

Pathway to the Zero Emission Utopia: a review

Zhaoyu Wang¹ , Xiangnan Yu^{1,*}, Heli Liu¹ , Xiao Yang¹ , Yuhai Jin¹ , Huifeng Shi¹ , Denis J. Politis², and Liliang Wang¹

¹ Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK

² Department of Mechanical and Manufacturing Engineering, University of Cyprus, Nicosia 1678, Cyprus

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Abstract. Attaining zero emissions stands as a key aspect of sustainable development. The conventional pathway, known as the “Zero Emissions Society (ZES)”, involves the use of renewable energy generation as an alternative to traditional fossil fuels and promotes the total de-carbonisation of the grid, ultimately leading to net-zero emissions. This requires the establishment of large-scale renewable energy power stations, increased transmission efficiency and energy storage facilities. In addition to this conventional pathway, this review introduces an innovative concept, termed “Zero Emission Utopia (ZEU)”, which originates from an individual-centric perspective. This novel approach enables the achievement of zero carbon emissions in human daily life activities and subsequent propagation of this practice extensively, actualising a zero-emissions scenario. An analysis of the available utopian sources of energy and distributed energy storage methods for this proposed pathway is conducted and presented. In addition, an evaluation case study, quantifying the renewable energy production capacity available to an individual, shows with the help of distributed energy storage methods, the ZEU pathway is feasible for normal families. Moreover, the constructive collaboration between these two pathways is explored, highlighting their potential for mutual enrichment and complementary advantages.

Keywords: Zero Emissions Society (ZES) / Zero Emission Utopia (ZEU) / renewable energy generation / Energy harvesting / de-carbonisation / photovoltaic energy / wind energy / all-solid-state battery / structural battery / distributed energy storage methods

1 Introduction

With the growing concern of the international community about climate change, geopolitical challenges and the instability in fossil fuel availability and prices, the concept of local energy production with zero emissions to lead humanity towards a stable and environmentally balanced future is not only a desirable goal but also a necessary requirement to protect our planet and the well-being of future generations [1].

Traditional approaches to harnessing renewable energy necessitate the construction of large-scale facilities, such as photovoltaic power plants, wind farms, hydroelectric stations, and other similar installations. Additionally, the establishment of large-scale energy storage systems is imperative to address the intermittency of renewable energy sources [2]. This top-down solution path, named as a Zero Emission Society (ZES) by this review, has obtained tremendous support from policy makers, government legislation, and investments [3,4]. Despite significant

efforts conducted for this conception to reduce carbon emissions, the results are still uncertain, due to concerns of energy production stability, efficient load balancing of the electrical grid and concerns on the scalability of cost effective energy storage for such large and complex systems [5]. On the contrary, the concept introduced in this review, referred to as Zero Emission Utopia (ZEU), embodies a bottom-up solution. In this approach, each individual is capable of autonomously achieving zero carbon emissions, attaining self-sufficiency in both energy generation and storage as well as consumption. By scaling up this individualistic approach, comprehensive zero carbon emission can be realised on the society scale. This strategy for net zero emissions aims to reduce the requirements for establishing extensive infrastructures that are complex, and heavily dependent on government financial support or political will.

Moreover, when contrasted with the ZES, the ZEU approach exhibits a multitude of advantages, including minimal capital investment, reduced construction expenses, lowered maintenance costs, minimisation of electrical transmission losses, heightened reliability through integrated fail safes, and energy security [6],

* e-mail: x.yu19@imperial.ac.uk

where both citizens and society may benefit. These attributes position the ZEU to play a critical role in the coming renewable energy transformation.

The collection of utopian sources of renewable energy and the deployment of distributed energy storage which enables renewable energy to be efficiently used for individuals are necessary for the implementation of ZEU. ZEU is only feasible if it can be proven that these two conditions are achievable. The two conditions will be reviewed in the following sections.

2 Utopian sources of renewable energy

The realisation of ZEU critically relies on the embodiment of Utopian Source of Renewable Energy (USRE). USREs are defined as the renewable energy sources for personal or household use that can be installed and integrated in personal dwellings or devices that can be used to generate electricity. USRE allows for the seamless integration of renewable energy into daily life, which can realise a self-sufficient, off-grid energy supply.

USREs normally require the allocation of certain resources, such as a specific amount of roof space, or land area. This section discusses each USREs energy generation output, which can be translated globally. In order to obtain an intuitionistic result, a specific case in UK will be given in the end of the section.

2.1 Photovoltaic solar panels

2.1.1 Rooftop solar panel

The most used renewable energy source for households is solar power, generated through photovoltaic panels. Figure 1 illustrates the operational principles of the most common photovoltaic solar cells. They are mainly constructed from semiconductor materials, and have been in use since the 1950s to harness solar energy and convert it directly into electrical current. The semiconductor material obtains photons, which lead to the formation of an electron-hole pair. The electrons move in the same direction in the internal electric field, thus producing a current. The internal field consists of a combination of positively charged (*p*-type) and negatively charged (*n*-type) materials [7]. The combination of several solar cells constitutes a solar panel module, which effectively functions as an electricity generator.

It has been demonstrated that the daily solar photovoltaic power potential (SPPP) in tropical regions is approximately 4.4 kWh/kWp daily, highlighting that two 450 W polycrystalline solar panels can suffice to provide a residential building with the basic energy consumption (about 3700 Wh) for one day [8].

Expanding the SPPP globally beyond the tropical regions, the average SPPP is approximately 3.5 kWh/kWp daily [8] and shown in Figure 2. This signifies that a standard, fixed peak 1000 W solar panel can generate roughly 2.4 kWh of electrical energy in a single day [9]. Furthermore, the production ratio η_{solar} is an important factor that should be considered and multiplied for

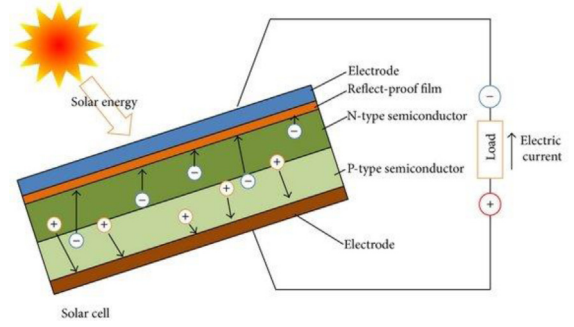


Fig. 1. Schematic operating principle of a photovoltaic solar cell [7].

evaluating the outcome of a photovoltaic solar panel, as including all energy losses independent of the orientation of the panels results in an efficiency of 0.75 [10].

However, as shown in Figure 3, employing components such as solar panel trackers that dynamically adjust the solar panels' orientation can increase the daily output by at least 10% [12]. A change in the azimuths of the solar trackers can increase annual energy production by a further 3% [13]. The panel tracker gain (H_{tracker}) can be calculated by the following equation.

$$H_{\text{tracker}} = 1 + H_o + \frac{H_a}{365}, \quad (1)$$

where H_o represents the gained by the orientation tracker, H_a represents the gained by the azimuths tracker.

At present, the most widely employed solar panels with the highest power output are approximately 400 W, encompassing an area of 1.6 m² [14]. The sample calculated area needed per 1 kWp solar panel (A_{1kWp}) can be given by the equation below.

$$A_{1kWp} = \frac{A_g}{P_g} \cdot 1000, \quad (2)$$

where, A_g is area of a specific given solar panel, P_g is power of the given solar panel. With the data obtained above, and the panel area available in the rooftop (A_{avail}), the total daily rooftop solar panel energy generated (E_{RSP}) is obtained by the equation below.

$$E_{RSP} = SPPP \cdot H_{\text{tracker}} \cdot \eta_{\text{solar}} \cdot \frac{A_{\text{avail}}}{A_{1kWp}}. \quad (3)$$

2.1.2 Solar energy harvesting

Photovoltaic (PV) power generation technology is not only restricted to household power supply, but has been applied to outdoor sensors and wearable devices. The amount generated by solar energy harvesting is limited, which means that it mostly can be applied in self-powered devices in most cases [15]. Moreover, the power management (PM) system has been developed to reduce the differences between power generation and requirements [16].

