AN ADAPTABLE NET ZERO MODEL TO ACCELERATE ACHIEVING GLOBAL CLIMATE TARGETS: A MONITORED CASE STUDY

A Dissertation

by

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ABSTRACT

With increased efforts toward planning for climate change mitigation and the design of carbon neutral and Net Zero (NZ), this study addresses five key barriers in achieving the targets: (1) the lack of consensus in the existing NZ definitions, which creates uncertainties and causes delays in actions; (2) the main focus of current definitions on buildings, while disregarding community power systems and energy use in transport sectors; (3) quantifying energy use reduction approaches; (4) obtaining measured data to track the NZ progress; and (5) verifying NZ achievements. Numerous definitions of NZ currently exist and a modification is needed to clearly show which definition was used. This research proposes an adaptable ($NZX\%_{\mathbf{ORG}}$) model to enable global understanding and standardized concepts that are applicable to different regions and requirements and enhance the reporting of NZ. The $NZX\%_{\mathbf{(ORG)}}$ model focuses on balancing on-site energy demand with renewable supply in buildings at a community level. The ‘X%’ presents the fraction of renewable energy to the total energy used, and “ORG” stands for the organization’s NZ definition that projects choose to follow. A case study of the Serenbe community in Georgia, US was analyzed to quantify the impact of energy efficiency measures and renewables on its energy performance and verify its NZ achievements. The results showed that Serenbe could generate 80% of its total energy from renewables. Assuming that the project uses the Environmental Protection Agency (EPA)’s NZ definition and generates, then Serenbe could become $NZ80\%_{\mathbf{(EPA)}}$. As a project adds renewable sources, their rating increases toward $NZ100\%_{\mathbf{(ORG)}}$. With this plan, the projects are required to have publicly available reports to show committed NZ

plans, the energy performance, and the percent of renewable energy used. The NZX%$_{\mathbf{(ORG)}}$ model is adaptable to different regions and requirements to enable projects to achieve and communicate their NZ achievements. The NZX%$_{\mathbf{(ORG)}}$ and total consumption for each project could then be aggregated to report the successes of cities and nations.

DEDICATION

To my father, mother, and brother who has shown me the power of love!

ACKNOWLEDGEMENTS

Among all who have helped me through my doctoral journey, I would like to express my deepest appreciation to my chair, Dr. Jorge Vanegas who believed in me from the first day I started the program and gave me a chance to grow with his continuous support. Also, I am greatly thankful to my co-chair, Dr. Charles Culp who has supported me all the way in pursuing my goals and provided me with continuous support, encouragement, and patience. Thank you both for extending a great amount of guidance and relentless support throughout this project. I am extremely grateful to my committee members Dr. Stephen Caffey and Dr. Mehrdad Ehsani for their insightful advice, constructive suggestions, and support. I am also very thankful to Dr. Hazem Rashed-Ali and Dr. Benjamin Welle, who have provided occasional advice when it was needed.

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All other work conducted for the dissertation was completed by the author independently.

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GLOSSARY / ENERGY TERMS

Net Zero Energy	To produce energy as much as used in a year from renewables (Supply and source requirements vary in concepts defined by different organizations.)
Site Energy	"Energy consumed at the building site as measured at the site boundary"[1]
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"[2]
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, and energy efficiency measures may vary in different definitions.

[1] Peterson, L., Torcellini, P., & Grant, R. (2015). A Common Definition for Zero Energy Buildings. Department of Energy (DOE). https://www.energy.gov/sites/prod/files/2015/09/f26/A%20Common%20Definition%20for%20Zero%20Energy%20Buildings.pdf

[2] Peterson, L., Torcellini, P., & Grant, R. (2015). A Common Definition for Zero Energy Buildings. Department of Energy (DOE). https://www.energy.gov/sites/prod/files/2015/09/f26/A%20Common%20Definition%20for%20Zero%20Energy%20Buildings.pdf

Total Energy Use	Total utility energy data and renewable generations.

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1. INTRODUCTION

The global population is predicted to increase to 8.5 billion by 2030 and reach 9.7 billion by 2100 (United Nations (UN), 2021b). This increasing population and continued use of non-renewable resources have caused severe environmental impacts on the climate (Halofsky et al., 2015; Perera, 2017; Webb et al., 2017). The global temperature is rising by about 0.2 °C per decade (Intergovernmental Panel on Climate Change (IPCC), 2019a). According to IPCC, by 2017, human-induced warming reached 1°C above pre-industrial levels and is projected to reach 1.5 °C by 2040, shown in Figure 1.1.

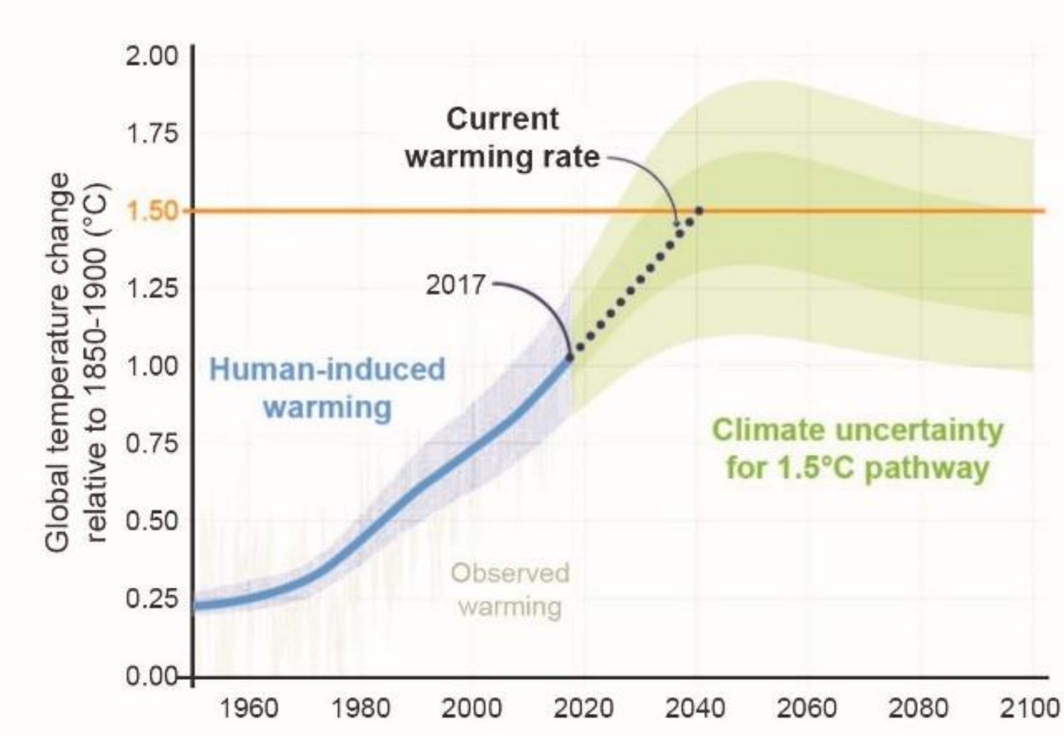


Figure 1.1: Stylized 1.5°C pathway. Source: IPCC 2019; FAQ Chapter 1, FAQ1.2: How close are we to 1.5°C? (page 82) (Intergovernmental Panel on Climate Change (IPCC), 2019a).

It is reported that “air pollution kills an estimated seven million people worldwide every year” (World Health Organization, 2021). In response to the Paris Agreement (United Nations (UN), 2015, 2019), 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 (International Energy Agency (IEA), 2021c; Rogelj et al., 2015). Recently, a “faster warning” is released on the global temperature rise that demands immediate reductions in Greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change (IPCC), 9 August 2021). In November 2021, at the UNFCCC Conference of the Parties (COP26) - the 26th UN climate change conference – the goal was set to limit global warming to well below 2 °C and pursue a target of 1.5 °C by 2050. Approaching the COP26 - 80 countries submitted new or updated NDCs to the UNFCCC (23 April 2021), covering 40% of global CO_2 emissions, shown in Figure 1.2.

