

Net Zero Energy Communities

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Net Zero Energy Community (NZC) is an emerging concept with multiple variations in the scope and calculation methods, which complicates uniformly quantifying its targets.

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1. Net Zero Community Definition

Existing NZC definitions have differing requirements that complicate the achievement of NZC objectives ^{[1][2][3][4][5]}. **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 ^[5]	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 ^[6]	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 ^[7]	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 ^[8]	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 ^[9]	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 ^[10]	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 ^[11]	International Living Future Institute (ILFI) US

NZC Definition	Net Zero Community/District	Onsite/Off-Site Energy	Source/Site Energy	Reference	Organization/Journal
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 ^[12]	Syn.ikia Norway
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 ^[13]	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 ^[14]	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)

^[8] 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. ^[15] noted that “stakeholders face a lack of documented processes, tools, and best practices to assist them in achieving zero energy districts”. Koutra et al. ^[10] 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 ^[16], 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. ^[5] 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 ^{[9][6][17][18]}.

Torcellini’s ^[17] NZ classification at the building level (NZB) from the National Renewable Energy Laboratory (NREL) was analyzed in ^[19]. Carlisle et al. ^[5] 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. ^[5] 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.

NZC	Buildings	Transport
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, NO _x , and SO _x are common emissions that ZEBs and transportation powered by renewable energy offset.

According to Carlisle et al. [5], 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 [5].

However, Brozovsky et al. [18] 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 [18]. Brozovsky et al. [19] 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 [19]. **Table 3** summarizes the review publications on the NZC concept and presents the main challenges, existing variations, and requirements for adopting NZC.

Table 3. Review of NZC variation by selected publications.

References	Review Focus	Challenges	Variations	Recommendations
Marique & Reiter 2014 [6]	A simplified framework to assess the feasibility of a zero-energy neighborhood/community	<ol style="list-style-type: none"> 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. 	<p>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.</p>	<ol style="list-style-type: none"> 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 [20]	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.	<ol style="list-style-type: none"> 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.

References	Review Focus	Challenges	Variations	Recommendations
Brozovsky et al. 2021 [18]	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.	<ol style="list-style-type: none"> 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.

From the literature in **Table 1**, **Table 2** and **Table 3**, the main variations in the existing NZC concept can be divided into five categories:

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

Many publications conducted energy analyses at the community level [10][21][22][23][24][25][26][27][28][29]. 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.

1.1. 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 [30][31]. 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. [30].

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 [30]. **Figure 1** presents the result of five scenarios using different renewable technologies from the goal programming model.

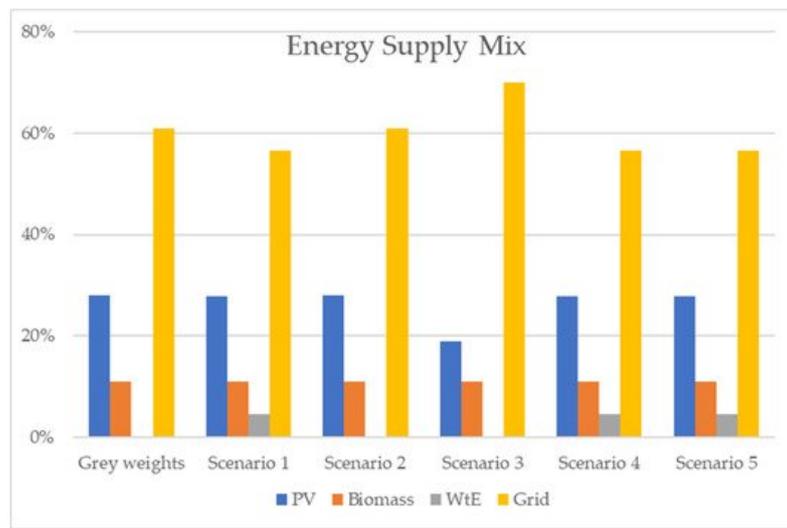


Figure 1. Optimal energy supply mix through different weighting scenarios, data from Bakhtavar et al. [30].

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% [30]. However, the increased cost from the investment, operation and maintenance of integrated renewable energy led to a payback period of 30 years [30].

1.2. 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 [32]. A case study of Jincheon, an eco-friendly energy city in South Korea (area of 72,000 m²), was selected; it has 200 dwellings and six public buildings [32].

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 [32].

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 CO₂ 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 [32].

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.

2. 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 [33][34][35][36][37][38][39][40][41][42][43] 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 5**.

Table 5. 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.

2.1. 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) [44]. The project's size is 1.7 hectares (ha), with 116 dwellings per hectare, including live/work units [37][39][45][46]. BedZED includes 99 homes, with 220 residents and 100 office workers [37][39]. 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 [45]. 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” [37]. The project aimed to cover emissions from office and local energy use, embodied energy from construction, transports, food, and waste [39]. 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 [39][44][45].

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 [39][45][47][48]. The community included a six-plot terrace with 18 dwellings with roofs being covered with 777 sqm of PV [39][44][49]. The total renewable energy cost breakdown (PV and CHP) was 5.8% of the total construction cost of the community (£15,250,000) [37].

The CHP system was planned based on a downdraft gasification method that converts woodchips into gas to produce electricity through a generator [39][50]. The local street tree surgery waste, certified by the Forest Stewardship Council, was used as a sustainable fuel for the CHP plant [39][45]. When fully operational, the CHP plant required 20 tonnes/week of woodchips with a cost of USD 34/tonne [51].

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 [45]. However, the restart programming caused complications with tar forming during system cool down [39][50]. It was concluded that the CHP system operates more efficiently if it runs constantly for a community as small as BedZED [39][50].

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) [37][51]. It is estimated that the CHP plant prevents about 326,000 kg of CO₂ emission per year from national grid electric production compared to gas-fired power systems [37]. However, the CHP plant was decommissioned due to its maintenance complications and running costs [39][45][51]. It was concluded that generating all energy on-site for a community as small as 2 ha is a challenging solution [39]. Chance [39] recommended the use of CHP plants only with advanced consideration of proper management in selecting, installing, and maintaining energy equipment [39].

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

- Reducing parking space (less than one per home compared to the UK's typical 1.5/home);
- Car club (London's first one);
- Solar-electric PV systems to power 40 electric vehicles;
- Electric charging station (free with every two of four parking spaces);
- Pedestrian and bike network (living streets);
- Public transport (bus stops, train stations);
- Mixed use and internet delivery supermarkets ^{[37][39]}.

As an outcome, the residents drove an average of 2318 km per year, which was 64% less than the local average ^[39]. 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" ^[44]. BedZED homes reduced their CO₂ emissions by 56% compared to the average UK home ^[39], which resulted in the community reducing its environmental impact by 20% to 30% by utilizing energy efficiency strategies in the construction stage ^{[37][51]}.

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.

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