Towards Climate Neutrality: Global Perspective and Actions for Net-Zero Buildings to Achieve Climate Change Mitigation and the SDGs

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> "Start carbon neutrality now! Each country, city, financial institution and company should adopt plans for transitioning to net-zero emissions by 2050 and take decisive action now".
> Antonio Guterres, Secretary General of the United Nations [1]

Box 1 Low-Carbon City

Low-carbon City (LCC) means a sustainable urbanisation approach that focuses on curtailing the anthropogenesic carbon footprint of cities by virtue of minimizing or eliminating the utilisation of energy sourced from fossil fuel. It combines the futures of Low-carbon society and low-carbon economy while supporting partnerships among governments, private sectors and civil societies. Sustainable Cities and Communities, Springer [2]

Introduction

It all begins with a question! Are buildings efficient enough to meet their energy demand and rely on renewable sources to generate clean energy? The term low-carbon city including low- carbon buildings (Box 1) has recently been used in response to the climate crisis. By and large, the answer simply is not, and buildings nowadays consume a large amounts of energy and emit a colossal amount of greenhouse gases (GHG), mainly carbon dioxide – CO_2 (Fig. 1). In the old days, buildings were built from locally sourced materials and responded effectively to climate

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conditions, hence, consuming less energy and emitting less carbon as shown in Figs. 2, 3, and 4.

The evolution of building solutions in the construction industry does not stop, and with the increasing consciousness about the depletion of resources and environmental awareness, the sustainability dimensions of any building is becoming mandatory in climate mitigation [3]. The concept of climate neutrality has been expanding in all building types to mitigate CO_2 emissions to a minimum level and offset the remaining emissions as well [4]. The avoidance of all building-related GHG emissions means that all buildings are considered “climate-neutral.” Global initiatives worldwide aimed at enhancing climate neutrality and achieving net-zero energy levels are considered one of the most important steps in pushing for creating climate action plans in cities. Action plans provide more specific guidelines and solutions required in order to mitigate climate change in each city [5]. The use of renewable energy resources is the first step utilized to reach net-zero energy models meaning that the production of the energy in the system will approximately cover the total system energy operational needs [6]. Figure 5 presents a vivid exemplary model of a net-zero complex, the Terra – The Sustainability Pavilion at Expo 2020 Dubai. Another significant step is the application of sustainable and green building solutions to act against pollution and emissions production, waste management, and energy saving by reducing total energy consumption [7]. Nevertheless, green building doesn’t mean net-zero. Box 2 presents the definition of net-zero.

Fig. 1 Buildings nowadays consume large amount of energy from nonrenewable sources and emit the same of carbon emissions. (Image credit and source: Mohsen Aboulnaga)

Fig. 2 Buildings were built in Brussels, Belgium, in the seventeenth century to respond to climatic conditions and use less amount of energy due to locally sourced materials. (Image credit and source: Mohsen Aboulnaga)

Energy consumption in buildings has been rapidly increasing in the past years more than in other main sectors such as the transportation and industrial sectors [8]. Residential and commercial buildings, according to Ortiz et al., have steadily increased their contribution to global energy consumption, with estimates ranging from 20% to 40% in developed countries [9]. It is highly expected that energy consumption will increase in the next few years due to the continuous demand for energy to achieve higher comfort levels inside buildings, as well as the increasing demand for building services due to the massive population growth all around the world. The energy demand and the growing energy use caused and still causing a lot of adverse effects on the environment, during the period from 1984 to 2004, carbon dioxide (CO_2) emissions have increased by 43%, so the energy usage in buildings could be considered as one of the main reasons of global warming and ozone depletion [10]. According to the International Energy Agency (IEA), global energy-related CO_2 emissions will increase by 6% to 36.3 billion tonnes in 2021, the highest level ever [11]. Hence, the urge to build low-carbon buildings (environment-friendly buildings) or net-zero buildings that use all energy needed from renewable and clean sources while reducing carbon emissions is exclaimed as net-zero building [12].

Box 2 Net-Zero-Energy Building

Net-zero energy building means a building that combines energy efficiency and renewable energy generation to consume only as much energy as can be produced onsite through renewable resources over a specified time period. Department of Energy – Office of Energy Efficiency & Renewable Energy, USA [13]

Fig. 3 Buildings in the medieval city of, in Belgium respond to climatic conditions and use less amount of energy due to locally sourced materials. (Image credit and source: Mohsen Aboulnaga)

Fig. 4 Medieval stones and slates of buildings in Ghent, Belgium, to respond to the climatic conditions and use less energy due to locally sourced materials. (Image credit and source: Mohsen Aboulnaga)

Why Net-Zero?

The energy crisis, in terms of skyrocketing prices increase and current shortage of supply in the third quarter of 2021, coupled with the impact of the COVID-19 crisis and rapid population growth, will force city leaders and local governments to rethink and develop cities to meet climate neutrality. In 2022, this crisis becomes catastrophic due to the Russian-Ukraine war, which not only forces the oil price to reach almost 120.00 US$ since June 6, 2022, but also severely distributes and/or halts the energy and food supply worldwide [14]. According to Khassan et al., a zero-energy building can be identified as a building that has zero-net energy consumption, or in other words, it is the building that depends on renewable energy only. This means that the overall consumption of a building is being used from renewable energy sources such as the solar panels, wind turbines, and any other clean sources [15]. According to Kaewunruen et al., the use of solar energy has become critical for obtaining a zero-energy building since it provides the building with a good amount of energy, especially at places where the sun is always available [16]. Referring to the European Union (EU), from the beginning of 2020, the new buildings should be near-zero-energy buildings. According to El Sayary and Omar, the first step towards achieving a net-energy balance of zero would be to reduce the amount of electricity

Fig. 5 A net-zero model (Solar Complex) Terra – The Sustainability Pavilion at Expo 2020 Dubai – by Grimshaw Global. (Image credit and source: Mohsen Aboulnaga & Amina El-Haggan)

committed and then meet the remaining demand with onsite renewable energy sources [17]. Hence, a net-zero-energy building (NZEB) cannot rely only on the amount of energy generated from clean energy, but it also depends on other techniques and materials used to reduce the need for excessive energy consumption. As part of a research project to create a detailed strategy to achieve net-zero-energy performance level in Egyptian office buildings, Suzuki and Sumiyoshi conducted building energy simulation towards developing a guideline for NZEBs in Egypt [18]. According to Pye et al., an existing residential building was modeled and redesigned to achieve net-zero-energy consumption; this residential building was mocked up in three different versions to compare enhancements in energy performance, such as boosting the thermal efficiency of the building envelope, increasing wall thickness, and inserting smart windows (switchable windows). When compared to the original townhouse, these three solutions can save energy and cost by 8.16%, 10.16%, and 14.65% respectively [19]. Fankhauser et al. also defined the net-zero meaning and how to get it right [20].

What Is a Net-Zero City?

The Climate Adaptation Platform (CAP) defined net-zero city as follows: "It is a city that promotes energy efficiency and renewable energy in all its sectors and activities, extensively promotes green solutions, applies land compactness with mixed land use and social mix practices in its planning systems, and anchors its local development in the principles of green growth and equity. The concept of net-zero carbon emissions operates through social, political, and financial considerations" [21]. However, another net-zero city definition is portrayed in Box 3 [22]. Figure 6 shows examples of renewable energy and energy efficiency manifested in Fujisawa smart, low-carbon, and sustainable city in Yokohama, Japan, and Masdar net-zero city in Abu Dhabi, UAE.

Box 3 Definition of Net-Zero City

It is a city that produces sustainable, carbon free energy in amounts equal to, or exceeding, the amount which it consumes, which may be accomplished through a combination of the following (as well other) strategies: (i) integrating renewable and distributed energy generation sources (i.e., supply side; (ii) Smart grid technologies to increase energy efficiency, increase the usage of clean power, ad reduce overall consumption, particularly at peak demand periods; and (iii) energy storage technologies. Council Climate Oversight Group (CCOG) [22]

What Is Climate Neutrality?

"Climate neutrality" is identical to the net phaseout of all GHG emanations, while "GHG neutrality" has the same sense, in spite of the fact that it is more particular than climate neutrality. However, "carbon neutrality" encounters the same perception but only includes CO_2 emissions. Climate neutrality in general indicates zero GHG emissions over the building's entire life cycle. The term "GHG neutrality" or

(a) Integrated solar PV panels with green roofs **(b)** Solar PV panels installed on buildings' rooftops

Fig. 6 Elements of net-zero in Fujisawa smart, low-carbon, and sustainable city in Yokohama, Grater Tokyo, Japan, and Masdar's net-zero city in Abu Dhabi, UAE (Source: Mohsen Aboulnaga). (**a**) Integrated solar PV panels with green roofs. (**b**) Solar PV panels installed on buildings' rooftops

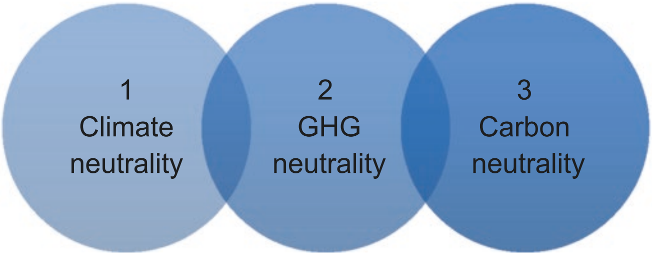


Fig. 7 Various types of building neutrality to mitigate climate change. (Source: developed by authors after [3])

“climate neutrality” refers to the total amount of different emission classifications, which include emissions from embodied energy, operational energy, industrial processes, and non-CO2 GHG emissions [3]. Figure 7 lists the various types of building neutrality to mitigate climate change, while Fig. 8 presents the definition of these types.