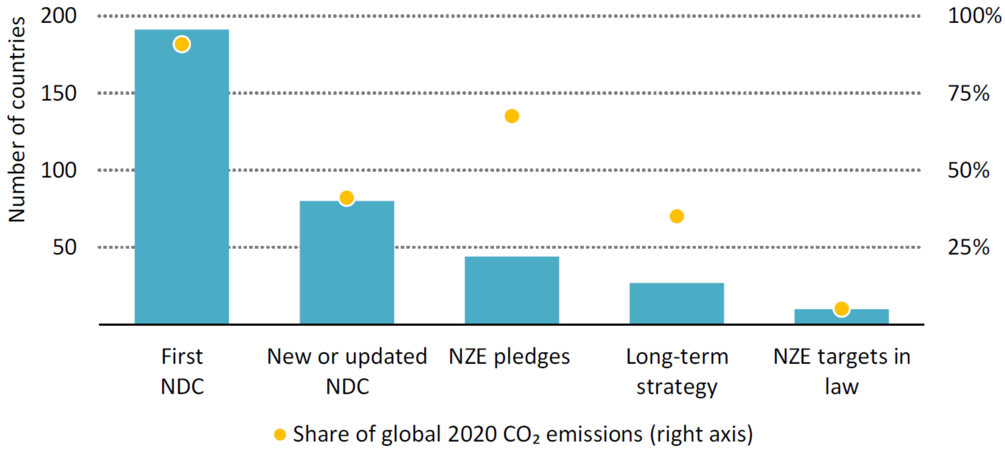


Figure 1.2: The number of countries with NDCs, long-term strategies and net zero pledges, and their shares of 2020 global CO_2 emissions. Source: (International Energy Agency (IEA), 2021c).

As Figure 1.2 shows, the European Union (EU) and 44 countries covering 70% of global CO_2 emissions agreed to pledge to achieve net zero emissions by 2050 (International Energy Agency (IEA), 2021c). Ten (10) of these countries made their net zero target commitments as a "legal obligation", eight (8) countries proposed to make it a legal obligation, and the rest pledged through "official policy documents." Based on IEA, however, most of these net zero commitments lack "detailed policies and firm routes to implementation," and vary in scope and timescale.

In 2020, although, CO_2 emissions were reduced by 5.8% as an outcome of the COVID-19 pandemic, the IEA's monthly data presented a 2% increase in global energy-related CO_2 emissions in December 2020 and a 4.9% increase in 2021 (International Energy Agency (IEA), 2021b, 2021c, March 2021). In March 2021, IEA hosted a net zero summit to focus on the necessary actions that countries and companies who pledged for net zero emissions need to take to transform the goals into practice (International

Energy Agency (IEA), 2021c). The three largest emitters of the world, China, the US, and the EU have released climate action targets to become carbon neutral by 2060, 2050, and 2050 respectively (United Nations (UN), 2021a). In the US, 33 states have adopted the Paris Agreement, and some states, including New York and California, released NZ projects as the primary solution to their GHG reduction targets by 2050, yet individual commitments vary in requirements. As an outcome of this variation, even if NZ meets the target "the pledges to date would still leave around 22 billion tons of CO_2 emissions worldwide in 2050" (International Energy Agency (IEA), 2021c).

Therefore, there is a need for a consensus NZ concept and firm routes and strategies to accelerate the actions in achieving global NZ emissions by 2050. This dissertation addresses the gap in the knowledge of NZ by investigating the current variations and implementation approaches to reorganize an adaptable NZ model. The outcome of the model will deliver design guidelines and systematic methods for stakeholders including policymakers, developers, and engineers to quantify the energy performance of their projects, verify their NZ objectives, and track the committed NZ progress.

1.1. Research Problem and Questions

This research has been centered around four issues regarding the NZ concept, including:

1. clarifying NZ's concept and requirements (source, supply, metrics);
2. quantifying energy use reduction approaches;
3. obtaining measured data to track the NZ progress; and

4. verifying NZ achievements.

These challenges are covered in Chapters 2, 3, and 4: first, the current variations in NZ are identified as the main cause of uncertainty and delay in action. A clarification process in concept, strategies, and requirements is needed before further implementations (Attia, 2018; Drury Crawley et al., 2009; Moghaddasi, Culp, Vanegas, et al., 2021; Wei & Skye, 2021). Second, to accelerate achieving the 2050's NZ targets, the NZ knowledge needs to be extended from the building level to the larger scale of communities (NZC) by including community power productions and energy use in transportation sectors. Further the results from analyses of three planned NZC concluded that lack of scientific publications reporting on measured energy data contributes to the failure of validating the NZ performance (Chen et al., 2017; Dorotić et al., 2019; International Energy Agency (IEA), 2021c; Klein & Coffey, 2016; Moghaddasi, Culp, & Vanegas, 2021). Third, a reorganized ($NZX\%_{\mathbf{ORG}}$) concept was proposed that is adaptable to different regions with different codes and requirements to provide a globally understandable NZ that includes all the current concepts.

The issue of current NZ variations has been addressed in this dissertation by providing design guidelines and systematic methods for the stakeholders including policymakers, developers, engineers, and designers to apply to their projects and accelerate achieving their NZ objectives. This research proposes to address the following questions:

- How to define an NZ that is adaptable to different regions and requirements?

- How to quantify NZ energy performance of buildings at the community level?
- How to verify NZ and track its progress?

1.2. Background

1.2.1. Global Pollution Generation

Studies by 97% of climate scientists show that climate change causes originated from human activities (Cook et al., 2016). Among those activities, electricity or "power", buildings and transport sectors (PBT) are the main consumers of primary energy and emitters of Greenhouse gases (GHG) (International Energy Agency (IEA), 2020b, 2021a; Masson-Delmotte, 2019; Nejat et al., 2015; Pablo-Romero et al., 2017; Ritchie, 2020, October 06, 2020; U.S. Energy Information Administration (EIA), 2016; U.S. Environmental Protection Agency (EPA), March 25, 2021).

Buildings are accountable for 33% of the global final energy use and around 40% of GHG emissions (International Energy Agency (IEA), 2020b, 2021a). The transport sector accounts for 25% of the world's total delivered energy consumption and 24% of global CO_2 emissions (Ritchie, October 06, 2020; U.S. Energy Information Administration (EIA), 2016). Electricity and heat production accounts for 25% of global CO_2 emissions (Masson-Delmotte, 2019; U.S. Environmental Protection Agency (EPA), March 25, 2021). This rate of fossil fuel-based energy consumption increases GHG emissions and causes environmental problems such as health issues, natural disasters, and global warming (Buis, 2019; Intergovernmental Panel on Climate Change (IPCC), 2019b).

1.2.2. Net Zero Variations and Uncertainties

Net Zero Energy (NZ) adoptions are the primary solutions to achieve GHG emission reduction targets by 2050 (Aelenei & Gonçalves, 2014; Gupta, 2019; International Energy Agency & United Nations Environment Programme (UNEP), 2018; International Energy Agency (IEA), 2021c; Lucon et al., 2014; Sun et al., 2015). However, numerous definitions of NZ currently exist with main variations in source and supply requirements from multiple organizations (European Commission, 2021; Jarek Kurnitski, May 2011; Peterson et al., 2015; U.S. Environmental Protection Agency (EPA), September 16, 2016). Previous literature identified current variations in NZ as the main cause of uncertainty that delay achieving the climate target goals (Carlisle et al. 2009; Koutra et al. 2018; Wells et al. 2018; Black et al. 2021). Developing a simplified model will lead to efficient standards and practical solutions (Moghaddasi, Culp, Vanegas, et al., 2021).