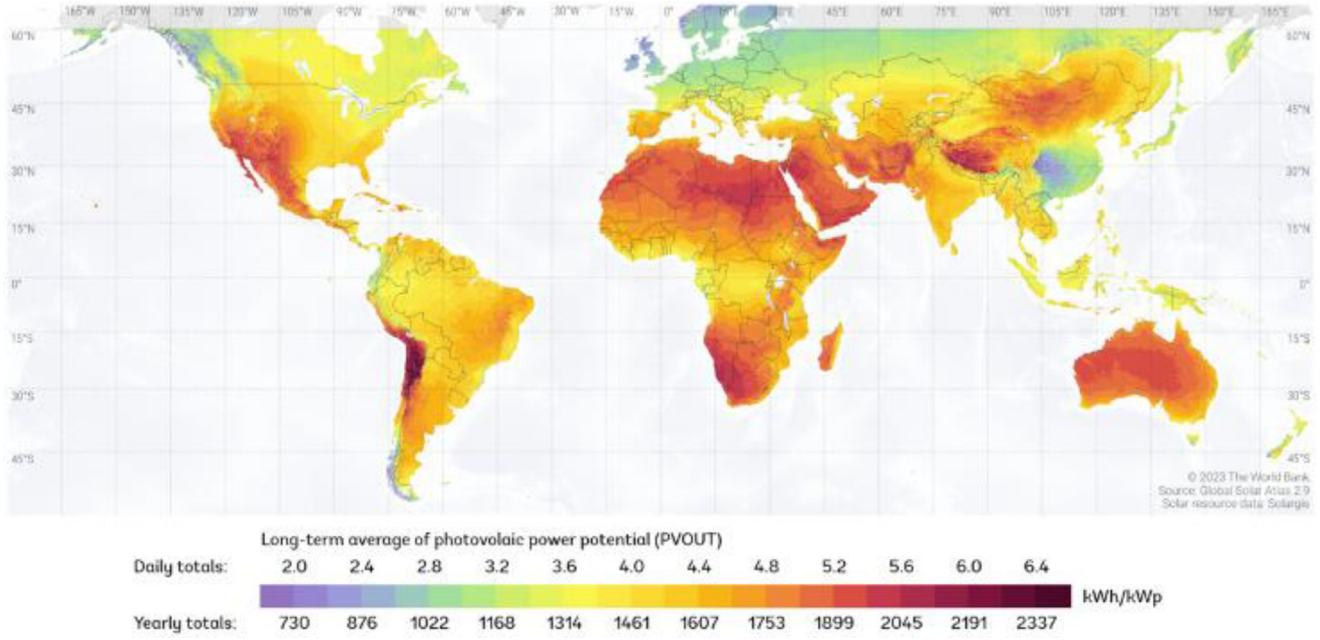


Fig. 2. Global practical solar energy potential map. [11].

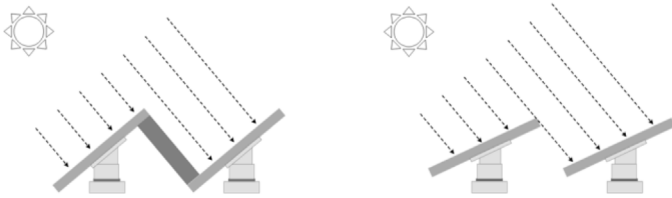


Fig. 3. Solar panel tracker mechanism [13].



Fig. 4. Various PV self-powered applications [6].

Several examples of these applications, including bicycles, cars, private road systems, wearable devices, yard lights, monitors, and window shades are shown in Figure 4. These examples, whilst capable of employing solar harvesting devices have decreased efficiencies (η_{solar}) due to suboptimal sun exposure including inefficient angles, shading, and duration of exposure. However, despite these inefficiencies, the large number of devices available can lead to a large cumulative output, as

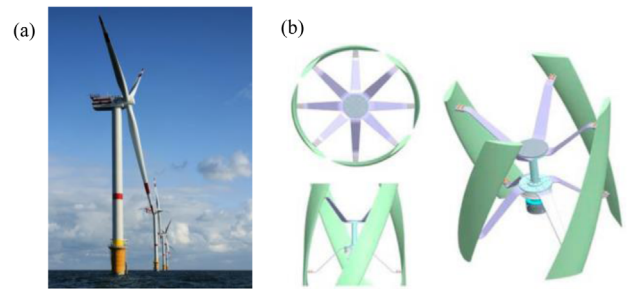


Fig. 5. HAWT (a) [17] and VAWT (b) configurations [18].

calculated by the equation below.

$$E_{SEH} = \sum_i^m SPPP \cdot \eta_{solar,i} \frac{A_{panel,i}}{A_{1kWp}}, \quad (4)$$

where m represents all different solar energy harvesting devices available.

2.2 Wind turbines

2.2.1 Household wind turbine

Similarly, residential-scale wind power is also a viable energy source. To efficiently harness wind energy, the design of high-performance wind turbine blade profiles is of paramount importance. Wind turbine designs are categorised into two main types: Horizontal Axis Wind Turbines (Fig. 5a) and Vertical Axis Wind Turbines (Fig. 5b).

HAWTs necessitate a mechanical yaw system to align them with the wind direction, as their blades solely rotate with the wind. The potential power generation is intricately linked to the swept area of the rotor, meaning

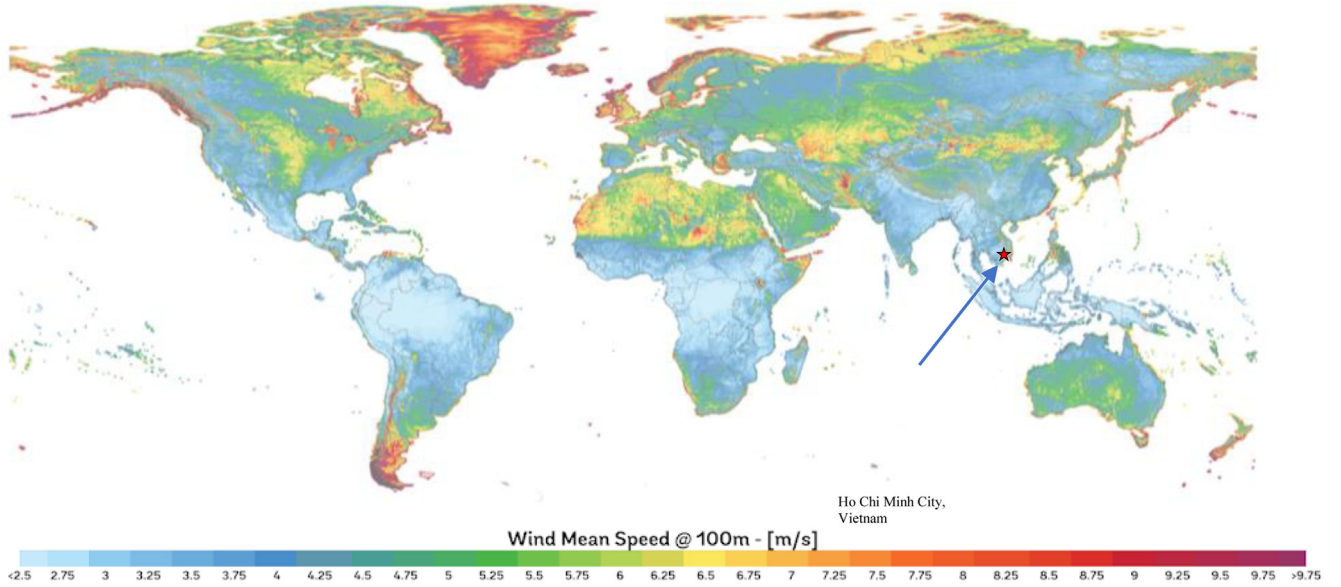


Fig. 6. Global Wind Resource Map [20].

