy system management. However, one of the most important challenges upon implementing battery energy storage systems is the determination of the optimal battery size for managing the trade-off between its technological advantages and the extra cost. For the optimization of battery energy storage systems, a variety of performance indicators including financial, technical, and hybrid factors need to be considered (e.g., smaller systems are desired from a financial perspective [171]).

The electricity from renewable sources could be buffered using vehicle-to-home systems. By charging during off-peak hours and discharging during peak hours, electric vehicles can modify or regulate the peak power profiles and load of buildings [172]. Hydrogen fuel cell vehicles with the benefit of zero pollutant emissions have also been demonstrated as a media of fuel storage for residential buildings [173].

Partial off-grid energy storage is valuable for load shifting and improved usage of on-site renewable generation, but it does not necessitate the large investment required for a fully off-grid NZEB. The energy storage arrangement and associated energy conversion equipment increase the complexity of NZEB design and planning, incurring additional expense. Off-grid NZEBs, on the other hand, could be a feasible choice for isolated regions without grid connections. Off-grid, self-contained NZEBs require large energy storage systems [170].

4. ANALYSIS METHODS

4.1 Cost-benefit Analysis (CBA)

CBA aims to supply decision-makers with a framework that can be used to assess economic attractiveness when there is an investment in renewable technology that will improve efficiency. CBA includes the benefit-cost ratio (CBR), the net present value (NPV), cash flow balance, and internal rate of return (IRR) [174]. The NPV marks the dissimilarity between the current value of cash inflows and the value of cash outflows considered over some time as shown below:

$$NPV=\sum_{t}^{T}\frac{C_t}{(1+r)^t}-C_0 \qquad (3)$$

where C_t is the net cash flow during the period t, C_0 is the total investment cost, T is the lifetime of the project, and r is the discount rate. The discount rate ranges from 5–10% depending on the ratio of equity financing and financing for projects.

It is noted that as the number of years (t) progresses, the discount rate diminishes. This means that the further away the cost or benefit is set in the future, the lower its discount factor becomes. A higher discount factor for renewable energy resources only means more preference for things now rather than in the future [175].

The discount rate is applied to the cash flows to account for the time value of money, due to factors such as inflation and interest rates. A positive NPV indicates that by constructing an NZEB the owner will have saved money over keeping with conventional means. The IRR is calculated by setting the NPV equal to zero and solving for the discount rate.

The renewable technologies described above each have different capital, maintenance, and material costs, as well as have varying feed-in tariff (FiT) incomes. The FiT scheme is a government program that promotes low-carbon electricity generation technologies and makes the uptake of small-scale renewable technologies more attractive [176].

4.1.1 Hydropower

Hydropower has been used for decades and is one of the most efficient and reliable renewable energy sources. Due to the high fuel prices, low-head micro-hydropower plants are a viable and cost-effective option to generate electricity in rural, isolated, and hilly areas [63].

The efficiency of the Turgo turbine can reach 91% at 3.5 meters head and 87 % at 1.0 meters head [177]. The efficiency of a Pelton turbine is 70–90%. Because of the uneven flow in the spinning buckets, the performance of a Pelton turbine is dynamic [178].

Another important turbine is a crossflow turbine. It's often used in both horizontal and vertical layouts. Unlike the Pelton and Turgo turbines, a cross-flow turbine is typically employed at higher flow rates and lower heads. [179]. For small and micro-power outputs, crossflow turbines have an average efficiency of around 80% but can achieve as high as 86 % for medium and large units. Micro-hydropower has an initial cost of nearly 6 cents per hour [180]. In the socio-economic development of isolated hills and mountain locations, micro-hydro power is a far more cost-effective option.

The cost of building a hydropower plant can be divided into four categories which are civil work, which was estimated to account for about 40% of the total cost, turbine and generator sets (30%), control equipment (22%), and management costs (8%), in that order [181]. The overall cost per kilowatt of power capacity ranges from $1500 to $2500 [182].