The Importance of Net-Zero Cities

The concept of net-zero carbon emissions operates through social, political, and financial considerations. In this context, seven characteristics of net-zero, which are basic to create a viable framework for climate action, were recognized [23]. The properties emphasize the necessity for social and characteristic judgment. This implies that carbon dioxide (CO_2) removals have to be utilized cautiously and the utilization of carbon offsets effectively.

Despite the fact that net-zero target being set, but a query arises on how current net-zero target align [23]. Net-zero must be balanced with broader viable progression objectives, which recommend an impartial net-zero move, socio-ecological supportability, and the interest of wide money-related support. Therefore, limiting temperature rise requires a change in the rate of CO_2 release into the atmosphere and removal into sinks. This point of view offers an arrangement of translations of what net-zero implies and how it ought to be accomplished. Nonetheless, these clarifications guarantee consistency with worldwide temperature objectives, while inserting net-zero into sociopolitical and lawful settings. In debate, it is conceivable to adjust net-zero with maintainable improvement targets, permit for distinctive stages of improvement, and secure zero-carbon success [24], and in any case, there are a few clear limitations.

Net-zero commitments are not an elective to critical and comprehensive outflows cuts. The “net” in net-zero is fundamental, but the requirements for social and natural keenness force firm imperatives on the scope, timing, and administration of both carbon dioxide expulsion and carbon offsets [24]. To understand the various actions to achieve net-zero, there are about six principles that assist in attaining such actions,

Fig. 8 Definitions of neutrality types to mitigate climate change. (Source: Developed by authors after [3]

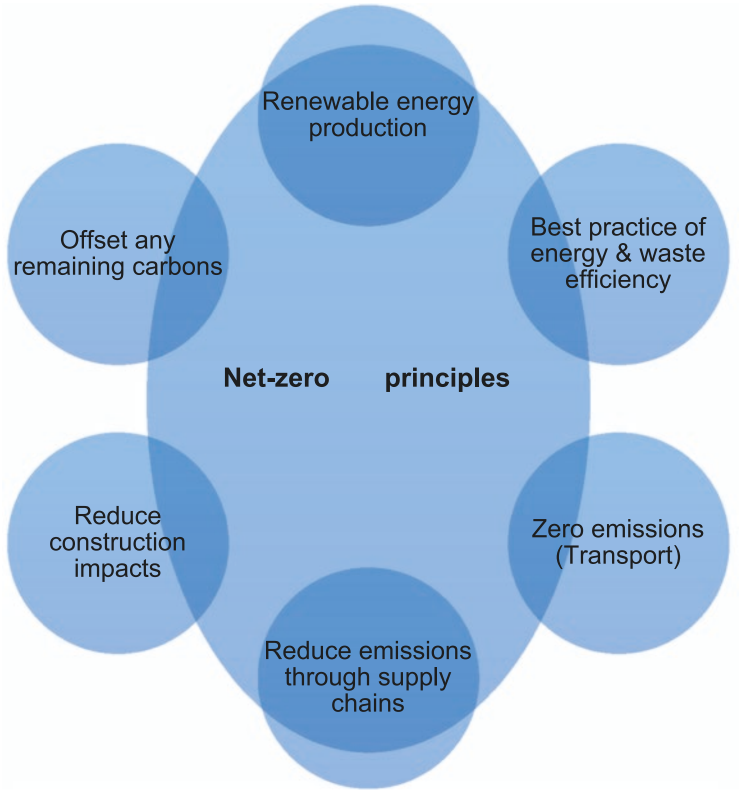


Fig. 9 Actions to achieve net-zero principles. (Source: Developed by authors)

including (a) renewable energy production, (b) best practice of energy and waste efficiency, (c) zero emissions (transport), (d) reduction of emissions through supply chains, (e) reduction of construction impacts, and (g) offset any remaining carbons (Fig. 9).

There are many examples of net-zero in various sectors in cities, but these are not enough to reach the COP26 and GCP 2021 aiming at mitigating 45% of CO_2 by 2030 (almost 8 years today) and achieve net-zero by 2050 [24]. Therefore, it is imperative to highlight that many examples that are considered low-carbon or near-zero buildings, net-zero energy, or net-zero heating whether in buildings or in transport worldwide could guide the architects and local authorities to follow if not enhance future models.

Recent Exemplary Model of Net-Zero Buildings, 2021 to 2022

Between the years 2021 and 2022, there are some vivid examples that have adopted the concept of low-carbon and NZEBs and have showcased clean energy manifestation. These are the iconic BEEAH Headquarters in Sharjah, UAE, designed by Zaha Hadid Architects; the UAE Pavilion, designed by Santiago Calatrava; and The Terra – The Sustainability Pavilion – designed by Sir Nicholas Grimshaw at EXPO 2020 Dubai (Fig. 10).

BEEAH Headquarters in Sharjah UAE by Zaha Hadid Architects

The smart and sustainable building – the last project, designed by the late renowned architect Zaha Hadid – reveals highly efficient operational energy performance and smart technologies. The building, the first fully artificially intelligent (AI) complex in the world, was recently inaugurated on March 31, 2022. The design concept is inspired from nature – the desert – and it mimics sand dunes while creating curvilinear roofs. The design is centered on a two-pillar strategy, which addresses sustainability and digitalization [25, 26]. In addition, a large number of solar

Fig. 10 Examples of net-zero and near-zero buildings. (Source: Developed by authors)

(a) Climatic building shape of interlocking dunes **(b)** Flowing efficient envelope of the smart building

Fig. 11 The iconic net-zero, smart, and artificial intelligent building – BEEAH Headquarters in Sharjah, UAE. (Images' credit and source: Fearandloathingindubai https://commons.wikimedia.org/wiki/File: BEEAH_headquarters.jpg). (**a**) Climatic building shape of interlocking dunes. (**b**) Flowing efficient envelope of the smart building

photovoltaic (PV) arrays are installed onsite to enhance the sustainable energy production, hence contributing to mitigating the CO_2 emissions of the building [27]. Its design concept incorporated overall shapes of interlocking dunes that respond to the desert climate with specific orientation as presented in Figs. 11 and 12. The LEED-certified building also exploited local materials and smart technologies, such as onsite water treatment, energy storage via Tesla batteries, and glass-reinforced skin that regulates solar heat gain [28].

By examining the BEEAH artificial intelligent and net-zero building, it is clear that such a building, which spreads over a floor area of 7000 m^2, incorporates the following smart and green technologies integrated within this iconic headquarters [27, 28]:

- Installed solar power plant to generate 20,000 kW (20 MW) to achieve net-zero emissions.
- Lightweight glass fiber reinforced concrete (GFRC) – approximately 4000 panels to reduce solar radiation and maximize emittance.
- AI integrated ERP systems' streamlines all business functions to ensure speed and efficiency in the workspace (smart meeting rooms).
- AI systems developed by Microsoft, Johnson Controls, and EVOTEQ.
- High-tech infrastructure allows the entire environment to be monitored in real-time.
- Analyze volumes of data to optimize building performance.
- A zero-energy strategy with optimum energy efficiency.
- Smart parking navigation and spot preservation.
- Smart security and access control using facial recognition.
- Office access and building navigation tools.
- Companion app for user guidance before entering the building.
- Productive visitor interactivity through AI concierge.
- Peak working conditions and comfort as well as light and temperature control.

Fig. 12 General view of the envelope and roof of BEEAH Headquarters' net-zero and smart building at night. (Image credit and source: Hufton Crow, https://www.zahahadidarchitect.com)

- Above 90% of materials used for constructing the building are locally sourced and recycled.
- Onsite solar PV farm with Tesla pack battery.

The Terra – The Sustainability Pavilion EXPO 2020 Dubai

The complex encompasses 19 energy trees (E-trees); each of the 18 E-tree canopies – 130 meters wide – emulates the sun flower as shown in Fig. 13. All E-trees rotate 180 degrees to increase the efficiency of the cells that generate 4 GWh of renewable energy as well as produce water from recycled rainwater [29]. There are 4912 ultraefficient monocrystalline PV panels, covering an area of more than 6000 sq.m, which are installed on the 18 trees (each ranging from 15–18 m in diameter) and implanted in glass panels [29, 30]. The Terra – Sustainability Pavilion – generates 28% of the energy needed to power the building [29 27] as presented in Fig. 13. The combination of the cell and the glass casing permits the building to harness solar energy, while granting shade and daylight for visitors. Each E-tree has a canopy serving as a large storm water harvesting and dew that replenishes the building's water systems [30] and harnesses energy (Fig.13). In addition, the Pavilion after Expo will be used as a museum of sustainability to reflect such legacy. Figure 14 illustrates the elements used in the Terra Pavilion.

