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Review

Net Zero Energy Communities: Integrated Power System, Building and Transport Sectors

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Abstract: A Net Zero Community (NZC) concept and its energy characteristics are presented in this paper. NZC is an emerging topic with multiple variations in terms of scope and calculated methods, which complicates quantifying its performance. This paper covers three key barriers in achieving NZC targets: (1) the main focus of current definitions on buildings, disregarding community power systems and energy use in transportation; (2) different requirements (source, supply, metrics, etc.) in the existing definitions; and (3) lack of updated published reports to track the progress of committed NZC targets. The importance of this research is summarized as due to increased savings in primary energy and greenhouse gas emissions related to the three main energy sectors, namely power systems, buildings, and transportation (PBT). To clarify the current NZC, this paper reviews: (1) variations in the existing definitions and criteria from peer-reviewed publications; (2) the latest climate projection models by policymakers to achieve net zero by 2050; (3) the literature on renewable-based power systems; and (4) three planned NZC cases in international locations, in order to study their NZC targets, energy performance, and challenges. The outcome highlights NZC design guidelines, including energy efficiency measures, electrification, and renewables in PBT sectors that help stakeholders including policymakers, developers, designers, and engineers speed up achievement of NZC targets.

Keywords: Net Zero Community; energy efficiency measures; electrification; renewable power systems; global energy mix; community energy balance; climate action targets; global warming

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1. Introduction

Cities consume over 60% of the source energy used and release 70% of the global carbon emissions while accounting for only 3% of the Earth's land area [1]. In cities, the electricity (or "power"), building, and transport sectors are the main consumers of primary energy and emitters of Greenhouse gases (GHG) [2–10]. Buildings are accountable for a third of global final energy use and around 40% of GHG emissions [2,3]. The residential building sector is responsible for 25% of global energy consumption and 17% of carbon dioxide (CO_2) emissions [4,5]. The transport sector accounts for 25% of the world's total delivered energy consumption and 24% of global CO_2 emissions [6,7]. Although more than one third (36.7%) of the global electricity supply comes from low-carbon sources (renewables, nuclear, and hydropower), they account only for a 15.7% share of the total global energy mix [8]. The other 84.3% (electricity, transport, heating), is sourced from fossil fuels [9]. According to the Intergovernmental Panel on Climate Change (IPCC), electricity and heat production account for 25% of global CO_2 emissions [8,10]. This rate of fossil fuel-based energy consumption increases GHG emissions and causes environmental problems such as health issues, natural disasters, and global warming [11,12]. Therefore, studies on climate change mitigation solutions are needed to address existing challenges.

1.1. Global Warming, Paris Agreement, and Climate Target Variations

According to the IPCC [13], global temperature is rising by about 0.2 °C per decade. By 2017, human-induced warming reached 1 °C above pre-industrial levels and is projected to reach 1.5 °C by 2040 [13]. On 9 August 2021, the IPCC [14] released a "faster warning" on the global temperature rise that demands immediate reductions in GHG emissions to limit the global warming "close to 1.5 °C or even 2 °C". In response to the Paris Agreement [15,16], 197 countries committed to reducing their emissions and are required to submit their Nationally Determined Contributions (NDCs) to the United Nations Framework Convention Climate Change (UNFCCC) every five years and report on the progress of their emission reduction target achievements [17,18]. The results from the 2020 reports showed a 5.8% reduction in CO_2 emissions as an outcome of the COVID-19 pandemic. However, the US Energy Information Administration (EIA)'s monthly data presented an increase in global energy-related CO_2 emissions in December 2020, projected to reach 33 gigatons (Gt CO_2) in 2021 [17,19]. Therefore, in March 2021, the International Energy Agency (IEA) hosted a net zero summit to focus on the necessary actions that countries and companies who pledged net zero emissions need to take in order to transform the goals into practice [17].

Approaching the 26th UN climate change conference (COP26) in November 2021, the European Union and 44 countries covering 70% of global CO_2 emissions agreed to pledge to achieve net zero emissions by 2050 [17]. Ten of these countries made their net zero target commitments a "legal obligation", eight countries proposed to make it a legal obligation, and the rest pledged through "official policy documents" [17]. Most of these net zero commitments lack "detailed policies and firm routes to implementation," and vary in scope and timescale [17].

1.2. Net Zero Community Characteristics in Response to the Climate Targets

Key solutions in achieving emission reductions are summarized as improved energy efficiency, electrification, and renewables [20–22]. For example, Chen et al. [23] noted that "retrofitting the existing building stock to improve energy efficiency and reduce energy use is a key strategy for cities to reduce GHG emissions and mitigate climate change". Previous literature reviewed Net Zero Energy (NZ) as the primary solution for achieving GHG emission reduction targets by 2050 [17,24–28]. By conducting a comprehensive NZ literature review at the building level in [20], the authors extended their analyses to communities and districts.

Net Zero Energy Community (NZC) is an emerging concept with multiple variations in the scope and calculation methods, which complicates uniformly quantifying its targets. Three main barriers are addressed: (1) the main focus of current definitions on buildings, which leave out community power systems and energy use in transportation; (2) the existing definitions, which have different requirements (source, supply, metrics, etc.); and (3) the lack of updated published reports to track the progress of committed NZC targets.

This paper is a review of current NZ knowledge applied to communities by including the application of three main global energy sectors: power systems, buildings, and transportation (PBT), in the following sections:

Section 2 reviews existing NZC requirements and categorizes the various criteria from the selected publications.

Section 3 reviews the latest climate projection models, and analyses the application of improved energy efficiency, electrification, and renewables in the PBT sectors.

Section 4 presents a systematic review of global climate targets and decarbonization requirements.

Section 5 reviews global energy transitions (solar, wind, and cogeneration).

Section 6 presents a systematic review of the three planned NZC communities worldwide and extrapolates their community power systems and energy efficiency measures in the building and transport sectors.

Section 7 recommends NZC design guidelines to minimize energy demand through applying energy efficiency measures in power, building, and transportation sectors and maximizing renewable supplies in communities.

2. Net Zero Community Definition

Existing NZC definitions have differing requirements that complicate the achievement of NZC objectives [29–33]. Table 1 shows variations in supply and source in the selected publications.

Table 1. Variations in the current net zero community concept.

NZC Definition	Net Zero Community/District	Onsite/Off-Site Energy	Source/Site Energy	Reference	Organization/ Journal
One that has greatly reduced energy needs through efficiency gains such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy.	Net Zero-Energy Community (ZEC)	Both	Site	Carlisle et al. 2009 [33]	National Renewable Energy Laboratory (NREL)
A neighborhood in which the annual energy consumption for buildings and transportation of inhabitants is balanced by the production of on-site renewable energy.	zero-energy neighborhood (nZEN)	On-site	Site	Marique & Reiter 2014 [34]	Energy and Buildings Journal
A cluster of residential units where the overall energy demand is low and is partly met by renewable energy self-produced within the neighborhood.	Nearly Zero energy Neighborhoods (ZenN)	Both	Site	Sørnes et al. 2014 [35]	IVL Swedish Environmental Research Institute
On a source energy basis, the actual annual delivered energy is less than or equal to the onsite renewable exported energy.	Zero Energy Community (ZEC)	On-site	Source	Peterson et al. 2015 [36]	US Department of Energy (DOE)
Aggregate multiple buildings and Optimize energy efficiency, district thermal energy, and renewable energy generation among those buildings so that on-site renewable energy can offset the energy use at the district scale.	Zero Energy Districts	On-site	Site	Pless et al. 2018 [37]	US National Renewable Energy Laboratory (NREL)
A district where energy supply/on-site potential is equalised by the final energy demand of its users.	Net Zero Energy District (NZED)	On-site	Site	Koutra et al. 2018 [38]	Sustainable Cities and Society Journal
All of the community's energy needs on a net annual basis must be supplied by on-site renewable energy. No combustion is allowed.	ZEC	On-site	Site	ILFI 2019 [39]	International Living Future Institute (ILFI) US
A group of interconnected buildings with associated infrastructure, located within both a confined geographical area and a virtual boundary. An SPEN aims to reduce its direct and indirect energy use towards zero adopted over a complete year and to increase use and production of renewable energy according to a normalization factor.	Sustainable Plus Energy Neighborhoods (SPEN)	Both	Site	Salom and Tamm 2020 [40]	Syn.ikia Norway

Table 1. *Cont.*

NZC Definition	Net Zero Community/District	Onsite/Off-Site Energy	Source/Site Energy	Reference	Organization/ Journal
Energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero GHG emissions and actively manage an annual local or regional surplus production of renewable energy.	Positive Energy District (PED)	Both	Site	Hinterberger et al. 2021 [41]	JPI Urban Europe and SET-Plan 3.2 Programme Austria
A group of interconnected buildings with distributed energy resources such as solar energy systems, electric vehicles, charging stations and heating systems, located within a confined geographical area and with a well-defined physical boundary to the electric and thermal grids.	Zero Emission Neighborhoods in Smart Cities (FME ZEN)	Both	Site	Wiik et al. 2021 [42]	Research Centre on Zero Emission Neighborhoods (ZEN) Norway

Note: The Key terms, on-site/off-site energy and source/site energy are defined at the US Department of Energy (2015) [36].

The existing variations in defining a community NZ present a challenge to stakeholders such as developers and policymakers when attempting to implement NZC and track its progress. Polly et al. [43] noted that "stakeholders face a lack of documented processes, tools, and best practices to assist them in achieving zero energy districts". Koutra et al. [38] claimed that "the term Net-Zero Energy District is an innovative concept still in progress growing prevalent during the last years and it is still restricted to the scientific literature review". According to Kennedy [44], many communities aim to become "zero carbon", yet "there are neither clear definitions for the scope of emissions that such a label would address on an urban scale, nor is there a process for qualifying the carbon reduction claims". Carlisle et al. [33] concluded that "a definition for a zero-energy community is different and more complex than that of a ZEB because a community uses energy not only for buildings but also for industry, vehicles, and community-based infrastructure".

To adapt an NZC concept, it is important to clarify existing variations in definitions and calculated methods. To do so, previous literature reviewed NZC variations, and the outcome presented different conclusions for each case [33,34,45,46].

Torcellini's [45] NZ classification at the building level (NZB) from the National Renewable Energy Laboratory (NREL) was analyzed in [20]. Carlisle et al. [33] have expanded the four NZB classifications into NZCs to evaluate their energy performance, where a community may achieve one or more of the defined NZC summarized in Table 2.

Table 2. Net zero community definition classifications. Modified from Carlisle et al. [33] at NREL (2009).

NZC	Buildings	Transport
NZ Site Energy	As much renewable energy is produced in the community for buildings and infrastructure as is needed by buildings and infrastructure in a year when accounted for at the site.	Measured vehicle miles traveled by community occupants regardless of whether they filled up their gas tank in the community or outside the boundary.
NZ Source Energy	A source ZEB produces at least as much energy as it uses in a year when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site.	For transportation fuel, source energy would include a multiplier to account for the energy required to transport the fuel to the fueling station.
NZ Energy Costs	In a cost ZEB, the amount of money the utility pays the building owners and the community (for renewable energy generated on all residential and community buildings and infrastructure) for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.	By including transportation, the cost of the fossil-based fuels is offset by the fuel generated from renewable sources.
NZ Energy Emissions	A net zero emissions community produces and uses at least as much emissions-free renewable energy as it uses from emissions-producing energy sources annually. To calculate the total emissions of buildings and transportation, imported and exported energy are multiplied by the appropriate emission multipliers based on utility emissions and on-site generation emissions (if there are any).	Carbon, NOx, and SOx are common emissions that ZEBs and transportation powered by renewable energy offset.

According to Carlisle et al. [33], if a community generates at least 75% of its energy demand through on-site renewable supply, it is considered a "near-zero community". Carlisle excluded off-grid communities from his classification [33].

However, Brozovsky et al. [46] commented on Carlisle's NZC classification that "it is not made clear why these different terms were used or if they are supposed to be used as synonyms". The authors concluded that although the interest in scientific NZC is growing, a variety of "coexisting terminologies" and different methodologies have been developed [46]. Brozovsky et al. [46] noted "this proliferation of terms causes not only confusion among the authors of scientific papers but makes it unnecessarily difficult for non-expert readers to follow".

The key NZ variation parameters, including boundary, energy balance, time scale, emission source, energy type, renewable supply, and grid connections were highlighted in [20]. Table 3 summarizes the review publications on the NZC concept and presents the main challenges, existing variations, and requirements for adopting NZC.

From the literature in Tables 1–3, the main variations in the existing NZC concept can be divided into five categories:

1. Multiple definitions, different terminologies and terms that create confusion and lack of clarity in adapting an NZC;
2. Lack of structured methods and inclusive energy modeling tools to verify committed NZC;
3. Lack of published reports and systematic literature on NZC characteristics;
4. Lack of clarity on system boundaries in definitions (i.e., mobility, travel distance, energy balance);
5. Variations in climatic and geographic context that directly impact energy loads and methodology.

Table 3. Review of NZC variation by selected publications.

