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Review

Net Zero Energy Buildings: Variations, Clarifications, and Requirements in Response to the Paris Agreement

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Abstract: Buildings contribute to greenhouse gas emissions that cause environmental impacts on climate change. Net Zero Energy (NZ) buildings would reduce greenhouse gases. The current definition of NZ lacks consensus and has created uncertainties, which cause delays in the adoption of NZ. This paper proposes a Process for Clarification to Accelerate the Net Zero (PC-A-NZ) through three integrated steps: variations, strategies, and requirements. We expand on the results in published NZ literature to clarify the differences in definition and strategy. The objective of this review is to (1) distinguish current variable parameters that are slowing the acceptance of NZ, and (2) focus the discussion internationally on moving faster toward applying NZ to a larger common agreement. The publications of global NZ target assessment and energy efficient strategies will be reviewed to address the main requirements in expediting NZ's successful progress. Our NZ review analysis highlights (1) how the existing NZ definitions and criteria differ, (2) how calculation strategies vary, and (3) how standards and requirements are often localized. The proposed PC-A-NZ will help policymakers and stakeholders to re-evaluate the existing definitions, standards, and requirements to optimize the use of renewable technologies, improved energy efficiency and electrification to speed up achieving the NZ targets. Definition: There are multiple NZ definitions that vary in source and supply requirement, timescale, emission source, and grid connection.

Keywords: climate action target; net zero energy building; net zero variation; energy efficiency strategy; electrification; renewable energy; decarbonization; net zero standard

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1. Introduction

Net zero energy (NZ) is an increasingly important topic to the environment and climate change mitigations. According to the United Nations (UN) [1], the global population is predicted to increase to 8.5 billion by 2030 and reach 9.7 billion by 2100. This increasing population and continued use of non-renewable resources have caused severe environmental impacts on the climate [2–4]. The World Health Organization (WHO) [5], reported that "air pollution kills an estimated seven million people worldwide every year." In 2015, the Paris Agreement [6] raised an international effort toward climate mitigations, where 197 countries, including the three largest emitters of the world, China, the United States (US), and the European Union (EU) have released climate action targets to become carbon neutral [7–12]. In the US, 33 states have adopted the Paris Agreement and some states, including New York and California, released carbon-neutral, NZ, or Net Zero Energy Building (NZB) projects, as the primary solution to their greenhouse gas (GHG) reduction targets by 2050 [13]. The Department of General Services [14] in California State considers NZ as "a strategy with tactical approach towards achieving the GHG reduction goal or a zero carbon [15]." A variety of technologies, standards, and strategies have been published for buildings to achieve NZ, including improved energy efficiency, fuel source shift, and on-site power generation [14,16–23]. The European Climate Foundation [24] presented that, despite "the urgency to decarbonize Europe's buildings, the sector is not currently on a trajectory to zero greenhouse gas emissions by 2050," and emphasized that the current policies are inadequate to meet the target [24]. It was reported that "under current policies, annual emissions from residential buildings will decrease by only 30% by 2050" [25]. Vasquez et al. [26] claimed that the NZ regulations were sufficient for achieving 20% energy efficiency by 2020, which is inadequate to meet the 2050 energy and carbon dioxide (CO_2) emission reduction targets.

The US and EU have committed to becoming carbon neutral by 2050, and China pledged for achieving the 100% NZ emission target before 2060 [9,12,27,28]. To achieve these goals, the current NZ regulations need to be clarified. Competing definitions from worldwide organizations with various calculation methods created uncertainties in defining a project NZ. Williams et al. [29] noted that "there are in excess of 70 low or zero energy/carbon building definitions/standards in circulation around the world. However, there are few zero energy or zero carbon buildings." The authors stated that "despite, or possibly because of, a continuing debate over definitions, aspiration has not been met by reality" [29]. Harkouss et al. [30] were concerned that "there is no common definition for NZEBs", and stated that "the definition depends completely on the purpose intended by the designer [30]."

Torcellini et al. [31] categorized the main variations in NZ into four definitions: NZ source energy, NZ site energy, NZ energy emissions, and NZ energy costs. The definitions were influenced by the national energy concerns on primary energy sources, designers' interest in site energy regarding the energy code requirements, climate concerns on CO_2 emission reductions, and stakeholders' desires on cost savings [31]. NZ concepts were analyzed to address the need for a common and clear definition, and its impact on achieving the targets [31]. The result from applying each definition to a set of selected low-energy buildings highlighted (1) the impact of each NZ definition on the design, and (2) the large variations in NZ definitions [31].

This review reports the current variations in the NZ concept as the main cause of uncertainty, thus a barrier for achieving the targets. Current NZ literature underlined the necessity of clarifying the NZ concept and energy analysis strategies, before further implementation, shown in Table 1.

Table 1. Limitations in NZ concept.

References	Year	Citations on NZ Clarification
Torcellini et al. [31]	2006	Despite the excitement over the phrase 'zero energy,' we lack a common definition, or even a common understanding, of what it means.
Crawley et al. [32]	2009	Broad definition leaves plenty of room for interpretation—and for misunderstanding among the owners, architects, and other players in an NZEB project. Agreeing to a common definition of NZEB boundaries and metrics is essential to developing design goals and strategies.
Marszasl et al. [33,34]	2011	Before being fully implemented in the national building codes and international standards, the ZEB concept requires clear and consistent definition and a commonly agreed energy calculation methodology.
Deng et al. [35]	2014	As for the definition of a NZEB, until now there is no consensus on a common expression, which can be satisfied by all participators in this research field.
Peterson et al. [36]	2015	Definitions differ from region to region and from organization to organization, leading to confusion and uncertainty around what constitutes a ZEB.
Lu et al. [37]	2017	There is no exact approach at present for the design and control of buildings to achieve the nearly/net zero energy target.
Wells et al. [38]	2018	The NZEB concept lacks a holistic, quantifiable and widely accepted definition. Some of the risks associated with a lack of a common definition are that NZEBs could be poorly executed and risk becoming a status symbol for building owners rather than a practical goal in alleviating environmental, social or ethical issues.