that a larger blade diameter equates to higher power output. However, blade size is constrained by their strength, as they endure substantial thrust and torque forces. In contrast, VAWTs do not require an orientation system to face the wind. The potential power generation hinges on the height and radius of the rotor. Consequently, achieving greater power output entails an increase in either height or radius. In the context of evaluation for small-scale capacity, it was found that VAWT requires lower wind speeds for motor start-up compared to HAWT and is not affected by wind direction.[19].

According to the experiment in Ho Chi Minh City, Vietnam [19], the dimensions of the selected VAWT wind turbine stand at a height of 1.1 meters and a radius of 0.55 meters, the wind turbine is projected to yield approximately 455 Wh/day [19]. As shown in Figure 6, the average wind speed in the referred experiment is approximately 3.75 m/s, whereas the global average wind speed is 5.5 m/s [20]. This means that the tested energy output in the referred experiment represents an achievable value (P_{WT}) in most regions worldwide.

$$P_{WT} = \frac{1}{2} \cdot \rho_{air} \cdot A_s \cdot u_{wind} \cdot C_p, \quad (5)$$

where C_p is the power coefficient, theoretical and experimental studies give the C_p value is usually 0.40 for VAWT [21], ρ_{air} is the density of air, A_s is the swept area of the blade, u_{wind} represents the speed of the wind.

The wind turbine can be combined with solar panel, called hybrid photovoltaic-wind system [22]. This allows both to be deployed at the same time and to arrange the number and type of device such that it is optimised based

on geographical factors.

$$E_{WT} = N \cdot \sum_i^m P_{WT}(u_{wind,i}) \cdot \frac{24 \text{ hours}}{m}, \quad (6)$$

where E_{WT} represents the energy amount generated by wind turbine, N represents the number of the wind turbines, m represents the number of measurements taken in a day.

2.2.2 Micro-wind turbine energy harvester

Centimetre-scale micro wind turbines have been proposed to power small devices, which can be added up to become a USRE. Unlike larger wind turbines, these micro wind turbines operate under distinctive design models and operating conditions due to their reduced size. In the research [23], the power output of the turbine was evaluated in an open-circuit suction wind tunnel facility. This micro wind turbine exhibited higher power density and efficiency than those of previously tested devices with slightly larger diameters. This advantage was maintained over a wide range of free-stream speeds, highlighting the effectiveness of the turbine utilised under varying wind conditions. In addition, the unique vortex configuration of this micro-wind turbine proved to be effective in generating power even at yaw angles of $\pm 30^\circ$, further highlighting its adaptability and versatility in energy harvesting.

The centimetre-scale micro-wind turbines have many shapes, resulting in different efficiency and power outputs under different wind speed conditions. After comparing multiple small turbines [24–28], the turbine with the highest efficiency under daily wind speed is shown in

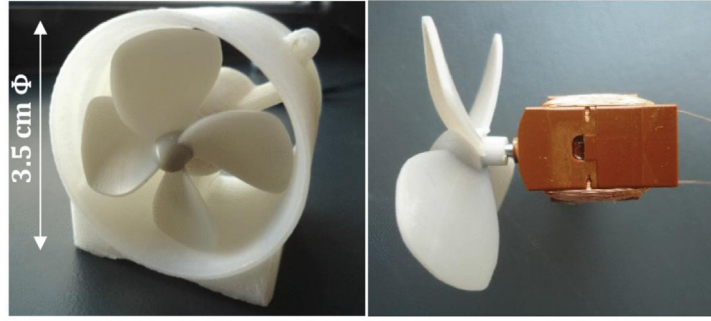


Fig. 7. Swirl centimetre-scale micro-wind turbine with shroud (left) without shroud (right). [24]

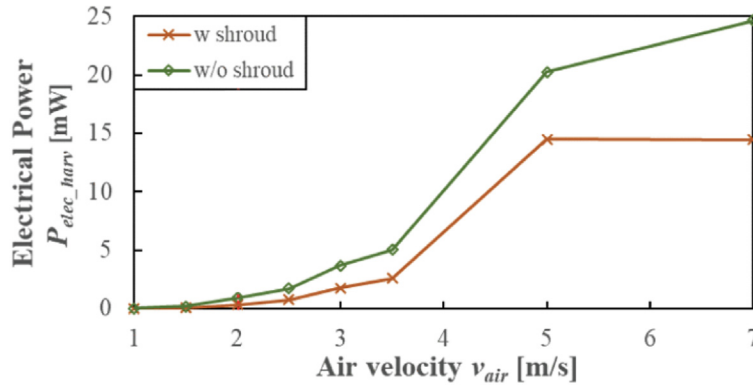


Fig. 8. Harvested electrical power against air velocity [24].

Figure 7 [24]. Figure 8 shows the turbine performance at different wind speeds, which indicates that the turbine without shroud has the better performance.

Using the technology of yaw systems for wind turbines [29], or in a location with a fixed wind direction, there is no need to consider the wind direction, and therefore this small HAWT will always be in the optimal orientation. Moreover, due to its small size, the number of units utilised by an individual could be significant, by for example deploying in a garden wall or beneath windows, which have access to wind.

The energy output for micro-wind turbine (E_{MWT}) can be calculated by the following equation.

$$E_{MWT} = N \cdot \sum_i^m P(v_{air}) \cdot \frac{24 \text{ hours}}{m}, \quad (7)$$

where m represents the number of measurements taken in a day; N represents the number of the wind turbines used; P is dependent on the v_{air} which can be read from Figure 8.

2.3 Micro hydropower system

Hydroelectricity can also be used as a USRE. Utilising a residential plumbing system, electricity can be generated by connecting a generator to the wastewater line or to the inlet of the water main, slightly reducing the water pressure

while in use. Employing a water turbine as the primary drive for the generator enables the kinetic energy of the flowing water to be harnessed [30].

This system is also an alternative form of electrical energy storage [31]. By utilising surplus energy generated through various means, water can be pumped to an upper reservoir for storage, subsequently released to generate electricity when needed. However, the implementation of this approach necessitates an additional water tower. The configuration of this setup is depicted in Figure 9.

The same setup can be used in the USRE system. The generator has an approximate power output of 0.115 W [32]. This can be approximately doubled if both inlet and outlet ducts are used. The energy outcome can be obtained by using power and time and then multiply by the number of the pipelines used. However, using the inlet pipe to generate electricity may reduce the water pressure and affect normal usage. Furthermore, the pipe installation setup would be more suited for situations where the user requires a large amount of water every day, or nearby continuous flowing water sources, like streams or rivers.