References	Review Focus	Challenges	Variations	Recommendations
Marique & Reiter 2014 [34]	A simplified framework to assess the feasibility of a zero-energy neighborhood/community	1. Impact of urban form on energy needs and on-site renewable energy production 2. Impact of location on transportation energy consumption. 3. Lack of reports, calculated methods, and tools to quantify energy use, GHG emissions, and energy efficiency of scenarios.	Concept of "zero energy" and "zero carbon", scale (focus on individual buildings), energy balance, grid connections, political targets, energy source and supply, emission source, mode and location of renewables, assessment tools, site configuration, building orientation and shape, urban form on transport, timescale (daily, monthly, yearly), primary energy.	1. The location of new buildings and developments is crucial in the total balance. 2. Consideration of renewable production, energy use in building and transportation sectors as an integrated system, rather than separated topics.
Amaral et al. 2018 [47]	Performance of Nearly zero-energy districts	Growth of complexity, lack of systematic literature, lack of inclusive energy modeling tools, interrelations between climatic and morphological indicators in methodology.	System boundaries, density, morphology, microclimates, public spaces, stakeholders, the concept of "community", travel distance, energy source and supply, energy use specifications, source accessibility, solar capacity, distribution systems.	1. Analysis of the correlation between geometric indicators and urban microclimate on the energy performance of districts. 2. Clarification of the metrics, calculation methods, and energy types in different methodologies.
Brozovsky et al. 2021 [46]	Definitions, public initiatives, research gap, future research possibilities of zero emission neighborhoods and positive energy districts	Lack of: Clarity on the definition, target, key performance indicators; published a systematic review of low, nearly zero, zero, and positive energy/emission/carbon communities; clear definitions for every term exist; structured approach; articles that include embodied energy/emissions, LCA, microclimates, and social aspects of NZC; attention to the dimensions of the space (people and mobility)	Different terminologies regarding reduced or minimized carbon emissions, different methodologies, balance boundary, mobility boundary, political, regulatory, economic, social, and technological features.	1. Need for clear definitions and a structured approach to developing them. 2. Consistent and uniform description of targets, standard set of categories, key performance indicators, system boundaries, and spatial scales. 3. Social, microclimatic, economic considerations in future NZC research. 4. More NZC research outside of Europe and China is needed to cover a broader spectrum of climates and a wider geographical context.

Many publications conducted energy analyses at the community level [38,48–56]. Two selected studies are reviewed in this section to show differences in NZC implementation. Their optimization strategies are summarized to present their NZC variations, including a lack of consensus on the methodologies, system boundary, energy balance, climatic and geographic contexts, and infrastructure connections.

2.1. Bakhtavar et al. in 2020, Assessment of Renewable Energy-Based Strategies for NZCs

Bakhtavar et al. presented a multi-objective model through weighted goal programming to assess renewable energy strategies and deliver the optimal energy mix in net zero energy communities [57,58]. The authors included the application of life cycle assessment (LCA) and life cycle costing (LCC) as input data in their optimization model. The proposed model was applied to a case study in Canada (Table 4) to find the best renewable supply (RE) mix with the lowest undesirable outcomes.

Table 4. Proposed model for the case study, a medium-scale community in the Okanagan Valley, BC, Canada. Data from Bakhtavar et al. [57].

Building Types	Number of Dwellings	Area of Units m^2	Average Energy Use (kWh)
Single-family detached house	40	210	2259
Single-family attached house	2115	185	21,111
Senior congregate care apartments	725	102	12,778

Grey-based and other differently weighted energy planning approaches were set to find the optimal decisions, where the grey weighting program prioritized environmental impact reduction [57]. Figure 1 presents the result of five scenarios using different renewable technologies from the goal programming model.

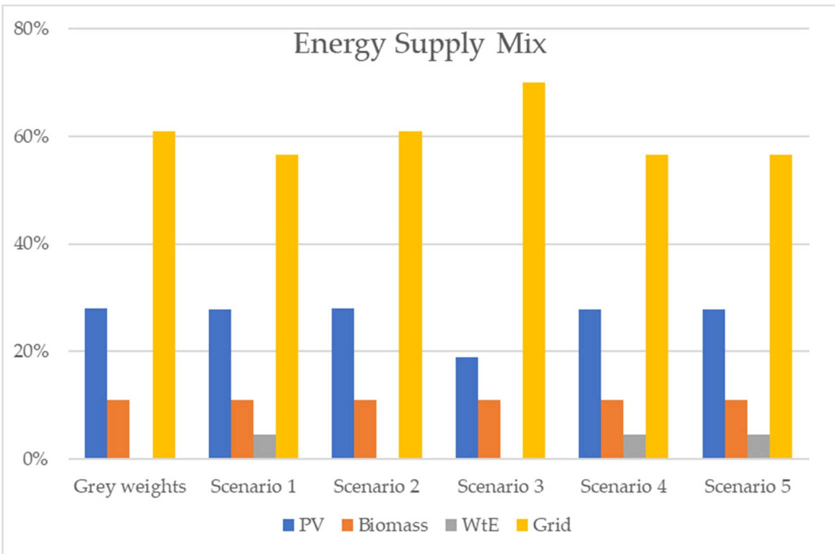


Figure 1. Optimal energy supply mix through different weighting scenarios, data from Bakhtavar et al. [57].

Grey weights and Scenario 2 presented the best solution for energy mix and RE fractions by recommending maximum biomass and PV with minimum waste-to-energy (WtE) capacities. Maximizing the capacity of RE caused reductions in total life cycle GHG emissions by 26.37%, life cycle impacts by 24.9%, and annual supply energy costs by 41.8% [57]. However, the increased cost from the investment, operation and maintenance of integrated renewable energy led to a payback period of 30 years [57].

2.2. Kim et al. in 2019, Techno-Economic Analysis of Hybrid Renewable Energy System with Solar District Heating for NZC

This study investigated a hybrid renewable energy system containing a heat pump, Seasonal Thermal Energy Storage (STES), solar thermal, and district heating networks in a net zero energy community through a techno-economic analysis [59]. A case study of Jincheon, an eco-friendly energy city in South Korea (area of 72,000 m^2), was selected; it has 200 dwellings and six public buildings [59].

Kim et al. studied the impact of the solar fraction on levelized cost of heat (LCoH) and the impact of shifting to renewables, and performed an economic analysis of integration of thermal energy storage systems into the electricity and heating sector. A comparative analysis was conducted between three cases by using Transient System Simulation (TRNSYS) software: case 1, a gas-fired boiler and packaged air conditioning system; case 2, a centralized heat pump system; and case 3, a proposed HERS system [59].

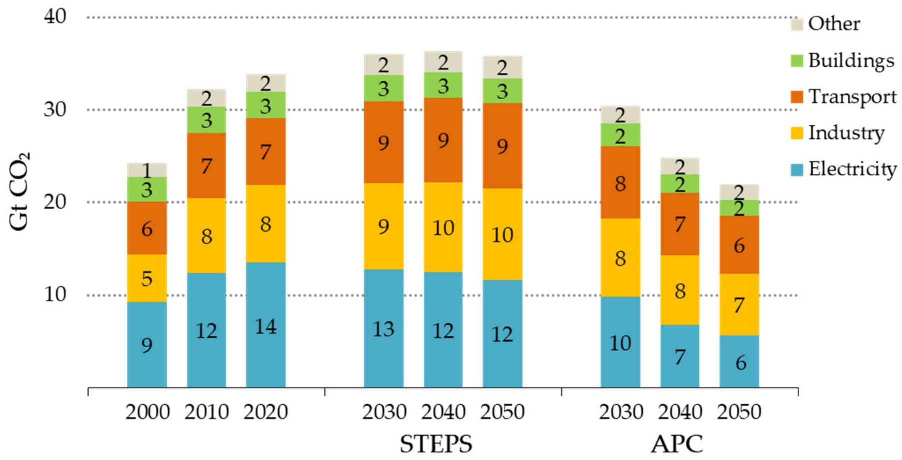
The result showed that by increasing the solar fraction of the proposed system from 42.8% to 91.8%, case 3 saved 73% and 61% of primary energy consumption compared to case 1 and case 2, respectively. In addition, the calculated equivalent CO_2 emissions presented a reduction of 17% compared to case 1 and 61% compared to case 2. The result of the LCoH analysis presented a 14% lower value for case 3 compared to case 1. Case 3 was selected as the best system pattern, and presented a benefit-cost ratio of 1.7 compared to both cases 1 and 2, with a six-year payback period [59].

The above studies underline the lack of a clear and common definition of NZC terms. For example, both studies use the term "net zero energy community", yet transport energy use is excluded, NZC targets and timescale are not clarified. The case studies are in different locations, Canada and South Korea, with different scales and building types, yet the direct effect of their climate and geographical contexts on the NZC methodology are not clarified. Bakhtavar et al. included LCA and LCC in their NZC optimization approaches, while Kim et al. did not. From these NZC studies by Kim and Bakhtavar, it can be concluded that supply–demand balancing optimization with renewables at a community level has positive outcomes but challenging solutions due to renewable source accessibility, uncertainties and variabilities, programming tools, the economic feasibility of the source shift, system efficiency and reliability, technical complications, and financial barriers. The mentioned challenges will be investigated by reviewing the projection models for the global energy sectors from 2020 to 2050, as well as current NZC projects.

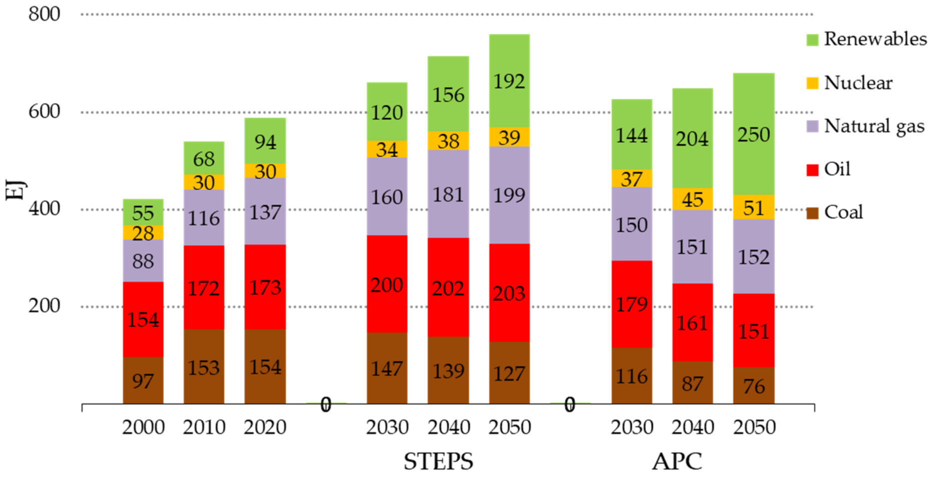
3. Global Climate Projection Model

The International Energy Agency (IEA) report in 2021 [17] presents a global roadmap toward achieving net zero emissions by 2050 (NZE), which requires all governments and policymakers to advance and implement their energy and climate policies. The primary CO_2 drivers are the increase in the world's population from 7.7 billion in 2020 to 9.7 billion in 2050 [60] and the world's economic growth, which is projected to be two times larger by 2050 when compared to 2020 [17]. There are different paths to achieving NZ emissions globally by 2050, and uncertainties that could affect those targets. According to the IEA, even if NZ meets the target "the pledges to date would still leave around 22 billion tonnes of CO_2 emissions worldwide in 2050" [17].

IEA categorized the NZ pledges into two groups: the *Stated Policies Scenario (STEPS)*, which considers "only the firm policies that are in place or have been announced by countries, including *Nationally Determined Contributions*" and the *Announced Pledges Case (APC)*, as "a variant of the STEPS that assumes that all of the net zero targets announced by countries around the world to date are met in full". Figure 2a,b presents the IEA's projections of the global CO_2 emissions and energy supply by 2050 based on both APC and STEPS NZ pledges.



(**a**)



(**b**)

Figure 2. IEA analyses of global CO_2 emissions and total energy supply between "State Policy Scenario" and "Announced Pledges Case". Source: IEA (2021) Net Zero by 2050 [17]. (**a**) Global CO_2 emissions by sector. Source: Modified from IEA (2021), Net Zero by 2050 [17]. All rights reserved. (**b**) Total energy supply by source. Source: Modified from IEA (2021), Net Zero by 2050 [17]. All rights reserved.

According to Figure 2, the NZ pledges announced by the APC group reduce CO_2 emissions in the electricity sector (60%), building (40%), transportation (25%), and industry (10%) in 2050 when compared to 2020.

In STEPS, however, there is a 15% reduction in electricity, 17% increase in building, 29% increase in transportation, and 4% reduction in industry sectors, with RE increasing from 16% to 25% from 2020 to 2050. The result is that even with optimistic APC projection data, the total fossil fuel-based energy supply reduces by 18% and CO_2 emissions by 35%, with a 38% increase in renewables. In STEPs even with doubling the renewables, total fossil fuel-based energy supply increases by 14%, and CO_2 emissions increase by 6% from 2020 to 2050. Therefore, there is a need for more firm policies and routes to regulate necessary actions in achieving NZ emissions targets by 2050.

Some of the key actions suggested by IEA at the larger scales include electric vehicles (EVs), electrifying end-uses in buildings, demand-side management (bioenergy, hydropower, battery storage), and on-site renewable-based energy systems [17]. EVs are around three times more efficient than combustion engine vehicles [17]. IEA predicted 60% total passenger EV car sales by 2030 (compared to 5% in 2020) and 100% electric or hydrogen-powered by 2050 [17]. When COVID-19 and economic crisis lowered car sales in 2021 (15% lower than in 2019) [61,62], countries such as China, Italy, and France released subsidies for promoting EVs. The Global EV Outlook 2020 [62] reported that global EV sales achieved a 3.2% overall market share in 2020.