1.2.3. Policy Regulations and Standards

To meet NZ emission targets, buildings need to follow zero carbon policies and strategies such as energy efficiency measures (EEMs), renewables, and electrification of end uses. However, the existing codes and regulations are insufficient to address the NZ targets or lack firm routes for implementations (Daniel Fournier et al., 2020; Ebrahimi et al., 2018; Economidou et al., 2020; Kumar & Alok, 2020). According to Kumar and Alok, codes and regulations need to promote electrification and renewables into buildings and transport sectors. Ebrahimi et al. highlighted the necessity of including electrified end-uses in buildings in energy policies besides decarbonized electric grid to reduce GHG emissions. Economidou et al. reviewed the impact of EU policies on the buildings' energy efficiency improvements and recommended policies with higher energy performance requirements; extension from building level to district level; use of electrification and smart technologies; and targeted financial mechanisms on energy efficiency in addressing decarbonization targets.

1.2.4. Variety in Optimization Approaches

Many competing optimization strategies and challenges exist in quantifying net zero building (NZB) and net zero community (NZC) performance (Almehizia et al., 2019; Dennis, 2015; Kelly et al., 2021; Lopes et al., 2016; Salom et al., 2014; Wills et al., 2021). Salom et al. analyzed building loads and grid interactions through hourly values in NZBs. The authors recommended the utilization of combined renewable energy production technologies, control strategies, energy storage systems, and electrification. Lopes et al. concluded that the use of demand-side management, a higher number of control devices, and a higher capacity on-site generation significantly improve load matching in a community of five detached NZBs compared to the individual NZB. Wills et al. proposed a hybrid statistical and engineering-based model to retrofit a community with improved envelope, mechanical and district renewable energy systems to achieve NZC. Kelly et al. showed that load shifting with thermal storage could add flexibility to the energy demand to meet the supply and suggested heat pumps as responsive options to variations of electrified heating systems.

1.3. Research Objectives and Significance

From the above discussion, the following objectives are presented:

1. verify primary parameters in current NZ that delay the global climate target actions;
2. provide NZC design guidelines;
3. present systematic methods to quantify total energy use in buildings at the community level;
4. propose an adaptable Net Zero model that includes all the current NZ concepts; and,
5. deliver optimized community production scenario analysis in respect to the installation cost and design limitation (i.e., roof space, orientation, resident interest, etc.).

Reorganizing the NZ to an adaptable model with design guidelines enables key stakeholders, including developers, engineers, building and grid designers plan their projects' carbon footprints and quantify NZ in their cases. In this research, the Serenbe community will be an example of NZC's achievement in the US and globally. Analyzing a monitored case study shows that (1) the NZ energy practices can be quantified and verified at the community scale; (2) savings in energy and CO_2 emissions need foresight both in the early phase of design and planning with careful implementation of the strategies; (3) documented annual reports on the monitored hourly and monthly utility data is necessary to track the NZ progress; (4) the adaptable NZ is a practical model that motivates stakeholders to take the first steps and improve. The results from $NZX\%_{\mathbf{(ORG)}}$ present a promising plan that Serenbe can apply and estimate its NZC by 2050, which is measurable, trackable, and adaptable to different regions and requirements. This paper conducted calculations based on a monitored case study analysis, measured utility electricity data and PV generation, and simulated assumptions on a square meter basis.

1.4. Research Methodology

"Make everything as simple as possible, but not simpler," Albert Einstein.

Based on (Creswell & Creswell, 2017), this dissertation is committed to deducting from the ideas and making it as small as a set of variables to test and conclude the hypothesis and answer the research question.

The methodology in this research is mixed methods, which comprise both quantitative and qualitative analysis using numerical data for evaluating energy practices. The analysis was conducted through literature review; interviews; comparative analyses of the measured data, calibrated models, improved simulation analyses in a monitored case study; and optimized community solar scenario analyses.

In the Second Chapter, a literature review was conducted on the published Net Zero Buildings (NZB) definitions and criteria variations from different organizations. As a result, current variable parameters that slow the acceptance of NZ were recognized and published in (Moghaddasi, Culp, Vanegas, et al., 2021).

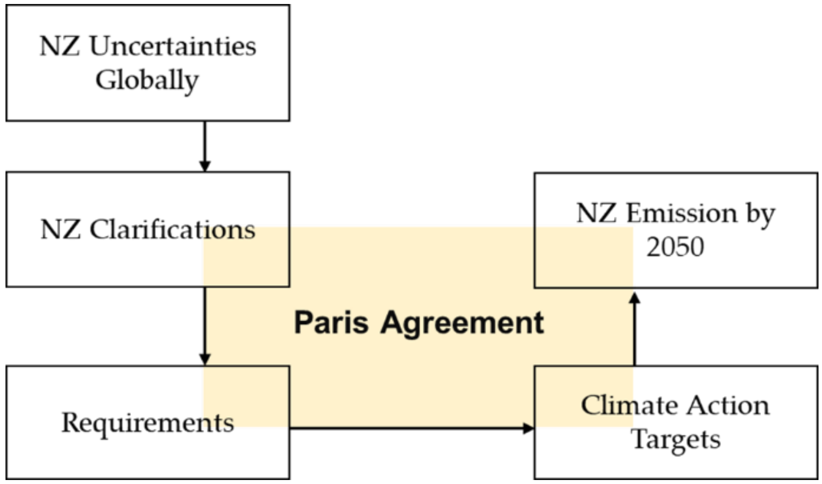


Figure 1.3: Graphical Abstract (Manuscript I). Source: (Moghaddasi, Culp, Vanegas, et al., 2021).

In the Third Chapter, the review analysis of the first published manuscript was extended to the Net Zero Communities (NZC) to highlight the impacts of energy efficiency measures and renewables in power production, building, and transportation (PBT) sectors in reducing energy use and emissions. This Chapter covers extrapolated NZC design guidelines by reviewing the latest climate policy projection models and studying three planned NZC cases in international locations (Moghaddasi, Culp, & Vanegas, 2021).

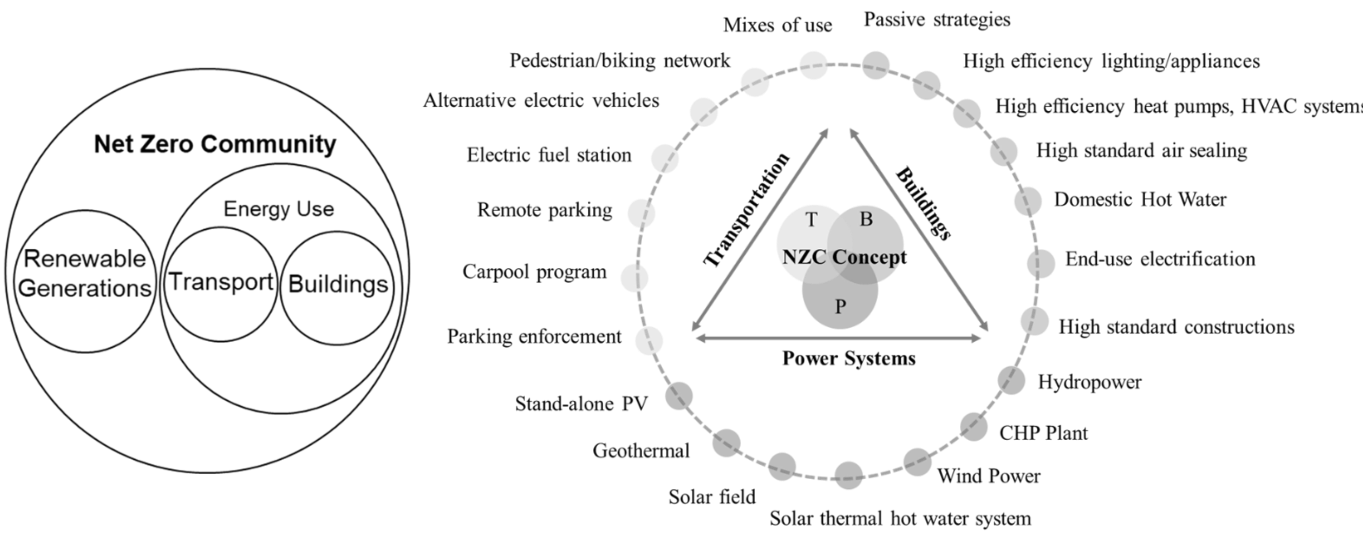


Figure 1.4: Graphical Abstract (Manuscript II). Source: (Moghaddasi, Culp, & Vanegas, 2021).