4.1.2 Solar Thermal

Solar thermal panels capture energy from the sun to heat water, and the heated water is stored in an insulated cylinder and is controlled until required [183]. Solar thermal combines well with other renewable technologies to produce high-efficiency levels, and the system can last approximately 25 years [184]. The cost of the solar thermal system is found by scaling up costs per m^2. The estimated cost per m^2 is £700 (944 USD) [185, 186]. The generation tariff is 20.66 p/kWh (USD 0.028/kWh) for the UK [187], making solar the highest thermal tariff. Installing solar thermal with biomass CHP system collectors reduces the possibility of operating the CHP system for longer periods [98]. In Portugal, solar thermal collectors were designed to cover around 60% of DHW needs. Solar thermal systems should be replaced after 14 years [188].

4.1.3 Wind Turbines

Domestic wind turbines have a lifetime of 25 years and require regular maintenance checks [189]. Parts such as the inverter will need replacing at some point in the turbine's lifetime, which costs approximately £1,500 (USD 2023) [190]. A 2.1 kW rated wind turbine cost is approximately £4,500 (USD 6,071) [191], and there is presently a generation tariff of 8.24 p/kWh (USD 0.11/kWh) [192]. The corresponding fixed O&M cost is £22.5/kW/year (USD 30.4/kW/year) [193]. The level of profitability of wind turbines is dependent on the average wind speed.

4.1.4 Solar (PV)

The worldwide solar PV capacity increased from 0.7 GW in 1996 to 139 GW in 2013 [194]. Solar PV turns solar energy into electricity with a lifetime of around 25 years [195]. The findings demonstrate that PV technology decreases the consumption of non-renewable main energy to a level below the approximate zero-energy threshold value, which is expected to be 15 kWh/(m^2·y) [196]. The results show that, at present, based on electricity charges and solar PV system capabilities and production levels, single-family houses, apartment buildings, and other building types need 0.044 €/kWh (USD 0.050/kWh), 0.037 €/kWh (USD 0.042/kWh), and 0.024 €/kWh (USD 0.027/kWh), respectively [197]. Statistics revealed that in Estonia in 2015, the nationally established PV capacity amounted to 6.5 MW, representing an increase of about 50% from 2014 [198].

4.1.5 Heat Pumps

Heat pumps could be both cost-effective and energy-efficient [199]. They can play a significant role in high-performance buildings planned to meet future NZEB requirements, not only owing to the energy and cost considerations but also because of the ability of demand response to back the process of associated energy grids [107].

When evaluating the balance of building technologies, heat pumps combined with PV are the most cost-effective systems for single-family buildings based on a 25-year life-cycle analysis of energy efficiency and annual cost [200]. Most NZEB projects opt for a GSHP as the core device of an HVAC system owing to its excellent performance. GSHPs can provide 30% more energy-efficient than ASHPs [201]. GSHPs can be activated professionally in cold winters. In certain areas where the air is not very cold in winter but is very hot in summer, an ASHP might be more sensible, particularly for limited uses [202].

GSHPs can last 25 years with regular maintenance, so they can be considered a long-term investment. The capital cost of a GSHP (4 kW) is approximately £14,000 (USD 18,891) [203]. ASHPs generally last for 15 years, although with regular maintenance they can be expected to last for much longer. The capital cost for an ASHP (10 kW) system is approximately £6,000 (USD 8,097) [204]. In the UK, the revenue of GSHPs is 9.36 p/kWh (USD 0.13/kWh). The cost of installation is £1,000/Kw (USD 1,349/Kw), and the O&M cost is £5/Kw (USD 6.8/Kw) [99].