Fig. 13 The Terra – The Sustainability Pavilion generating 4 GWh annually from renewable energy. (Images' credit and source: Mohsen Aboulnaga and Aya Ghobashy)

The Sustainability Pavilion is designed by the famous British firm Grimshaw Global. According to Grimshaw Global, key sustainability issues are centered on six main factors, including (a) project site, (b) transect zone/climate zone, (c) ecoregion, (d) operation energy/carbon, (e) embodied energy, and (f) water [31]. In alignment with the SDGs, the Pavilion achieved five SDGs, including goal 6 (clean water and sanitation), goal 7 (clean and renewable energy), goal 9 (innovation and infrastructure), goal 12 (responsible consumption and production), and goal 13 (climate action), in addition to goal 4 (quality education in the Legacy mode). A summary of the key sustainability features are listed below [31]:

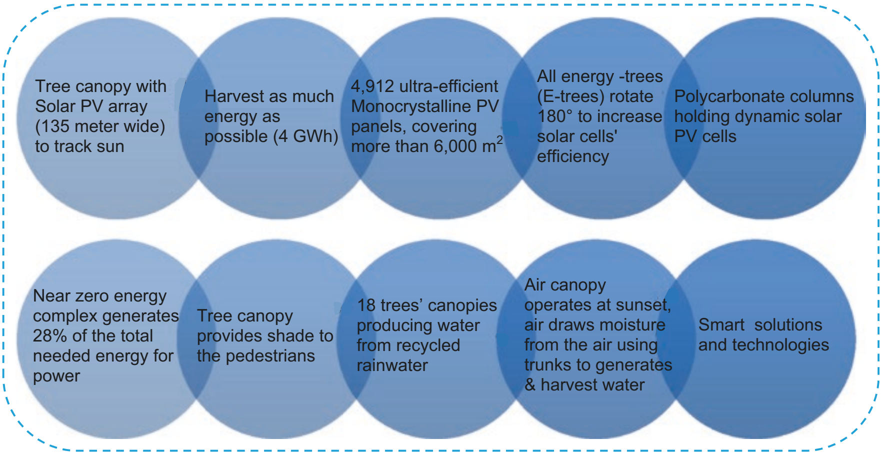


Fig. 14 Elements exploited in the Terra – The Sustainability Pavilion at EXPO 2020 Dubai. (Image source: Developed by authors after Grimshaw Global)

- Energy trees – Eighteen E-trees that support a smaller axially rotating PV array dish on a long stem, furnishing 4000 m^2 of solar PV panels generating about 2.6 GWh power yearly.
- Canopy – The 135-meter-wide multifunction canopy encompasses 1055 solar PV panels covering an area of 8000 m^2.
- The Pavilion energy demand – Produces its own power of 4 GWh which is made available by energy-saving techniques through the building passive design.
- Daylight – Captured where appropriate and a range of light pipe and fiber-optic systems are incorporated to furnish daylight to deep spaces.
- Canopy shading – The shading provided by the canopy reduces energy use of the internal exhibition spaces by decreasing the solar radiation impinging on them.
- Buried accommodation – The Pavilion sits partially below ground, providing a thermal effect which is generally cooler than the ambient temperature in summer.
- Night cooling – Low landscape to southeast of the site maximizes inflow of cool night air.
- Canopy materials – It was built from steel with 97% recycled content and manufactured at a site 15 minutes away from the Pavilion.
- Cement and embodied carbon reduction – Strategies to mitigate the use of cement included constructing about 10,900 m^2 of upper floors with bubble decks that uses around 25% less concrete and resulting in less steel compared to solid concrete slabs.
- Comfort – Earth below ground is fairly cooler due to its high thermal mass; this provides comfort during used periods.
- Water – Rainwater is harvested and percolated into landscape to recharge the groundwater, which is then being extracted and treated for use as potable water within the building, corresponding to a net-zero water ambition.

- Ecology – Integrated into this landscape of native and adapted species are new crops that produce zero-km food and biofuels.
- Education – The design of each exhibit space promotes learning by school groups and other arranged uses, specifically after Expo and in Legacy.

UAE Pavilion EXPO 2020 Dubai

The second recent near-zero-energy building is the UAE Pavilion, which was inspired from the desert nature biodiversity (Falcon). The iconic pavilion features many green technologies and smart solutions (Fig. 15). The pavilion, which was designed by the famous architect, Santiago Calatrava, is spread over 15,000 square meters as illustrated in Fig. 16 [32]. The building has 28 floating movable wings that emulate the falcon’s wings and cover the building’s roof. Each wing has solar PV arrays to generate clean energy and is covered by dynamic rips to protect these panels from rain and dust during sand storms [33–35] as presented in Figs. 16 and 17 .

Global Examples of Net-Zero-Energy Buildings

NZEBs around the world incorporate different feasible vitality arrangements that consolidate and progress the building CO_2 outflows, i.e., cooling framework coefficient of execution COP26 and producing clean energy. All these arrangements

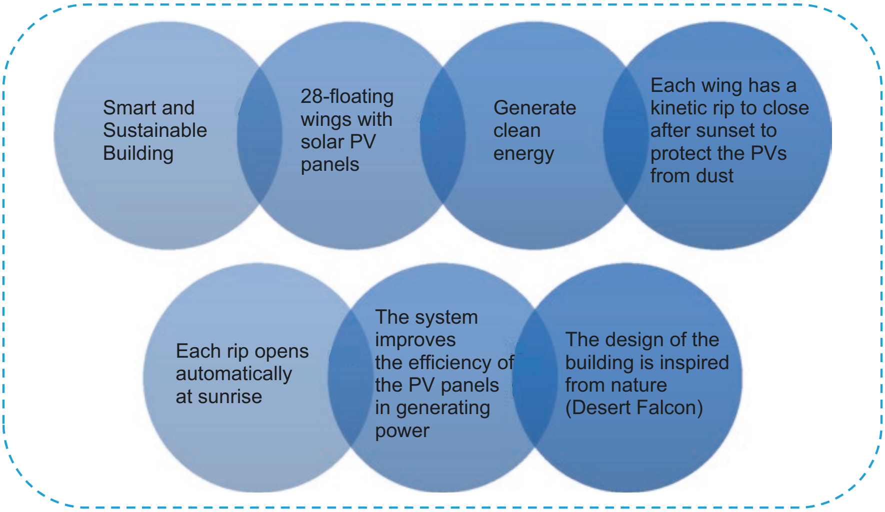


Fig. 15 Features integrated in the UAE Pavilion at EXPO 2020 Dubai. (Image source: Developed by authors)

Fig. 16 The iconic UAE Pavilion with 28 floating wings integrating solar PV panels, EXPO 2020 Dubai. (Image credit and source: Mohsen Aboulnaga and Amina El-Haggan)

Fig. 17 The floating wings generate clean energy from renewable sources for the building energy annual consumption. (Image credit and source: Mohsen Aboulnaga and Amina El Haggan)

have a more noteworthy viewpoint towards climate moderation and offered to worldwide directions and developments [36]. Global examples of net-zero buildings have exempted huge transitions in terms of innovation and clean energy production to ensure the lowest carbon emissions by buildings and adoption of GHG offset measures. There are multiple techniques and strategies that can be applied that serve the needs of each case to adapt to the surrounding conditions. Figure 18 portrays the examples selected for case studies that address net-zero energy targets.

Dalian Convention Centre in Dalian, China

The new conference center and opera house of Dalian are living proof of the Chinese sustainable construction goals. It is designed by Austrian architect Wolf D. Prix, where energy consumption levels are kept at minimum through the use of thermal energy, passive ventilation, and solar energy [37]. Allowing the building to produce energy using seawater helps in cooling the building in summer and its heating in winter as presented in Figs. 19. As illustrated in Fig. 19a, the building is covered by a huge number of integrated PV cells on the curved roof to generate clean energy. Figure 19b portrays the magnificent flowing building at night. The façade is created to protect the building from solar radiation, while maintaining an adequate amount of sunlight and natural light inside the center's spaces (Fig. 19c, d). In the smart and green buildings, the following features are adopted and integrated:

- Net-zero building
- Use of renewable energy (solar PV) covering the rooftop to generate clean energy
- Integrate high emissivity and reflectance metal material on the building's smart envelope
- Achieve energy efficient, smart, and green building to mitigate CO_2 emissions
- Use seawater for cooling and heating by virtue of heat pumps
- Enhance comfort by controlling daylight
- Provide good sunlight inside the spaces while minimizing heat and glare

National University of Singapore, Singapore

Within Asia, another net-zero building has been developed and operated in Singapore. This net-zero building is the Singapore Design and Environmental School where solar PV arrays are integrated to generate clean energy. At the National University of Singapore, the University Hall, which is a remarkable net-zero building, is designed by Serie Architects and Singapore studio, Multiply Architects (Fig. 20). As shown in Fig. 20a, b, the building is intended to operate as a NZEB and generate its own energy needs from clean sources [38]. Figure 21 presents a side view of the University Hall, while Fig. 22 shows the shaded glass by the roof

1. Dalian Convention Centre in Dalian, China

2. University Hall, National University of Singapore

3. CIC zero-carbon Building, Hong Kong

4. The NIER–CCRC Building, Incheon, SK

5. Incheon-Seoul Int’l Airport, Incheon, S. Korea

6. Incheon National University, S. Korea

7. UN Headquarters, G-Tower in Incheon, SK

8. Lumen building, Wageningen University, The Netherlands

9. The Edge Office building in Amsterdam

10. GSK’s Lab. building, Nottingham University, UK

11. DeepStone House in Scotland, UK

12. Solar Settlement & Sun ship, Germany

13. Plus-energy house, Germany

14. Kunsthaus Bregenz Ar Museum, Austria

15. A Holiday Home, Spain

16. Unisphere Building, USA

17. NREL campus, Colorado, USA

18. La Jolla Commons, CA

Fig. 18 Selected global buildings’ examples integrating net-zero-energy strategies. (**1**) Dalian Convention Centre in Dalian, China. (**2**) University Hall, National University of Singapore . (**3**) CIC zero-carbon Building, Hong Kong. (**4**) The NIER–CCRC Building, Incheon, SK . (**5**) Incheon-Seoul Int’l Airport, Incheon, S. Korea . (**6**) Incheon National University, S. Korea. (**7**) UN Headquarters, G-Tower in Incheon, SK. (**8**) Lumen building, Wageningen University, The Netherlands. (**9**) The Edge Office building in Amsterdam. (**10**) GSK’s Lab. building, Nottingham University, UK. (**11**) DeepStone House in Scotland, UK. (**12**) Solar Settlement & Sun ship, Germany. (**13**) Plus-energy house, Germany. (**14**) Kunsthaus Bregenz Art Museum, Austria. (**15**) A Holiday Home, Spain. (**16**) Unisphere Building, USA. (**17**) NREL campus, Colorado, USA. (**18**) La Jolla Commons, CA

(a) Dalian Conference Center's external façade acts as a screen light penetration

(b) General view of the vivid Dalian Conference Center in Dalian city at night.