In the Fourth Chapter, the author used both published manuscripts of NZB and NZC as the data input to the proposed NZX%$_{\mathbf{(ORG)}}$ to standardize a universal NZ concept and systematic methods, as shown in Figure 1.3.

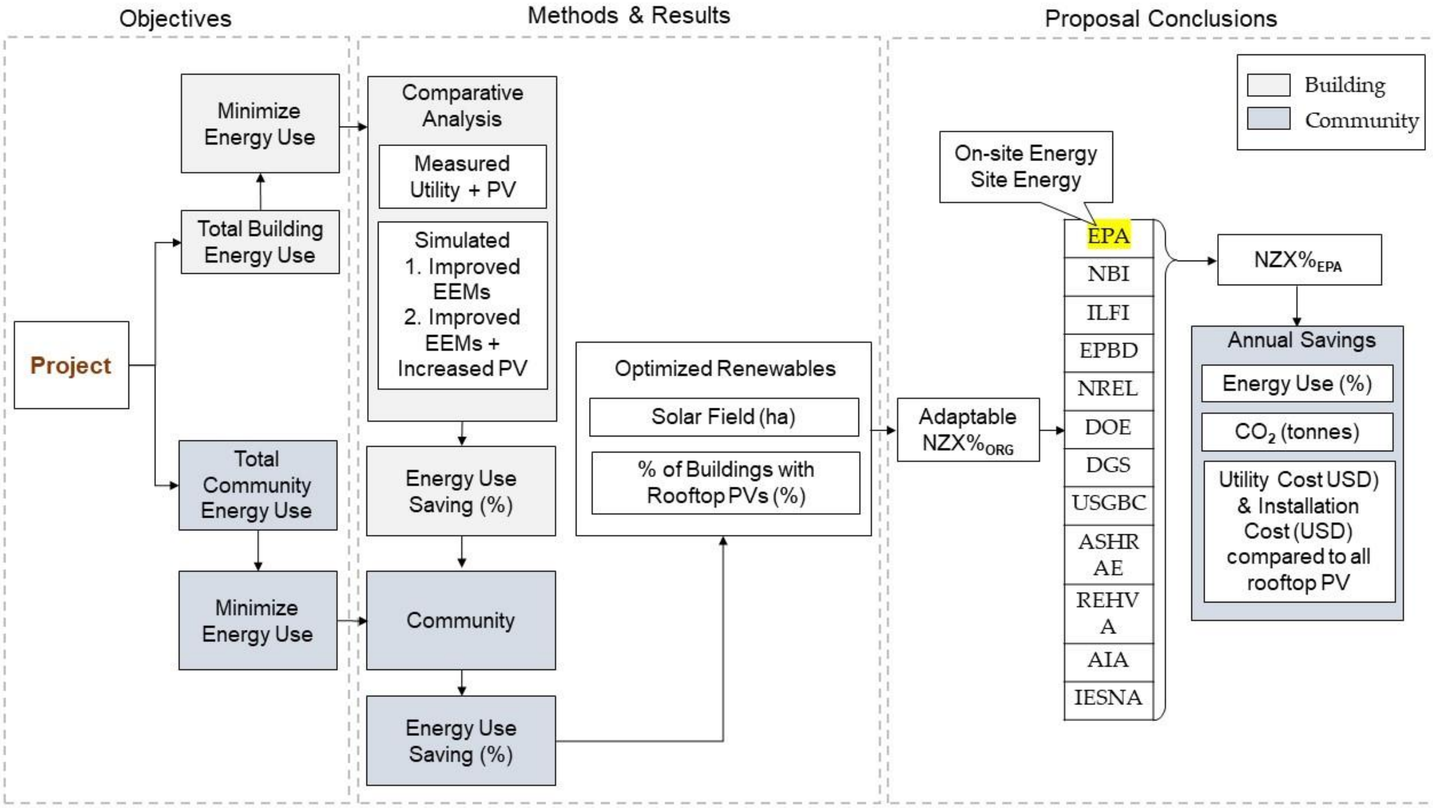


Figure 1.5: Research Design (Manuscript III). The systematic method for a project to become NZX%.

To test the validity of this proposal, it was applied to a monitored case study of the Serenbe community and a single-family house as a base building C in Serenbe to (1) analyze the community's total energy use; (2) recommend additional improved energy efficiency measures; (3) estimate a renewable-based community power production; and, (4) verify the community's path to the global net zero emissions target.

The analysis was conducted by monitoring the daily and monthly utility energy data and solar PV generation in "base building C" and "total buildings (residential and commercial) in Serenbe" from 01 January 2020 to 31 December 2020 (600 buildings).

The research strategy included a set of questionaries from the Serenbe resident regarding their building's energy use, a collection of interviews with the master planner (Dr. Phillip Tabb), founder and developer (Mr. Steve Nygren), the Serenbe Development Team, and the Graystone Power Company. The author spent around two years for data collection and monitoring energy use (utility energy and solar PV generation) of the base building C and total community in 2020. With acquiring the measured data, the author has created simulation energy modeling to conduct comparative analyses of the measured data and improved simulations. Figure 1.6 shows snapshots of models of Building C created in Design Builder energy modeling software.

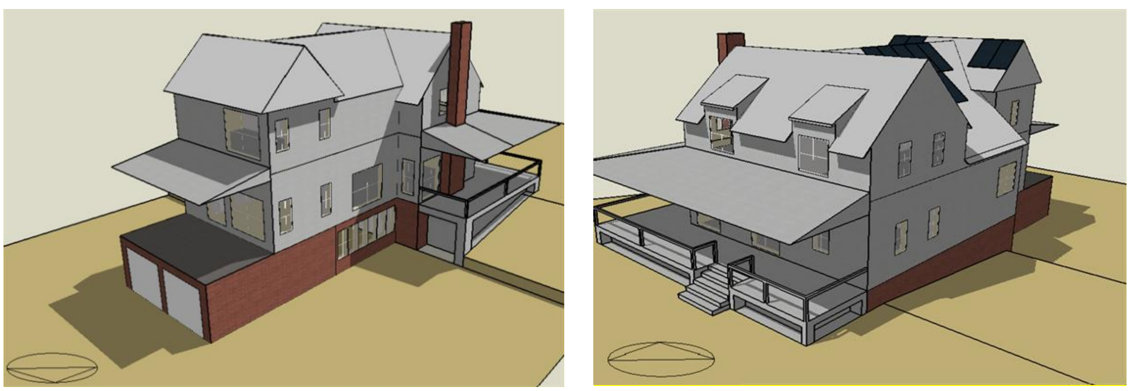
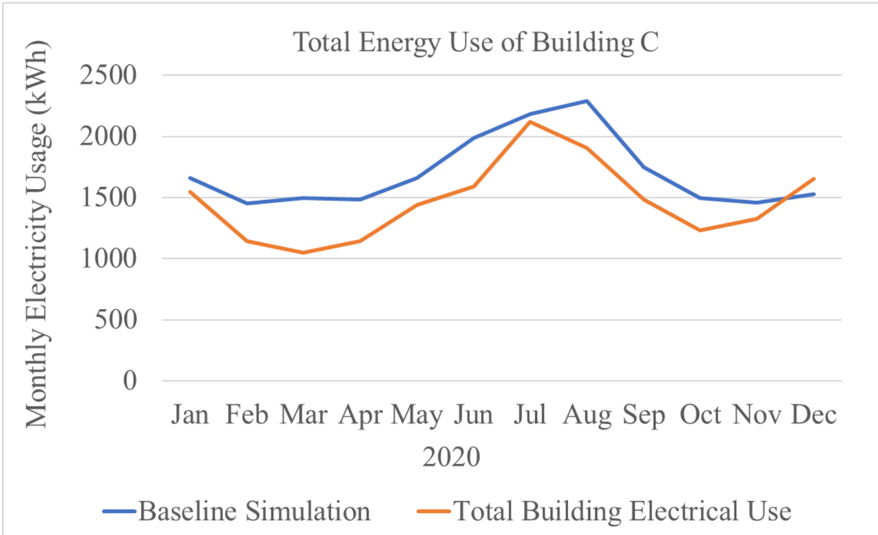