Buildings are projected to demand 66% of their total energy use from electricity in 2050 (57 Exajoule (EJ)), which is a 35% increase from 2020 (42 EJ) [17]. This increasing rate of electricity demand requires demand-side management to stabilize the electricity supply through renewables and low-emission power production such as bioenergy, hydropower, and battery storage [17,63,64]. The main energy consumer end-uses in buildings are space heating and water heating, which are the major parts of renewable coverage. IEA projected that the direct use of renewables in global heating demand increases from 10% in 2020 to 40% in 2050; geothermal and solar thermal cover 75% of this [17]. Electricity demand is also controlled by improved efficiency in heating, cooling, appliances, lighting, and building envelopes. IEA recommended the adaptation of energy-related building codes and deep retrofits with renewables, including wind and solar power, hydropower, bioenergy, and geothermal [17,65].

Statistics show that the global gross domestic product (GDP) was about USD 85 trillion in 2020 and is projected to reach USD 122 trillion by 2026 [66]. IEA reported the NZE's projection on expanding the annual clean energy investment globally from USD 2 trillion (average over 2015–2020) to about USD 5 trillion by 2030 and USD 4.5 trillion by 2050 [17,67].

4. Decarbonization: Energy Efficiency, Electrification, and Renewables

According to the Organization for Economic Co-operation and Development (OECD) Environmental Outlook for 2050 [68], without new policy action, a four times larger world economy in 2050 is projected to use 80% more energy and produce 50% more GHG emissions compared with the year 2010. The atmospheric GHG concentration is predicted to reach 685 parts per million (ppm) carbon dioxide equivalent (CO_{2e}), with 530 ppm CO_2 concentration by 2050 [68,69]. This causes the global average temperature to increase to 3 °C to 6 °C higher by the end of the century compared to pre-industrial times [66]. While the atmospheric CO_2 concentration is calculated at the monthly average of 419 ppm in 2021, scientific analyses project that with a stabilizing GHG concentration at 450 ppm CO_{2e}, the possibility of limiting the global temperature rise below 2 °C could be between 40% to 60% [18,68,70–74]. To address decarbonization strategies and requirements, Table 5 summarizes climate targets, improved energy efficiency measures (EEMs), electrification, renewables, and future requirements by three main emitters of the world, China, the EU, and the US [68].

Table 5 highlights variations in climate target plans extrapolated from policy documents, including timescales, emission sources, political commitments, renewable accessibility, energy security, energy codes and standards, and optimization approaches. The pledges vary and are unclear: China, carbon neutral by 2060; the EU, NZ GHG emissions by 2050; and US, NZ emissions by 2050; it needs to be clarified if the emission source is only CO_2 or if other emission sources are included. However, most of the policy documents globally address EEMs, electrification, and renewable supplies as the main approaches toward achieving NZ emissions by 2050.

According to the IEA [17], the expansion of solar and wind power triples renewable generation by 2030 and increases it eightfold by 2050. Solar PV and wind power account for 50% of the growth in the RE supply, and bioenergy accounts for 30% [17,63]. In addition, it is projected that the total battery capacity will increase to 1600 GW by 2050 (70% more than in STEPS) [17]. Accordingly, China's electricity-related coal consumption is predicted by IEA to decline by 85% between 2020 to 2050 [17]. Therefore, IEA recommended increasing the annual global investment in clean energy from USD 380 billion in 2020 to USD 1.6 trillion by 2030 [65].

Table 5. Climate targets and approaches toward achieving net zero goals globally and by China, the EU, and the US.

Organization	Targets	Energy Efficiency Measures (EEMs)	Electrification	Renewables	Requirements
International Energy Agency (IEA) [17,75,76]	Global NZ emissions by 2050	High standard insulation, solar thermal, heat pumps, LED lighting and efficient appliances, electric vehicles (EV), EV private chargers, electricity demand-side management.	Space heating, water heating, appliances, EV, electric trucks and buses.	Wind and solar power, rooftop PV, hydropower, bioenergy, geothermal, battery storage.	Near-term policies for building energy code and standards, fossil fuel phase-out, low-carbon gases, acceleration of retrofits and financial incentives; decarbonization of the entire value chain (not only building); near-term government action on zero-carbon-ready compliant energy codes; revision of tariff design to include electricity (remote transmission, grid capacity, EV charging); expanding land use for bioenergy; clean energy investments; international co-operation.
European Union (EU) [77,78]	EU climate-neutral by 2050—an economy with NZ GHG emissions	Advanced HVAC equipment, smart building/appliances management systems, cogeneration (CHP), renovation with high insulation materials, modern technology (smart meters and thermostats), large-scale energy storage.	EV charging infrastructure, power-to-heat, power-to-chemical, hydrogen production, grid-connected electrolysis, automated mobility in all modes.	Solar heating systems, solar power, biofuels, onshore and offshore wind power, ocean and hydropower, biomass boiler, battery storage.	Concrete actions to achieve the EU 2050 decarbonization objectives; stronger incentives for electrification and new renewables (hydrogen); bolder energy saving targets; stronger regulation and incentives for renewable energies; commission for consistency; more focus on the heating and cooling sector in decarbonization policy.
China [65,79,80]	China carbon neutral (CO_2) by 2060	Solar thermal hot water, green technology and economy, incentives, modernization, emission management plan.	EV charging stations, high-voltage power grid, ground-source heat pumps, air-source heat pumps, hydrogen production.	Solar power, centralized renewable powered water heating, offshore and onshore wind, hydropower, Innovative grid system, storage.	More clarity on climate target metrics; shutting down insufficient industries; ambitious environmental laws and programs; shift away from coal with political commitment; planned reduction in the deployment of coal; clarification on peak emissions and economy-wide 'carbon cap'; short-term urgency.

Table 5. *Cont.*

Organization	Targets	Energy Efficiency Measures (EEMs)	Electrification	Renewables	Requirements
US Department of Energy (DOE) [81,82], New Building Institutes (NBI) [83], American Council for an Energy-Efficient Economy (ACEEE) [84]	US NZ emissions by 2050	LED lighting, EV, hybrid EV (HEV), plug-in EV (PEV), EV charging infrastructure, demand-side management, smart grid, high-quality walls and windows, high-performance appliances and equipment, optimized building designs, control system.	Space heating, water heating, cooktops, clothes drying and laundry, nuclear and hydrogen production.	Solar, wind, water, geothermal, biomass, energy storage, hydropower,	Updated code language to include electric infrastructure; state and federal energy efficiency code and standards; innovative technologies and strong policies; reestablishing U.S. global leadership on climate change; cost-effective solutions, equitable transition; climate resilience, predictability to drive long-term investment; stronger policy and regulations, case studies, outreach, education, supporters.

At the community level, the first step is to create an energy efficient plan and design measures. EEMs reduce energy use and demand in order to achieve lower energy use for a community [29–31,85]. IEA [17] presented electrification and renewables as the fastest way to reduce global emissions toward *NZ by 2050* (NZE), where 90% of all electricity generation, 25% of non-electric energy use in buildings and industry, and 60% of energy use in transport are from renewables. IEA projected 2.5% of the existing residential buildings in advanced economies will be retrofitted annually until 2050 to comply with "zero-carbon-ready building" standards, which is defined as a building that is "highly energy efficient and uses either renewable energy directly or from an energy supply that will be fully decarbonized in the NZE (such as electricity or district heat)" [17].

The American Council for an Energy Efficient Economy (ACEEE) 2019 [84] modeled the impact of combined energy efficiency, including electric vehicles (EV) and efficient transport systems, decarbonization and efficient industry, upgrades to existing buildings, new NZ buildings, and efficient appliances on the CO_2 emission reduction. The Annual Energy Outlook (AEO) 2019 [62], modified with additional renewables in the energy mix, was used as the baseline. ACEEE projected that the proposed EEMs could "cut US energy use and GHG emissions in half by 2050," (49% reduction in primary energy use and 57% in CO_2), shown in Figure 3.

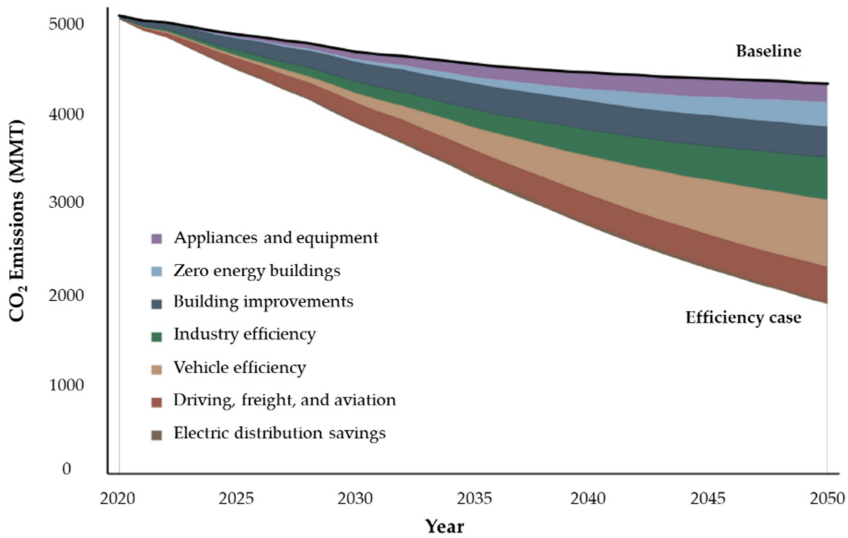


Figure 3. Energy-related carbon dioxide emissions in the reference and efficiency cases. Source: Modified from ACEEE (2019) [84]. Note: MMT means a million metric ton.

5. Global Energy Transitions toward Achieving NZ by 2050

Three existing planned NZ communities were selected for this section as they all use community renewable energy systems, incorporate energy efficiency measures, and are growing their renewable portion of electric power, as shown in Table 6.

As shown in Table 6, solar and wind power are the main renewable supplies in the precedent cases, along with CHP plant as an energy efficient system to reduce electricity and heating demand. To fully understand these technologies and their performance at the community level, this section reviews their energy characteristics, benefits, and challenges toward achieving NZ targets.

Table 6. Snapshot of three worldwide planned net zero communities with their main energy indicators.

Precedent Cases	Site Plan ©2021 Google Map	Renewable Supplies EEMs in Buildings	EEMs in Transportation
BedZED in London, UK		777 square meters of PV 130 kW biomass CHP	Solar-electric power systems Car club Bicycle/pedestrian network EV and charging station
West Village in California, US		5.4 MW of centralized PV 300 kW on-site biogas fuel cell generator	Solar canopies parking Public transit On-demand autonomous cars
Kronsberg, in Germany		Two decentralized CHP stations Three wind turbines	Parking enforcement Tramline Carpool programs

5.1. Solar Photovoltaic (PV)

According to the IEA, Photovoltaic Power Systems Programme (IEA-PVPS) [86] solar PV covered 42% of the total renewable electricity production in 2020—over 5% of global electricity production [87]. The location and size of the solar facility define whether it is a utility-scale or small-scale/distributed system [88]. Total generation capacity in utility-scale generation facilities is more than 1 MW unless multiple power technologies are available [88,89]. The small utility-scale facilities mainly depend on state-level practices and policies, and they function based on the independent grid in the form of rooftop PV and solar water heater systems [88–90]. The solar community strategies support the low utility-scale PV capacity, where off-site consumers can buy/import a portion of the solar power if solar production is not accessible. Based on the EIA [89], the consumers can also subscribe to the community solar facility to receive monthly credits on their electric bills.

The utility-scale solar energies (USSE) are often located far from the residential center [88]. In the US, the USSE capacity was increased by beyond 60% (both residential and non-residential) from 2009 to 2010—other countries showed increasing rates, including China, Australia, Spain, Italy, India, and Germany [88,91–94]. The outcome of COVID-19 caused an increase in the PV capacity globally in 2020 (total 760 gigawatts), where PV utilization covered about 3.7% of the world's electricity demand (6.2% China; 6% EU; 3.4% US), saved around 875 million tons of CO_{2e} by the end of 2020, and is on a path to decarbonizing the energy mix [86,95].

5.2. Wind Power

Wind power produced over 5% of the global electricity supply, with a total capacity of 591 GW (568.4 GW onshore) in 2018 [96]. To meet the IEA's NZE, 160 GW wind installation is needed by 2025 and 280 GW by 2030 [65]. According to the Global Wind Energy Council (GWEC) Market Intelligence [65], the world's wind power installation will exceed 1 TW by 2025, which estimates a 4% increasing compound annual growth rate (CAGR) for newly installed wind capacity, or adding 96 GW of new installations per year (total 469 GW) until 2025.

With the COVID 19 pandemic, global new wind power installations reached 93 GW, both onshore (86.9 GW) and offshore (6.1 GW) in 2020, a 53% growth compared to 2019 [65,97]. In 2020, Asia Pacific (60%) become the largest regional market for new wind installation in the world due to the significant installation rate in China. North America (18.4%) and Europe (15.9%) become the second and third largest regional market for new wind installation in the world [65]. Based on DOE [97], long-term growth in wind power capacity depends on incentives from the government such as renewable electricity production tax credits (PTC) at the US federal tax credit of 2.5 cents/kWh for generating from wind, biomass, and geothermal resources, as well as economic improvements to make it competitive with solar power and natural gas, clean energy demand, and state-level policies to upgrade the transmission infrastructure [98]. Near-term growth is influenced by wind power's performance and cost improvements, which reduce power sale prices, wind energy purchases, and state-level renewable power policies [97].