Table 1. *Cont.*

References	Year	Citations on NZ Clarification
Attia [39]	2018	Without a clear and consensus-based national NZEB definition, we cannot achieve environmental targets to reduce greenhouse gas (GHG) emissions from buildings. Definitions are essential to benchmark NZEB performance and be able to push building codes while training designers and workers and perform appropriate monitoring for different building types.
Wei et al. [40]	2021	There is a lack of systematic literature review focused on recent progress in residential NZEBs.
Black et al. [27]	2021	Entities should be clear about what they are pledging—which greenhouse gases, on what timescale, with what use of offsets. An entity that has not published these essential details cannot reap any of the benefits of declaring a predictable path to net zero, such as sending an unequivocal signal to investors, nor can it expect every observer to take its commitment seriously.

Studying the current comprehensive NZ literature, this paper proposes a Process for Clarification to Accelerate Net Zero (PC-A-NZ) through three steps: variations, strategies, and requirements. Clarifying the ambiguity of the current concept, and thus the existing calculated methodologies before further development of the NZ is highlighted. We expand on the existing NZ literature to address the variations in definition and strategy from the commonly used NZ developments and the potential requirements to clarity the NZ and enhance its acceptance. The PC-A-NZ is a process to re-evaluate how to improve or modify what has been done on NZ by presenting three flowcharts.

This review covers (1) background on the Paris Agreement and climate action targets; (2) current NZ definition variations and uncertainties; (3) existing NZ reviews from peer-reviewed publications; (4) different metrics in NZ requirements; (5) global NZ target assessments; (6) energy efficient strategies; and (7) results and recommendations.

2. Climate Action and Net Zero Targets

In 2015, 197 countries adopted the Paris Agreement [6] to reduce their GHG emissions and limit the global temperature rise from 2 °C to 1.5 °C [41]. The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C [42] simplified the required actions to take by the governments to achieve their emission reduction pledge. A report by the Energy and Climate Intelligence and Oxford Net Zero (ECIU-Oxford NZ) [27] presented IPCC's timescale in achieving 45% CO_2 emission reduction by 2030 and becoming NZ CO_2 emission by 2050 (from 2010 level) globally. IPCC's timescale provides a 50% chance of keeping global warming below 1.5 °C [43]. Currently, 121 countries released climate action targets to become NZ or carbon neutral along with 509 cities, and 2163 companies [44].

3. Net Zero Definitions and Uncertainties

The European Performance of Buildings Directive (EPBD) [45] requires all new buildings from 2021 to become nearly NZ, defined it as "Nearly Zero-Energy Building (NZEB)—a building that has a very high energy performance, as determined in accordance with 'Annex I'." The EPBD's Annex I emphasizes HVAC systems, sensitivities of climate, and orientation of the buildings [38,45]. EPBD stated that "the nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby" [45]. The Federation of European Heating, Ventilation and Air-conditioning Associations (REHVA) [46] defined nearly NZBs as "nZEB—a grid connected building with very high energy performance", where nZEB "balances its primary energy use so that the primary energy feed-in to the grid or other energy network equals to the primary energy delivered to nZEB from energy networks." According to REHVA [46], "annual balance of 0 kWh/(m^2 a) primary energy use typically leads to the situation where significant amount of the on-site energy generation will be exchanged with the grid."

The US Department of Energy (DOE) [36] released a standard definition for NZBs as "Zero Energy Building (ZEB)—an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the onsite renewable exported energy." A list of key terms defined by the DOE is shown in Table 2.

Table 2. DOE's key terms definition in NZ standard release (2015).

DOE, 2015 [36]	Key Terms Definition in NZ Energy by DOE
Delivered energy	Any type of energy that could be bought or sold for use as building energy.
Building site	Building and the area on which a building is located where energy is used and produced.
Site boundary	Line that marks the limits of the building site(s) across which delivered energy and exported energy are measured.
Site energy/building energy	Energy consumed at the building site as measured at the site boundary.
Source energy	Site energy plus the energy consumed in the extraction, processing and transport of primary fuels such as coal, oil, and natural gas; energy losses in thermal combustion in power generation plants; and energy losses in transmission and distribution to the building site.
Renewable energy	Energy resources that are naturally replenishing but flow-limited, and include biomass, hydro, geothermal, solar, wind, ocean thermal, wave action and tidal action.
On-site renewable energy	Includes any renewable energy collected and generated within the site boundary that is used for building energy and the excess renewable energy could be exported outside the site boundary.
Exported energy	On-site renewable energy supplied through the site boundary and used outside the site boundary.

According to the International Living Future Institute (ILFI) [47], NZB is defined as "NZEB—one hundred percent of the building's energy needs on a net annual basis must be supplied by on-site renewable energy. No combustion is allowed." The US Environmental Protection Agency (EPA) [48] defined NZB as "Net Zero Energy (NZE)—producing, from renewable resources, as much energy on-site as is used over the course of a year." The New Buildings Institute (NBI) [49] defined NZB as "Zero Energy (ZE)—buildings, or groups of buildings, with greatly reduced energy loads such that, totaled over a year, 100% or more of the energy use can be met with renewable energy generation." The Department of General Services (DGS) in California [50] issued NZ definition for buildings as "Zero Net Energy Building (ZNEB)—an energy-efficient building where, on a source energy basis, the actual annual consumed energy is less than or equal to the on-site renewable generated energy."