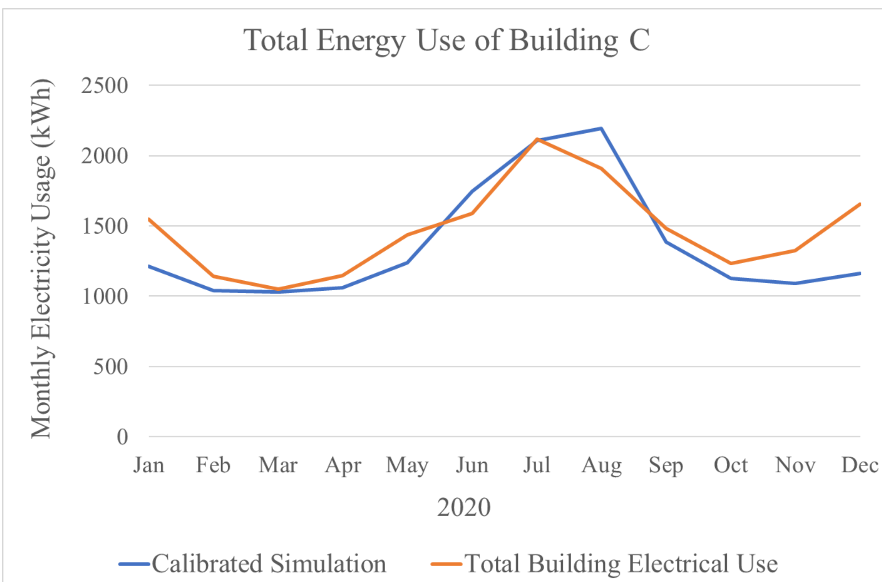
Figure 1.6: Simulated model of base building C in Design Builder Software.

Initially, built-in EEMs from two energy-efficient buildings in Serenbe were improved in base building C. A comparative analysis was conducted in Building C, in three steps: (the following graphics are further details that were space limited from putting into the paper (Chapter 3)):

1. calibrate a base case by simulating the total building electrical use (Figure 1.7);



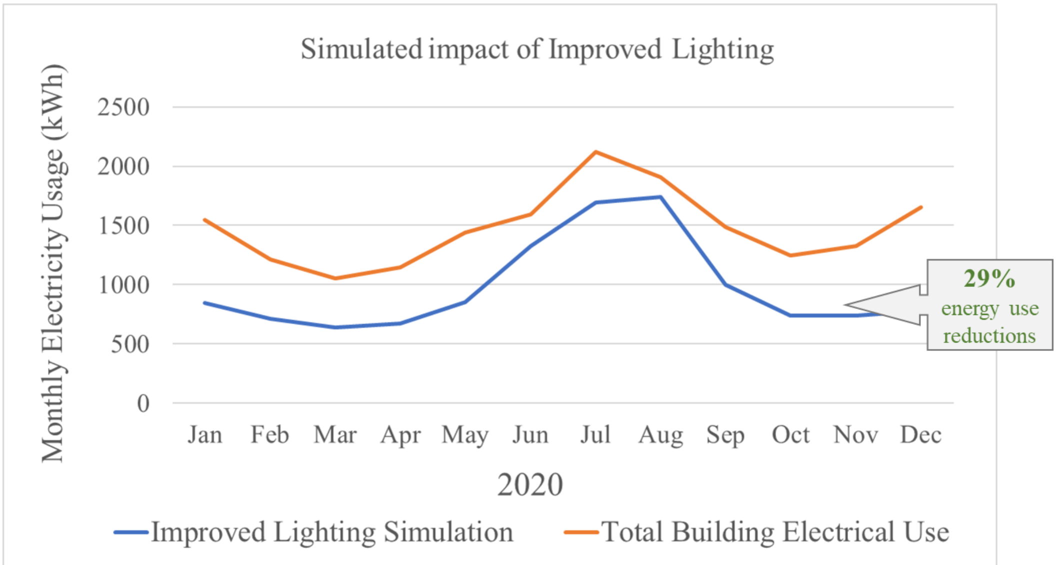
a. Baseline Model.



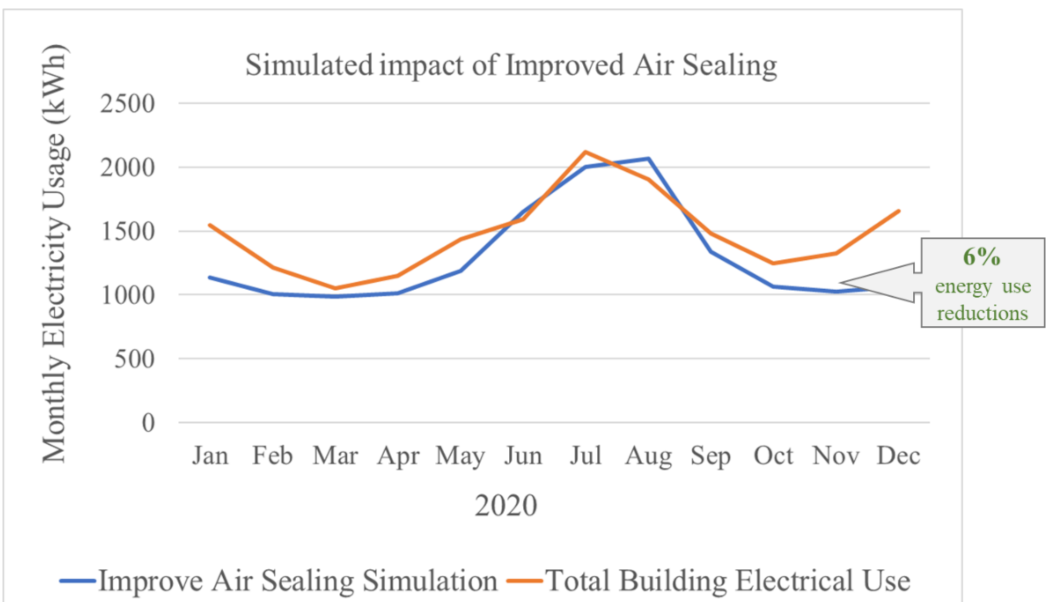
b. Calibrated Model.

Figure 1.7: Total energy use of building C was modeled and calibrated using Design Builder Simulation.