5.3. Combined Heat and Power (CHP) Plant

A CHP system, also known as cogeneration, is a higher efficiency approach to generating on-site electricity and thermal energy which would otherwise be wasted [99,100]. Based on the DOE, if properly designed and utilized, the overall efficiencies in CHP plants can exceed 80% [101,102]. CHP saves utility costs by reducing the need to purchase electricity from the grid. Different sizes include small-scale, which serves municipal or industrial users with less than 1 MW capacity, and large-scale, which serves cities [103]. CHP applies to places with hot water or steam requirements with higher heat loads [104]. The primary source for CHP plants is natural gas, due to its accessibility and cost effectiveness in countries such as Qatar, Iran, Russia, and the US [100]. Although the CHP's high initial investment, maintenance costs, and harmful gas releases restrict its usage, renewable sources such as biomass fuels as well as wood, oil, and processed waste can be used [105].

In 2019, a revenue share of 79.5% was reported for the large-scale CHP plants and 20% for the small-scale plants, with an expected 5.5% growth rate from 2020 to 2027—compared to the total capacity of all the plants [105]. Europe covered over 50% of the CHP installation demand in 2019 [100]. In the US, more than 4600 CHP sites provided 81 GW, which covered 10% of its total electric generation capacity [105]. Also, CHP provided more than 30% of electric generation capacity in countries such as Finland, Denmark, and the Netherlands, and around 27% in the Asia Pacific region [100,105]. The CHP plant positively impacts the local economy and supports national policy goals, including progressive climate change and the environment. It improves diversity in energy supply, business effectiveness, and resiliency of energy infrastructure [106].

The literature above show that solar, wind, and CHP are major global energy transition strategies toward achieving NZ by 2050, where China is the world's largest market for wind and solar, followed by the EU and US in 2020 [107].

6. Planned NZC Precedent Cases

These cases were selected from the world's pioneer planned NZ communities opened in 2000, 2002, and 2011 in Germany, London, and the US, respectively. The main energy technologies used in these cases included solar, wind, and CHP plant. Further EEMs and electrifications were used to reduce the peak loads including EV, EV charger/station, solar heating hot water, geothermal, heat pumps, high standard construction/lighting/appliances, and passive strategies. However, the communities have not achieved their NZ targets. The selected projects are the example of the world's NZC cases from the literature [108–118] with supporting resources and potential to address their NZ targets. This section reviews NZC targets, energy strategies, savings, and challenges in each case.

The key challenges for data collection were the lack of updated literature in the last five years on the existing communities with NZC targets and of peer-reviewed publications to present the calculated measures and track the projects' NZ progress. Most of the available documents are either old (before 2016) and/or published as technical reports, white papers, webpages, or handbooks. In some cases, the presented data varies between sources. For review purposes, approximate values were used to present data from the publications, as shown in Table 7.

Table 7. Planning characteristics of the worldwide precedent cases.

Master Plan	Area (ha)	Population	Dwellings	Density (du/ha)	Year (Project Opened)
BedZED	1.7	240	160	116	2002
West Village	83	4350	1006	~14 (4.5 du/acre)	2011
Kronsberg	1200	15,00	6000	47	2000

Note: ha = hectare; and du/ha = dwelling units/hectare.

6.1. Beddington Zero Energy Development (BedZED), London

BedZED is the UK's first and largest mixed-use eco-community. The project was completed in 2002 and is located in Hackbridge, London. BedZED community was designed by Bill Duster Architects in collaboration with the Peabody Trust (client) and Bioregional Development Group (environmental consultants) [119]. The project's size is 1.7 hectares (ha), with 116 dwellings per hectare, including live/work units [112,114,120,121]. BedZED includes 99 homes, with 220 residents and 100 office workers [112,114]. The project was planned as a response to the UK's Climate Change Action Act (1998–2002) to reduce CO_{2e} emissions by 80% by 2050 compared to 1990 levels [120]. The NZC in BedZED was defined as "an excellent passive building envelope that reduces the demand for heat and power to the point where it becomes economically viable to use energy generated on-site from renewable resources" [112]. The project aimed to cover emissions from office and local energy use, embodied energy from construction, transports, food, and waste [114]. An 81% reduction in energy use for hot water (5.2 kWh/person/day) and a 45% reduction in electricity use (3.4 kWh/person/day) was reported, compared to the average in Sutton, London [114,119,120].

The primarily utilized energy strategies were solar PV to cover 20% of the electricity demand and a 130 kW-biomass CHP plant for the rest of the electricity and all the heating related to hot water [114,120,122,123]. The community included a six-plot terrace with 18 dwellings with roofs being covered with 777 sqm of PV [114,119,124]. The total renewable energy cost breakdown (PV and CHP) was 5.8% of the total construction cost of the community (£15,250,000) [112].

The CHP system was planned based on a downdraft gasification method that converts woodchips into gas to produce electricity through a generator [114,125]. The local street tree surgery waste, certified by the Forest Stewardship Council, was used as a sustainable fuel for the CHP plant [114,120]. When fully operational, the CHP plant required 20 tonnes/week of woodchips with a cost of USD 34/tonne [126].

One of the challenges regarding the CHP plant was related to noise. The CHP plant was planned to switch off between 1:00 am and 4:00 am, which lowered the noise [120]. However, the restart programming caused complications with tar forming during system cool down [114,125]. It was concluded that the CHP system operates more efficiently if it runs constantly for a community as small as BedZED [114,125].

CHP's environmental savings were calculated as the generation of 726,000 kWh of electricity and 1,452,000 kWh of heat per year (with an average running time of 85% of the year) [112,126]. It is estimated that the CHP plant prevents about 326,000 kg of CO_2 emission per year from national grid electric production compared to gas-fired power systems [112]. However, the CHP plant was decommissioned due to its maintenance complications and running costs [114,120,126]. It was concluded that generating all energy on-site for a community as small as 2 ha is a challenging solution [114]. Chance [114] recommended the use of CHP plants only with advanced consideration of proper management in selecting, installing, and maintaining energy equipment [114].

Regarding the transport sector, BedZED is committed to the Green Transport Plan (GTP) to reduce car energy use by 50% in 10 years by:

1. Reducing parking space (less than one per home compared to the UK's typical 1.5/home);
2. Car club (London's first one);
3. Solar-electric PV systems to power 40 electric vehicles;
4. Electric charging station (free with every two of four parking spaces);
5. Pedestrian and bike network (living streets);
6. Public transport (bus stops, train stations);
7. Mixed use and internet delivery supermarkets [112,114].

As an outcome, the residents drove an average of 2318 km per year, which was 64% less than the local average [114]. The literature noted that "while it may not have met the original goals, BedZED was still an important step in the right direction towards a sustainable future" [119]. BedZED homes reduced their CO_2 emissions by 56% compared to the average UK home [114], which resulted in the community reducing its environmental impact by 20% to 30% by utilizing energy efficiency strategies in the construction stage [112,126].

The data reported on energy analyses and savings at the BedZED community are old (2007) and insufficient to track the project's NZC progress. A detailed energy evaluation of the project with updated measured data needs to be included in the published documented reports.

6.2. UC Davis West Village (West Village) Community, California

West Village is the largest planned "zero net energy" residential development in the US [127]. It is a mixed-use community that was opened in 2011 and is located on the University of California at Davis Campus. The project is owned and operated by West Village Community Partnership (WVCP) following the principles of New Urbanism linking walkability, sociability, and efficient transportation [110,128]. The community's size is 83 hectares, and it was planned for an ultimate capacity of 4350 residents including 663 apartments and 343 single-family homes [34,108,111,128,129]. The NZC in West Village was defined as "zero net electricity from the grid measured on an annual basis," where NZ is attained when the community generates 100% of its energy demand from on-site renewables [127,130]. The main NZC goal was to reduce the community's energy use and GHG emissions below California's Title 24 standards through on-site renewable generation and extensive use of energy efficiency measures [111,131,132]. Based on DOE [133], "Title 24 compliance savings were 31–39% depending on building and orientation". The West Village Energy Initiative (WVEI) targeted attainment of the NZ energy, where the WVEI Annual Report was a "snapshot of progress towards this goal" [128]. According to the 2013–14 WVEI report [128], the supply met the demand of the community by 82%. The project was planned to reduce energy use in single-family homes (65%), multiple-family homes (58%), commercial/mixed-use (45%), and common area lighting (50%) [111,134].

The primary on-site renewable energy utilized at the community included a centralized PV array, a Renewable Energy Anaerobic Digester (READ) system, and a 1 MW battery [110,134]. In 2012, 123 tonnes/day of waste was produced at UC Davis, with more than 85% organic waste [130]. The READ project was utilized to convert organic waste to renewable energy [110]. The outcome of the READ system was generating 5.6 GWh of renewable electricity, reducing up to 13,500 tonnes of GHG emissions annually, and delivering over 4 million gallons of fertilizer—enough to cover 56 ha of California's farmlands daily [110]. A 300 kW biogas fuel cell generator was utilized as a backup for the CHP plant [134]. Due to the insufficiency of the CHP to cover all the required demands of the community, a 5.4 MW PV was utilized to provide 9.2 million kWh electricity annually [111,134]. Regarding transportation energy use, the West Village utilized:

1. An integrated smart grid to support EV' charging stations;
2. A method developed to assess energy use from plug-in vehicles;
3. Battery-coupled solar charging stations for single-family homes;
4. EV and solar-based activities;
5. A street bicycle and pedestrian network;
6. Bus transit stops within a 5-min walk from residences;
7. Parking controls and car sharing programs;
8. Solar canopies for parking spaces;
9. Mixed use automated shuttles [111].

The NZC's energy use target in West Village was 9.2 million kWh [134]. According to Hammer et al. [135], "While West Village is close to achieving ZNE, it is not quite there as revealed from the energy modeler assumptions". The Energy Efficiency Center's modeling estimated a 58% reduction in total electricity use compared to the base case (23,295,000 kWh/yr) per the California Energy Efficiency Building Code (Title 24, 2008) [111,133]. The recommendations for achieving NZC at West Village were highlighted as a combination of aggressive EEMs, passive solar design, and renewable energy generation, as well as planning for NZC from the initial design phase.

There is a conflict between published reports and the project's NZC target plans, which might be due to the lack of published reports on the updated measured data. More details on EEMs and saving analyses need to be included in the publications that verify the NZC progress of the project.

6.3. Kronsberg District, Germany

Kronsberg district in Hannover, Germany was planned as a future sustainable urban development model [118,136]. The district was developed in the late 1990s to address the housing shortage problem in the city of Hannover. The first phase of the project was completed in 2000 and included 3000 units [116,118,137,138]. Kronsberg is a mixed-use residential district located on 1200 hectares, with 47 units per hectare and 68% open space [118,138]. The project was planned for an ultimate 6000 dwellings to accommodate 15,000 residents [116,139]. Kronsberg is the City of Hannover's vision for sustainable development and the first eco-settlement called "passive house settlement" in 2016. The project has contributed to the city's EXPO and its commitments under the United Nations' Agenda 21, with the motto of "Humankind—Nature—Technology" [136,138]. The planning of Kronsberg was influenced by 'Agenda 21', defined as a "vision for development that simultaneously promotes economic growth, improved quality of life and environmental protection" and the City of Hannover's climate plan of 1992 to reduce CO_2 emissions by 25% from 1990 levels [116].

Hannover's vision for sustainable development led to a planning process with energy reduction, mixed-income residential zones, and transit-oriented design goals [138]. Kronsberg's main energy strategies included EEMs, CHP plants, and renewable energy supplies. The NZC target at Kronsberg was to reduce CO_2 emissions by 60%, compared to the national construction standards, with the same upfront costs, and by an additional 20% by using renewable energy, particularly wind power. The result presented a 17% CO_2 reduction by applying the passive house (LEH) standard to all buildings (with subsidies) to use less than 55 kWh/m^2/y energy for space heating, and 13% reductions by incentivizing high efficiency lighting and appliances [116,140,141].

The primary energy strategies utilized in Kronsberg were district heating from two decentralized CHP stations, covering energy use for one-fifth of the community on the north side (700 homes, one school, and children's daycare center) and the rest on the south side [116]. The use of renewable technologies and CHP plants reduced CO_2 emission by 45% compared to conventional systems [142]. Three wind turbines utilized in 2001 generated 280 kW, 1.5 MW, and 1.8 MW, respectively [56,116,136].

Regarding the transport energy at Kronsberg, the goal was to reduce daily car trips by 20% through:

1. Public transit routes and bus stops, along with residential planning;
2. Bicycle and pedestrian networks;
3. A tramline that links Kronsberg with Hannover city center with a 20 min travel time (with 8–12 min intervals and five stops at every 300 m interval);
4. Locating the dwellings within a 1/2 km diameter from the stop stations;
5. Parking enforcement (0.8 cars per unit allowance);
6. A carpool program;
7. Mixed use neighborhood parks and sports, community gardens, organic farms, a primary school, a community center, district arts, three child daycare centers, a shopping center, a church, and a health center all provided a pedestrian friendly network [116,118,136,138].

The result showed a 71% carbon emission reduction and 3.6 MW electricity supply from combined wind power (37 $kWh/m^2/y$) and PV systems (0.04 $kWh/m^2/y$) by 2001 [116,118]. Fraker [116] noted that "in spite of not reaching the targets, these are excellent performance results". The goal of reducing electricity use by 30% was only covered by 5–6% reductions, yet the result of energy use for heating exceeded the goal of 55 $kWh/m^2/y$ in 2001 [116,141]. Although the goal for supply line losses regarding the district heating system was not fully met, the total energy use target exceeded by 12–18% at 125 $kWh/m^2/y$, mainly from CHP line losses, excluding solar [116,141]. It was concluded that energy efficiency strategies, even the "aggressive standard of the passive house", are the most cost-effective carbon reduction approaches [116].