The existing definitions declared variations, mainly in supply and source requirements. According to ASHRAE [51], a single definition is necessary to determine "if a building can be universally considered as being an NZEB." ASHRAE noted that the only way to count a building NZB is "to look at the energy crossing the boundary" [51]. To estimate the source, emission, and cost in NZ definitions, conservation coefficients are required for the metric of interest [30,51]. Due to the complexity of assessing coefficients, ASHRAE along with the US Green Building Council (USGBC), the American Institute of Architects (AIA), and the Illumination Engineering Society of North America (IESNA) agreed to adapt site energy measures in defining their NZB [51]. ASHRAE defined NZB as "NZEB—as much energy collect from renewable sources as the building uses on an annual basis while maintaining an acceptable level of service and functionality," where "buildings can exchange energy with the power grid as long as the net energy balance is zero on an annual basis [51]."

4. Existing Review Publications on Net Zero Variations

Four types of variations, including definitions, calculation methodologies and tools, climate zones, and energy load balance extrapolated from the existing NZ reviews [22,26,29–38,40,45–47,49,51–72] shown in Table 3, are summarized below:

Table 3. A comprehensive literature list on NZ variations and uncertainties.

Reference	Def.	Calc. Method Tools	Climate Zones	Load-Balance	NZ Analysis	NZ Limitations	NZ Recommendation	NZ Future Study
Torcellini et al., 2006 [31]	✓			✓	Definitions and building design	Lack a common understanding	Consistency	
Crawley et al., 2009 [32]	✓					Lack a common understanding	Clarification on source requirements	-Community and campus -Energy storage
Marszal et al., 2011 [34]	✓	✓			Key parameter variations in definitions	-Lack a clear definition -Lack a common energy methodology -Lack a requirement	-Fixed value for max allowed energy use -Indoor air requirements	-Economic analyses and Life Cycle Cost (LCC) -Renovation of existing buildings
Mlecnik et al., 2011 [52]	✓					Lack a common international concept and standardized method		
Sartori et al., 2012 [63]	✓			✓	Load matching and grid interactions	-Lack an internationally common definition -Insufficiency of annual balance regarding the energy grid analyses	-Mandating energy efficiency and energy supply requirements -Measured rating in NZ targets	Hourly time resolution data to address energy price fluctuations and peak loads
Attia et al., 2013 [54]	✓	✓			Optimization of NZB performance	Uncertainty, computation time, and complexity of the model		Improved methodology, visualization, and standardized costs
Berggren et al., 2013 [60]		✓			Life Cycle Energy (LCE) analysis of embodied energy	-Lack of embodied energy requirements -Lack of a standard method for LCE -Lack a common national database for building materials	-Set a requirement to include embodied energy in buildings -Preform embodied energy analysis on structural elements	-Accepting and utilizing the total LCE analysis in building design -Using low embodied energy insulation material in new construction

Table 3. *Cont.*

Reference	Def.	Calc. Method Tools	Climate Zones	Load-Balance	NZ Analysis	NZ Limitations	NZ Recommendation	NZ Future Study
Deng et al., 2014 [35]	✓	✓		✓	Life Cycle Assessment (LCA) and its role in defining NZ Load Match (LM), Grid Interaction (GI), and energy storage	-Lack of comprehensive review on evaluation energy and environmental impact -Uncertainty on definition and method	-Clarifying NZ and energy efficiency measures -Including LCA application in NZB verifications	-LCA application in NZB and the updates -Developing evaluation indicator for LM and GI -Standard NZ evaluation process
Peterson et al., 2015 [36]	✓	✓		✓	Energy measurements and source energy calculations	Lack a commonly accepted definition and calculation methods	Annual delivered energy to be less or equal to the on-site renewable exported energy	
Harkouss et al., 2018 [30]	✓	✓	✓	✓	A comprehensive literature on design, optimization, and classification	-Lack a common definition -Purpose-based on the existing NZ definitions	-Demand reductions -Energy efficiency -Renewable productions	Maintenance of existing NZBs with integrating energy-efficient technologies
Koutra et al., 2018 [70]		✓			Sustainable planning model with NZ character	Limited evaluation literature and optimization method at the district level		Optimize urban strategic planning
Wells et al., 2018 [38]	✓		✓	✓	-Comprehensive literature on low-energy buildings and NZ -Why current buildings are not NZ?	-Ambiguity of NZ -Poorly execution for the building owners -Energy demand unpredictability	-Existing buildings -Occupant behavior -Renewables -Energy storage technologies	-Update demand regulations to meet the 2050 NZ targets -Building code with a higher compliance
Feng et al., 2019 [66]	✓		✓	✓	Energy performance of case studies in hot and humid climates	-Lack of NZ policies -Lack of energy efficiency requirements	Passive strategies, energy-efficient systems, and renewable sources	Documentation of NZBs' best practices

Table 3. *Cont.*

Reference	Def.	Calc. Method Tools	Climate Zones	Load-Balance	NZ Analysis	NZ Limitations	NZ Recommendation	NZ Future Study
Gupta et al., 2019 [68]	✓		✓		Literature on NZ concepts	A small number of NZBs that are highly energy efficient	Use of solar source for energy savings and cost-efficiency	
Wimbadi et al., 2020 [58]	✓		✓		Systematic Literature Review (SLR) method for data collection	Lack of consensus concept on climate change mitigation and decarbonization	Clarifying visions and approach to achieve it	Expansion of current CO_2 reduction factors toward NZ to different geographic contexts
Wei and Skye 2021 [40]	✓	✓			Literature on successful residential NZBs (last 10 years)	Lack of schematic literature review on recent progress in residential NZBs	-Set of technologies and building parameters based on local specifications -Annual performance simulations for design comparisons	Impact of technology advancement and energy performance on economic factors

1. Definition: There are multiple NZ definitions that vary in source and supply requirement, timescale, emission source, and grid connection.
2. Calculation Methodologies and Tools: Different definitions create various strategies that demand different measured ratios and calculated method tools.
3. Climate Zones: Climate affects energy consumption patterns and the use of renewable technologies. The NZ codes and standards need to be adaptable to include worldwide climate zones, including cold, hot–humid, and hot–dry.
4. Energy balance: When energy supply meets the demand, which can be identified as load–generation balance or import–export balance. The parameters, including renewable sources, period, energy type, indoor comfort, load matching and grid interactions, energy infrastructure, and energy efficiency vary in different definitions.