4.1.6 Bioenergy Technologies

Each of the waste-to-energy technologies and their selection (e.g., process parameters and capacity) depends on the waste origin, technological efficiency, capital and operational cost, and geographical locations of the plants. In the UK, the average capital costs of gasification (2MW) are £16,708 million (USD 22,643 million). The O&M costs for gasification plants in the UK are around 17% of the capital cost [205]. The average O&M cost of gasification is £ 2,860 million (USD 3,857 million) and the AD cost is £ 11,329 million (USD 15,287 million). In Europe, the investment costs of waste incineration plants are £18–140 million (USD 24- 188 million) for 50–400 kt/a [206]. In the UK, the investment cost for pyrolysis plants ranged from £11–130 million (USD 14- 175 million) [207]. In Finland, the Lahti plant is a 250 kt/a power plant based on gasification with an entire investment cost of roughly £160 million (USD 216 million) [208]. In the UK, the capital cost of a 5,000 kW gasification-based combined heat and power unit has a capital cost of £201 million (USD 271 million) in 2015 [209]. Anaerobic digestion plants in the UK with a power ranking of up to 100 kW have a unit cost of £7,500/kW (USD 10,119/kW) [210]. Anticipated revenues in waste-to-energy processes are mainly electricity and heat sales, and the sale of recovered materials. In Europe, a major waste incineration plant charges a fee of approximately 100 £/t (USD 135/t), compared with £50–77/t (USD 67-104/t) in the UK [207]. In Italy, the revenue from digestate sales amounted to 15 £/t (USD 20/t) [210]. In Australia in 2015, the average biochar price was about 674 £/t (USD 909/t) [211]. When the by-products are sold, profits can increase by 68-98%. [158].

Biomass boilers can last 20 years, leading to major savings in CO_2 emissions throughout the lifetime of a boiler [212]. Pellet costs are approximately £255/t (USD 344/t) across the UK, but this depends on the size of the order and method of delivery [122]. The estimated capital cost of a biomass boiler is £4,218 (USD 5,690), and the generation tariff is 6.74 p/kWh (USD 0.09/kWh) for the UK [213]. In Austria, the price of pellets was €232/t (USD 262/t) in 2016, while in France, due to an increase in the VAT rate on pellets from 5.5% to 10%, the cost was €272/t (USD 308/t) [214]. Additionally, on-demand heat is essential to creating an NZEB that can always produce thermal energy throughout the year. Table 7 shows the cost components for a gasification system with combined heat and power generation.

Table 7. Gasification plus combined heat and power generation (2 MWe) cost [215]

Items	k€
Capital costs	
Consultancy / design	650.4
Civil works	1409.3
Fuel handling/preparation	617.7
Electrical/balance of plant	433.6
Converter system (gasifier)	6753.8

Prime mover (CHP)	2732.7
Annual operating costs	
Personnel	120
Power consumption	91.8
Inertization system	26.5
Water treatment	182
Waste disposal	171.5
Consumables	35
Maintenance	629.9
Unit of hourly cost	232.0

To consider the effect of inflation, the following equation can be used [215]:

$$C=C_0\times\left(\frac{P}{P_0}\right) \quad (4)$$

where C is the current cost, C_0 is the original value referred to its reference year, P/P_0 is the fraction of producer price indices calculated based on the actual inflation rate. To consider the potential effect of scale, the following equation has been used:

$$C=C_0\times\left(\frac{S}{S_0}\right)^f \quad (5)$$

where C is the scaled cost referred to the commercial-scale S and C_0 is the reference cost referred to the reference scale S_0. In general, biomass-based energy generation has four main income sources: electricity, gate fees, metal recycling, and carbon credits.

It's critical to examine component interactions, such as on-site and off-site renewable energy supplies upon the design of NZEBs. Marszal et al. used cost analysis to ascertain the optimal levels of energy efficiency and renewable energy generation, including on-site (photovoltaic - micro combined heat and power) and off-site (windmill and purchase from a 100% renewable energy electrical grid) choices [216]. The findings revealed that for designing a cost-effective NZEB with on-site generation, energy efficiency should be prioritised over renewable power. Meanwhile, it is more cost-effective to invest in renewable energy systems rather than energy efficiency for off-site choices. Table 8 compares the overall costs and payback periods of typical renewable energy systems.

Table 8. Economic performance (cost and payback period) of different renewable energy systems [217, 218, 219, 220, 221, 222, 223].