2.4 Motion energy harvesting

2.4.1 Energy-harvesting shoe

Motion-driven microgenerators include direct force generators and inertial force generators [33]. Figure 10 shows the principle of the direct force generator: the driving force

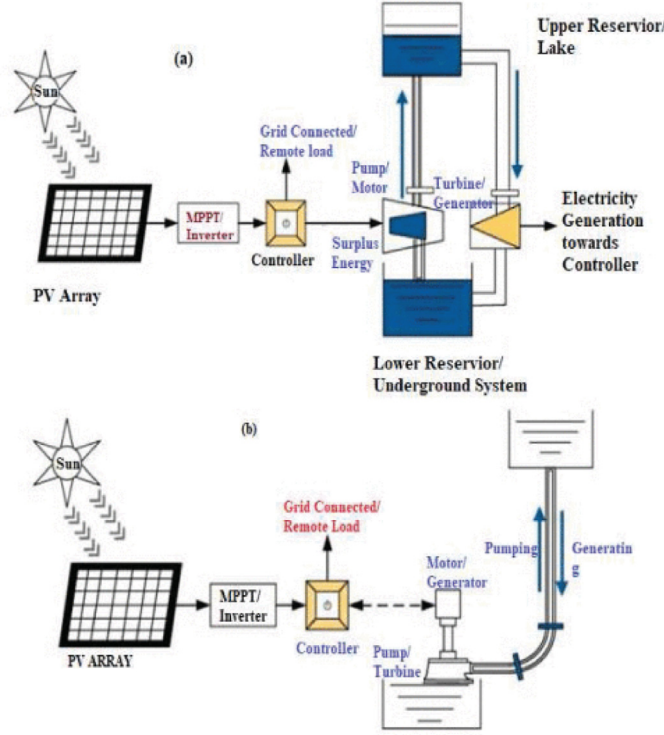


Fig. 9. Two different solar-pump hydro storage setups [30].

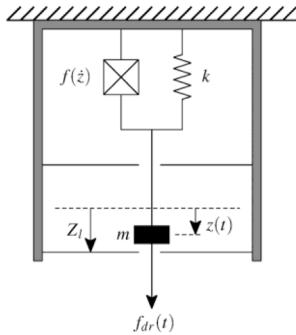


Fig. 10. Direct-force generator generic model [34].

f , $dr(t)$ is applied on a suspended mass m , which is connected to a spring and a microgenerator as the damper. Given a force against the motion, the generator transforms mechanical energy into electrical energy. The displacement limit of the mass is dependent on the device size. This type of generator must contact the moving structures to apply the force to the damper.

A typical application of the direct-force generator is the running motion energy harvesting shoes, of which there are three types. Figure 11 shows two widely used types of generators: the piezoelectric transducer (PZT) unimorphs attached to a curved steel plate that bends under the pressure of a heel strike (Position A in Fig. 11), and a piezoelectric stave made from PVDF (polyvinylidene fluoride) placed on the sole of a shoe that bends during a

person's gait (Position B in Fig. 11) [34], and the effect of them on gait is almost negligible. The electromagnetic generator is the third type of direct-force generator, with much higher power output (250 mW). However, it significantly impacts the gait of the wearers, which is not applicable in this case.

The power generated ($P_{unimorphs}$) is approximately 2.44 mW for unimorphs and 8.4 mW for PVDF (P_{PVDF}) stave respectively [35], with a stride rate of 0.9 Hz. The output energy of the energy harvesting shoes (E_{EHS}) calculation equation is shown below.

$$E_{EHS} = (2.P_{unimorphs} + P_{PVDF}).T, \quad (8)$$

where represents the energy generated by the energy harvesting shoes, T represents the walking hours per day of the user.

2.4.2 Power generation floor tile

Figure 12 shows the generation floor tile, which is another representative application of the direct-force generator. Therein, the generation floor tile structure consists of a top plate, bottom plate, support column, return spring and transmission mechanism. The bottom plate is fixed to the ground. The general height of the bottom plate is 10 cm, as a square shape, the side lengths are 40 cm. The thicknesses are 5 mm and 8 mm for the top and bottom plates, respectively [36]. The top plate works as a footpath. The support column can move upwards and downwards with an approximately 10 mm stroke. When standing on the floor tile, the rack is moving downwards driven by the top plate.

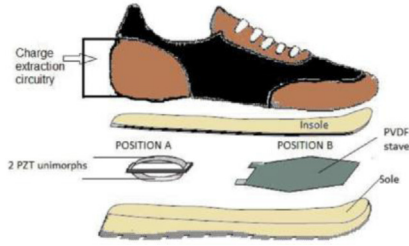


Fig. 11. Energy-harvesting shoe [35].

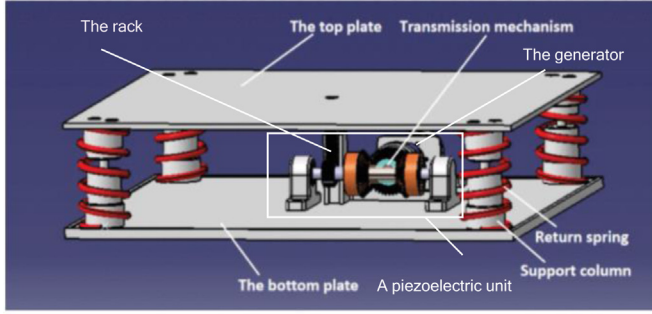


Fig. 12. Power generation floor tile structure [36].

Based on the transmission mechanism, this linear motion is transformed into a rotary motion, allowing the motor to generate energy. Then, the return spring will return the top plate to its initial height [36].

The performance of this structure was evaluated by experiments. The experimental results with varied step frequencies revealed that increasing the step frequency improved the power instead of the voltage amplitude. The Fourier transform method can be used to calculate the optimal resistive force and peak power. The experimentally verified results show that the highest power of a single piezoelectric unit is $134.2 \mu\text{W}$, with a 1.81 Hz step frequency and a 5 mm stroke. A single-floor tile allows 40 units in parallel, which means the power output of one floor tile (P_{tile}) can be up to 5.368 mW [36]. Thus, the energy output can be simply calculated by using power multiplied by the walking time and then multiplied the number of the tiles used.

This technology is more suitable for use in public, densely populated places. The experiment [37] showed that if this technology is applied to the Sydney Library, it can produce 9.9 MWh of energy per year, which is equal to 27.1 kWh/day , allowing 45 LEDs (50 W) to be lit for 12 hours a day.

2.4.3 Wearable electronic device

The second type of motion-driven microgenerators are inertial microgenerators, which is widely used in the wearable electronic device, with the operating principle shown in Figure 13. Similar to the direct force microgenerators, a suspended given mass is supported by a spring with stiffness k , and the mass inertia has relative displacement $z(t)$ when the outside case moves. The absolute displacement is $y(t)$, and the kinetic energy of motion $z(t)$ in the $\pm Z_l$ is converted by the microgenerator,

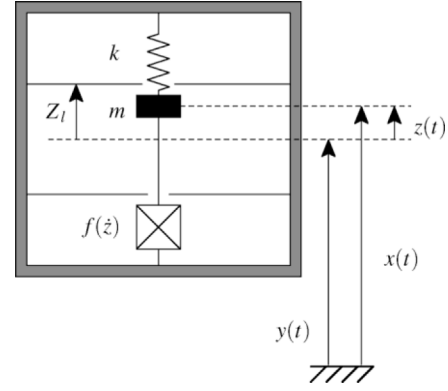


Fig. 13. Inertial generator principle [34].

which has a damping force $f(\dot{z})$ opposite to the moving direction. Inertial generators require just one attachment point with the moving component, which gives the inertial generators a greater possibility to be applied within small-scale applications.