(c) The building system controls facades and maintains ventilation and provides sunlight

(d) The interior consists of green areas to purify the atmosphere and skylights permit daylight.

Fig. 19 Dalian Convention Center in Dalian China, a near-zero-energy building. (Image credit and source (**a**–**d**): Forgemind ArchiMedia, https://commons.m.wikimedia.org/wiki/File:Dalian_International_Conference_Center.jpg). (**a**) Dalian Conference Center's external façade acts as a screen light penetration. (**b**) General view of the vivid Dalian Conference Center in Dalian city at night. (**c**) The building system controls facades and maintains ventilation and provides sunlight. (**d**) The interior consists of green areas to purify the atmosphere and skylights permit daylight

canopy and inclined columns of Yong Siew Toh Conservatory at the National University of Singapore in Singapore.

The CIC Zero Carbon Building in Hong Kong, China

The third example of net-zero-energy building is the CIC Zero Carbon Complex in Hong Kong, China. It is a pioneering project that exhibits the state of the art in zero-carbon building (ZCB) technologies and raise community awareness of sustainable living in Hong Kong, China. The CIC Zero Carbon Building achieves significant energy savings through daylighting, cross-ventilation, a high-performance façade, high-volume-low-speed fans, radiant cooling, and desiccant dehumanization (Figs. 23 and 24). The entrance of the Zero Carbon Building is covered by a large area of solar PV arrays which is illustrated in Fig. 25. Besides, local materials, such

(a) The entrance of the University Hall building, National University of Singapore

(b) Close up of the University Hall building, the National University of Singapore

Fig. 20 The net-zero University Hall Building, National University of Singapore, Singapore (Images credit and source: (**a**) Sengkang, https://commons.wikimedia.org/wiki/File:NUS,_University_Hall,_Nov_06.JPG); (**b**) Alex.ch, https://commons.wikimedia.org/wiki/File:University_Hall,_National_University_of_Singapore_-_20070125.jpg). (**a**) The entrance of the University Hall Building, National University of Singapore. (**b**) Close-up of the University Hall Building, the National University of Singapore

Fig. 21 Side view of the net-zero University Hall, National University of Singapore, Singapore. (Image credit and source: Joshua Rommel Hayag Vargas https://commons.wikimedia.org/wiki/File:University_Hall,_National_University_of_Singapore,_February_2020.jpg)

as glass and timber, were used to further lower the carbon footprint of the building and onsite PVs as well as a large-scale biodiesel generator that produces more energy than the building consumes [39].

Fig. 22 Glazed façade of the Yong Siew Toh Conservatory at the National University of Singapore, Singapore. (Image credit and source: Joshua Rommel Hayag Vargas, https://commons.wikimedia.org/wiki/ File:YST_ Conservatory, _National_University_of_Singapore,_February_2020.jpg)

National Institute of Environmental Research (NIER) Building in Incheon, South Korea

The fourth iconic example that demonstrates solutions and technologies for zero-carbon building is the National Institute of Environmental Research (NIER) in Incheon, South Korea. The NIER and Climate Change Research Building in Incheon is South Korea's first zero-carbon building; it was completed in 2010 and ranked the world's first carbon-neutral and net-zero-energy commercial-scale office building as well as the world's fourth largest NZEB as of 2012. The building includes the

Fig. 23 The CIC Zero Carbon Building layout. (Image credit and source: Wpcpey, https://commons.m.wikimedia.org/wiki/File:CIC_Zero_Carbon_Building_Overview_201708.jpg)

Fig. 24 Back view of the CIC Zero Carbon Building showing the solar PV panels on top of the roof. (Image credit and source: Ceeseven, https://commons.m.wikimedia.org/wiki/File:CIC_Zero_Carbon_Building.jpg)

office of Climate Change Research Center (CCRC). It is considered as the world's 4th zero-carbon building as of 2012. The building's facades are cladded by solar PV arrays as shown in Fig. 26. The NIER building exhibits the state of the art in zero-carbon building technologies [40]. Figure 27 also illustrates different types of solar

Fig. 25 The entrance of the CIC Zero Carbon Building showing the solar PV arrays. (Image credit and source: Ceeseven, https://commons.m.wikimedia.org/wiki/File:CIC_Zero_Carbon_Building.jpg)

PV panels installed on the façade of the building to generate the whole energy demand needed to power and operate the building over the year.

Incheon International Airport Transportation Center in Incheon, South Korea

Incheon-Seoul International Airport in South Korea is portraying not only a low-carbon building but also a smart and efficient transportation center. Incheon Aerotropolis is a global leader in aviation-linked commercial development and smart technology applications. The building is integrating panoramic curved glass walls allowing generous natural light to nurture extensive interior gardens as shown in Figs. 28, 29, and 30. The center's sustainable techniques include water and waste management, low-carbon management, maximization of the use of natural illumination and ventilation, and reduction of carbon footprint [41].

Most conventional solar cells use visible and infrared light to generate electricity. In contrast, the innovative new solar cell also uses ultraviolet radiation. It replaces conventional window glass, or placed over the glass, and installation surface area could be large, leading to potential uses that take advantage of the combined

Fig. 26 The NIER and CCRC zero-carbon building in Incheon, South Korea. (Image credit and source: Mohsen Aboulnaga)

Fig. 27 Various types of solar PV panels installed on the façade of NEIR/CCRC building and solar collector arrays on rooftop. (Image credit and source: Truth Leem, Reuters https://www.reuters.com/articles/us-korea-green-/south-korea-unveils-completely-eco-friendly-building-idINTRE74J1FE20110520)

Fig. 28 Incheon-Seoul Airport Terminal envelope engulfs cells that contain titanium oxide coats with a photoelectric dye for generating electrical power for lighting and temperature control. (Image credit and source: Mohsen Aboulnaga, 2015)

functions of power generation, lighting, and temperature control. Another type of transparent PVs is "translucent photovoltaics" (transmit half of the light that impinges on them). Similar to inorganic PVs, organic PVs are capable of being translucent. Incheon-Seoul airport solar panels' curved structure uses a tin oxide coating on the inner surface of the glass panes to conduct current out of the cell as illustrated in Figs. 28, 29, and 30. The cell contains titanium oxide that is coated with a photoelectric dye [42, 43].

Incheon National University Campus in Songdo – Incheon, South Korea

The new campus of Incheon National University (INU) in the smart city of Songdo in Incheon, South Korea, is another vivid example of a low-carbon campus, with nearly 20% of the electricity energy consumption in the campus and its buildings generated from clean sources, as shown in Fig. 31. As illustrated in Fig. 31a, a solar

(a) The terminal’s façade fixed with smart glass by Saint Gobain to protect it from sun radiation.

(b) Incheon International Airport Station with low carbon transportation.

Fig. 29 Incheon-Seoul Airport Terminal, South Korea, a near-zero-energy building (Image credit and source: (**a**) Minseong Kim, https://commons.m.wikimedia.org/wiki/File:IncheonTerminal1.jpg#mw-jump-to-license (**b**) Siqbal, https://commons.m.wikimedia.org/wiki/File:Incheon_Hall.jpg). (**a**) The terminal’s façade fixed with smart glass by Saint-Gobain to protect it from sun radiation. (**b**) Incheon International Airport Station with low-carbon transportation

Fig. 30 Interior of Incheon-Seoul Airport Terminal, South Korea, a near-zero-energy building. (Image credit and source: Eliazar Parra Cardenas, https://commons.m.wikimedia.org/wiki/File:Incheon_airport.jpg)

plant comprising 80 solar PV panels, each produces 6 kWp. Hence, the total power of this array amounts to 480 kWp. Figure 31b also shows another solar plant with a 90 PV array that generates 540 kWp output. Figure 32 depicts the installation of two additional solar PV plants with 90 panels each (360 panel array) within the landscape of the INU Campus. According to a campus visit conducted by the lead author from October 18 to 21, 2015, the INU campus manifests near-zero-energy buildings.

United Nations' Headquarters in G-Tower, Incheon, South Korea

The United Nations Economic and Social Commission for Asia and Pacific (ESCAP) Headquarters in Incheon is an excellent example of a smart and net-zero-energy building, where smart solutions and technologies are incorporated in each floor and the building as a whole to achieve a near-zero-carbon exemplary facility as shown in Figs. 33, 34, and 35. The 33-storey high building is also equipped with smart light movement and occupancy sensors to reduce energy usage (Fig. 33). Th building is also a zero-waste system, where all waste is collected, burned in a special container in the basement floor, and then converted into energy at zero waste. This was observed during the visit by the lead author with A.NERGY delegates to the UN building in Incheon in November 2016 (Figs. 34 and 35).