No.	Renewable energy generation type	The average cost (£/kw)	(USD/kw)	The average payback periods (Year)
1	Hydropower	(1,800- 2,000)	(2,428- 2,699)	4-7
2	Heat bumps	(6000-14,000)	(8,095-18,888)	5-15
3	Wind turbine	(4,500-6,000)	(6,071-8,095)	13-19
4	Solar	(3,000-5,000)	(4,047- 6,745)	7-10
5	Biomass	(7,500-9,000)	(10,118- 12,142)	12-13

4.2 Life Cycle Assessment (LCA)

LCA involves the analysis and assessment of the environmental effects of a specified product or service based on the energy and material inputs and the emissions released into the environment [224]. It is an iterative process that comprises the following stages: (1) the definition of the goal and scope, (2) the inventory of the life cycle, (3) the impact of life-cycle analysis, and (4) the interpretation of the result [225].

In stage 1, goal definition includes information such as the planned use of the study, the reasons for conducting the study, and the targeted audience. Defining the scope involves providing information such as the system boundary, functional unit, data sources, data requirements, and suppositions used. In stage 2, data is gathered for each unit process incorporated within the system. The data can be calculated or estimated and are used to measure the inputs and outputs of a unit process. In stage 3, the potential environmental impacts are evaluated. This is done to highlight the significance of all environmental loads attained in stage 2 by analyzing their effect on defined environmental loads. In the final stage, the aim is to analyze the findings based on the scope and goals and to draw conclusions from all the information gathered.

Biomass produces approximately ten times less CO_2 per MWh compared to conventional fuels and is almost on par with renewable sources such as wind [226]. Matthews and Mortimer stated that the approximate life cycle of CO_2 emissions for wood pellets is 7 kg/GJ. Their definition of life cycle covers the entire process of utilizing wood pellets, beginning from the original resource to its final disposal. Using this value, the total amount of CO_2 that will be released per annum for a domestic building is 608 kg [227]. Kang, Sim, and Kim carried out experiments on wood pellets and discovered that after gasification, the mass of the biomass reduced by 37% from a starting mass of 0.8065 g [228]. This suggests that for every 1kg of wood pellets, 370g of emissions will be produced [229]. Table 9 summarises the emissions levels of sources of energy.

Table 9. Sources of energy generation and their respective emission levels [229]

Electricity generation	kg CO_2/MWh
Wind	6.9 - 14.5
Biomass	15 – 49
Coal	547-733
Hydroelectric	2-26
Nuclear	2-29
Solar PV	13-85
Lignite	1.06-1.69
Industrial gas	0.86-2.41
Space heating	**kg CO_2/MWh**
Biomass (Woodchip)	10 – 23
Natural gas	263 – 302
Oil	338 – 369

Table 10 shows the life cycle assessment of NZEBs using different approaches. NZEB designs that have high thermal insulation and airtightness have low levels of embodied energy and do not affect the environment. Appliances and office equipment contribute to global warming as does building construction, depending on the type of material used. Besides, the type of material used in constructing NZEBs determines the factors that can influence their global warming potential.

Table 10. LCA of NZEBs.

Reference	NZEB design	Functional unit	Global warming potential impact ratio	Major influential factors	Findings
[230]	NZE in poultry housing	Cradle-to-farm gate environment	34%	Most emissions and embodied energy are associated with the construction of the housing and renewable energy generation systems	• Based on the life cycle impacts, NZE poultry housing with solar PVs can generate net environmental benefits in most impact categories in provinces with greener electricity grid mixes.
[231]	The convergence of life cycle assessment and nearly zero-energy buildings	German thermal insulation ordinance	-	Raw materials for construction	• The reduction of energy consumption has progressed in building construction.
[232]	Energy life-cycle approach to NZEB balance	Operation and embodied energy	-	-	• Adopting the life cycle perspective and the concept of embodied energy has transformed the NZEB targets. • The demand for primary energy increases twice when compared to demand in conventional primary energy cases.