The best example of an inertial generator is the Seiko kinetic watch, which uses electromagnetic transducers. Besides the mechanical self-winding watches, an electrically operated self-winding watch was invented, which has a small inertial energy harvester inside. The Seiko kinetic watch is already a commercial product, with a power output of only $5 \mu\text{W}$, which is sufficient for basic watch functions [38].

There are many other wearable electronic devices with a higher output power, Figure 14 shows an exploded view of a watch, with the three units of the proposed energy harvester: motion capture unit, magnetic upconverter and power generation unit comprising the energy harvester design. The units are arranged in a coaxial pattern, aiming for a slim form factor and reduced size. When a person's arm swings, the detection mass is excited, causing it to oscillate and capture the kinetic energy of the arm's motion. The watch has a power of 1.74 mW at an excitation frequency of 0.65 Hz , which corresponds to the standard arm swing frequency [39].

The energy output can be simply calculated by using the power and the walking time. However, there are a variety of human activities other than walking, such as hopping, grasping, writing, and jogging, that can serve as excitation for the device to generate electricity. Besides walking, humans usually spend much time on these activities every day, which is difficult to simulate and difficult to measure due to its trivial complexity, so the energy obtained is significantly underestimated.

2.4.4 Magnetolectrical clothing generator

Another representative motion harvesting method is electromagnetism. Figure 15 shows the principle of a magnetolectrical clothing generator using motion harvesting. Unlike traditional electromagnetism-based techniques which require rigid and heavy setups, the presented method is more flexible and scalable and can be applied on a diverse range of clothing [41]. The fabrics and conductive wires can

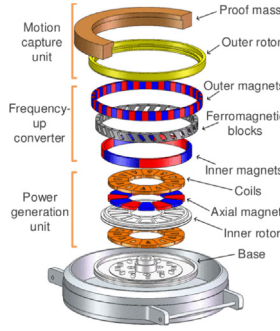


Fig. 14. Exploded view of embedded energy harvester [40].

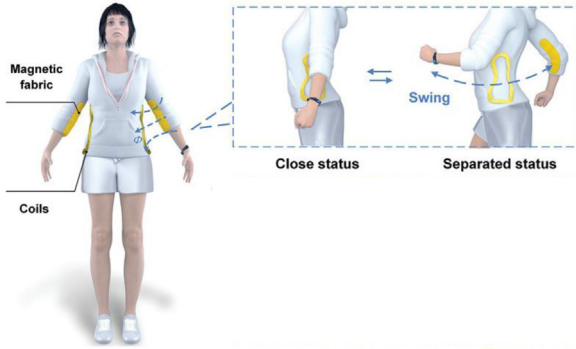


Fig. 15. Magnetic clothing generator schematic and working mechanism [42].

be implemented strategically on regions that experience maximum oscillation. When the user moves their arms, in a swinging motion during exercise, a stable and persistent voltage (14.3 V peak) and current (31.2 mA peak) can be generated, which leads to a peak power of 96 mW with a low impedance load (750 ohm) [42]. Moreover, magnetic fabrics fit in various environmental conditions including underwater, mildly acidic, or alkaline environments and cold or hot environments varying from -10°C to 80°C [42].

The total energy available can be calculated by using the power and walking time similar to previous examples, and can be multiplied by the number of the generators available, which is two in the case of Figure 15.

2.5 Bioenergy technologies

Bioenergy such as the biowaste and waste cooking oil (WCO) can be used as one of the USREs in combined heat and power (CHP) systems, which can be deployed in the community to several households. While in service, the starting material is converted into a fuel suitable for power generation in the second stage of the CHP systems. Depending on the type of biological waste or residual biomass, the process can be transformed thermally, thermochemically, and biochemically. Subsequently, followed by combustion, the boilers, dryers, furnaces, and ovens can be used to generate heat varying from kilowatt-level to megawatt-level, which is ready-to-use as a heat source or transform into electrical energy through secondary conversion technologies [43].

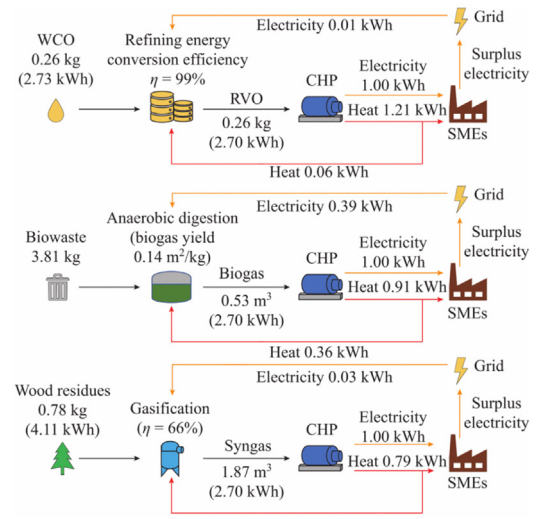


Fig. 16. Graphic scheme of CHP of WCO, biowaste, and wood residues [43].

Figure 16 shows the operational processes and the recourse needed of the CHP system with 1 kW electricity production output as a functional unit. Therein, 0.26 kg of WCO can generate 1 kWh of electricity (requiring 0.01 kWh input) and 1.21 kWh of heat. In contrast, 3.81 kg of biowaste is required to produce 1 kWh of electricity, 0.91 kWh of heat, and to generate surplus energy for the initial anaerobic digestion process.

The use of 0.26 kg of WCO, 3.81 kg of biowaste, or 0.78 kg of wood residue is suitable for small and medium size enterprises (SMEs), and can be perceived as representative of a large household or small-sized community. Thus, the total energy obtained through bioenergy (E_{Bio}) can be calculated by the equation below.

$$E_{Bioenergy} = \sum_i^m \frac{E_i - E_{input,i}}{N_i}, \quad (9)$$

where m represents the three different types of the bioenergy technologies; N_i represents the number of users at specific i method, which will be different due to the different production rate of biological materials.

2.6 Human power generation

Human power generation is a power conversion process that obtains energy from fitness and sports, such as pedalling, running and rowing. It utilises the kinetic energy of people to drive a generator to produce electricity. Fitness has become a daily routine for many people today, but given its nature of requiring additional human input, it can be considered as an emergency source of power in times of power shortages.

Figure 17 shows the experimental setup to measure the power output by human physical power. The electricity generation experiments were performed by five people with ages ranging from 20 and 25, and with different weights

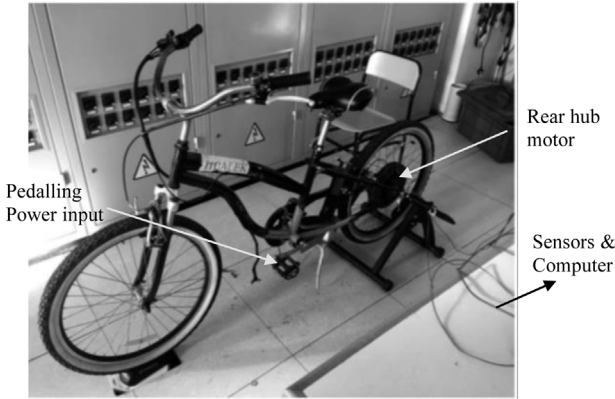


Fig. 17. E-bike experimental setup [44].

Table 1. All USREs energy generation summary.

Methods	Energy generation (Wh/day)
Rooftop solar power	7,425
Solar energy harvesting	1,200
Household wind turbine	1121.88
Micro-wind turbine energy harvester	156.25
Micro hydropower system	0.115
Energy-harvesting shoe	0.053
Power generation floor tile	0.021
Watch energy harvester	0.003
Magnetoelectrical clothing generator	0.384
Bioenergy	159
Human power generation	77.5
Total	10,139.96
Principal USREs Only	10,139.38

from 64 kg to 78 kg and heights from 175 cm to 180 cm. According to the data presented in the article [44], the energy conversion efficiency of this type of system can reach 94%. The average power production falls within the range from 65 W to 90 W. The energy generation output can be calculated by this power multiplied by the hours worked.