Table 3 presents previous NZ review publications on these four variations and summarizes (1) NZ analysis, the key investigation; (2) NZ limitations, main cause of current uncertainties; (3) NZ recommendations, required clarifications; and (4) NZ future studies, potential solutions to achieve NZ targets.

Selected papers from Table 3 reviewed different concepts, strategies, and recommended solutions toward clarifying NZ. Each review highlighted different categories that contribute to current NZ variation, which are summarized below.

4.1. Marszal et al. in 2011, NZ Variation Parameters

This study reviewed the NZ topics and proposed the adaptation of a "common and unambiguous" definition as well as calculation methodologies in analyzing the energy balance [34]. The main differences in current NZ definitions were recognized as a lack of agreements in:

1. Metrics (primary energy, CO_2 emissions, exergy [64], cost);
2. Timescale (annual, monthly, hourly);
3. Energy types (cooling, heating, embodied energy);
4. Balance types in grid-connected NZBs;
5. Renewable energy supply alternatives (on-site or off-site);
6. Energy infrastructure connections (on-grid or off-grid);
7. Requirements (energy efficiency measures, indoor climate, comfort, grid interactions).

Marszal et al. [34] emphasized deliberating the mentioned issues before further development of NZBs.

4.2. Sartori et al. in 2012, NZ Energy Balance Concept and Requirements

The cause for the existing NZ variations at the international level was presented due to each country's specific conditions and different political targets [63]. Sartori et al. proposed a consistent framework as a set of adaptable NZ characteristics for different regions. The main variation criteria were recognized as balancing energy demand and supply, which was suggested to be verified at:

1. Building boundary (physical, balance, conditions);
2. Weighting system (metrics, symmetry energy carrier, time);
3. NZB balance (period, type, energy efficiency, energy supply);
4. Temporal energy match (load matching, grid interaction);
5. Measurement and verification [63].

Sartori et al. prioritized the importance of energy efficiency and renewable supply in achieving NZ targets and recommended enforcing minimum requirements for these parameters in NZ definition. The authors also suggested including measured rating, operational energy use, and boundary condition specifications (comfort, climate, occupancy, and period) in defining NZB [63].

4.3. Harkouss et al. in 2018, NZ Design, Optimization, Classification

A comprehensive NZ review was conducted on definitions, measured ratios, optimization strategies, and climate zones [30]. A lack of a global NZ definition that covers all the mentioned concepts and the limited number of literature in existing NZ energy performance buildings were presented [30]. The most common definition from the literature was summarized as "a building with considerably low energy demands which are assured by both: the grid and site RE resources in an annual balance that is at least zero or in favor of the RE," where RE is an acronym for renewable energy [30]. The authors recommended demand reduction strategies, energy efficient systems, and renewable energy generations as key solutions to achieve NZ targets [30]. Harkouss et al. emphasized the importance of energy optimization methods in providing solutions for different objectives, including energy (saving, thermal loads, renewables); environment (CO_2 emissions); and economy (investment cost, life cycle cost) [30].

4.4. Wells et al. in 2018, Common NZ Limitations

This paper reviewed case studies that meet NZ targets through different definitions and strategies [38]. Two factors were found in common in most cases: the use of renewable technologies and energy efficiency measures. The embodied energy, as the main factor in building material, and transport energy were ignored from most of the definitions [38]. Wells et al. raised the question of "what is required to ensure that every building is a NZEB?" The authors presented the current limitations in NZ due to the lack of agreements on a universal definition; energy efficiency standard; governmental NZ documentation; manufacturing energy usage; and economic feasibility validation. Well et al. recommended policies with stronger building codes to promote and ensure a higher level of compliance [38].

4.5. Feng et al. in 2019, High Performance Net Zero Building (NZB) Analyses

The authors investigated 34 worldwide NZB cases, and the result recommended the integration of passive design, energy efficient systems, and renewable technologies as primary NZ solutions in hot and humid climates in developing countries [66]. The reason for lacking NZBs in these areas was presented as the high initial investment costs and payback periods. Passive strategies were suggested as a cost-effective solution to the economic barriers [66]. Feng et al. used the ASHRAE 90.1-2016 standard's energy intensity for climate zone 1 to analyze the energy performance of middle-size office NZB cases. The result for some of the NZBs showed a higher energy intensity rate than the ASHRAE 90.1-2016 standard. It was concluded that NZBs are not necessarily high energy performance. Buildings can become NZ by providing ample on-site renewable energy, even without severe energy efficiency measure requirements [66]. Feng et al. recommended the adaptation of NZB's advanced technology based on the buildings' local codes and standards; incentives to alleviate the high initial cost; documentation of occupant comfort and air quality; and publication of successful governmental NZBs.

4.6. Results from Current Net Zero Review Studies

Previous reviews highlighted key barriers in achieving the NZ targets including (1) lack of consensus in the existing NZ definitions and strategies; (2) lack of consistent standard and code requirements in different regions; and (3) lack of recent documented reports to track the progress on NZ cases. These barriers need to be addressed, otherwise they create uncertainties and cause delays in actions. This paper emphasized the need to clarify and update the NZ to include all the current concepts and requirements with adaptable codes and standards.