[233]	Environmental impacts of appliances in NZEBs	Furniture and appliances	Appliances: 30%, non-renewable energy: 15%	Office appliances and computer equipment make up 30% of greenhouse gas emissions	• Appliances contribute to global warming potential. • Labels describing the energy efficiency of appliances should include the life cycle perspective and the user's point of view.
[234]	Nearly zero-energy multifamily buildings	Building materials and energy production devices	Building structures: 50%, system: 12%	The pre-use phase of the building contributes 56% of the environmental impacts and the operation energy contributes 31%	• The consumption of operative energy affects only one-third of the buildings' environmental impacts.
[235]	Materials life cycle assessment	Meet living building criteria	10%	The largest environmental impacts are the building materials, structural steel, and photovoltaic panels	• The environmental impacts associated with the use phase are very low relative to standard structures.
[236]	Integrated assessment framework	Integration of LCA and multi-criteria analysis	31%	Environment, human health, and energy efficiency	• The approach can be used for entire buildings or components and assemblies in buildings.

5. NZEB CASE STUDIES

Currently, the concept of NZEBs is quite new, and there are limited cases of practical applications in Europe [237]. In a detailed report on 32 NZEBs in the European region, four buildings had service systems powered by biomass boilers, and a total of six buildings used direct biomass heating [238]. For example, a building in Belgium used a biomass boiler together with photovoltaic panels, solar thermal panels, and a gas boiler. The energy use of the building showed a 78% improvement compared to national requirements. Another building in Ireland used biomass heating with a combined heat and power system based on natural gas and photovoltaic electricity production. The energy use of the building showed a 50% improvement compared to national requirements. However, one must also consider the costs involved in using bioenergy. The difference in the initial investment cost compared to current legislation for the building in Belgium versus a reference building that uses biomass heating is 6% higher. Also, the difference in net present value over 30 years is €7,100 (USD 8,036) less than the reference building [239].

In Cyprus, the first regulation concerning the energy performance of buildings was presented in 2007, and the Energy Performance Certification for buildings was advanced in 2010, making energy conservation in buildings relatively new [240]. Despite numerous shortcomings, the regulations and legislation for NZEBs in Cyprus are heading in the right direction. One drawback is that there are no guidelines regarding thermal comfort within a building. Also, there are no strict calculation methodologies applied to normal buildings or NZEBs for construction engineers to use for reference [238]. Thus, one can infer that practical experience and knowledge of NZEBs are still missing in Cyprus. The NZEB design here is also challenged by humidity and condensation, thermal insulation methods, mould growth, air-tightness issues, and the question of how to use renewables in combined systems [240].

In Greece, NZEB adaptation is in its infancy. No definition has been provided for the minimum energy efficiency threshold for NZEBs about either primary energy or end-uses. No bounds have been established for CO_2 emissions. There are also no records of any net-zero energy building restorations for any buildings in Greece [240]. There are currently no indicators for using renewable energy systems in NZEBs, either. Solar energy is most commonly utilized and is regarded as the most effective renewable energy system. The chief obstacle for more widespread use in urban areas is the cost and the inadequate space allowed for solar access [241]. Another cause of concern for NZEB development in Greece is the quality of the construction materials, due to the lack of essential equipment and components. Furthermore, similar to the case of Cyprus, building professionals in Greece lack knowledge about the construction and design of NZEBs [240].

In Portugal, sustainable engineering is part of the energy revolution that applies the principles of NZEBs. The country regards NZEB principles in its architectural drive to comply with the implementation requirements of the European directive of 2010/2013 [188]. Despite achieving milestones in the creation of energy-efficient homes, some obstacles still hinder the move towards NZEBs. Some of these obstacles include financial constraints and legal as well as professional confines [242]. For NZEBs in Portugal, the cost-optimal solution is to make use of green energy that is tapped and used on-site or nearby to ensure the fulfillment of significant extra energy use [243]. There is a gap in the law and the requirements regarding upgrades or the redesigns of energy systems in already existing houses or architectural designs. It is also impractical in Portuguese cities to optimize solar orientation, the layout of internal spaces, and the window to floor areas in ways that make NZEBs most effective and efficient. The consequence of such obstacles is that they limit the scope of passive building design elements [244].