2.7 Summary of the USREs

In order to provide an intuitionistic demonstration, this paper gives an example, by substituting the data of a normal person near London on an ordinary date, and calculates the total electric energy production that can be obtained by using USREs. The calculation process and assumptions can be found in the [Appendix A](#).

Table 1 summarizes all the USREs. The principal methods are defined as the methods that generate more than 1 Wh/day of electricity, including rooftop solar power, solar energy harvesting, small wind turbine, micro-wind turbine energy harvester, bioenergy, and human power generation. USREs with output below 1 Wh/day, are not

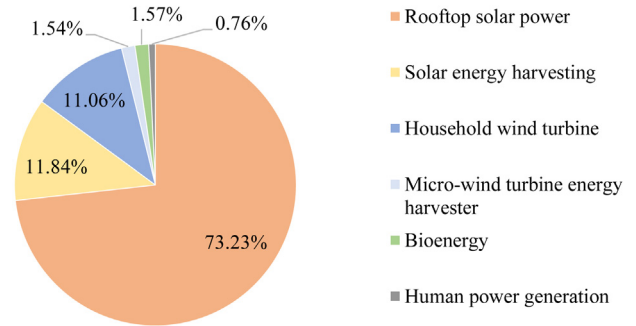


Fig. 18. Summary of Principal USREs.

suitable as an energy source. However, these non-principal USREs also have the potential to become a principal USREs in certain environment, such as the application of micro hydropower systems in nearby rivers, or a power generation floor tile in high traffic areas.

Table 1 shows that there is no significant difference in the data after removing non-principal USREs. The electricity production using Principal USREs only is 10,139.96 kWh/day. Figure 18 shows the proportion of each principal USREs.

From Figure 18, it can be found that above 70% of the electricity output comes from rooftop solar power, while the two USREs based on solar power account for more than 85%, and household wind turbine is similar to solar energy harvesting. Solar power and wind energy consists of approximately 97.67% of the total output, which are energy sources that may have significant intermittence [45], and can be inconsistent with electricity consumption depending on the time of the day or weather. Therefore, distributed energy storage is crucial to prevent electrical shortages.

3 Distributed energy storage for households

Since renewable energy generation is intermittent and the amount of the outputs of the USREs are various, it is important and necessary to integrate renewable energy with distributed storage systems in ZEU. Distributed energy storage compared to centralised energy storage, can be equipped to every building, which allows every DC electricity generated can be stored directly, and no matter the amount and time, instead of connecting to the grid with many restrictions. There are various battery storage technologies can be used to integrate with renewable energy sources in a distributed manner. In this section, three types will be reviewed, which are liquid-state lithium-ion batteries, all-solid-state batteries, and structural batteries.

3.1 Liquid-state lithium-ion battery

The liquid-state lithium-ion batteries with high energy density and long cycle life have been widely applied in electrical devices nowadays. Figure 19 shows the schematic of a typical liquid-state electrolyte lithium-ion battery,

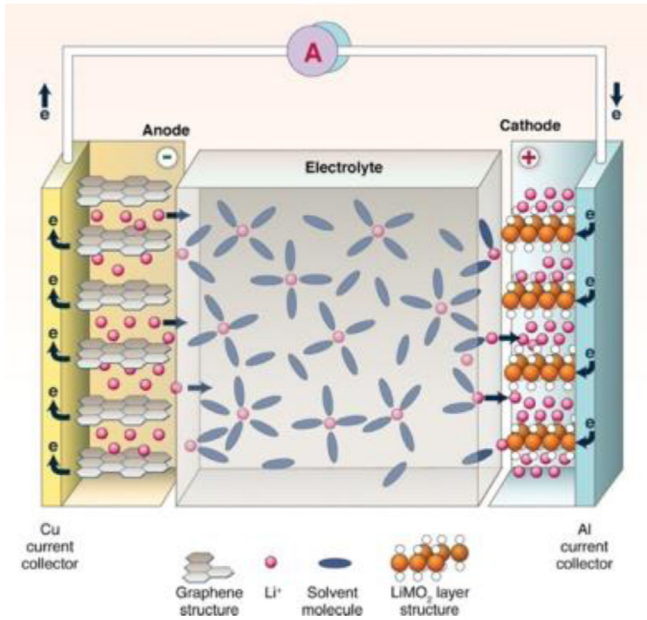


Fig. 19. Lithium-ion battery cell fundamental structure, which is the same for different cell types [46].

which is composed of an anode – usually the graphitic carbon material that holds Li in its layers, a cathode – usually an oxide with a layered structure and a nonaqueous liquid electrolyte in between. Both electrodes can reversibly insert and remove Li-ions from their respective structures. During the charging process, Li-ions are deintercalated from the cathode and intercalated into the anode through the electrolyte while the process is reversed during the discharging process [46–49]. The charging and discharging processes of liquid-state lithium-ion batteries generate significant heat due to Li^+ shuttling [46]. In addition, the organic liquid electrolytes used in these batteries are inherently flammable [47]. These properties can lead to cascading thermal runaway events, which are important safety considerations associated with these batteries. When the battery temperature rises above about 80°C , the rate of exothermic chemical reactions inside the battery increases, which can cause the temperature to rise even higher to the point of causing fires and explosions [48]. Although the incidence of battery accidents is relatively low compared to the overall use of lithium-ion batteries, this potential risk still exists, especially in critical applications such as automobiles and home devices [49]. However, Scientists have developed many thermal management systems to minimise this risk [50], making liquid-state lithium-ion batteries the most mature type of battery available and widely used in a variety of electronic devices and even electric vehicles.

The energy densities of the more common liquid-state lithium-ion batteries are around 320 Wh/L and 150 Wh/kg [51], and as batteries continue to evolve, the densities are approaching their intrinsic limits [51], with advanced batteries now reaching $600\text{--}650\text{ Wh/L}$ or 248 Wh/kg [51]. Liquid-state lithium-ion batteries are relatively stand-

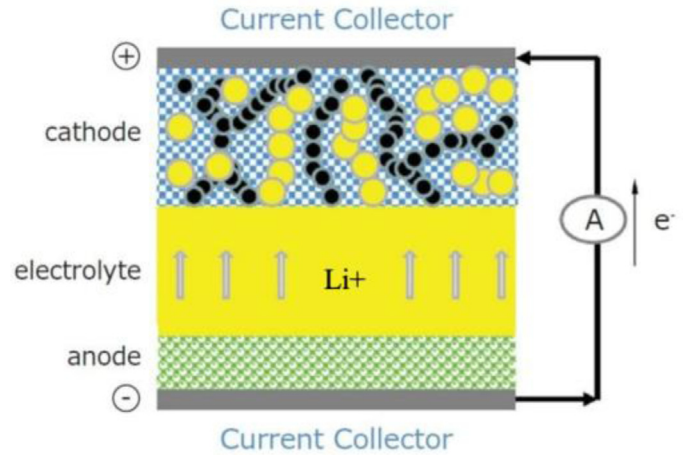


Fig. 20. Structure of the All-solid-state lithium battery [54].

ardised in terms of form factor, with cylindrical, prismatic, button and soft pack batteries being the most commonly used types of liquid-state lithium-ion battery components with limited creativity [52].

However, liquid-state lithium-ion batteries, as the most mature battery type today, are the most realistic solution for distributed energy storage [51–53].