Many buildings located in Asia, and Europe, particularly in the Netherlands, the United Kingdom, Germany, and Austria, demonstrate the concept of low-carbon, zero-carbon, and net-zero building through the use of smart and green solutions and innovative technologies. These examples include Lumen Building at Wageningen University in Wageningen and the Edge Office Building in The Netherlands; GlaxoSmithKline net-zero Laboratory at Nottingham University Jubilee Campus in England and DeepStone House in Scotland, UK; and The Solar Settlement and Sun Ship and the Plus-Energy House in Frankfurt, Germany, as well as Kunsthaus Bregenz Art Museum in Bregenz, Vorarlberg, Austria.

The Lumen Building at Wageningen University, Wageningen, The Netherlands

The Lumen, known as the Lumen Greenhouse Building, Wageningen University in The Netherlands, portrays a model when it comes to low-energy and near-zero-carbon concept. The interior has a green space under a glass controlled roof, in a high-quality environmental condition at the campus [44]. Figure 36 shows the interior of the building spaces, which fully receive natural light through a glazed wide atrium. The green areas reduce the cooling loads, hence the energy needed (Fig. 36a, b). In terms of a zero-carbon transport on campus, students, staff, and visitors at the

(a) Font view of a 180-solar PV array installed at Incheon National University green campus

(b) View of a 180-solar PV plant installed at Incheon National University (INU) campus

Fig. 31 Solar PV plants to generate clean energy at INU low-carbon campus in Songdo, Incheon, South Korea. (Image credit and source: Mohsen Aboulnaga). (**a**) Front view of a 180 solar PV array installed at INU green campus. (**b**) View of a 180 solar PV plant installed at INU campus

campus are traveling using a clean means of transportation electrical bus called "self-moving WEpod shuttle buses" at the Wageningen University Campus [45]. The driverless six-seater shuttle bus drives at 40 km/h [45] as illustrated in Fig. 37.

(a) Another Solar PV plant with 90 panels capacity installed at Incheon National University

(b) A close up view of two arrays of 180-soalr panels, each 90 PV panels installed at INU

Fig. 32 Solar PV plants (540 cells) to generate clean energy at INU low-carbon campus in Songdo, Incheon, South Korea. (Image credit and source: Mohsen Aboulnaga). (**a**) Another solar PV plant with a 90-panel capacity installed at INU. (**b**) A close-up view of two arrays of 180 solar panels, each 90 PV panels installed at INU

Fig. 33 View of the smart and net-zero G-Tower, the United Nations Headquarters in Songdo, Incheon, South Korea. (Image credit and source: Piotrus, https://commons.m.wikimedia.org/wiki/Category:G-Tower,_Incheon#/media/File%3ASongdo_International_Business_District_11.JPG)

Fig. 34 The interior of the UNDP Asia Headquarters, fully equipped with a smart and near-zero-carbon technologies, Songdo, Incheon, South Korea. (Image credit and source: Mohsen Aboulnaga)

Fig. 35 General view of the smart and net-zero G-Tower, the headquarters of United Nations offices in Songdo, Incheon, South Korea. (Image credit and source: http://www.undog.org/page/sub3_1_view.asp?sn=37&page=4&search=&SearchString=&BoardID=0004)

The Edge Smart and Net-Zero Office Building in Amsterdam – The Netherlands

The Edge net-zero office building of Deloitte Headquarters in Amsterdam, The Netherlands, is the greenest and smartest building globally based on the British Rating Agency BREEAM at a score of 98.4%. The iconic building design strategy is centered on resource efficiency, information technology, and Internet of Things (IoT) as well as rentable energy through solar energy, where the building generates more electricity than it consumes [46]. The 15-storey north-facing glass atrium smart building is equipped with about 28,000 sensors to control motion, light, temperature and humidity, and infrared to provide excellent indoor environmental quality as shown in Fig. 38. The atrium is the building's key center of solar system, and its air volume has mesh panels between each floor to let musty air fall into open spaces, where it rises and is exhausted through the roof creating natural ventilation and assuring excellent air quality as depicted in Fig. 40 [47].

On the southern façade of the Edge building, there is a checkerboard of solar panels and windows as shown in Figs. 39a, b. The thick load-bearing concrete assists in regulating heat, and deeply recessed windows reduce the need for shades, though they are directly exposed to the sun [46]. The roof incorporates solar PV (OVG) panels to enable the office building to generate more electricity than it uses. The Edge building also consumes 70% less electrical energy than any typical office

(a) Interior of Lumen greenhouse building illuminated naturally by daylight through glazed atrium.

(b) Large green space covering most the interior under glass roof to cool and save energy.

Fig. 36 Lumen Greenhouse Building at Wageningen University, a low-energy concept and near-zero-carbon building, Wageningen, The Netherlands. (Image credit and source: (**a**) Vincent, https://upload.wikimedia.org/wikipedia/commons/9/99/Lumen_Builiding_Greenhouse.jpg (**b**) Vincent, https://upload.wikimedia.org/wikipedia/commons/f/f0/Wageningen_Uinveristy_-_Building_Lumn.JPG). (**a**) Interior of Lumen Greenhouse Building illuminated naturally by daylight through glazed atrium. (**b**) Large green space covering most of the interior under glass roof to cool and save energy

building. In addition, the building pumps warm water (more than 37 m^2 deep) into the aquifer beneath the office building in the summer months, where it sits, insulated, until winter, when it's exploited for heating. This is considered the most efficient thermal storage worldwide [47]. Moreover, the Edge building is an open smart space with no office desks and is naturally illuminated (Fig. 40a, b). It uses superefficient LED panels, powered by the same cables that carry Internet data. The building is wired with a vast network of two types of long blue tubes: one binds data (Ethernet cables) and the other holds water for radiant heating and cooling (Fig. 40c).

Fig. 37 The self-moving WEpod shuttle bus, a clean means of transportation passing by the Lumen Greenhouse Building at Wageningen University campus, Wageningen, The Netherlands. (Image credit and source: ArjanH, https://commons.m.wikimedia.org/wiki/File:Wepods_WUR.jpg#)

GlaxoSmithKline Carbon-Neutral Building, Nottingham University, Nottingham, UK

The GlaxoSmithKline (GSK)'s carbon-neutral building (CNB) at Nottingham University Jubilee Campus in Nottingham, England, United Kingdom, is the first laboratory building with neutral carbon life cycle. The GSK building presents an excellent example of a low-energy building or a zero-carbon building. The CNB is constructed according to the highest energy efficient standards and is cladded by timber (a high-performance insulation material) to protect the building from heat losses in winter and heat gain in summer (Fig. 41) [48]. The remaining energy requirements are also met by onsite sustainable biomass. The excess energy generated onsite will pay back the embodied carbon associated with its construction within 25 years [48]. Figure 42 shows the façades with efficient glass and roof solar chimneys exploited for natural ventilation and cooling in summer. Figure 42a, b present the entrance, façade, and timber cladding. In addition, the CNB has green roofs on 45% of its surface [49].

The building occupies 4500 square meters over two floors in addition to laboratory space for around 100 researchers. This building, which was opened on February 27, 2017, is part of GSK's target of reaching a carbon-neutral value chain by 2050. The GSK's building was awarded both the BREEAM Outstanding and LEED Platinum certifications [50]. Such a facility has energy-intensive cooling systems

Fig. 38 The Edge, the greenest office building in Amsterdam. (Image credit and source: MrAronymous, https://upload.wikimedia.org/wikipedia/commons/c/c1/Zuidas_20210512_%286%29_uitsnede.jpg)

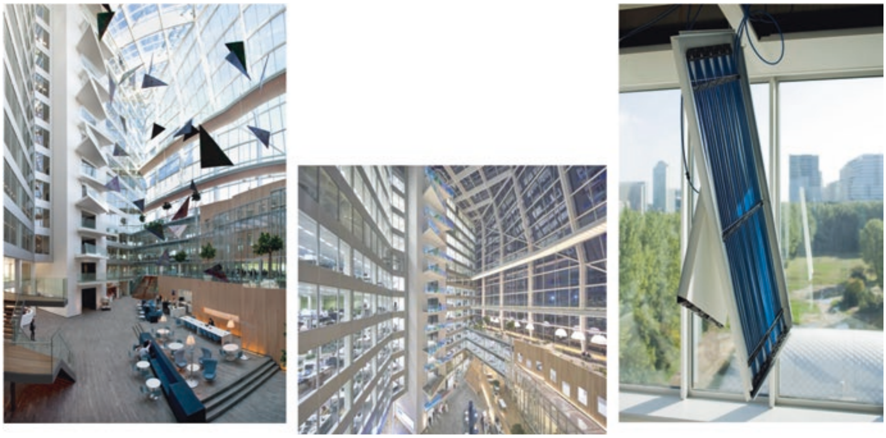
that are necessary to stop temperatures reaching levels where solvents will evaporate. In the meantime, recovering access heat from processes can be challenging due to the risk of chemical and fume corrosion on the ventilation systems. In terms of power generation, the GSK building has an onsite system that produces 125 kWe of biofuels combined heat and power (CHP) furnishing the majority of heat required for the buildings. In addition to mitigating carbon emissions, the CHP system exports the excess heat to nearby buildings on the Nottingham University Jubilee Campus [50].