In Romania, there are no limits specified for cooling, heating, or total energy demand for a building to be considered as an NZEB [245]. There are no renovations associated with NZEBs so far. The supply chain is also split between the market for products and construction materials and marked by poor quality and limited product performance categories, making it difficult for engineers to choose good quality NZEB components. A method to standardize product quality is required to overcome certain monopolistic practices and allow easy access to good quality products at reasonable prices [240].

In Spain, every building that can satisfy the least requirements of the present technical building code will be regarded as an NZEB [246]. However, the latest Spanish technical building code is not yet available, and, at present, only a draft of the future building energy indicators exists [247]. One major challenge of NZEB operation in Spain is the huge variation in climate zones. This necessitates several indicators that are flexible enough to evaluate different approaches to achieving NZEB status. The obstacles to NZEB application comprise the slow process of providing a definition and the problematic economic market situation. Concerning energy-saving building restorations, large socio-economic obstacles restrict the process of key renovations in the housing sector [240].

Because of the numerous technology possibilities, it is critical to choose an "optimal" configuration to maximize the overall economic and environmental benefits. It is also important to accommodate local climates and other circumstances in the optimisation for greater design flexibility. As shown above, although several countries have made headway to establishing national standards, the effort to incorporate the concept of NZEBs into international standards and national codes needs to be strengthened. How to incorporate the idea of NZEB into building processes and routines, particularly for renovated buildings, is still an open question. Table 11 summarises the NZEB development and challenges in Europe.

Table 11. Summary of NZEB status in Europe [240].

Regions	Status	Opportunities	Challenges
Europe	• Large-scale deployment of NZEB.	• The EU can benefit from future innovation and grow the market • in NZEB.	• Requiring a large turnover of existing buildings.
Belgium	• Belgium was set a definition for NZEB in 2009.	• Biomass boilers together with photovoltaic panels can be used for NZEB.	• The high costs involved in using bioenergy should be considered. • The diffusion of NZEBs is complex due to regulatory, economic, social, and technological barriers.
Ireland	• New labels regarding positive energy building and low carbon are set up.	• Biomass could be a dominant renewable energy source for residential NZEBs.	• Bioenergy must be combined with other renewable energy systems, like PV to generate electricity.
Cyprus	• National Plan is in place. Definition of NZEB has been set for the design of NZEB.	• The regulations and legislation for NZEBs are heading in the right direction	• No guidelines regarding thermal comfort within a building. • No strict calculation methodologies were applied to NZEBs for construction engineers to use for reference.
Greece	• No National Plans	• Solar energy is	• The cost and limited

	are yet available.	most utilized and is regarded as the most effective renewable energy source.	space available for solar access.
Portugal	• Definition of NZEB depends on numerous variables including technical viability, climate, type of construction, traditions, etc.	• Energy revolution applied in the creation of energy-efficient homes.	• Financial and legal constraints as well as limited professional support.
Romania	• National Plan is under development.	• The easy availability of renewable energy.	• No guidelines are specified for cooling, heating, or total energy demand for a building to be considered as an NZEB.
Spain	• A draft of NZEB indicators for Spain was published in 2016.	• The design of buildings complying with the basic criteria and the current regulatory framework is meet the requirements of NZEB.	• Large socio-economic obstacles restrict the process of renovation in the housing sector, no building code for future building energy indicators.

6. CHALLENGES

NZEB development faces a variety of challenges during the decision-making process [240]. One of the major challenges stems from the limited tools for guiding the decision-making process regarding different aspects of NZEB development such as technical, policy, and financial [248]. For example, an NZEB needs to meet yearly energy consumption with a varied renewable energy system to guarantee supply in different weather conditions [249]. Financially, it is critical to determine the optimal renewable energies and efficiency improvements to minimize capital costs and maximize income. Policy-wise, it is necessary to ensure that NZEB designs are consistent with government regulations to receive export and generation tariffs [7]. Detailed information is summarised in Table 12.