5. Assessment of Global Net Zero Targets

5.1. International Energy Agency (IEA) in 2020, Analysis of Global NZE2050

The analysis provided the requirements for the next 10 years (2019–2030) to be on a pathway of NZ CO_2 emissions by 2050 globally (NZE2050) [73]. In the NZE2050 analysis, IEA addressed the required level of investments and implementation of clean energy technologies, and fuel mix to track the process of CO_2 emission reduction by 2030 and NZ emission by 2050 [73]. With consideration of the impact of the COVID-19 pandemic on behavior changes, IEA reported the result from the NZE2050 analysis as follows:

1. A 17% reduction in primary energy demand and a 15% reduction in total final energy use between 2019 to 2030 (from 2006 level), due to the application of electrification, improved efficiency, and behavior changes.
2. A 60% CO_2 emission reduction from the power sector, mainly based on the increased share of renewable sources in electricity supply globally.
3. A 33% CO_2 emission reductions from end-uses through retrofitting "existing buildings in advanced economies," where both the number of retrofits and the achieved savings from each retrofit needed to be increased. The retrofits were supposed to be improved enough to make the buildings NZ or near NZ emission by 2022 through highly insulated floors, walls, and ceilings; triple or double glazing windows; and passive heating and cooling alternatives [74]. IEA noted that energy retrofit causes a 50% reduction in heating energy demand and lowers the need for cooling [73].
4. Triple investment levels in the power sector from $760 billion in 2019 to $2.2 trillion in 2030, which is considered the largest investment in renewables in history [73]. IEA reported a $3 trillion required investment in clean energy technologies over the next three years. This investment was projected to enhance the economic recovery, create more jobs, and provide significant structural emission reductions globally [73].

By August 2020, 125 countries announced NZ emission targets [73]. The targets varied in scope and timescale. Most timescales were set to meet the targets in 2050, and some in 2030. GHG considerations also varied in different regions with including all GHG versus only CO_2 emission reduction in defining the NZ targets. With analyzing the current NZ commitments, IEA recommended the use of NZ carbon power systems with consideration of integrated, long-term planning; electrification, based on low emission electricity; innovative technologies; increases in the installed capacity of PV, wind power, and energy storage systems; electrification of end-use sectors; improved efficiency; electric storage, water heater, and heat pumps; and planned regulations and markets for NZ emissions [73].

5.2. International Energy and Climate Intelligence and Oxford Net Zero (ECIU-Oxford NZ) in 2021, Systematic Analysis of Global NZ Targets

This study conducted a systematic analysis of the main emitters and NZ targets globally [27]. Black et al. [27] noted that "the growth in net zero target-setting has been matched by a growth in the volume of criticism, from civil society, academia, and some businesses." Current projects lack consistency in defining a common emission source, timescale, and offsetting (eventual CO_2 removal) on NZ targets [27,75–77]. The report's objective was to provide an "opening snapshot" to track the progress on the claimed NZ targets over time [27]. "The Race to Zero" was identified as a widely agreed criterion for tracking NZ and GHG reduction targets, with setting steps in pledge, plan, proceed, and publish [27,78–82]. This analysis [27] reviewed 202 countries, 806 states from the world's 25 largest emitting countries, 1170 cities with 500,000 populations, and 2000 companies to study their commitments on "net zero emissions," or "carbon neutrality," and "climate neutrality" [27]. The analysis considered the fraction of global emissions, population, and economic value set by the targets. The covered parameters included:

1. Timing, the expected year that target reaches NZ in CO_2 emission.
2. Status, documentation, and publication of the commitment and its progress.
3. Coverage, clarifications on the type and source of emissions.

4. Offsetting, the complications of emissions removal and thus the importance of offsetting in NZ commitments [83,84].
5. Governance, publication of a plan to meet the target, and a clear timescale for accountability, report, and documentation of the progress [27].

The analysis presented that overall, 769 entities of the samples (19% of total) have committed to NZ, including 124 countries (61%), 73 states (9%), 155 cities (13%), and 417 companies (21%) [27]. Most targets were set to meet NZ by 2050, with 212 entities planning for 2030. The status presented that the defined targets by the entities were either aspirational or in a policy document, and only seven countries and four cities have met their commitments in law. The result showed a net negative for 21 countries, while 44 companies met their NZ targets [27]. The source of GHG emissions was not clarified by 14% of the targets. Most entities presented an unclear commitment to carbon offset utilization. Only 10% of the total entities accounted for the quality while defining their NZ targets [27].

The importance of NZ was highlighted with the commitment of the world's three largest emitters to the climate action targets: China, the US, and the EU [27,85]. However, the report stressed the need for robust NZ plans and progress assessments to meet the target. The authors advised that "if nations, states & regions, cities and companies are serious about reaching their net zero targets it is entirely reasonable to expect them to enact measures that will help them get there; net zero is a land inaccessible to those without a plan" [27]. Three levels of improvements were recommended to the existing NZ concept, including:

1. Expansion, setting a common target and planning to meet it;
2. Clarification, mandating publication of the specific requirements (emission source, offsetting, timescale);
3. Upgrades, gauging the efficiency and adequacy of the NZ commitments [27].

6. Efficient Strategies and Recommendations in Achieving Net Zero Targets

Recent studies highlight the significance of electrification, renewable resources, integrated grid, and NZ codes as critical strategies in achieving the NZ target [39,71–73,86–89]. NREL [87] introduced electrification as an emerging movement in energy markets globally, and defined it as "the shift from any non-electric source of energy to electricity at the point of final consumption" [73]. EIA [90] presented that most end-uses are electrified with the main exceptions in water heating, space heating, and cooktop, which account for 46% of the total energy use [91]. Electrification could provide up to 52% of water heating, 61% of space heating, and 94% of cooking services in combined residential and commercial sectors by 2050 [87]. NREL stated that electrification promotes power production economic enhancements besides mitigating fossil fuel use [87]. The Energy and Environmental Economics [92] evaluated the GHG savings, economics, and gird impacts of electrification in six residential homes in six different climate zones in California and stated that "electrification is found to reduce total greenhouse gas emissions in single-family homes by ~30–60% in 2020, relative to a natural gas-fueled home." The study also noted that "as the carbon intensity of the grid decreases over time, these savings are estimated to increase to ~80–90% by 2050" [92].