3.2 All-solid-state battery

The solid electrolytes are used in all-solid-state batteries, there are many types with different material [54]. Figure 20 shows the structure of an all-solid-state lithium battery (SSLB), consisting of a cathode, solid-state electrolyte, anode, and current collectors. The solid-state electrolyte functions as both an ionic conductor and separator to prevent a short circuit. The all-solid-state lithium battery could address the safety issue caused by flammable liquid electrolyte. The working principle of an SSLB is similar to the liquid-state lithium-ion battery. During charging, lithium ions are decalcified from the lattice of the cathode and transferred to the anode through an ion-conducting solid electrolyte, while electrons are transferred to the anode through an external circuit. During discharge, lithium ions are decalcified from the anode and transferred to the cathode through the solid electrolyte while electrons pass through the external circuit and drive the device [54].

The SSLB can achieve energy densities of 810 Wh/L (lithium ceramics battery) or 521 Wh/kg (zinc–air batteries) [55]. Furthermore, the energy density has the potential for further augmentation, by methods like improvement of electrolyte-electrode interface compatibility, improvement of the solid electrolyte conductivity, etc. [54].

However, there remain several challenges to be surmounted, such as low ionic conductivity of the solid-state electrolytes at room temperature, and inadequate interfacial compatibility between electrodes and electrolytes [54]. Moreover, similar to liquid-state lithium batteries, the all-solid-state counterparts exhibit limited flexibility.

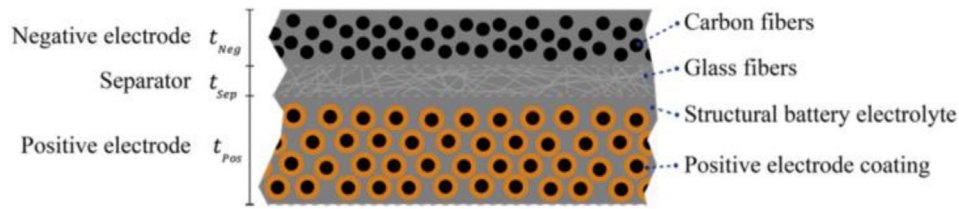


Fig. 21. Schematic build-up of one structural battery cell [56].

3.3 Structural battery

The structural battery is composed of multi-functional materials, which allows simultaneous electrical energy storage to act as battery as well as load bearing capacity to act as a mechanical structure. This combination offers the potential to minimise the total mass and volume, which is an efficient solution for distributed energy storage.

Figure 21 depicts a typical structural battery cell, which consists of a negative electrode, positive electrode, and separator. Carbon fibres in the structural battery can be used as current collectors due to their good conductivity. Both the positive and negative electrodes are made of carbon fibres, but for the positive electrode, they are coated with positive electrode active material (LiFePO_4), and the separator is constituted of randomly oriented glass fibres [56]. The electrolytes used are mostly liquid, but it is possible to apply a solid electrolyte [57].

For the target design values of the structural battery, the model shows a potential mass saving of 26%. Thus, considerable mass savings can be achieved compared to a conventional carbon fibre composite plate and standard LIB. The energy density of the structural battery can reach up to 110 Wh/kg [56], which is lower than conventional LIBs.

The unique properties of structural batteries make them compatible with ZEU's for distributed energy storage. In transportation scenarios, these batteries can reduce the mass burden on vehicles and reduce the space burden caused by battery cells by replacing a part of structural components and a part of batteries [58]. In residential scenarios, they have the potential to be made into furniture or appliances and be seamlessly integrated into a building, thus preserving as much of the original living space as possible.

However, there are still several issues with structural batteries that must be resolved. Battery materials' constituents usually experience volumetric changes during the charge and discharge process. These variations are driven by the migration of lithium ions and alterations in ion concentrations, inducing swelling and contraction within the composite structure. Consequently, this interaction fosters the initiation of material damage, consequently leading to a diminished lifespan of the battery. Furthermore, in comparison to conventional materials, the fabrication of multifunctional structural batteries from composite materials are notably intricate, necessitating the utilisation of resin infusion manufacturing through the Flexible Tooling approach. Both manufacturing complexity and costs are significantly elevated [59].

Due to the early stage of research and development of structural batteries, numerous challenges must be overcome. Nonetheless, this does not undermine the fact that the conceptualisation of such multifunctional batteries continues to be a promising solution for energy storage in future ZEU scenarios.

3.4 Summary of distributed energy storage technologies

As one of the indispensable conditions for distributed energy storage in ZEU, all the three battery types given in this section can be used, and all have their own characteristics. Liquid lithium-ion batteries, as the most mature battery type at present, are the most realistic option for distributed energy storage by taking up a certain amount of space; all-solid-state batteries, because they allow for higher energy densities, make it necessary to take up less space; and structural batteries, which allow for the combination of support and energy storage, are available as a theoretical option that can be used without taking up any additional space, although there are still many difficulties and uncertainties, it is still the best solution for ZEU distributed energy storage.

4 Discussions

4.1 Analysis of the feasibility of zero emission utopia

A comparison between the potential energy obtained through USREs and the energy consumption requirements of an individual on a daily basis can verify the achievability of ZEU. The available energy outputs by USREs were summarised in Table 1, which is 10,139 kWh per person. Table 2 lists the typical daily electrical consumption activities for an adult, including commuting via an electric vehicle (1.5 h), working on a computer (divided into 6 hours light loads and 2 hours heavy loads), using electronic devices such as cell phones or tablets for work or entertainment (7 h), watching television (2 h), lighting (6 h), cooking (1.5 h), and using small devices such as smart watches and headphones (6 h).

As shown in Table 2, the total daily electricity consumption of an individual is estimated as 24.43 kWh. If transportation consumption is excluded, the consumption is 9.43 kWh, which agrees well with the average daily electricity consumption of households in England in 2021 (approximately 9.4 kWh) [60]. This data can be reduced by using other greener methods or devices, such as using

Table 2. Electricity consumption model for the example person per day.

Activities	Hours(h)	Est. Power(W)	Electricity consumption (Wh)
Transportation	1.5	10,000	15,000
Heating/Air Con.	2	2,500	5,000
Phone/Tablet	7	10	140
Computer (light load)	6	30	360
Computer (heavy load)	2	300	1200
Cooking	1.5	2,000	3,000
Television	1	250	250
Lighting	3	100	300
Small devices	6	5	60
Total			24,430
W/o Transportation			9,430

public transportation or cycling to commute, or using heat pumps instead of traditional high power heating or air conditioning systems.

The data presented in Tables 1 and 2 shows that relying on the USREs, the generated electricity (10,139 Wh) is sufficient for meeting everyday electricity demands (9,430 Wh) with the exception of transportation, with a surplus 709 Wh per day that can be stored to reduce the impact of renewable energy intermittency. Even taking into account the charging and discharging losses of the batteries, this output can still meet the daily demands.

In practice, the number of USREs generation units can be adjusted to better fit local situations, allowing higher energy outputs to be obtained compared to the general model provided by this article. In addition, considering the generated energy data obtained in Table 1 were performed on a personal basis, and a household typically consists of more than one person, some energy consumption activities can be shared. Even if energy generation output can be increased, surplus capacity should be stored by distributed energy storage system to meet emergency energy demand or used to meet household travel transport demand. The use of distributed energy storage can solve the problem of uneven distribution of renewable energy in a single day and solve the problem of uneven daily distribution. Therefore, the capacity of the distributed energy storage should be greater than the daily power generation and should be such that the stored energy can meet at least two days of electricity demand, in this case 18,860 Wh.