These challenges occur at different stages throughout the project life cycle and have to be considered to ensure the long-term success of an NZEB design. For example, Marszal and Heidelberg selected a multi-story residential property in Denmark as a case study to identify the necessary lifetime analysis involved in an NZEB design. They explored the issues from the building owner's perspective, which generated valuable information for prospective homeowners looking to invest in an NZEB [250]. Their results have shown that investment in energy efficiency is made more cost-effective by reducing the energy used to deliver the NZEB's design.

Table 12. List of barriers in the decision-making of new construction and retrofitting processes [251].

Field	Barriers in decision making	Retrofitting processes	New construction
Technical	• The building's structure and design limit the choice of technical	• The existing building's structure and design limit the choice of technical solutions and NZEB-related	• There is a disparity between the different energy needs, due to the challenges

	solutions and NZEB-related renovation. • There is no one-size-fits-all solution since every building is different. Solutions have to be highly customized. • Personnel with a high level of knowledge are required to carry out NZEB renovations. • An NZEB needs to ensure the security of renewable energy supply in different weather conditions throughout the year.	renovation. • There are insufficient proven and cost-efficient solutions for NZEB renovation.	created by climate change, dense urbanization, noise pollution, air pollution, and population aging. • Fulfilling NZEB requires changing the rules of the building's design.
Financial	• Investment costs can be high. • The payback period is long and may require long-term ownership of the building, which is not always possible. • Greater financial incentives are needed for higher energy-efficiency goals. • It is critical to	• Building owners are probably unable to make money from investments in NZEBs. • It is difficult to ensure that the project is financially justifiable without public funding.	• Unawareness among investors and citizens about the multiple benefits and feasibility of NZEBs (energy costs over the lifetime) • Financial incentives are needed for renewable energies to support NZEB.

	figure out the optimal renewable energies and efficiency improvements to minimize capital costs and maximize income.		
Social	• Residents and owners lack the knowledge or interest needed to improve energy efficiency. • Architectural and cultural values restrict the extent of NZEB renovations that can be done.	• There is a need to communicate and provide information early in the renovation stage to increase acceptance among residents. • Architectural and cultural values restrict the extent of NZEB renovations that can be done.	• More attempts are needed to raise awareness about energy-neutral buildings and to discuss the strategic approach of enterprises to develop a suitable conceptual model for NZEBs.
Organizational	• If the building is owned by several parties, all or the majority of the stakeholders have to agree before renovations can begin.	• Planning and preparation are needed to reduce the impact of the renovation process on the building's occupants. • Communication should take place between all involved parties early in the process.	• Need new building design concepts that respect climate sensitivity and technological state. • Need to harmonize actions between countries and consider the knowledge transfer between countries to accelerate the implementation of NZEB.
Environmental Health Policy	• It is necessary to ensure that NZEB designs are in line with	• If the residents stay in the building during renovation, issues such as	• Making energy neutrality of buildings desirable, and to use it as

	government regulations to receive generation and export tariffs.	noise and dust need to be taken into consideration. • There is a risk of increased moisture when making a building more airtight.	a self-esteem and social status perspective. • Legislation is subject to extreme uncertainty.

7. DISCUSSION

This section summarises the development of main renewable energy technologies for NZEBs, focusing on renewable energy supply, energy storage, CBA, and LCA to help the priorities of future development. Solar energy has long been the most popular renewable energy source for NZEBs, owing to its widespread availability, relatively low cost, and a unit cost that is generally unaffected by installation size. When there is limited installation space for solar energy, a wind turbine could be used to augment the solar energy or to lessen the dependence on a single energy source. Wind energy is often less accessible and feasible compared to solar energy, although it has the advantage of more availability during cloudy days and nights. However, the deployment of wind energy for NZEBs is limited by its relatively high cost. Biomass energy is weather-independent, making it appealing, especially when biomass sources such as locally generated waste, are easily accessible. CHP generation can be exploited to achieve higher process efficiencies. ASHPs are appealing for home applications because of their simple setups, and low maintenance and their expense . High-efficiency, low-temperature ASHPs must be designed to work in very cold climates to compete with the operating costs and major fuel consumption of fossil fuel systems. GSHP systems are also appropriate for residential NZEBs, particularly in colder locations, due to their higher efficiency. However, GSHP systems are expensive which continues to be a significant barrier to their widespread adoption.