2. simulate the improved EEMs to estimate the energy savings (Figure 1.8);

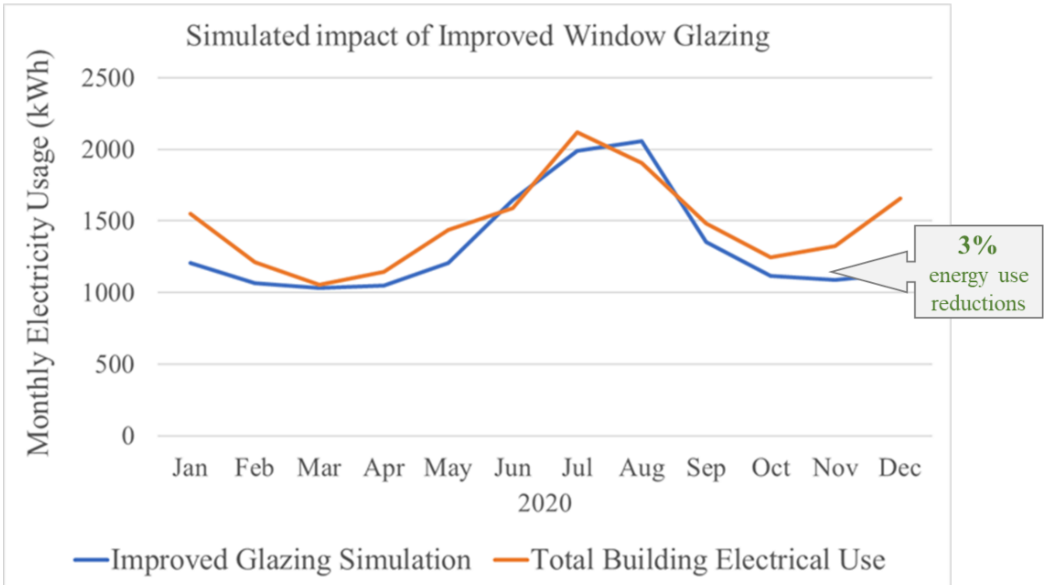


a. Improved lighting power from 7.5 (W/m²) to 3.5 (W/m²)



b. Improved air sealing from 0.7ACH to 0.2ACH

Figure 1.8: Energy savings with the use of high efficiency lighting, air sealing, and window glazing in building C using Design Builder Simulation.



c. Improved window glazing from 0.6 to 0.27 SHGC

Figure 1.8: Energy savings with the use of high efficiency lighting, air sealing, and window glazing in building C using Design Builder Simulation.

As the results from analyses in Figure 1.8a-c show, improved lighting caused a significant amount of saving in energy use. This is because of shifting all incandescent lighting bulbs to LED technology. Residential LEDs use at least 75% less energy than incandescent lighting and last up to 25 times longer (Department of Energy (DOE), 2022). Savings results from improved air sealing and window glazing showed that the existing measures used in building C are reasonably efficient.

3. increase rooftop PV coverage to lower the utility energy consumption (Figure 1.9):

a) from 10% of the roof space (24m²) to 25% (58m²)

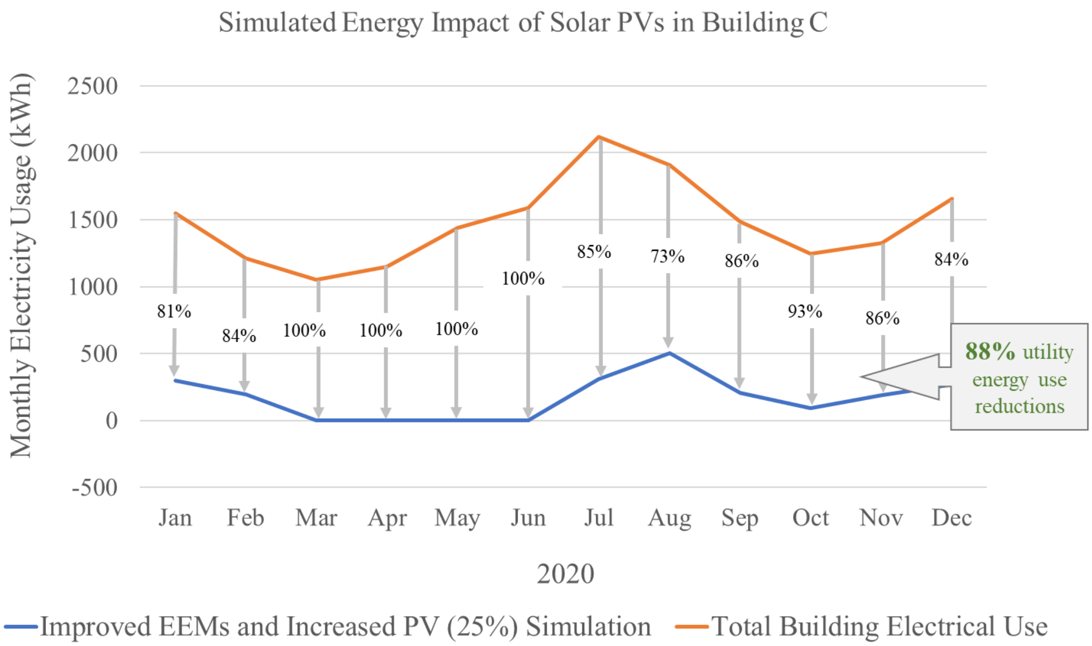


Figure 1.9: Monthly utility energy savings with additional rooftop PV in building C using Design Builder Simulation.

Next, the analysis extrapolated building C to estimate the energy savings of total buildings in the Serenbe community in 2020. The results showed that the community could either become NZ46% and increase its utility energy savings by 65% by retrofitting the existing buildings with rooftop PV (10% of roof space), or it could become NZ80% with covering 88% of roof spaces with rooftop PV systems in all 600 buildings, as shown in Figure 1.10.

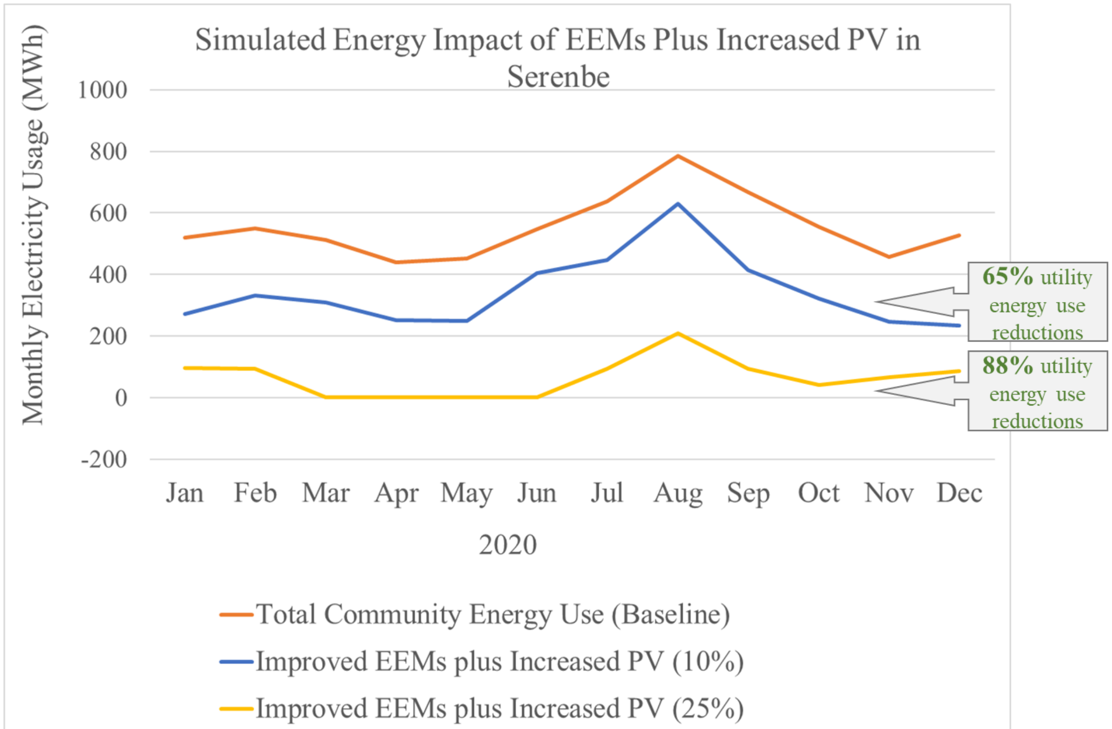


Figure 1.10: Monthly utility energy savings with additional rooftop PV in the Serenbe Community, using Design Builder Simulation.