Ebrahimi et al. [93] calculated a detailed model to evaluate the emission impact of electrifying end-uses on the GHG emission reductions in two cases: (1) decarbonizing power production, and (2) partially electrifying end-use sectors. The result presented 2% and 20.3% GHG reductions for cases (1) and (2), respectively (from 1990 level). Dennis [94] assessed decarbonized electricity supply and recommended incentivizing end-use electrification policies in supporting heat pump technology; promoting the use of renewable sources; and balancing on-site energy demand with supply to minimize CO_2 emissions. Wei et al. [95] presented the existing fossil fuel-related source policies as appropriate short-term yet insufficient long-term solutions to address the GHG reduction targets. The authors recommended renewable energy for an extra 80% reduction in electricity-related emissions [95]. Williams et al. [96] noted that the long-term cost stability for electrification reduces investment risk compared to the volatile oil and gas prices, shown in Figure 1.

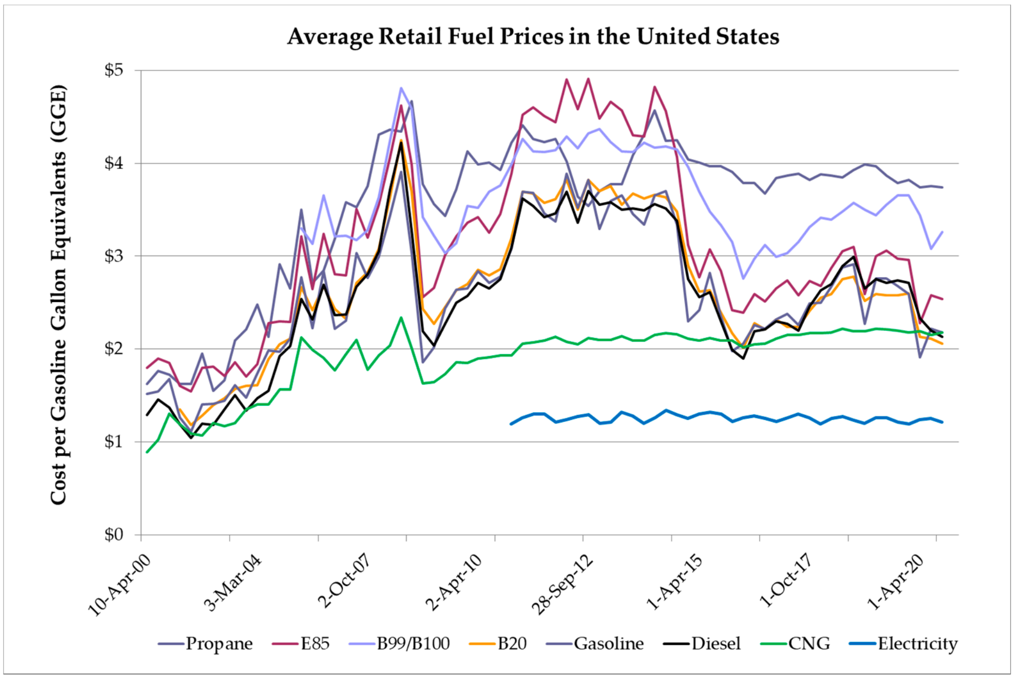

Figure 1. Average retail fuel prices in the US. Source: Clean cities alternative fuel price reports, U.S. Department of Energy [97]. Electricity data from U.S. Energy Information Administration [98].

Current debates identify electrifications as the major step in reaching NZ and GHG reduction targets, where building code accounts as a requirement to accomplish this goal [99–102]. NBI [103] identified pathways to get to NZ goals, including:

1. Zero Energy Construction Code, where projects are required to assure that the submitted building plans are designed to meet the NZ outcome;
2. Zero Carbon Code or Policy, where carbon is considered as the metric and covers two aspects of the policy such as combustion removal at the building level and shift from energy (cost/site/source) to GHG metrics.

The literature on efficient strategies showed a significant impact of electrification and renewables on GHG emission reductions. NBI recommended that building codes need to be upgraded at the national level to include electrification and mandate all new construction to be electric and carbon neutral by local code [99–102]. The main end-use sectors that have not yet been fully electrified were summarized as space heating, water heating, and cooktop, which are required to be further investigated.

7. Results and Discussion

Numerous worldwide organizations have come a long way in advancing and promoting NZ today. On 22 April 2021, President Biden declared that the US "has resolved to take action" on climate change and pledged that his country would cut its GHG emissions by at least 50% from the 2005 level by 2030 [104]. The literature presented that advanced technology and scientific calculation methods are available to perform NZ, yet commitments on 2020 NZ targets have failed to meet the goals. The reviews in this paper presented the main cause for this failure as the lack of clarity and uncertainty of the existing definition due to the large variation in requirements and confusion due to this variation.

Using comprehensive reviews on NZ, this paper proposed a Process for Clarification to Accelerate the Net Zero (PC-A-NZ) to clarify what needs to be accomplished. Developing advanced technologies and well-calculated methodologies upon an ambiguous NZ concept leads to inefficient standards and unpractical solutions, which eventually causes delays in the adoption of NZ. We defined the PC-A-NZ as a process to clarify the existing variations and update a common NZ concept to enhance NZ's applicability and increase its acceptance. The proposed PC-A-NZ will help policymakers, building and grid designers, and lead engineers to re-evaluate the existing definitions, standards, and requirements to promote and optimize the use of renewable technologies, improved energy efficiency, and electrification toward achieving 2050′s NZ targets. The PC-A-NZ process is categorized into three integrated steps: (1) verification; (2) strategy; and (3) requirement, where strategy follows the verification that depends on the requirement, shown in Figure 2.