Moreover, the GSK's building exhibits the state-of the-art technologies where about 231 kWp solar PV array is mounted on the main building's roof covering 45% of its area. For energy efficiency, the building is fitted throughout with LED lighting at an average of 5.4 watts per square meter [50]. In general, the GSK building saves more than 60% on energy and uses only 15% of the heat required by a conventional building design. Excess energy generated by this building (near 40 MWh) provides enough carbon credits over 25 years to offset the construction phase as well as being utilized to heat the nearby office development onsite [50].

(a) A checkerboard of solar panels and windows to regulate heat and respond to weather conditions to minimise energy use

(b) The façade with smart glazing to control heat losses in winter and heat gain in summer months

Fig. 39 The Edge's smart façade in Amsterdam. (Image credit and source: (**a**) MrAronymous, https://upload.wikimedia.org/wikipedia/commons/9/9e/Zuidas_20210512_155017_uitsnede.jpg (**b**) MrAronymous, https://upload.wikimedia.org/wikipedia/commons/9/9e/Zuidas_20210512_155017_uitsnede.jpg). (**a**) A checkerboard of solar panels and windows to regulate heat and respond to weather conditions to minimize energy use. (**b**) The façade with smart glazing to control heat losses in winter and heat gain in summer months



(a) Open office spaces fitted with IoT and mobiles' App to provide livable and social prolific space **(b)** Close up of the open and smart spaces inside the Edge net-zero office building **(c)** Long blue tubes, one binds data (Ethernet cables); and second holds water.

Fig. 40 The Edge's smart interior utilizing IoT in operation, Amsterdam. (Images' credit and source: (**a**, **c**) Raymond Wouda, (**b**) Tom Randall https://www.bloomberg.com/features/2015-the-edge-the-worlds-greenest-building/). (**a**) Open office spaces fitted with IoT and mobiles' app to provide livable and social prolific space. (**b**) Close-up of the open and smart spaces inside the Edge net-zero office building. (**c**) Long blue tubes, one binds data (Ethernet cables), and the other holds water

DeepStone House in Scotland, United Kingdom

The DeepStone House in Scotland, United Kingdom, is an example of a near-zero-energy small building, where it generates its electrical energy demand from renewable sources. The house – designed by Simon Winstanley Architects – is overlooking the Solway Firth in southwest Scotland, UK. The low-energy house has inclined roof fitted with an array of solar PV panels to track the sunlight and produces electrical energy it nearly consumes. Figure 43 presents the near-zero-energy building with its tilted solar PV array on the rooftop as well as the high-insulation exterior walls and triple-glazed thermal windows. It is clear from Fig. 43 that the envelope is cladded with timber to conserve energy in winter and reduce heat gain in summer [51].

The Solar Settlement and Sun Ship in Schlierberg, Germany

The Solar Settlement and Sun Ship complex in Schlierberg, Germany, is considered one of the first housing communities in the world. All houses are net-zero and generate a positive energy balance and are emission-free and CO_2 neutral [52]. As of 2022, it is the largest residential roof-integrated PV system. The south-facing roofs

Fig. 41 GlaxoSmithKline Carbon-Neutral Building at Nottingham University Jubilee Campus, England, UK. (Image credit and source: Michael Thomas, https://upload.wikimedia.org/wikipedia/commons/e/e1/GlaxoSmithKline_Carbon_Neutral_Building._Nottingham_University_Jubilee_Campus.jpg)

are covered with solar PV arrays. Figure 44 shows a bird's-eye view of the solar settlement, while Figs. 45, 46, and 47 present the houses with solar PV arrays on top of the tilted roofs.

The concept is centered on achieving the structure's extreme energy efficiency, so that it holds a positive energy balance and produces more energy than it uses. Each house is built from a timber skeleton and integrated with eco-friendly materials with 91 solar PV arrays (Figs. 46 and 47). Also, the Sun Ship's building consists of retail, commercial, and residential functions. The premises remain vehicle-free, thanks to the parking garage underneath the Sun Ship as shown in Fig. 48 [52].

Prototype of a Plus-Energy House, Frankfurt, Germany

Frankfurt City in Germany showcases many prototypes of plus-energy houses. The basic concept of the energy system utilized in the project is mainly to reduce the energy demand and produce it sensibly and efficiently. This has been achieved by an optimal interplay of various passive (low-tech) and active (high-tech) elements [53]. In this concept, the integral and sensible combination of the individual subsystems

(a) Entrance to GSK Laboratory and its façades with efficient glass and cladding to save energy.

(b) Close up of the roof line with chimneys on the rooftop to promote natural ventilation and clean air

Fig. 42 The façade and roof of the first laboratory building with neutral carbon life cycle at Nottingham University, UK. (Image credit and source: (**a**) Michael Thomas, https://upload.wikimedia.org/wikipedia/commons/c/c7/GlaxoSmithKline_Carbon_Neutral_Building_Entrance._Nottingham_University_Jubilee_Campus.jpg (**b**) Michael Thomas, https://upload.wikimedia.org/wikipedia/commons/e/e8/GlaxoSmithKline_Carbon_Neutral_Building_for_Sustainable_Chemistry._-_40557421815. jpg). (**a**) Entrance to GSK laboratory and its façades with efficient glass and cladding to save energy. (**b**) Close-up of the roof line with chimneys on the rooftop to promote natural ventilation and clean air

Fig. 43 Side view of DeepStone net-zero House in Scotland, UK. (Image credit and source: Aswinstanley, https://upload.wikimedia.org/wikipedia/commons/c/c5/Side-view1-photoshop-filtered.jpg)

Fig. 44 The Solar Settlement in Schlierberg, Germany. (Image credit and source: Andrewglaser https://commons.m.wikimedia.org/wiki/File:SoSie%2BSoSchiff_Ansicht.jpg#mw-jump-to-license)

Fig. 45 Close-up of the Solar Settlements houses with PVs covering rooftops. (Image credit and source: Andrewglaser, https://commons.m.wikimedia.org/wiki/File:LuftSS.jpg#mw-jump-to-license)

is very important for an optimized and innovative overall energy system that combines building components and technologies and exploits synergies. In the interests of an integral view of the building, already in the design process, construction materials and systems were taken into consideration in order to provide a comfortable

Fig. 46 A Plus-energy house in the Solar Settlement in Germany. (Image credit and source: Andrewglaser https://commons.m.wikimedia.org/wiki/File:SSHaus.jpg#mw-jump-to-license)

Fig. 47 View of the 91 solar PV array covering the tilted roof of the net-zero houses. (Image credit and source: Andrewglaser, https://commons.m.wikimedia.org/wiki/File:SoSie%2BSoSchiff_Ansicht.jpg#mw-jump-to-license)

Fig. 48 The Sun Ship's retail, commercial, and residential integrated building. (Image credit and source: Andrewglaser, https://commons.m.wikimedia.org/wiki/File:SoSchiff_Ansicht.jpg#mw-jump-to-license)

Fig. 49 Plus-Energy House in Frankfurt, Germany. (Image credit and source: DontWorry https://commons.wikimedia.org/wiki/File:Plus-energie-haus-ffm-033.jpg#mw-jump-to-license)

Fig. 50 Kunsthaus Bregenz Art Museum in Bregenz – Vorarlberg, Austria. (Image credit and source: Raymond, https://commons.wikimedia.org/wiki/File:Bregenz_kunsthaus_zumthor_2002_01.jpg)

and an energy-efficient indoor climate without technical aids as depicted in Fig. 49 [53].

Kunsthaus Bregenz Art Museum in Bregenz – Vorarlberg, Austria

Another example which is not far from Germany is the Kunsthaus Bregenz Art Museum in Bregenz – Vorarlberg, Austria. The art museum, which is made of glass and steel and a cast concrete stone mass, stands in the light of Lake Constance. The vivid glass building endows the interior of the building with texture and spatial composition as presented in Fig. 50. The exterior of the museum absorbs the changing light of the sky and the haze of the lake and then reflects light and color to furnish an intimation of its inner life according to the angle of vision, the daylight, and the weather as illustrated in Fig. 51 [54].

Fig. 51 Exterior and facades of the Art Museum. (Image credit and source: DVD RW, https://commons.wikimedia.org/wiki/ File:Bregenz_kunsthaus_zumthor_2002_02.jpg)

Fig. 52 The holiday housing in Natural Park of Valles Pasiegos, Northern Spain. (Image credit and source: Lizzie Crook, https://www.dezeen.com/2019/04/19/villa-slow-laura-alvarez-architecture/)

A Holiday Home in Rural Spain

Spain also showcases a small-scale zero-energy building model. The holiday home in the Natural Park of Valles Pasiegos located in northern Spain is designed by Architect Laura Alvarez (Fig. 52). This home is living proof of a NZEB, and it produces energy more than it consumes. Also, a heat pump system is connected to the city electric grid, and it is able to generate five times the energy it uses from the grid. In addition, the building uses local ancient stones to maximize heat insulation and minimize the heat gain into indoor spaces as shown in Fig. 52. Because of the locally sourced materials, the NZEB not only provides a good indoor environment but is also considered a sustainable building [55].

From Europe to USA, the concept of NZB has been adopted in many buildings, such as the Unisphere Building in Maryland, the National Renewable Energy Laboratory (NREL) in Colorado, and the La Jolla Commons net-zero-energy office building in San Diego, California, USA.