The saving results at Kronsberg district are reported based on data measured in 2001–2003, which seems unimpressive compared to today's data and the project's NZC targets. New houses can meet this level of performance. Updated published data needs to be included in the publications to reflect the project's NZC progress.

6.4. NZC Analyses in Precedent Cases

The analyses from the previous cases present the way that NZC definition, requirements, primary sources, savings, and challenges vary for each project regarding demand reduction strategies and power production systems. One common NZC strategy in all of the cases is balancing on-site energy demand through improved EEMs and renewable supply. Table 8 presents a comparative analysis of the energy performance of each case based on their planned targets by showing the key drivers at the planning phase, the main requirements (emission source, site boundary, energy systems, renewable technologies), the planned energy saving targets, published measured data to verify energy performance and NZC achievements, and recommendations on the requirements necessary to achieve NZC objectives by 2050.

Table 8 shows that although different NZC targets could improve savings in energy and CO_2 emissions, the projects encountered barriers in achieving their NZ goals. The previous studies recommend the need for concrete regulations, incentives for renewables, planning for NZC strategies at early phases, and education on NZC and energy efficiency implementation in order to accelerate achieving targets.

Table 8. Analysis of NZC variation, strategy, and requirements from three preceding cases worldwide.

Precedent Cases	NZC Drivers	EEMs	Renewables	Main Challenges	NZC Outcome		Recommendations
					Planned	Measured (%)	
BedZED [112–114,120,121,123,142]	60% CO_2 emissions reduction by 2025 80% emission reductions by 2050	Passive strategies, energy efficient appliances and lighting, smart energy meters in kitchens, natural ventilation, high level insulation, daylighting, triple-glazed windows, south-facing sunspaces, EV solar charging station	PV, wind powered ventilation with heat recovery, biomass CHP with district heating, solar thermal	CHP's small-scale size to justify the maintenance cost, generate all energy on-site for small size sites, high construction cost (30%), lack of policy support for sustainable housing development	90% energy demand reduction for heating, cooling, ventilation from UK average home	- 81% reduction in hot water energy use - 45% reduction in electricity use (2007) - 56% CO_2 reductions in homes Need to publish ongoing data obtained.	Selecting proven technologies, proper management for the energy systems, improvements in transport infrastructure, stronger governmental regulations on energy efficiency
West Village [111,133,134,143]	80% GHG emissions reduction by 2050 50% Emissions reduction below California's Title 24 standards	Passive solar design, solar thermal rooftops, high level of insulation, radiant barrier roof sheathing, solar reflective roofing, plug-in electric and Hybrid EV, EV smart controls, high efficiency HVAC/lighting fixtures/Energy Star appliances, natural ventilation/daylighting, LED lighting with vacancy sensors,	PV arrays, Renewable Energy Anaerobic Digester (READ) system, battery storage, biogas, battery storage	Lack of regulations for small-size communities, cost of fuel cell battery, lack of low tariffs for biogas electricity, lack of no-solar renewable incentives, lack of financial incentives for renewable strategies, cost of inverter infrastructure, technical complications of the biodigester,	60% Energy use reduction from baseline 58% energy use reductions from energy modeling estimates	Need for published reports on the measured data to verify calculations.	Incentive programs for residents to reduce energy consumption; detailed studies of actual energy use, renewable power generation, and resident behavior; combining main strategies of passive solar design, energy efficiency measures, and renewable energy to achieve NZ status; designing NZ strategies at early stages,
Kronsberg District [116,118,141,143]	60% CO_2 reductions compared to the national construction standards without increasing the costs	Mandated Low Energy House (LEH) standard buildings, airtight construction, high efficiency lighting and appliances, CHP plants and district heating, passive standards, solar thermal, pedestrian/biking networks, tramline,	Wind turbines, PV, solar storage	Lack of comprehensive transport survey to confirm energy use by private cars, human behavior in opting for high efficiency appliances, higher energy consumption than predicted, CHP line losses, building orientation regarding passive solar design	- Reducing electricity use by 30% - Total energy use (105 kWh/m^2/y) - 60% CO_2 reductions plus 20% from wind power (80%), compared to the national construction standards	- 5–6% electricity use reduction, - 12–18% increase in energy use - 46% CO_2 reductions (2001) and 71% reduction with including the solar PV and wind powers. Need to publish ongoing data obtained.	Devise new legal and regulatory instruments to assure the planned targets are met; update and refine tools over time; the need for broad NZ education; identifying regulatory and legislative barriers and solutions for adopting NZ.

The NZC performance in the West Village community was estimated with energy modeling, without presenting updated measured data. Also, the presented measured data in the Kronsberg district and BedZED community are as old as 2001 and 2007, respectively. From 2001 to 2021, the projects' energy performance and savings could have changed, yet there are not any updated measured data to track and verify their NZ progress.

Further, the analyses from the preceding cases highlight the impacts of NZC planning in the early design phases on energy efficiency, emissions, and utility and operational costs. For example, the BedZED community's initial plan was to generate energy from small wind turbines, thermal collectors, and PV systems, while the community shifted to a bio-fueled CHP plant to make the project cost-viable [114]. The CHP plant was removed in 2005 due to maintenance complications [125]. In 2017, a 240-kW biomass boiler was installed as an NZ carbon fuel alternative to provide all the required heat from the community's district heating system [120,125]. The BedZED project acquired a green tariff on its purchased grid electricity, where all supplied energy needed to achieve its carbon-neutral goal had to be generated by wind turbines and hydropower plants [121,125]. It took BedZED over ten years to justify wind power as a proper system to fulfill its NZC goal [125].

In the West Village community, PV arrays initially generated more than 100% of the electricity used by buildings, which later was modified to combine solar thermal rooftop and PV systems; solar arrays were planned to generate electricity off-site, but due to financial and infrastructure complications the PVs were placed on the rooftops and canopies. The biodigester system initially used anaerobic decomposition of liquid waste to generate power; however, in 2006, Professor Ruihong Zhang addressed the challenges in economics, speed of digestion, and material processing to utilize and commercialize mixed wet and dry wastes [111].

The review of the preceding cases provides knowledge regarding improved EEMs, community power systems, efficient transportation for communities with different sizes, locations, and requirements in achieving energy efficiency plans. However, the cases insufficiently reflect their commitments to NZC, mostly due to the lack of updated measured data to track their progress and the lack of peer-reviewed publications to document their performance and practices. To strengthen the projects as the world's example of NZCs, they need to provide publicly available published reports to track the performance of their ongoing NZC cases and objectives.

7. Results and Recommendations

A key finding of this review is the lack of quality data. As community organizations approach adopting an NZC, the need for supporting standards and published information on accessing the measured data is crucial for the success of a project in order to verify its NZC objectives. Previous studies showed that planned NZC communities with aggressive energy efficiency strategies and renewables have not met their NZC targets. The main challenges were lack of policy documents that support their strategies and lack of updated published measured data to report their savings. The communities need to upgrade their data with publicly available websites to track their progress.

Two requirements are recommended for NZC design guidelines: (1) minimize the community's total energy demand and (2) maximize renewables in the community energy supply. Figure 4 presents demand reduction strategies extrapolated from the global climate policy documents (Table 5) and the NZC performances in previous cases (Table 8), which are emphasized and recommended by selected publications on NZC [17,65,75–84,111,112,114,116,118,120,133,134,141,143].

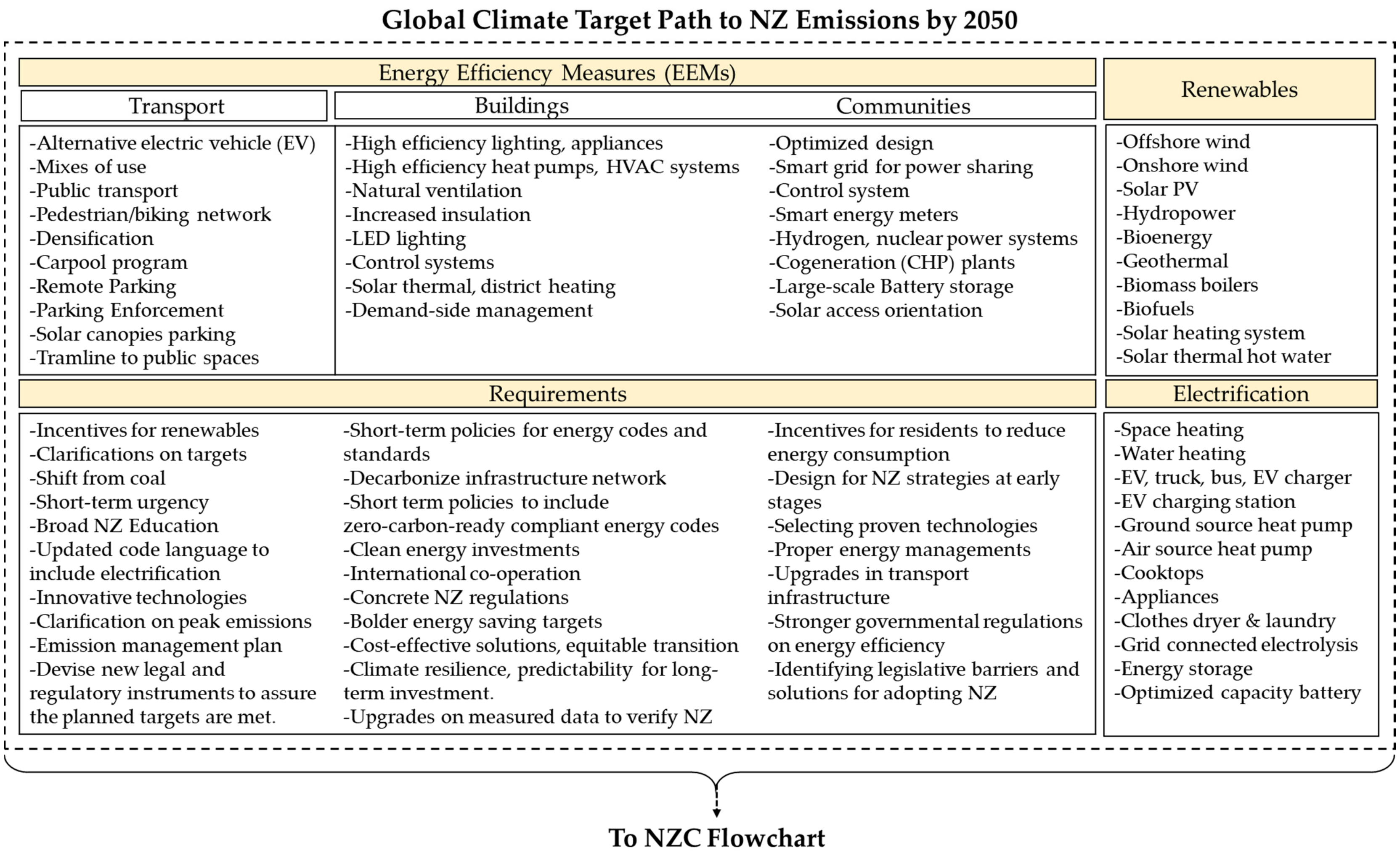


Figure 4. Highlighted climate mitigation strategies to accelerate achieving global NZ emission targets.

Figure 5 presents an NZC Flowchart as a design guideline applicable to communities in accelerating their NZ targets. The NZC flowchart recommends reducing the community's fossil fuel-based energy demand through EEMs and electrification strategies, and generating the rest of the required energy from renewables (from Figure 4). In this paper, the NZC path is considered based on Carlisle's [33] near-zero community concept, where 75% of energy demand is generated from on-site renewable supplies. If a community is not on an NZC path, additional requirements are needed to support energy efficiency strategies through governmental legislation to help the community meet its NZC objectives.

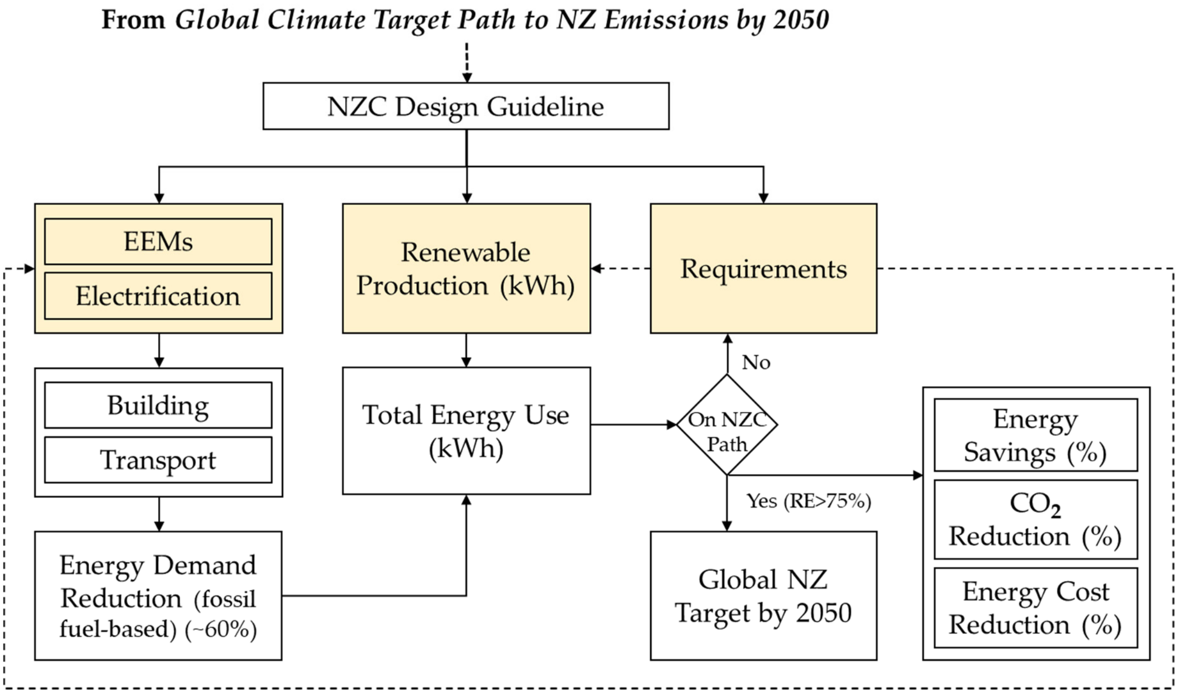


Figure 5. NZC Flowchart, energy balance in a community through EEMs, electrification, and renewables.