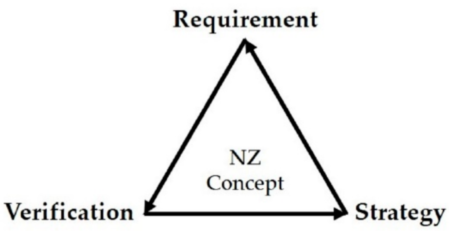

Figure 2. Schematic net zero clarification diagram.

The primary differences between NZ strategies were recognized as fundamentally defining NZ in balancing out the energy demand and supply over a year from the literature. Current definitions mainly differ in supply and source requirements. Torcellini et al. [31] presented four renewable energy supply options that a building can utilize, shown in Table 4.

Table 4. Net zero renewable energy supply options, Torcellini et al. [31].

Options	Net Zero Supply Side Options	Examples
0	Reduce site energy use through low-energy building technologies	Daylighting, high-efficiency HVAC equipment, natural ventilation, evaporative cooling, etc.
	On-Site Supply Options	
1	Use renewable energy sources available within the building's footprint	PV, solar hot water, and wind located on the building.
2	Use renewable energy sources at the site	PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building.
	Off-Site Supply Options	
3	Use renewable energy sources available off site to generate energy on site	Biomass, Wood pellets, ethanol, or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat.
4	Purchase off-site renewable energy sources	Utility-based wind, PV, emissions credits, or other "green" purchasing options. Hydroelectric is sometimes considered.

Torcellini et al. defined the NZ site energy for a building that "produces at least as much energy as it uses in a year when accounted for at the site," and the NZ source energy as a building that "produces at least as much energy as it uses in a year, when accounted for at the source" [31]. The source and site energy were defined in Table 2.

The PC-A-NZ is presented by three flowcharts. Flowchart I summarizes the existing source and supply requirements that are defined differently in current NZ definitions, extrapolated from the literature [23,31,36,45–49,51,105], shown in Figure 3.

Allowing only on-site generation would exclude purchasing power from remote wind and solar farms as an acceptable source when counting toward NZ. As shown in Flowchart I, NBI, ASHRAE, USGBC, AIA, and IESNA used site energy and allowed for off-site energy use (i.e., windfarm and solar farm power) to count for their NZ definition; however, the DOE, DGS, EPBD, and REHVA used source energy and on-site energy in defining NZ [23,31,36,45–49,51,105].

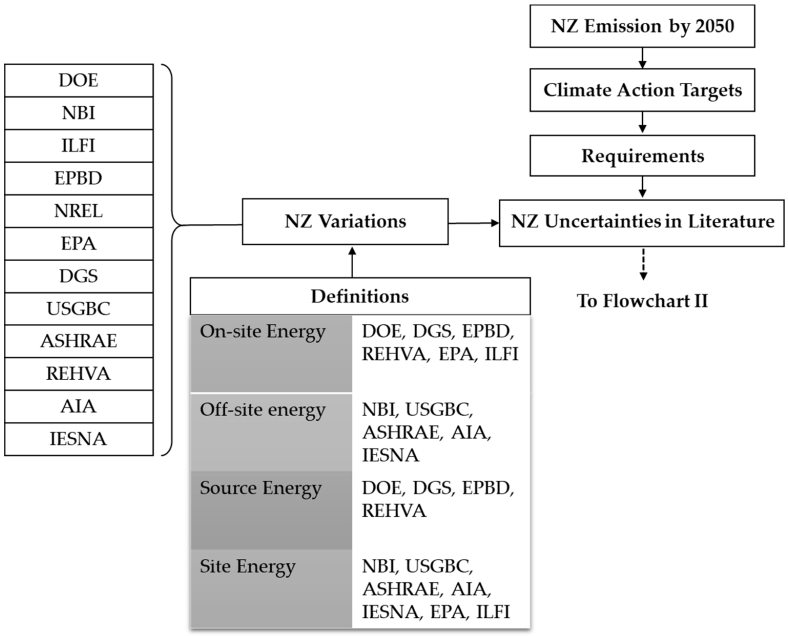

Figure 3. Flowchart I, supply and source requirements variation in net zero definitions.

Flowchart II highlights parameters that vary in different NZ definitions and require verifications in defining a common concept, included period, metric, energy type, balance type, infrastructure connection, and requirements from review [21,22,30,34,38,39,63,66], as shown in Figure 4.

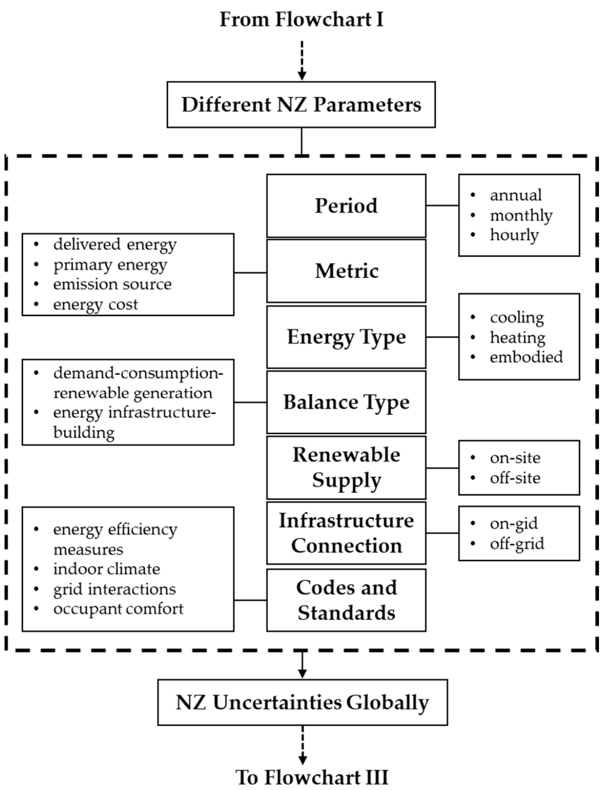

Figure 4. Flowchart II, net zero variable parameters in energy balance.