The Unisphere, Maryland, USA

The Unisphere office building in Maryland incorporates a wide range of zero-energy solutions including a geothermal system that relies on soil heating-cooling context in addition to an electromagnetic building envelope that provides a high insulation level by changing the tint level based on weather conditions. The 3000 panels of PV roof array provide 1175 MWh of clean energy every year, in excess than the building consumes, enough to power 100 homes, and the excess power is sent back to the utility grid [56]. The façade's operable windows and panels of the building are naturally ventilated and harvest daylighting to minimize artificial lighting, thus reducing energy demand as shown in Fig. 53. Additionally, the Unisphere building has 52 closed-loop, dual circuited geo-exchange wells 46.5 m^2 beneath it to provide energy storage [56].

National Renewable Energy Laboratory, Colorado, USA

The National Renewable Energy Laboratory (ENRL) is among the first buildings that were developed based on a NZEB's concept. The ENRL was built in 1947 and is considered a state-of-the-art example of sustainable features and technologies for energy production including solar energy, wind energy, and aiming at mitigating emissions and setting example for others.

The building integrates a wide range of energy-efficient strategies and solutions that are continuously developed to achieve climate mitigation as shown in Figs. 54a, b. These developments include renewable energy solutions such as biochemical

Fig. 53 The Unisphere net-zero office building and its efficient glazed envelope, Maryland, USA. (Image credit and source: Rdellbillings, https://www.wikiwand.com/en/United_Therapeutics)

(a) The NREL campus in Colorado fully covered by Solar PV panels to generate clean energy

(b) The NREL buildings integrated with energy systems for a zero-energy target

Fig. 54 The National Renewable Energy Laboratory Campus in Colorado, USA. (Images credit and source: (**a**) NREL, https://www.nrel.gov/workingwithus/partnering-facilities.html (**b**) NREL, https://www.nrel.gov/workingwithus/partnering-facilities.html). (**a**) The NREL campus in Colorado fully covered by solar PV panels to generate clean energy. (**b**) The NREL buildings integrated with energy systems for a zero-energy target

(a) Façades with low-emissive coating reflects IR heat **(b)** Fuel cells to generate 5.4 MWh at the back

(c) Close up of the buildings' fuel cells generating 5.4 MWh

Fig. 55 The La Jolla Commons net-zero building in San Diego, CA, USA. (Source: (**a**–**c**) https://www.researchgate.net/publication/341264745_Net-Zero_Energy_Buildings_Principles_and_Applications). (**a**) Façades with low-emissive coating reflects IR heat. (**b**) Fuel cells to generate 5.4 MWh at the back. (**c**) Close- up of the buildings' fuel cells generating 5.4 MWh

conversion, thermochemical conversion, micro-algal biofuels, and biomass processing [57].

La Jolla Commons, San Diego, California

Another example of a large-scaled zero-energy building is La Jolla Commons in San Diego, California, USA. The building, which is a 13-storey office space and is one of the largest NZEBs in the United States, was designed by architect Paul Danna (AECOM) between 2006 and 2008. It is one of the first examples built in the USA with a net-zero-energy strategy. Figure 55 presents the La Jolla Commons zero-energy building's façades and fuel cells [58]. The envelope incorporates an insulated double glazing (Figs. 55a) in addition to an efficient systems to assist in reducing energy use by controlling heat losses and gains [58]. Fuel cells are also used at a capacity of 5.4 MWh, while the historical consumption of the La Jolla Commons building consumption is about 4.5 MW as presented in Figs. 55b, c [58].

Net-Zero Heating Building's Concept

The concept of net-zero-heating building (nZHB) or near-zero-heating building is a strategy in which such a building has essentially zero-heating energy demand described to be less than 3.0 kWh/m^2 annually. It is intended for use in heating-dominated areas, and it is used to supersede NZEBs as a way to bring building-related GHG emissions to zero [59]. Many examples will be presented and discussed in the following section, such as (a) the American Geophysical Union (AGU) headquarters in Florida, USA; (b) the zero-heating Samling Library in Nord Odal, Norway; (c) the net-zero-heating office building in Rakvere, Estonia; and (d) the net-zero-heating office building in the Netherlands.

The American Geophysical Union Headquarters in Florida, USA

The American Geophysical Union (AGU) headquarters in Florida, USA, has been upgraded into a model of energy efficiency to achieve net-zero goals. The changes encompass strategy in shading and envelope better insulation, daylighting, and new window glass leading to energy efficient walls, and it has a 4.88-meter-tall rooftop solar PV array installed on a projecting canopy as presented in Fig. 56. Also, it uses a sewer heat exchange, through which AGU would capture the energy flowing through a large Florida Avenue sewer main and run it back into the building [60]. As shown in Fig. 56, the retrofitted envelope and solar PV array on rooftop generate clean energy and mitigate carbon emissions.

The Zero-Heating Samling Library in Nord Odal, Norway

The Samling Library, located in the village of Sand at Nord Odal in Norway, is another example of net-zero-heating building (nZHB). The façades consist of a timber batten cladding of vertical wooden slats around the entire building in horizontal bands. The building has an efficient fabric with Air® 6-pane glazing by Reflex, Slovenia, and glass U-value of 0.26 W/m^{2}K [61]. The timber cladded skin and the large glass surfaces of the public spaces provide a depth effect, yet create a transparent skin between the interior and exterior, enriching the visual connection (Fig. 57). The interior materials and environment are also constructed from timber. The nZHB inspires a more sustainable approach by utilizing a significant amount of local wood, representing the cultural tradition of wooden buildings and the local wood industry. The distinctive timber ceiling hides the integrated technical fixtures, while serving as bookshelves and sunshades [61].

Fig. 56 The American Geophysical Union Headquarters. (Image credit and source: APK, https://commons.wikimedia.org/wiki/File:American_Geophysical_Union_Headquarters.jpg)

Fig. 57 The exterior of the Samling net-zero heating library in Nord Odal, Norway. (Image credit and source: Alek14, https://commons.wikimedia.org/wiki/File:Six-pane_application_in_Nord_Odal,_Norway.jpg)

Fig. 58 The main façade of the near-zero-heating office building in Rakvere, Estonia. (Image credit and source: Alek14, https://www.wikiwand.com/en/Zero_heating_building)

The Near-Zero-Heating Office Building in Rakvere, Estonia

The third example of near-zero-heating building (nZHB) is the office building in Rakvere, Estonia (Fig. 58). The façades are composed of a metal and timber batten cladding. There is a large canopy standing over a 3-storey floor with staggered black columns to provide shading on building facades. The fabric of the nZHB is also created from Air® 6-pane glazing by Reflex, Slovenia, and glass U-value of 0.26 W/m^2K. Also, horizontal breakers are installed on the façade to reduce sunlight impinging on the building facades as presented in Fig. 58. In addition, the building has a double skin façade with glazed windows to provide the interior spaces with daylight and control glare, enhancing the visual connection with the outside view (Fig. 58) [59, 62–64].

The Net-Zero-Heating Office Building in The Netherlands

The fourth example of near-zero-heating buildings is an office building in The Netherlands, where the building adopted the same strategy for the envelope efficiency to achieve the goal, i.e., exploiting Air® 6-pane glazing by Reflex, Slovenia, and glass U-value of 0.26 W/m^2K. The building was built in 2017, and its façades are composed of metal reflective materials on the façade vertical long windows to provide enough daylight inside the indoor space and reduce energy demands. In this building, ultralow U-value glazing is used; thus the window U-values approach 0.3 W/m^{2}K and the heating demands diminish as shown in Fig. 59. In this context, the nZHB would not require a winter power reserve, and obviously it would not need any seasonal energy storage [59].

How Net-Zero Buildings Contribute to the Net-Zero Target and Climate Neutrality?

Net-zero-energy building (NZEB) is a term, subject to uncertainty, that might be utilized to portray a building with characteristics such as breakeven with energy utilization, altogether reducing energy consumption and energy costs equaling zero or net-zero (GHG) outflows. In spite of missing a definitive description of NZEBs, this moderately unused developing concept in Australia gives critical options to diminish GHG emissions, energy utilization, and operational energy costs for building properties. This chapter points to investigate the existing NZEB models, survey the movement of NZEB technologies, recognize key arrangements empowering NZEB improvement, and perceive potential ranges of global policies [65]. Since buildings consume about 40% of global energy and emit 33% of GHG [66], in Europe buildings are responsible for 40% of EU energy consumption and 36% of the energy-related GHG emissions [67]. In the MENA region, the share of building sector is 31% and 25% of the total primary energy supply and total final energy consumption, respectively [68]. Therefore, developing net-zero buildings would reduce almost the same percent of energy and mitigate related carbon emissions.

Current Policies, Actions, and Initiatives Worldwide

Polices, laws, action plans, and initiatives globally play a vital role in promoting NZEBs. Wang et al. (2020) provided a comprehensive sustainable management agenda which covers the sustainable principles of planning, transformation, environmental awareness, and climate mitigation [69]. The agenda summarizes low-carbon transformation policies followed in international cities, to prepare a new management matrix for enhancing the sustainable development of cities. More global policies and regulations are applied to leakage of pollutants such as GHG emissions and similar gases.

With special consideration to imposing rewards to low-pollution production firms [70], it is critical to notice that the climate mitigation has multidimensional aspects including political, social, and economic facets, whereas the social dimension confirms the gap between the future-oriented society and the present-oriented

Fig. 59 The exterior of the net-zero-heating office building in The Netherlands. (Image credit and source: Alek14, https://sl.m.wikipedia.org/wiki/Slika:Six-pane_application_in_Netherlands.jpg)

society in accepting high costs in return for long-term benefits. The most enduring firms and entities are those who are willing to adopt policies and regulations for climate change mitigation [71].