As Serenbe uses only on-site renewable generation and considers site energy for its energy calculation, EPA's NZ definition was used. The model estimated Serenbe to become NZ80%$_{\textbf{(EPA)}}$ by improving EEMs and increasing rooftop PV systems. The calculated savings are approximate and practical for stakeholders to easily estimate the planned reductions and NZC level in their projects. Monitoring and reporting will provide the actual NZC levels achieved year by year.

2. NET ZERO ENERGY BUILDINGS: VARIATIONS, CLARIFICATIONS, AND REQUIREMENTS IN RESPONSE TO THE PARIS AGREEMENT*[3]

2.1. Overview

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

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*[3] Reprinted from "Net Zero Energy Buildings: Variations, Clarifications, and Requirements in Response to the Paris Agreement" by Moghaddasi, H., Culp, C., Vanegas, J., & Ehsani, M., 2021. Energies, 14(13), 3760. Open Access Journal.

optimize the use of renewable technologies, improved energy efficiency, and electrification to speed up achieving the NZ targets.

2.2. Introduction

Net zero energy (NZ) is an increasingly important topic to the environment and climate change mitigations. The global population is predicted to increase to 8.5 billion by 2030 and reach 9.7 billion by 2100 (United Nations (UN), 2021b). This increasing population and continued use of non-renewable resources have caused severe environmental impacts on the climate (Halofsky et al., 2015; Perera, 2017; Webb et al., 2017). The (World Health Organization, 2021), reported that “air pollution kills an estimated seven million people worldwide every year.” In 2015, the Paris Agreement (United Nations (UN), 2015) 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 (Center for Climate and Energy Solutions, 2020; European Union (EU), 2021a; Lu et al., 2020; Myers, September 2020; Schreurs, 2016; United Nations (UN), 2019). 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 (International Energy Agency & United Nations Environment Programme (UNEP), 2018). The California state considers NZ as “a strategy with tactical approach towards achieving the GHG reduction goal or a zero carbon” (Gupta, 2019)" (U.S. General Services Administration (SGC), 2011). 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 (Abergel et al., 2017; Almehizia et al., 2019; Intergovernmental Panel on Climate Change (IPCC), 2012; Lopes et al., 2016; Salom et al., 2014; Shanti Pless and Paul Torcellini, 2010; Solar Heating and Cooling Technology Collaboration Programme SHC Task 40 (EBC Annex 52), 2015; U.S. General Services Administration (SGC), 2011; Wright & Klingenberg, 2015). It was 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 (European Climate Foundation, September 2020). Based on a report, "under current policies, annual emissions from residential buildings will decrease by only 30% by 2050" (Fenneke van de Poll, June 2020). Literature shows 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 (Vásquez et al., 2016).

The US and EU have committed to becoming carbon neutral by 2050, and China pledged for achieving the 100% NZ emission target before 2060 (Black et al., 2021; European Union (EU), 2021a; Lu et al., 2020; United Nations (UN), 2020a). 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. It is 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" (Williams et al., 2016). The authors added, "despite, or possibly because of, a continuing debate over definitions, aspiration has not been met by reality". Harkouss et al. were concerned that "there is no common definition for NZEBs", and stated that "the definition depends completely on the purpose intended by the designer" (Harkouss et al., 2018).

Torcellini et al. 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. Torellini et al. analyzed NZ concepts to address the need for a common and clear definition and its impact on achieving the targets. 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 (Torcellini et al., 2006).

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 2.1.

Table 2.1: Limitations in NZ concept.		
References	**Year**	**Citations on NZ Clarification**
(Torcellini et al., 2006)	2006	Despite the excitement over the phrase ‘zero energy,’ we lack a common definition, or even a common understanding, of what it means.
(Drury Crawley et al., 2009)	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.
(Marszal & Heiselberg, 2009; Marszal et al., 2011)	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., 2014)	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., 2015)	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., 2017)	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., 2018)	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.
(Attia, 2018)	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 & Skye, 2021)	2021	There is a lack of systematic literature review focused on recent progress in residential NZEBs.
(Black et al., 2021)	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 clarify 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 tar-get assessments; (6) energy efficient strategies; and (7) results and recommendations.

2.3. Climate Action and Net Zero Targets

In 2015, 197 countries adopted the Paris Agreement (United Nations (UN), 2015) to reduce their GHG emissions and limit the global temperature rise from 2 °C to 1.5 °C (United Nations (UN), 2021a). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C (Masson-Delmotte, 2019) 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) (Black et al., 2021) 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 (Energy and Climate Intelligence (ECIU), 2021). Currently, 121 countries released climate action targets to become NZ or carbon neutral along with 509 cities, and 2163 companies (United Nations Framework Convention on Climate Change (UNFCCC), 2021b).

2.4. Net Zero Definitions and Uncertainties

The European Performance of Buildings Directive (EPBD) (European Commission, 2021) 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 (European Commission, 2021; Wells et al., 2018). 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" (European Commission, 2021). The Federation of European Heating, Ventilation and Air-conditioning Associations (REHVA) (Jarek Kurnitski, May 2011) 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 (Jarek Kurnitski, May 2011), "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) (Peterson et al., 2015) 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 2.2.

Table 2.2: DOE's key terms definition in NZ standard release, (Peterson et al., 2015).

DOE, 2015	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 (International Living Future Institute (ILFI), 2016), 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 (U.S.

Environmental Protection Agency (EPA), September 16, 2016) 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), January 2018) 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 Energy Commission Efficiency Division, 2016) 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 Vision 2020 Committee, 2007), a single definition is necessary to determine "if a building can be universally considered as being an NZEB." It was noted that the only way to count a building NZB is "to look at the energy crossing the boundary" (ASHRAE Vision 2020 Committee, 2007). To estimate the source, emission, and cost in NZ definitions, conservation coefficients are required for the metric of interest (ASHRAE Vision 2020 Committee, 2007; Harkouss et al., 2018). 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 (ASHRAE Vision 2020 Committee, 2007). 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 (ASHRAE Vision 2020 Committee, 2007).”

2.5. Existing Review Publications on Net Zero Variations

Four types of variations were emphasized in the existing NZ reviews, including definitions, calculation methodologies and tools, climate zones, and energy load balance, shown in Table 2.3 (ASHRAE Vision 2020 Committee, 2007; Attia et al., 2013; Berggren et al., 2013; Chastas et al., 2017; Coakley et al., 2014; Drury Crawley et al., 2009; D Crawley et al., 2009; Deng et al., 2014; European Commission, 2021; Feng et al., 2019; Gupta et al., 2019; Harish & Kumar, 2016; Harkouss et al., 2018; International Living Future Institute (ILFI), 2016; Ismail et al., 2019; Jarek Kurnitski, May 2011; Kilkis, 2007; Koutra et al., 2018; Lopes et al., 2016; Lu et al., 2017; Marszal et al., 2010; Marszal & Heiselberg, 2009; Marszal et al., 2011; Mlecnik et al., 2011; Moghaddasi et al., 2020; New Buildings Institute (NBI), January 2018; Parra et al., 2017; Peterson et al., 2015; Sartori et al., 2010; Sartori et al., 2012; Singh & Verma, 2014; Taherahmadi et al., 2021; Torcellini et al., 2006; Vásquez et al., 2016; Voss et al., 2010; Wang & Gorrisse, 2012; Wei & Skye, 2021; Wells et al., 2018; Williams et al., 2016; Wimbadi & Djalante, 2020), which are summarized below:

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 2.3: 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)	✓			✓	Definitions and building design	Lack a common understanding	Consistency	
(D Crawley et al., 2009)	✓					Lack a common understanding	Clarification on source requirements	- Community and campus - Energy storage
(Marszal et al., 2011)	✓	✓			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)	✓					Lack a common international concept and standardized method		
(Sartori et al., 2012)	✓			✓	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

Table 2.3: 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**
(Attia et al., 2013)	✓	✓			Optimization of NZB performance	Uncertainty, computation time, and complexity of the model		Improved methodology, visualization, and standardized costs
(Berggren et al., 2013)		✓			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
(Deng et al., 2014)	✓	✓		✓	- 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