In addition, ZEU and ZES are not mutually exclusive, and combine the two pathway is a potential more feasible and more realistic pathway with more benefits. In the case of ZES, distributed energy storage can store low-cost off-peak electricity to reduce electricity costs for individual users. From a social perspective, they can reduce the construction of distributed energy storage system and reduce the cost of grid renewable energy transformation [61]. These advantages can be addressed when developing ZEU, making it widely available and applicable in many scenarios, while benefiting both society and individuals.

4.2 Future prospect

In the envisioned future of ZEU applications, households will no longer require external power supply and incur electricity bills. Through a diverse array of USREs, families will be able to meet all their electricity needs. Each household will be equipped with a distributed energy storage system, prominently featuring structural batteries that can be seamlessly integrated into furniture and even used for constructing buildings, thereby eliminating the need for additional space utilisation. These batteries can also find application in transportation to reduce vehicle weight and consequently conserve energy [58], thereby facilitating the realisation of ZEU.

Furthermore, large energy consumption corporations can achieve complete off-grid electricity by strategically locating their facilities in areas with abundant in solar, wind, or hydroelectric resources. In remote and less inhabited regions, particularly those rich in renewable energy potential, ZEU can independently address power supply challenges, attracting more residents and fostering the development of new towns. Existing urban areas can also benefit from a combination of ZEU and ZES, ensuring a more abundant and stable electricity supply. This integrated approach can significantly reduce the number of standalone renewable energy power plants and energy storage stations required by ZES, subsequently lowering government investments in infrastructure construction and maintenance costs, leading to a reduction in tax burdens. Ultimately, reduced electricity costs and tax burdens will alleviate a substantial amount of pressure on the general populace.

5 Conclusions

By reviewing the currently available USREs, especially those capable of generating substantial amounts of electricity by methods such as rooftop solar, micro hydropower system and small wind turbines, it is possible to generate enough electricity to meet people's daily energy consumption, and the surplus to be stored to solve the

problem of intermittent supply of renewable energy with the construction of household distributed energy storage systems. In this field, the all-solid-state batteries have beneficial performance and features than conventional LIBs, and the application of structural batteries also avoids occupying additional space within the home, while also helping to reduce the size of EVs and other mobile devices.

By reviewing the currently available USREs, and base on the given example, the total electricity output stands at 10,139 kWh per person, especially the principal USREs such as rooftop solar panel, which is surpassing the average daily electricity demand of 9,430 kWh per person. This surplus could be stored using household distributed energy storage systems, this demonstrates that the concept of ZEU has been proven feasible.

All-solid-state batteries demonstrate better performance compared to liquid state batteries and could play a crucial role in ZEU storage system. Structural batteries, which do not require extra space within homes, also contribute to downsizing electric vehicles or other portable devices, theoretically is the best solution for distribution storage system. The capacity of batteries should meet at least two days demands, which is 18,860 Wh in the given example.

Moreover, combining ZEU with ZES is a more feasible pathway, which will not only reduce the government's investment in infrastructure, but also reduce the people's daily expenses, realising a more sustainable and environmentally friendly energy system.

Appendix A

A.1 Rooftop solar power calculations

$$H_{tracker} = 1 + 10\% + \frac{3\%}{365} = 1.10008,$$

$$A_{1kWp} = \frac{1.6m^2}{400W} \times 1000W = 4m^2,$$

$$\begin{aligned} E_{RSP} &= 2.4kWh/kWp \times 1.1 \times 0.75 \times \frac{60m^2 \div 2 \div 2}{4m^2} \\ &= 7425Wh/day. \end{aligned}$$

Figure 3 shows the solar energy potential of UK is about 2.4kWh/kWp.

Estimate the available rooftop area is 60 m² [62], and only half with sunshine, suitable for solar panel deployed, family has two people to share the electricity outcome. Cross-checked the number with reference [14].

A.2 Solar energy harvesting

$$E_{SEH} = 2.4kWh/kWp \times 50\% \times \frac{4}{4} = 1200Wh/day.$$

To sample the assumption, estimate the total area of all solar energy harvesting devices is 4 m² and all have 50% efficiency.

A.3 Household wind turbine

$$\frac{P_1}{P_2} = \frac{u_1}{u_2} \Rightarrow P_{UK} = \frac{455Wh/day}{24} \times \frac{u_{UK}}{3.55m/s} = 5.34u_{UK}W.$$

Estimate 1 person can have 2 wind turbine units.

Wind speed data used is 31st Oct 2023, London [63], data converted from mph to m/s.

Crosschecked with the UK average wind speed [64], the wind speed data is representative.

A.4 Micro-wind turbine energy harvester

$$\begin{aligned} E_{MWT} &= 500 \\ &\times (1mW + 2.5mW \times 4 + 4mW \times 2 + 5mW \\ &\times 5 + 10mW \times 2 + 15mW + 20mW + 22.5mW \\ &+ 25mW \times 8) \times \frac{24}{24} = 156.25Wh/day. \end{aligned}$$

Estimate the number of units is 500, due to the small diameter of the wind turbine.

Wind speed data used is 31st Oct 2023, London [63], same as household wind turbine.

All wind speed round up to the nearest 0.5 for ease of calculation.

A.5 Micro hydropower system

$$E_{EHS} = 0.115W \times \frac{30}{60} hour \times 2 = 0.115Wh/day.$$

The average household in the UK uses around 146 litres of water per day, according to the UK 2022 statistics [65]. This output can keep the generator running for about 20 to 30 minutes according to [32].

A.6 Energy-harvesting shoe

$$\begin{aligned} E_{shoe} &= (2 \times 2.44mW + 8.4mW) \times 2shoes \times 2hours \\ &= 0.0532Wh/day. \end{aligned}$$

A.7 Power generation floor tile

$$E_{tile} = 5.268mW \cdot 2hours = 0.0211Wh/day.$$

Estimate each person can walk two hours per day, and the best-case scenario of always stepping on a floor tile with both two feet.

A.8 Watch energy harvester

$$E_{watch} = 1.74mW \cdot 2hours = 0.00348Wh/day.$$

Estimate each person can walk two hours per day, same as power generation floor tile.

A.9 Magnetoelectrical clothing generator

$$E_{Clothes} = 96\text{mW} \times 2\text{hours} \times 2\text{sides} = 0.384\text{Wh/day}.$$

Estimate each person can walk two hours per day, same as power generation floor tile.

A.10 Bioenergy technologies

$$E_{Bioenergy} = \frac{1\text{kWh} - 0.01\text{kWh}}{10} + \frac{1\text{kWh} - 0.39\text{kWh}}{15} + \frac{1\text{kWh} - 0.03\text{kWh}}{50} = 159\text{Wh/day}.$$

Estimate 10 users can produce 0.26kg WCO per day, 15 users can produce 3.81 kg biowaste per day, 50 users can produce 3.81 kg wood residues per day.

A.11 Human power generation

$$\bar{P}_{Human} = \frac{65\text{W} + 90\text{W}}{2} = 77.5\text{W},$$

$$E_{Human} = 77.5\text{W} \times 1\text{hour} = 77.5\text{Wh/day}.$$

Estimate 1 person can do 1 hour panelling exercise per day.

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Conflicts of Interest

The authors declare no competing financial interest.

Data availability statement

All data supporting the findings of this study are included in the appendix of this article.

Authors contribution statement

Z.W. X.Y. and L.W. conceived the project. Z.W. performed Information collection and collation and wrote the manuscript, with significant contributions from X.Y. and D.J.P., Y.J. H.L. X.Y. H.S. provided valuable input, revisions, and feedback during manuscript development. L.W. supervised and administered the project.

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