According to the flowchart, a community could be on the NZ path by minimizing its total peak loads in the building and transportation sectors and generating at least 75% of its total energy use through renewables.

8. Conclusions and Future Work

The Net Zero Community is an emerging concept in the field of global energy and the built environment. This paper summarized the multiple definitions of NZC.

Three ongoing NZC studies showed that:

1. NZ design principles can be achieved at the community level by addressing EEMs, electrification, and renewables in the PBT sectors;
2. The energy savings process needs to happen in the early phases of the planning;
3. NZC requirements and structured approaches must be defined;
4. Published measured data is needed to verify the NZC commitments of each project.

The literature showed that the existing NZC concepts vary in their definitions of terms, emission sources, timescales, and energy source/supply requirements. These differences complicate tracking NZC successes. The current global climate mitigation solutions, although they improve savings in energy and CO_2 reduction, are still insufficient to achieve the global NZ emission targets by 2050. In addition, the cases reviewed here showed that most communities have not published updated measured data on their NZC success and that there is a lack of data to quantify their energy performances.

Planning measures are necessary for a community to achieve its NZC objectives. The authors recommend:

1. Clarification of NZC targets by specifying all NZC requirements;
2. Setting concrete regulations and policies to incorporate the use of EEMs, electrification, and renewables into current energy codes and standards;
3. Mandating public availability of the measured data on projects' NZC performance.

Providing NZC energy design guidelines to enable stakeholders, including policymakers, developers, engineers, building and grid designers, and researchers in this field to quantify and track the progress of the NZC concept.

Comprehensive analysis on the existing climate target plans and metrics of the current 121 countries and 33 states in the US are required to evaluate their NZ emission commitments and practices. A detailed community energy analysis of the measured data is required to develop a formulated NZC model.

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Nomenclature

NZ	Net zero energy
NZB	Net zero energy building
NZC/ZEC/nZEN	Net zero energy community/neighborhood
ZenN/	Nearly net zero energy neighborhood
PED	Positive energy district
SPEN	Sustainable plus energy neighborhood
FME ZEN	Zero emission neighborhoods in smart cities
NZED	Net zero energy district
NZEB/nZEB	Nearly net zero energy building
NZE	Net zero by 2050
PBT	Power systems, building and transport sectors
GHG	Greenhouse gas
CO_2	Carbon dioxide
CO_{2e}	Carbon dixide equivalent
EJ	Exajoule
PPM	Parts per million
EEMs	Energy efficient measures
STEPS	Stated policies scenario
APC	Announced pledges case
EVs	Electric vehicles
PEV	Plug-in EV
HEV	Hybrid EV
TWh	Terawatt-hours
GWdc	Gigawatts, direct current
GDP	Gross domestic product
CAGR	Compound annual growth rate
RE	Renewable energy
LCC	Life cycle cost
LCA	Life cycle assessment
HVAC	Heating, ventilation, and air conditioning
CHP	Combined heat and power plant
PV	Photovoltaic

WtE	Waste-to-energy
STES	Seasonal thermal energy storage
LCoH	Levelized cost of heat
TRNSYS	Transient system simulation
HERS	Hybrid renewable energy systems
USSE	Utility-scale solar energies
READ	Renewable energy anaerobic digester
LEH	Low energy house
IEA-PVPS	Photovoltaic power systems programme
NDCs	Nationally determined contributions
UNFCCC	United nations framework convention climate change
COP26	The 26th United Nations Climate Change conference
GWEC	Global wind energy council
AEO	Annual energy outlook
DOE	Department of energy
ACEEE	American council for an energy-efficient economy
OECD	Organization for economic co-operation and development
AIA	American institute of architects
DGS	Department of general services
NBI	New buildings institute
ILFI	International living future institute
EPBD	European performance of buildings directive
REHVA	Federation of european ventilation and air-conditioning associations
USGBC	Green building council
IESNA	Illumination engineering society of north america
IPCC	Intergovernmental panel on climate change
ECIU	Energy and climate intelligence
NREL	National renewable energy laboratory
EIA	Energy information administration
IEA	International energy agency
WVCP	West village community partnership
WVEI	West village energy initiative

References

1. United Nations (UN). The Sustainable Development Agenda. 2020. Available online: https://www.un.org/sustainabledevelopment/development-agenda/ (accessed on 24 October 2021).
2. International Energy Agency (IEA). Energy Efficiency: The First Fuel of a Sustainable Global Energy System. 2020. Available online: https://www.iea.org/topics/energy-efficiency (accessed on 24 October 2021).
3. International Energy Agency (IEA). Buildings: A Source of Enormous Untapped Efficiency Potential. 2021. Available online: https://www.iea.org/topics/buildings (accessed on 6 July 2021).
4. Pablo-Romero, M.D.P.; Pozo-Barajas, R.; Yñiguez, R. Global changes in residential energy consumption. *Energy Policy* **2017**, *101*, 342–352. [CrossRef]
5. Nejat, P.; Jomehzadeh, F.; Taheri, M.M.; Gohari, M.; Muhd Zaimi Abd, M. A global review of energy consumption, CO_2 emissions and policy in the residential sector (with an overview of the top ten CO_2 emitting countries). *Renew. Sustain. Energy Rev.* **2015**, *43*, 843–862. [CrossRef]
6. U.S. Energy Information Administration (EIA). International Energy Outlook: Chapter 8—Transportation Sector Energy Consumption. 2016. Available online: https://www.eia.gov/outlooks/ieo/pdf/transportation.pdf (accessed on 6 July 2021).
7. Ritchie, H. Cars, Planes, Trains: Where do CO_2 Emissions from Transport Come from? 6 October 2020. Available online: https://ourworldindata.org/co2-emissions-from-transport (accessed on 6 July 2021).
8. U.S. Environmental Protection Agency (EPA). Greenhouse Gas Emissions: Global Greenhouse Gas Emissions Data. 25 March 2021. Available online: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (accessed on 6 July 2021).
9. Ritchie, H. Electricity Mix. 2020. Available online: https://ourworldindata.org/electricity-mix (accessed on 6 July 2021).
10. Masson-Delmotte, V.; Zhai, P.; Pörtner, H.-O.; Roberts, D.; Skea, J.; Shukla, P.R.; Pirani, A.; Moufouma-Okia, W.; Péan, C.; Pidcock, R.; et al. Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. 2019. in press. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf (accessed on 2 May 2021).
11. Buis, A. A Degree of Concern: Why Global Temperatures Matter. NASA's Global Climate Change Website. 2019. Available online: https://climate.nasa.gov/news/2865/a-degree-of-concern-why-global-temperatures-matter/ (accessed on 23 July 2021).

12. Intergovernmental Panel on Climate Change (IPCC). Global Warming of 1.5 °C. 2019. Available online: https://www.ipcc.ch/sr15/ (accessed on 23 July 2021).
13. Intergovernmental Panel on Climate Change (IPCC). FAQ Chapter 1. Why Are We Talking About 1.5 °C? 2019. Available online: https://www.ipcc.ch/sr15/faq/faq-chapter-1/ (accessed on 23 July 2021).
14. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 9 August 2021. Available online: https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/ (accessed on 13 September 2021).
15. United Nations (UN). United Nations Secretariat Climate Action Plan 2020–2030. 2019. Available online: https://www.un.org/management/sites/www.un.org.management/files/united-nations-secretariat-climate-action-plan.pdf (accessed on 24 October 2021).
16. United Nations (UN). Paris Agreement. 2015. Available online: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf (accessed on 2 May 2021).
17. International Energy Agency (IEA). Net Zero by 2050: A Roadmap for the Global Energy Sector. May 2021. Available online: https://iea.blob.core.windows.net/assets/4482cac7-edd6-4c03-b6a2-8e79792d16d9/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf (accessed on 30 May 2021).
18. Rogelj, J.; Luderer, G.; Pietzcker, R.; Kriegler, E.; Schaeffer, M.; Krey, V.; Riahi, K. Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Chang.* **2015**, *5*, 519–527. [CrossRef]
19. International Energy Agency (IEA). Global Energy Review 2021. Assessing the Effects of Economic Recoveries on Global Energy Demand and CO_2 Emissions in 2021. 2021. Available online: https://iea.blob.core.windows.net/assets/d0031107-401d-4a2f-a48b-9eed19457335/GlobalEnergyReview2021.pdf (accessed on 9 August 2021).
20. Moghaddasi, H.; Culp, C.; Vanegas, J.; Ehsani, M. Net Zero Energy Buildings: Variations, Clarifications, and Requirements in Response to the Paris Agreement. *Energies* **2021**, *14*, 3760. [CrossRef]
21. International Energy Agency (IEA). World Energy Outlook 2020. October 2020. Available online: https://doi-org.srv-proxy2.library.tamu.edu/10.1787/20725302 (accessed on 24 October 2021).
22. Attia, S. *Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmap for Project Analysis and Implementation*; Elsevier Science: Oxford, UK, 2018.
23. Chen, Y.; Hong, T.; Piette, M.A. Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis. *Appl. Energy* **2017**, *205*, 323–335. [CrossRef]
24. Sun, Y.; Huang, P.; Huang, G. A multi-criteria system design optimization for net zero energy buildings under uncertainties. *Energy Build.* **2015**, *97*, 196–204. [CrossRef]
25. Aelenei, L.; Gonçalves, H. From Solar Building Design to Net Zero Energy Buildings: Performance Insights of an Office Building. *Energy Procedia* **2014**, *48*, 1236–1243. [CrossRef]
26. Gupta, S.; Smith, J.; Itron. Research Gap Analysis for Zero-Net Energy Buildings: Final Project Report. 2019. Available online: https://ww2.energy.ca.gov/2019publications/CEC-500-2019-031/CEC-500-2019-031.pdf (accessed on 3 February 2021).
27. Lucon, O.; Vorsatz, D.; Ahmed, A.Z.; Akbari, H.; Bertoldi, P.; Cabeza, L.; Eyre, N.; Gadgil, A.; Harvey, D.; Jiang, Y.; et al. *Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
28. International Energy Agency and United Nations Environment Programme (UNEP). Global Status Report towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. 2018. Available online: http://hdl.handle.net/20.500.11822/27140 (accessed on 2 February 2021).
29. Hammon, R.W. Applications for Large Residential Communities: What is Net-zero Energy? *Strateg. Plan. Energy Environ.* **2010**, *29*, 26–55. [CrossRef]
30. Leibowicz, B.D.; Lanham, C.M.; Brozynski, M.T.; Vázquez-Canteli, J.R.; Nicolás Castillo, C.; Zoltan, N. Optimal decarbonization pathways for urban residential building energy services. *Appl. Energy* **2018**, *230*, 1311–1325. [CrossRef]
31. Vera, I.; Langlois, L. Energy indicators for sustainable development. *Energy* **2007**, *32*, 875–882. [CrossRef]
32. Kallushi, A.; Harris, J.; Miller, J.; Johnston, M.; Ream, A. Think Bigger: Net-Zero Communities. Proceedings of ACEEE 2012. pp. 115–127. Available online: https://www.aceee.org/files/proceedings/2012/data/papers/0193-000355.pdf (accessed on 8 August 2021).
33. Carlisle, N.; van Geet, O.; Pless, S. *Definition of a'Zero Net Energy'Community*; National Renewable Energy Lab.(NREL): Golden, CO, USA, 2009.
34. Marique, A.-F.; Reiter, S. A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale. *Energy Build.* **2014**, *82*, 114–122. [CrossRef]
35. Sørnes, I.S.K.; Fredriksen, E.; Martinsson, F.; Romero, A.; Rodriguez, F.; Schneuwly, P. Nearly Zero Energy Neighborhoods. Final Report on Common Definition for nZEB Renovation. D.1.2 Report. 2014. Available online: https://smart-cities-marketplace.ec.europa.eu/sites/default/files/zenn_final_report_on_common_definition_for_nzeb_renovation.pdf (accessed on 14 September 2021).
36. Peterson, L.; Torcellini, P.; Grant, R. A Common Definition for Zero Energy Buildings. Department of Energy (DOE). 2015. Available online: https://www.energy.gov/sites/prod/files/2015/09/f26/A%20Common%20Definition%20for%20Zero%20Energy%20Buildings.pdf (accessed on 3 February 2021).