This paper recommends the PC-A-NZ, rather than delivering a single solution, to clarify the current NZ's ambiguities and enhance its acceptance through three steps as follows:

1. Variations: Consensus parameters need to be included in NZ definitions, including source and supply requirements, energy type, timescale, emission source, balance type, NZ progress, and grid connection.
2. Strategies: Electrification, load balancing, renewable technologies, integrated grid, fuel shifts, and electrification of the end-use consumers (space heating, water heating, and cooktops) need to be optimized.
3. Requirements: Standard measured rating and calculated NZ methods adaptable to different geographic and climate contexts, updated building codes and standards to promote electrification and renewables, track and documentation of the progress on the committed NZ practices, renovation of existing NZBs, and energy efficiency and supply requirements need to be included or mandated as required.

Flowchart III summarizes the PC-A-NZ process in addressing variations, strategies, and requirements, which is adaptable to different geographic contexts, Figure 5.

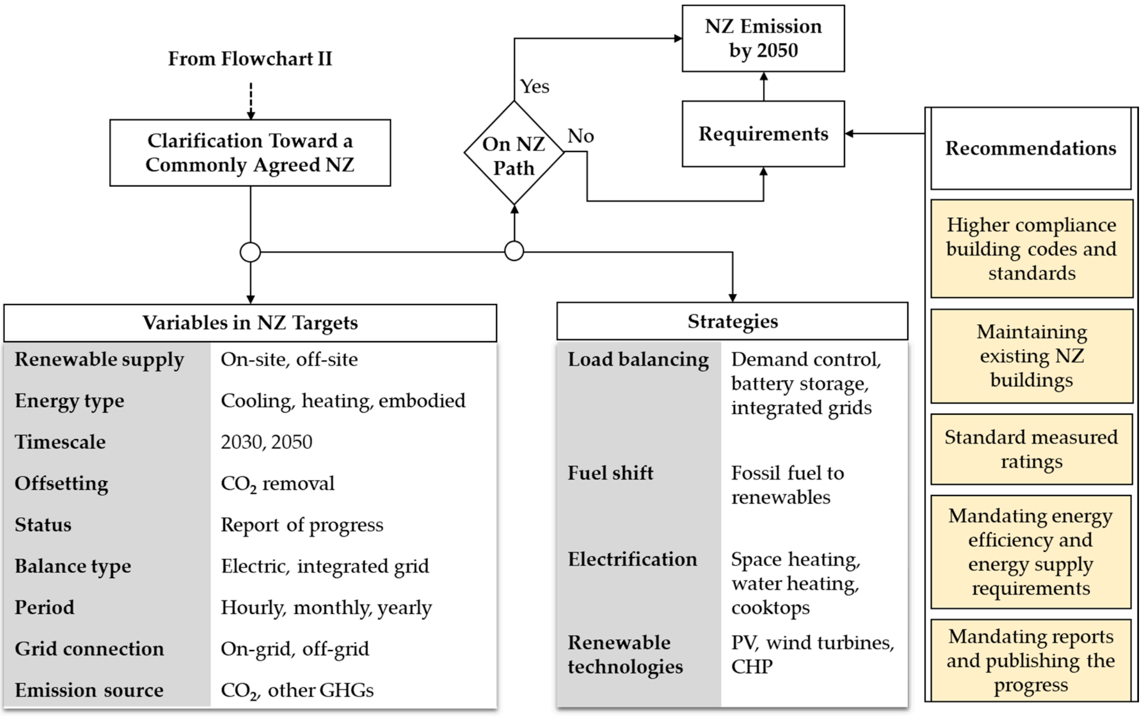

Figure 5. Flowchart III, hierarchical proposed Process for Clarification to Accelerate Net Zero (PC-A-NZ) through variations, strategies, and requirements.

8. Conclusions

This paper summarized:

1. NZ design principles can be realized at the building level;
2. Transforming a building to NZ requires clarifications and fully verified parameters and strategies;
3. Integration of energy efficient strategies, renewable technologies, and optimization approaches would cause a shift in source and consumption patterns.

The Net Zero concept has become an increasingly important topic in response to the climate action targets. NZ for buildings is recognized as a promising solution toward decreasing source energy consumption and GHG emissions by promoting renewable energy productions. An increasing number of countries are targeting to become 100% renewable energy and achieve zero emission by 2050. A common standard definition and strategy is needed with adaptable codes and standards to achieve NZ targets and enhance practical solutions to support stakeholders, including policymakers, building and grid designers, operators, and engineers in attaining their goals. This paper proposed a Process for Clarification to Accelerate the Net Zero (PC-A-NZ) through variations, strategies, and requirements shown in three flowcharts.

The NZ literature analysis is mainly focused on the building sectors. Additional research is needed toward achieving 2050's NZ targets by extending the NZ knowledge to a larger scale of communities and nations. Tracking successes need to be reported so that others can better understand the difficulties and how to solve these. Future studies are needed in (1) community level solutions to reducing energy/emissions including buildings, community power systems, and transportation sectors; (2) standardizing electrification systems so that a wider range of individual buildings and communities can move toward full electrification; and (3) developing new methods and technologies to enable achieving NZ in 2050.

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Nomenclature

NZ	Net Zero Energy
NZB/NZEB/ZNEB/ZEB/NZE/ZE	Net Zero Energy Building
NZEB/nZEB	Nearly Net Zero Energy Building
NZE2050	Net zero CO_2 emissions by 2050
PC-A-NZ	Process for Clarification to Accelerate the Net Zero
GHG	Greenhouse gas
RE	Renewable energy
LCC	Life cycle cost
LCE	Life cycle energy
LCA	Life cycle assessment
SLR	Systematic literature review
LM	Load matching
GI	Grid interaction
HVAC	Heating, ventilation, and air conditioning
CHP	Combined heat and power plant
PV	Photovoltaic
DOE	Department of Energy
EPA	Environmental Protection Agency
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

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