Current Policies, Activities, and Initiatives in Egypt Towards Net-Zero-Energy Buildings

Policies, laws, and initiatives relating to low-carbon buildings and cities in Egypt have recently grown and manifested in order to achieve green and sustainable cities. The following studies revealed successful applications, strategies, and attempts for the local private and public authorities. The local practice of climate change mitigation in Cairo has been highlighted by Dabaieh et al. in 2021, in which they listed the main factors and current adaptation measures including low-carbon buildings, cities, and transportation activities [72]. In addition, sustainable cities have become a priority over individual sustainable buildings and in the forefront of Egypt's current urban development policies and strategic plans. All new cities, including Madinaty, New Al-Ameen City on Egypt's northwest coast, and the New Administrative Capital, east of Cairo, are designed not only to be low carbon but also to mitigate climate change by focusing on carbon and air pollution reduction and utilizing renewable energy to generate clean energy [73].

The capital sustainable cities in the world are studied and examined by Armanuos et al. (2021), to provide learned lessons for the creation of sustainable cities. The study focuses on providing sustainable guidelines for the creation of Egypt's new capital city by 2050 [74]. The research analyzes existing cases and provides alternative scenarios for the new urban development to be considered as low-carbon city [74]. Another study reviewed and analyzed Egyptian and non-Egyptian new cities with a focus on achieving both high thermal performance in urban spaces and high energy efficiency inside building spaces. A new evaluation tool has been provided to allow for enhancing urban cluster forms coupled with efficient ground green cover and vegetation [75]. This study also focused on housing projects as a new sustainable model for low-carbon cities. In 2018, Dabaieh and Johansson examined a high-energy-efficient building which is located in Bahira – Delta region, Egypt, where the building is fitted with solar PV panels to generate 3.5 kWp. The building is analyzed, and sustainability measures are recommended and applied; it is provided as one of the main elements in the sustainable urban development strategies to mitigate climate change and rely on renewable energy resources [76].

Low-Carbon Cities and Zero-Carbon Emission Transportation in Egypt

In the context of low-carbon cities, the government strategy is mainly centered on a revolutionary approach to reach zero-emission transport. The new monorail was built to link the New Administrative Capital (NAC) to New Cairo and Adly Mansour main interconnected station (Fig. 60). The New Administrative capital has manifested many projects that address the concept of low-carbon city such as Cairo Monorail with a length reaching 56.5 km and passes through 21 stations [77] as depicted in Fig. 61. The aim is to achieve an eco-friendly transportation plan in greater Cairo, specifically the NAC. The green transportation plan reveals the significance of providing a variety of low-carbon to zero-emission transportation modes, and green alternatives to current vehicles, mainly electrical buses. In the same context, 6th of October has manifested a bold project that addresses the concept of low-carbon city (LCC) by virtue of the new monorail, which has been also constructed at a length of 42 km connecting Mohandiseen district to 6th of October City, and it passes by 12 stations [77] as shown in Fig. 61. In 2020, an analysis of new sustainable solutions to existing spaces in Alexandria, Egypt, was carried out [78]. The study revealed an example for carbon-neutral spaces via applying

Fig. 60 The Cairo Monorail, a zero-carbon emission transportation means to the NAC, Egypt. (Image credit and source: Ahram, https://english.ahram.org.eg/Media/News/2021/10/6/41_2021-637691497718843259-884. jpg)

Fig. 61 The 6th of October City new monorail, zero-carbon emission transportation in Giza, Egypt. (Image credit and source: Ahram, https://English.ahram.org.eg/NewsContent/50/1202/393529/ AlAhram_Weekly/ Economy/Egypts-first-monorail-Building-the-high-ride.aspx

environmental analysis and sustainable urban development concepts such as solar PV parking covers, shaded pedestrian paths, smart infrastructure, solar panels installation on a roof top example, wind energy, waste allocation, solar heating, gray water utilization, envelope installation, and green transportation alternatives [78].

Role of Zero-Carbon and Managing "Transition" in Cities and Regions

Numerous nations have transferred long-term objectives with respect to climate change by coupling these goals with innovation thinking for the future. The Paris agreement, signed at COP21 by 196 nations to address low-carbon challenges and achieve a circular economy, was the first step towards such global goal [79]. Further to COP21, it is clear that COP22, COP23, COP24, COP25, and recently COP26 manifested global determination towards mitigating GHG emissions and asked governments to work on developing Climate Adaptation Plans (CAP).

Can Cities Meet COP26 Outcomes and the Glasgow Climate Pact 2021?

In context with COP21 meeting in Paris in December 2015, the EU committed itself to limit GHG emissions' outcomes required to remain below 2 °C rises in normal worldwide temperature. The EU has agreed on energy policies which was proposed by the European Commission (EC) in November 2016, entitled "Clean energy for all Europeans." The adopted climate mitigation targets and new energy levels are coupled with GHG emission reduction (40% to 45%) less than 1990 levels, enhanced energy efficiency (32.5% lower than estimated in 2007), and renewable energy production (32% as a share of gross energy consumption) within the year 2030. The EU 2030 aims at reducing CO_2 emissions by 80% in 2050. On the other hand, the Paris agreement stated that the optimum efforts could only limit the temperature to rise above 1.5 °C, phasing out GHG emissions by 2050. However, carbon neutrality is still considered [80, 81].

Therefore, more approaches to reach climate neutrality, including energy utilization, have been added to the current policies to consider the possibility of a decarbonized long-term economy by 2030 climate and energy approach. What if climate neutrality by 2050 cannot be achieved by conventional fuel utilization? What if carbon neutrality is not affordable? What elements should be added to promote the current agenda? The deployment of current neutrality approaches can only be utilized with cost subsidiaries and support to overcome the additional cost barriers.

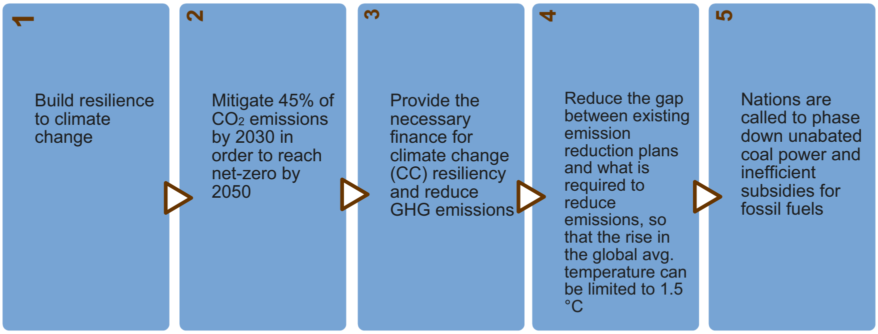


Fig. 62 Glasgow Climate Pact's decisions – COP26. (Image credit and source: Developed by authors after COP26)

Glasgow Climate Pact 2021 and Net-Zero?

The GCP, part of COP26 outcomes, revealed five agreed global decisions as shown in Fig. 62. The most imperative goal that requires vast mobilization is decision two, which states "Mitigate 45 percent of CO_2 emissions by 2030 in order to reach net-zero by 2050." Such mobilization is urgently required in view of the recent IEA analysis in 2021, which reveals that the global energy-related CO_2 emissions rose by 6 percent to 36.3 billion tones, which is considered the highest level recorded.

However, to achieve the net-zero target, it is imperative to digest the definition of low-carbon city and net-zero city, which is highlighted in Box 4, and consequently it can assist in achieving the COP26 goals [82].

Box 4 Definition of Carbon Neutrality or Low-Carbon Cities

Carbon neutrality is a state of net-zero carbon dioxide (CO_2) emissions. This can be achieved by balancing emissions of CO_2 with its removal or by eliminating emissions from society by vertical green walls. It is used in the context of CO_2-releasing processes associated with transportation, energy production, agriculture, and industry [82]

Conclusion

From the above review of global examples of low-carbon and net-zero buildings, it is still not enough to meet the COP26 goal. It is clear from these examples that low-carbon or net-zero buildings are gaining momentum, but not enough to reach COP26 goals and GCP of mitigating carbon emissions by 45% in 2030 and reach net-zero by 2050.

Low-carbon city or net-zero city including buildings can be achieved to mitigate 45% CO_2 emissions by 2030 and to reach net-zero goal by 2050 – a goal set by

COP26 and GCP in November 2021 – if mobilization and finance of US$ 100billion per year, agreed by COP26 for developing countries, are provided.

As indicated by research, low-carbon measures could cut emissions from urban areas by almost 90% by 2050. This would be achieved through four main sectors by 58%, 21%, 16%, and 5% from buildings, transport, materials efficiency, and waste, respectively [83]. Furthermore, investing in 16 low-carbon measures in cities could reduce global urban emissions by 90% by 2050 and has a net present value of nearly $24 trillion, which is nearly one-third of global GDP in 2018 [83]. Moreover, investments required to reduce urban emissions by 2050 are estimated to be US$ 1.83 trillion – about 2% of global GDP per year [83].

As of 2021, all new buildings in the EU member state countries must be NZEBs, and since 2019, all new public buildings in the EU should be NZEBs [67]. Finally, carbon-neutral hydrocarbons are to be considered in the future zero-energy emission models. Low-carbon cities including net-zero carbon buildings have recently been used in response to the climate crisis, but the current world perspective is looming.

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