It is worth noting that the weather has an impact on the applicability of various energy-saving strategies. For example, in heating-dominated buildings, higher insulation and airtightness usually result in greater savings. For cooling-dominated structures, these efforts are less efficient, and they may also be unproductive in case the insulation hinders natural cooling during lengthy periods of lower external temperature [252].

Smart controls, energy-efficient lighting, and energy-efficient appliances, among other things, all contribute to NZEBs by lowering building energy consumption. Furthermore, energy-efficient lights and appliances can reduce the cooling load on HVAC systems. Smart controls can result in a net-zero building if the residents have relatively energy-efficient behaviours.

Energy storage can be used to boost process performance while also lowering resource costs and minimizing environmental impacts if properly designed and configured. The fundamental components of energy storage include energy generation, storage, and supply. NZEBs become more complex due to all the energy storage systems and accompanying energy conversion equipment, which requires further expenditure. On the other hand, off-site NZEBs could be a good choice for isolated regions without grid connections. Off-grid, self-contained NZEBs necessitate large energy storage systems.

CBA is used to assess economic attractiveness when there is an investment in renewable technology. In the UK, the estimated capital cost of a biomass boiler is £4,218 (USD 5,690), and the generation tariff is 6.74 p/kWh (USD 0.09/kWh). The estimated cost of a solar thermal system is £700 (USD 944), with a generation tariff of 20.66 p/kWh (USD 0.027/kWh). A 2.1 kW rated wind turbine costs £4,500 (USD 6,070), and there is a generation tariff of 8.24 p/kWh (USD 0.11/kWh). The capital costs for an ASHP system are approximately £6,000 (USD 8,094). The cost of a GSHP is approximately £14,000 (USD 18,887). Their capital costs for an

ASHP are much cheaper than a GSHP, which has the highest implementation and maintenance costs, therefore, is one of the least attractive renewable technologies.

LCA involves the analysis and assessment of environmental effects based on the energy and material inputs and the emissions released into the environment. Combusting biofuels do not contribute to the greenhouse effect because biomass is renewable, leading to CO_2-neutral conversion. Biomass produces approximately ten times less CO_2 per MWh compared to conventional fuels. It has been found that for every 1kg of wood pellets, 370g of CO_2 emissions will be produced. The average emissions levels of wind energy and solar PV are 10.7 and 49 kg CO_2/MWh, respectively.

8. CONCLUSIONS

This paper has presented an inclusive review covering the crucial issues related to NZEBs, the contributions of renewable energy generation to the development of NZEBs, the role of NZEBs in tackling the issues of reducing CO_2 emissions and saving energy. NZEBs reduce energy use through two strategies: diminishing the need for energy use in buildings via the use of energy-efficient measures and embracing renewable energy technologies to meet the remaining energy needs.

Although no single "best" configuration can be suggested, the goal of this review is to highlight potential design methods and renewable energy options for NZEB development. Different NZEB configurations are available for varied climate and building codes, and building industry practitioners need to choose the technologies and architectural components that conform to local conditions and limitations. It is essential to develop a universal decision instrument that directs the management and design of NZEBs. Future research should also focus on how to better integrate renewable energy generation technologies into the designing and analysis of NZEBs. For example, upon the use of waste-to-energy technologies to support the development of NZEBs, its ability for facilitating sustainable waste management can be considered as an additional benefit. The use of waste in the generation of energy minimizes the environmental impact of uncontrolled disposal, and the decomposition of organic wastes often encourages environmental sustainability.

AUTHOR CONTRIBUTIONS

Asam Ahmed: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Validation; Writing; Original draft preparation. **Siming You**: Supervision; Review & editing; Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Validation; Writing; Review & editing. **Tianshu Ge**: Reviewing and Editing. **Jinqing Peng**: Reviewing and Editing. **Wei-Cheng Yan**: Investigation; Reviewing and Editing. **Boon Tuan Tee**: Reviewing and Editing.

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