37. Pless, S.; Polly, B.J.; Zaleski, S. Communities of the Future: Accelerating Zero Energy District Master Planning. 2018. Available online: https://www.nrel.gov/docs/fy18osti/71841.pdf (accessed on 8 August 2021).
38. Koutra, S.; Becue, V.; Gallas, M.-A.; Ioakimidis, C.S. Towards the development of a net-zero energy district evaluation approach: A review of sustainable approaches and assessment tools. *Sustain. Cities Soc.* **2018**, *39*, 784–800. [CrossRef]
39. International Living Future Institute (ILFI). The Living Community Challenge (LCC) Handbook: A Visionary Path to a Regenerative Future. In *Living Community Challengesm 1.2*; International Living Future Institute: Seattle, WA, USA, 2019.
40. Salom, J.; Tamm, M. *WP3* Technology Integration in Smart Managed Plus Energy Buildings and Neighbourhoods D3.1 Methodology Framework for Plus Energy Buildings and Neighbourhoods. 30-09-2020/M9. 2020. Available online: https://www.synikia.eu/wp-content/uploads/2020/12/D3.1_Methodology-framework-for-Plus-Energy-Buildings-and-Neighbourhoods.pdf (accessed on 14 September 2021).
41. Hinterberger, R.; Gollner, C.; Noll, M.; Meyer, S.; Schwarz, H. Reference Framework for Positive Energy Districts and Neighbourhoods. 23 March 2020. Available online: https://jpi-urbaneurope.eu/wp-content/uploads/2020/04/White-Paper-PED-Framework-Definition-2020323-final.pdf (accessed on 9 September 2021).
42. Wiik, M.R.K.; Fufa, S.M.; Fjellheim, K.; Lien, S.K.; Krogstie, J.; Ahlers, D.; Wyckmans, A.; Driscoll, P.; Brattebø, H.; Gustavsen, A. Zero Emission Neighbourhoods in Smart Cities. Definition, Key Performance Indicators and Assessment Criteria: Version 2.0. ZEN Report 2021. Available online: https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/2738744/ZEN%2bReport%2bno%2b32.pdf?sequence=1&isAllowed=y (accessed on 14 September 2021).
43. Polly, B.; Kutscher, C.; Macumber, D.; Schott, M.; Pless, S.; Livingood, B.; Van Geet, O. From zero energy buildings to zero energy districts. In Proceedings of the 2016 American Council for an Energy Efficient Economy Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 21–26 August 2016.
44. Kennedy, S.; Sgouridis, S. Rigorous classification and carbon accounting principles for low and Zero Carbon Cities. *Energy Policy* **2011**, *39*, 5259–5268. [CrossRef]
45. Amaral, A.R.; Rodrigues, E.; Gaspar, A.R.; Gomes, Á. Review on performance aspects of nearly zero-energy districts. *Sustain. Cities Soc.* **2018**, *43*, 406–420. [CrossRef]
46. Brozovsky, J.; Gustavsen, A.; Gaitani, N. Zero emission neighbourhoods and positive energy districts—A state-of-the-art review. *Sustain. Cities Soc.* **2021**, *72*, 103013. [CrossRef]
47. Torcellini, P.; Pless, S.; Deru, M.; Crawley, D. *Zero Energy Buildings: A Critical Look at the Definition*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2006. Available online: https://www.nrel.gov/docs/fy06osti/39833.pdf (accessed on 25 December 2020).
48. Ravindra, K.; Iyer, P.P. Decentralized demand–supply matching using community microgrids and consumer demand response: A scenario analysis. *Energy* **2014**, *76*, 32–41. [CrossRef]
49. Neves, D.; Silva, C.A.; Connors, S. Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies. *Renew. Sustain. Energy Rev.* **2014**, *31*, 935–946. [CrossRef]
50. Petersen, J.-P. Energy concepts for self-supplying communities based on local and renewable energy sources: A case study from northern Germany. *Sustain. Cities Soc.* **2016**, *26*, 1–8. [CrossRef]
51. Vindel, E.; Berges, M.; Akinci, B. Energy sharing through shared storage in net zero energy communities. In *Journal of Physics: Conference Series*; IOP Publishing: Lausanne, Switzerland, 2019.
52. Gjorgievski, V.Z.; Chatzigeorgiou, N.G.; Venizelou, V.; Christoforidis, G.C.; Georghiou, G.; Papagiannis, G. Evaluation of Load Matching Indicators in Residential PV Systems-the Case of Cyprus. *Energies* **2020**, *13*, 1934. [CrossRef]
53. Parra, D.; Swierczynski, M.; Stroe, D.I.; Norman, S.A.; Abdon, A.; Worlitschek, J.; O'Doherty, T.; Rodrigues, L.; Gillott, M.; Zhang, X.; et al. An interdisciplinary review of energy storage for communities: Challenges and perspectives. *Renew. Sustain. Energy Rev.* **2017**, *79*, 730–749. [CrossRef]
54. Parra, D.; Norman, S.A.; Walker, G.S.; Gillott, M. Optimum community energy storage system for demand load shifting. *Appl. Energy* **2016**, *174*, 130–143. [CrossRef]
55. Palacios-Garcia, E.J.; Moreno-Munoz, A.; Santiago, I.; Moreno-Garcia, I.M.; Milanés-Montero, M. Smart community load matching using stochastic demand modeling and historical production data. In Proceedings of the 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016.
56. Moghaddasi, H.; Tabb, P.; Rashed-Ali, H. What It Takes to Become a Net Zero Development: Case Study of Serenbe, Georgia. *Prometheus* **2020**, *4*, 84–89. Available online: https://prometheus.library.iit.edu/index.php/journal/article/view/58 (accessed on 25 October 2021).
57. Bakhtavar, E.; Prabatha, T.; Karunathilake, H.; Sadiq, R.; Hewage, K. Assessment of renewable energy-based strategies for net-zero energy communities: A planning model using multi-objective goal programming. *J. Clean. Prod.* **2020**, *272*, 122886. [CrossRef]
58. Xie, N. Interval grey number based project scheduling model and algorithm. *Grey Syst. Theory Appl.* **2018**, *8*, 100–109. [CrossRef]
59. Kim, M.-H.; Kim, D.; Heo, J.; Lee, D.-W. Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community. *Energy* **2019**, *187*, 115916. [CrossRef]
60. United Nations (UN). World Population Prospects 2019: Highlights. 17 June 2019. Available online: https://www.un.org/development/desa/publications/world-population-prospects-2019-highlights.html (accessed on 6 August 2021).

61. Statista Research Department. Global Car Sales 2010–2021. 8 April 2021. Available online: https://www.statista.com/statistics/200002/international-car-sales-since-1990/ (accessed on 23 July 2021).
62. U.S. Energy Information Administration (EIA). Annual Energy Outlook 2019, with Projections to 2050. 24 January 2019. Available online: https://www.tealnr.com/sites/default/files/resourcesAnnualEnergyOutlook_0.pdf (accessed on 23 July 2021).
63. International Energy Agency (IEA). What Does Net-Zero Emissions by 2050 Mean for Bioenergy and Land Use? 31 May 2021. Available online: https://www.iea.org/articles/what-does-net-zero-emissions-by-2050-mean-for-bioenergy-and-land-use (accessed on 11 August 2021).
64. Rogers, J.N.; Stokes, B.; Dunn, J.; Cai, H.; Wu, M.; Haq, Z.; Baumes, H. An assessment of the potential products and economic and environmental impacts resulting from a billion ton bioeconomy. *Biofuels Bioprod. Biorefining* **2017**, *11*, 110–128. [CrossRef]
65. Global Wind Energy Council (GWEC). Global Wind Report: Wind Energy's Role on the Road to Net Zero. 25 March 2021. Available online: https://gwec.net/wp-content/uploads/2021/03/GWEC-Global-Wind-Report-2021.pdf (accessed on 11 July 2021).
66. O'Neill, A. Global Gross Domestic Product (GDP) 2026. 30 July 2021. Available online: https://www.statista.com/statistics/268750/global-gross-domestic-product-gdp/ (accessed on 5 August 2021).
67. International Energy Agency (IEA). Electricity Market Report. July 2021. Available online: https://www.iea.org/reports/electricity-market-report-july-2021 (accessed on 19 July 2021).
68. Pomázi, I. OECD Environmental Outlook to 2050. The Consequences of Inaction. *Hung. Geogr. Bull.* **2012**, *61*, 343–345. [CrossRef]
69. Meinshausen, M.; Smith, S.J.; Calvin, K.; Daniel, J.S.; Kainuma, M.; Lamarque, J.; Matsumoto, K.; Montzka, S.; Raper, S.; Riahi, K. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim. Chang.* **2011**, *109*, 213–241. [CrossRef]
70. National Oceanic and Atmospheric Administration (NOAA). NOAA Research News. 7 June 2021. Available online: https://research.noaa.gov/article/ArtMID/587/ArticleID/2764/Coronavirus-response-barely-slows-rising-carbon-dioxide (accessed on 6 August 2021).
71. Rogelj, J.; den Elzen, M.; Höhne, N.; Fransen, T.; Fekete, H.; Winkler, H.; Schaeffer, R.; Sha, F.; Riahi, K.; Meinshausen, M. Paris Agreement climate proposals need a boost to keep warming well below 2 C. *Nature* **2016**, *534*, 631–639. [CrossRef]
72. Meinshausen, M.; Meinshausen, N.; Hare, W.; Raper, S.C.; Raper, S.; Frieler, K.; Knutti, R.; Frame, D.; Allen, M. Greenhouse-gas emission targets for limiting global warming to 2 C. *Nature* **2009**, *458*, 1158–1162. [CrossRef]
73. Van Vuuren, D.P.; de Vries, B.; Beusen, A.; Heuberger, P.S. Conditional probabilistic estimates of 21st century greenhouse gas emissions based on the storylines of the IPCC-SRES scenarios. *Glob. Environ. Chang.* **2008**, *18*, 635–654. [CrossRef]
74. Van Vuuren, D.; Meinshausen, M.; Plattner, G.; Joos, F.; Strassmann, K.; Smith, S.; Wigley, T.; Raper, S.; Riahi, K.; De la Chesnaye, M.; et al. Temperature increase of 21st century mitigation scenarios. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 15258–15262. [CrossRef] [PubMed]
75. International Energy Agency (IEA). Energy Efficiency. 2020. Available online: https://iea.blob.core.windows.net/assets/59268647-0b70-4e7b-9f78-269e5ee93f26/Energy_Efficiency_2020.pdf (accessed on 15 September 2021).
76. Schreurs, M.A. The Paris Climate Agreement and the Three Largest Emitters: China, the United States, and the European Union. *Politics Gov.* **2016**, *4*, 219–223. [CrossRef]
77. European Union (EU). 2050 Long-Term Strategy. 2021. Available online: https://ec.europa.eu/clima/policies/strategies/2050_en (accessed on 16 September 2021).
78. Potrč, S.; Čuček, L.; Martin, M.; Kravanja, Z. Sustainable renewable energy supply networks optimization—The gradual transition to a renewable energy system within the European Union by 2050. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111186. [CrossRef]
79. Black, R.; Cullen, K.; Fay, B.; Hale, T.; Lang, J.; Mahmood, S.; Smith, S. Taking Stock: A Global Assessment of Net Zero Targets, Energy & Climate Intelligence Unit and Oxford Net Zero. 2021. Available online: https://eciu.net/analysis/reports/2021/taking-stock-assessment-net-zero-targets (accessed on 29 April 2021).
80. New Climate Institute & Data-Driven EnviroLab. Navigating the Nuances of Net-Zero Targets. 2020. Available online: https://newclimate.org/wp-content/uploads/2020/10/NewClimate_NetZeroReport_October2020.pdf (accessed on 3 May 2021).
81. U.S. Department of Energy (DOE). A National Roadmap for Grid-Interactive Efficient Buildings. 17 May 2021. Available online: https://gebroadmap.lbl.gov/ (accessed on 24 October 2021).
82. U.S. DEpartment of Energy (DOE). Statutory Requirements. 2021. Available online: https://www.energycodes.gov/statutory-requirements (accessed on 16 September 2021).
83. Alexi Miller and Cathy Higgins. The Building Electrification Technology Roadmap (BETR). New Buildings Institute (NBI). January 2021. Available online: https://newbuildings.org/wp-content/uploads/2021/01/BuildingElectrificationTechnologyRoadmap.pdf (accessed on 3 May 2021).
84. Nadel, S.; Ungar, L. Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050. Report u1907 American Council for an Energy-Efficient Economy (ACEEE). 2019. Available online: https://www.aceee.org/sites/default/files/publications/researchreports/u1907.pdf (accessed on 21 July 2021).
85. Svensson, N.; Roth, L.; Eklund, M.; Mårtensson, A. Environmental relevance and use of energy indicators in environmental management and research. *J. Clean. Prod.* **2006**, *14*, 134–145. [CrossRef]
86. International Energy Agency (IEA). Task 1 Strategic PV Analysis and Outreach—2020 Snapshot of Global PV Markets. Photovoltaic Power Systemsms Programme. Report IEA-PVPS T1-39. April 2021. Available online: https://iea-pvps.org/wp-content/uploads/2021/04/IEA_PVPS_Snapshot_2021-V3.pdf (accessed on 11 July 2021).

87. Our World in Data based on BP Statistical Review of World Energy & Ember. Share of Electricity That Comes from Solar. 2021. Available online: https://ourworldindata.org/renewable-energy (accessed on 12 August 2021).
88. Hernandez, R.R.; Easter, S.B.; Murphy-Mariscal, M.L.; Maestre, F.T.; Tavassoli, M.; Allen, E.B.; Barrows, C.W.; Belnap, J.; Ochoa-Hueso, R.; Ravi, S. Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.* **2014**, *29*, 766–779. [CrossRef]
89. U.S. Energy Information Administration (EIA). Most U.S. Utility-Scale Solar Photovoltaic Power Plants Are 5 Megawatts or Smaller. 2019. Available online: https://www.eia.gov/todayinenergy/detail.php?id=38272# (accessed on 25 October 2021).
90. Dale, V.H.; Efroymson, R.A.; Kline, K.L. The land use–climate change–energy nexus. *Landsc. Ecol.* **2011**, *26*, 755–773. [CrossRef]
91. Pavlović, T.M.; Radonjić, I.S.; Milosavljević, D.D.; Pantić, L.S. A review of concentrating solar power plants in the world and their potential use in Serbia. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3891–3902. [CrossRef]
92. Sharma, A. A comprehensive study of solar power in India and World. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1767–1776. [CrossRef]
93. Sharma, N.K.; Tiwari, P.K.; Sood, Y.R. Solar energy in India: Strategies, policies, perspectives and future potential. *Renew. Sustain. Energy Rev.* **2012**, *16*, 933–941. [CrossRef]
94. Zhang, D.; Chai, Q.; Zhang, X.; He, J.; Yue, L.; Dong, X.; Wu, S. Economical assessment of large-scale photovoltaic power development in China. *Energy* **2012**, *40*, 370–375. [CrossRef]
95. Feldman, D.; Wu, K.; Margolis, R. H1 2021 Solar Industry Update. NREL/PR-7A40-80427. 22 June 2021. Available online: https://www.nrel.gov/docs/fy21osti/80427.pdf (accessed on 12 August 2021).
96. Center for Climate and Energy Solutions (C2ES). Technology Solutions. 29 April 2021. Available online: https://www.c2es.org/content/renewable-energy/ (accessed on 8 August 2021).
97. U.S. Department of Energy (DOE). Land-Based Wind Market Report: 2021 Edition. 2021. Available online: https://emp.lbl.gov/wind-technologies-market-report (accessed on 17 September 2021).
98. U.S. Environmental Protection Agency (EPA). Renewable Electricity Production Tax Credit Information. 14 July 2021. Available online: https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information (accessed on 17 September 2021).
99. U.S. Department of Energy (DOE). *Combined Heat and Power (CHP) Technical Potential in the United Stat*; U.S. Department of Energy: Washington, DC, USA, 2016.
100. U.S. Department of Energy (DOE). Advanced Manufacturing Office: Fall 2020 Combined Heat and Powe (CHP)Virtual Workshop. 8–10 September 2020. Available online: https://www.energy.gov/sites/prod/files/2021/02/f82/CHPWorkshopReportSeptember2020_compliant.pdf (accessed on 12 July 2021).
101. Gvozdenac, D.; Urošević, B.G.; Menke, C.; Urošević, D.; Bangviwat, A. High efficiency cogeneration: CHP and non-CHP energy. *Energy* **2017**, *135*, 269–278. [CrossRef]
102. U.S. Department of Energy (DOE). Combined Heat and Power Technology Fact Sheet Series. November 2017. Available online: https://www.energy.gov/sites/default/files/2017/12/f46/CHP%20Overview-120817_compliant_0.pdf (accessed on 12 August 2021).
103. Beatley, T. *Green Urbanism: Learning from European Cities*; Island Press: Washington, DC, USA, 2012.
104. Department of Energy (DOE). Combined Heat and Power Technology: Fact Sheet Series. 2016. Available online: https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Steam%20Turbine.pdf (accessed on 3 March 2021).
105. Grand View Research (GWR). Combined Heat & Power Installation Market Size, Share & Trends Analysis Report by Type (Large Scale, Small Scale), By Fuel (Natural Gas, Coal, Biomass), By Technology, By Region, And Segment Forecasts, 2020–2027. Report ID 978-1-68038-552-6. July 2020. Available online: https://www.grandviewresearch.com/industry-analysis/combined-heat-power-installation-market (accessed on 12 July 2021).
106. U.S. Department of Energy (DOE) office of Energy Efficiency and Renewable Energy. *Flexible Combined Heat and Power (CHP) Systems*; Office of Energy Efficiency and Renewable Energy: Washington, DC, USA, 2018.
107. International Renewable Energy Agency (IRENA). World Energy Transitions Outlook: 1.5 °C Pathway, International Renewable Energy Agency, Abu Dhabi. 2021. Available online: https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook (accessed on 17 September 2021).
108. Gaiser, K.; Stroeve, P. The impact of scheduling appliances and rate structure on bill savings for net-zero energy communities: Application to West Village. *Appl. Energy* **2014**, *113*, 1586–1595. [CrossRef]
109. Fraker, H. A Road Map for the United States and Beyond. In *The Hidden Potential of Sustainable Neighborhoods*; Springer: Berlin/Heidelberg, Germany, 2013.
110. Raibley, T.J. *West Village Energy Initiative: Community Renewable Energy Deployment Project Renewable Energy Anaerobic Digester Feasibility Study*; HDR Engineering, Inc.: Folsom, CA, USA, 2011. Available online: https://www.osti.gov/servlets/purl/1157557 (accessed on 28 June 2021).
111. Wheeler, S.M.; Segar, R.B. Zero net energy at a community scale: UC Davis West village. In *Energy Efficiency towards the End of Demand Growth*; Sioshansi, F.P., Ed.; Elsevier Science: Amsterdam, The Netherlands, 2013; pp. 305–324.
112. Dunster, B. BedZED: Beddington zero-fossil energy development. In *Sustainable Urban Design*; Taylor & Francis: Abingdon, UK, 2013; pp. 157–174. [CrossRef]
113. Lovell, H. Discourse and innovation journeys: The case of low energy housing in the UK. *Technol. Anal. Strateg. Manag.* **2008**, *20*, 613–632. [CrossRef]

114. Chance, T. Towards sustainable residential communities; the Beddington Zero Energy Development (BedZED) and beyond. *Environ. Urban.* **2009**, *21*, 527–544. [CrossRef]
115. Voss, K.; Musall, E. *Net Zero Energy Buildings: International Projects of Carbon Neutrality in Buildings*; Detail: München, Germany, 2012; pp. 94–108. [CrossRef]
116. Fraker, H. *The Hidden Potential of Sustainable Neighborhoods: Lessons from Low-Carbon Communities*; Island Press: Washington, DC, USA, 2013. [CrossRef]
117. Coates, G.J. Sustainable urbanism: Creating resilient communities in the age of peak oil and climate destabilization. *Environ. Policy Is Soc. Policy–Soc. Policy Is Environ. Policy* **2013**, 81–101. [CrossRef]
118. Eppinger, J. *Towards the Sustainable City: Planning and Urban Development for the Year 2000 World Exposition in Hanover, Germany*; Routledge: London, UK, 2003. [CrossRef]
119. Zhu, D.; Kung, M.; Zhou, L. Analysis of sustainable energy systems in ecovillages: A review of progress in BedZED and Masdar City. *Low Carbon Econ.* **2015**, *6*, 1. [CrossRef]
120. Hodge, J.; Haltrecht, J. BedZED Seven Years on: The Impact of the UK's Best Known Eco-village and Its Residents. Wallington, London. 2010. Available online: https://storage.googleapis.com/www.bioregional.com/downloads/BedZED-7-years-on_Bioregional_Peabody_2009.pdf (accessed on 6 June 2021).
121. Saheb, Y.; Shnapp, S.; Johnson, C. The Zero Energy concept: Making the whole greater than the sum of the parts to meet the Paris Climate Agreement's objectives. *Curr. Opin. Environ. Sustain.* **2018**, *30*, 138–150. [CrossRef]
122. Hodge, J.; Haltrecht, J. *BedZED Monitoring Report 2007*; BioRegional: London, UK, 2009.
123. Twinn, C. BedZED. Arup Journal 2003. pp. 10–16. Available online: https://www.researchgate.net/profile/Chris-Twinn/publication/281980973_BedZED/links/56d95fc508aee73df6cf5096/BedZED.pdf (accessed on 25 October 2021).
124. Bioregional. BedZED—The UK's First Major Zero-Carbon Community. Available online: https://www.bioregional.com/projects-and-services/case-studies/bedzed-the-uks-first-large-scale-eco-village (accessed on 23 September 2021).
125. Schoon, N. *The BedZED Story: The UK's First Large-Scale, Mixed-Use Eco-Village*; BioRegional: Wallington, UK, 2016.
126. Lazarus, N. *BedZED: Toolkit Part II: A Practical Guide to Producing Affordable Carbon Neutral Developments*; BioRegional: Wallington, UK, 2003.
127. Braun, M.; Stetz, T.; Bründlinger, R.; Mayr, C.; Ogimoto, K.; Hatta, H.; Kobayashi, H.; Kroposki, B.; Mather, B.; Coddington, M.; et al. Is the distribution grid ready to accept large—Scale photovoltaic deployment? State of the art, progress, and future prospects. *Prog. Photovolt. Res. Appl.* **2012**, *20*, 681–697. [CrossRef]
128. UC Davis West Village. UC Davis West Village Energy Initiative Annual Report 2013–2014. West Village, Davis, CA, USA. 2013–2014. Available online: https://energy.ucdavis.edu/wp-content/uploads/2017/06/UC-Davis-West-Village-Energy-Initiative-Annual-Report-2013-2014.pdf (accessed on 28 June 2021).
129. Finkelor, B.; Sudhakaran, B.; Hayakawa, M.; Kurtovich, M.; Zail, N.; Dickinson, B.; England, S.; Segar, B.; Dakin, B.; Idrees, O.; et al. West Village: A Process & Business Model for Achieving Zero-Net Energy at the Community-Scale. UC Davis Energy Efficiency Center. 2010. Available online: https://www.aceee.org/files/proceedings/2010/data/papers/2271.pdf (accessed on 7 August 2021).
130. England, A.S.; Barr, T.; Eggert, A.; Finkelor, B.; Hayakawa, M.; White, B.; Zhang, R. *UC Davis West Village RESCO Technical Integration Project: Final Report. California Energy Commission. Publication Number: CEC-500-2015-005*; California Energy Commission, Energy Research and Development Division: Livermore, CA, USA, June 2014.
131. Braun, G. Net Zero Davis Project: Net Zero Goals and Strategies for Davis, California. In *Part 2: White Paper*; UC Davis Energy Institute University of California: Davis, CA, USA, 2011.
132. German, A.; Bell, C.; Dakin, B.; Hoeschele, M. *West Village Student Housing Phase I: Apartment Monitoring and Evaluation*; U.S. Department of Energy, Office of Scientific and Technical Information: Golden, CO, USA, 2014. [CrossRef]
133. Dakin, B.; Backman, C.; Hoeschele, M.; German, A. *West Village Community: Quality Management Processes and Preliminary Heat Pump Water Heater Performance*; U.S. Department of Energy, Office of Scientific and Technical Information: Golden, CO, USA, 2012. [CrossRef]
134. Dakin, B.; Hoeschele, M.; Petouhoff, M.; Zail, N. Zero Energy Communities: UC Davis' West Village Community. ACEEE Summer Study on Energy Efficiency in Buildings Proceedings. 2010, pp. 11–35. Available online: https://www.aceee.org/files/proceedings/2010/data/papers/2276.pdf (accessed on 20 September 2021).
135. Hammer, C.; Design, S.; LaRue, B.A.; Risko, L.G. West Village Case Study: Designers and Occupants. ACEEE Summer Study on Energy Efficiency in Buildings 2014. Available online: https://www.aceee.org/files/proceedings/2014/data/papers/7-1068.pdf (accessed on 28 June 2021).
136. Low, N. *The Green City: Sustainable Homes, Sustainable Suburbs*; Routledge: London, UK, 2005.
137. Coates, G.J. The city as garden: A study of the sustainable urban district of Kronsberg (Hannover), Germany. *Doc. Set* **2009**, *57*, 1–14.
138. Farr, D. *Sustainable Urbanism: Urban Design with Nature*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
139. Wang, F.; Prominski, M. *Urbanization and Locality: Strengthening Identity and Sustainability by Site-Specific Planning and Design*; Springer: Berlin/Heidelberg, Germany, 2015. [CrossRef]
140. Granvik, M.; Wlodarczyk, D.; Rydén, L. 3. Building a Sustainable Neighbourhood: Kronsberg. 2003. Available online: http://uu.diva-portal.org/smash/get/diva2:611386/FULLTEXT01.pdf (accessed on 4 July 2021).

141. Rumming, K. Hannover Kronsberg Handbook Planning and Realisation. 2004. Available online: http://www.landscape.cn/special/shengtai/kronsberg_hannover_handbook.pdf (accessed on 1 July 2021).
142. Forrest, N.; Wiek, A. Success factors and strategies for sustainability transitions of small-scale communities—Evidence from a cross-case analysis. *Environ. Innov. Soc. Transit.* **2015**, *17*, 22–40. [CrossRef]
143. England, A.S. UC Davis West Village RESCO Technical Integration Project: Final Report. 2014. Available online: https://books.google.com/books?id=WuuqHGA3HmMC (accessed on 19 September 2021).