Table 2.3: 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
(Peterson et al., 2015)	✓	✓		✓	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)	✓	✓	✓	✓	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)		✓			Sustainable planning model with NZ character	Limited evaluation literature and optimization methods at the district level		Optimize urban strategic planning
(Wells et al., 2018)	✓		✓	✓	- 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

Table 2.3: 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**
(Feng et al., 2019)	✓		✓	✓	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
(Gupta et al., 2019)	✓		✓		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 & Djalante, 2020)	✓		✓		Systematic Literature Review (SLR) method for data collection	Lack of consensus concept on climate change mitigation and decarbonization	Clarifying visions and approaches to achieve it	Expansion of current CO_2 reduction factors toward NZ to different geographic contexts
(Wei & Skye, 2021)	✓	✓			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

Table 2.3 presents previous NZ review publications on these four variations and summarizes (1) NZ analysis, the key investigation; (2) NZ limitations, main cause of cur-rent 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:

2.5.1. Variation Parameters

Marszal et al. reviewed the NZ topics and proposed the adaptation of a "common and unambiguous" definition as well as calculation methodologies in analyzing the energy balance (Marszal et al., 2011). The main differences in current NZ definitions were recognized as a lack of agreements in:

1. Metrics (primary energy, CO_2 emissions, exergy (Kilkis, 2007), 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).

The authors emphasized deliberating the mentioned issues before further development of NZBs.

2.5.2. 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 (Sartori et al., 2012). 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.

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.

2.5.3. Design, Optimization, Classification

A comprehensive NZ review was conducted on definitions, measured ratios, optimization strategies, and climate zones (Harkouss et al., 2018). 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 by the authors. 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. Harkouss et al. recommended demand reduction strategies, energy efficient systems, and renewable energy generations as key solutions to achieve NZ targets. The authors 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).

2.5.4. Common Limitations

Wells et al. reviewed case studies that meet NZ targets through different definitions and strategies (Wells et al., 2018). 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. 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.

2.5.5. High Performance Building Analyses

Feng et al. 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 (Feng et al., 2019). 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. 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. 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.

2.5.6. 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.

2.6. Assessment of Global Net Zero Targets

2.6.1. Analysis of Global Net Zero by 2050

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) (International Energy Agency (IEA), October 2020). 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. 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 the electricity supply globally.
3. A 33% CO_2 emission reduction 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 (International Energy Agency (IEA), July 2020). IEA noted that energy retrofit causes a 50% reduction in heating energy demand and lowers the need for cooling (International Energy Agency (IEA), October 2020).

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 (International Energy Agency (IEA), October 2020). 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.

By August 2020, 125 countries announced NZ emission targets (International Energy Agency (IEA), October 2020). 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 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.

2.6.2. Systematic Analysis of Global NZ Targets

International Energy and Climate Intelligence and Oxford Net Zero (ECIU-Oxford NZ) conducted analyzed the main emitters and NZ targets globally (Black et al., 2021). Black et al. 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 (Allen et al., 2020; Black et al., 2021; Kelly Levin, July 2020; New Climate Institute & Data-Driven EnviroLab, 2020). The report's objective was to provide an "opening snapshot" to track the progress of the claimed NZ targets over time (Black et al., 2021). "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 (Black et al., 2021; The University of Oxford, May 2020) (Alberto Carrillo Pineda, September 2020; C40 Cities Climate Leadership Group, April 2019; César Dugast (Carbone 4), April 2020; Natural Capital Partners, January 2020). This analysis by Black et al. 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". 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 (Martin Cames, 2016; Schneider & La Hoz Theuer, 2019).
5. Governance, publication of a plan to meet the target, and a clear timescale for accountability, report, and documentation of the progress.

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%) (Black et al., 2021). 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 (Black et al., 2021). 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.

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 (Black et al., 2021; Peters et al., 2017). However, the report stressed the need for robust NZ plans and progress assessments to meet the target. Black et al. 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". 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.

2.7. 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 (Attia, 2018; International Energy Agency (IEA), October 2020; Mai et al., 2018; New Building Institute (NBI), 2021a; Tumminia et al., 2020; Wilson et al., 2017). NREL (Mai et al., 2018) 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" (International Energy Agency (IEA), October 2020). EIA (U.S. Energy Information Administration (EIA), January 2017) 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 (Jeff Deason et al., 2018).

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 (Mai et al., 2018). NREL stated that electrification promotes power production economic enhancements besides mitigating fossil fuel use (Mai et al., 2018). The Energy and Environmental Economics (Energy and Environmental Economics, 2019) 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” (Energy and Environmental Economics, 2019).

Ebrahimi et al. 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) (Ebrahimi et al., 2018). Dennis 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 (Dennis, 2015). Wei et al. presented the existing fossil fuel-related source policies as appropriate short-term yet insufficient long-term solutions to address the GHG reduction targets (Wei et al., 2013). The authors recommended renewable energy for an extra 80% reduction in electricity-related emissions. Williams et al. noted that the long-term cost stability for electrification reduces investment risk compared to the volatile oil and gas prices (Williams et al., 2012), shown in Figure 2.1.

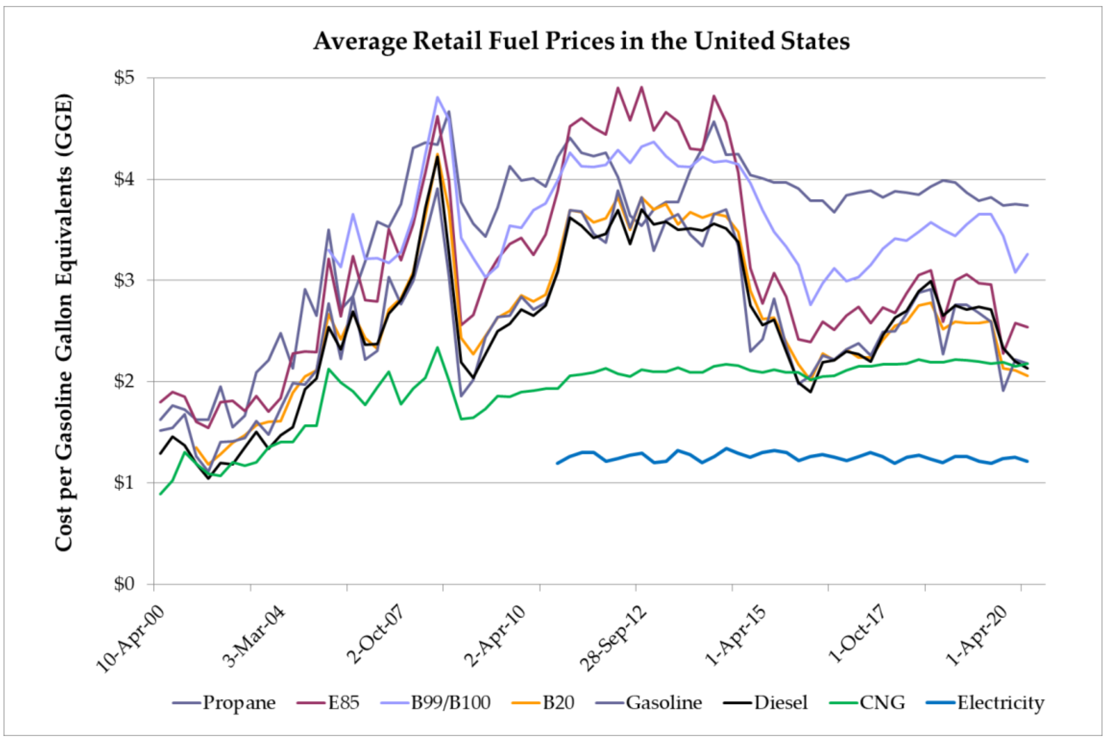


Figure 2.1: Average retail fuel prices in the US. Source: Clean cities alternative fuel price reports, Source: (Department of Energy (DOE), 2020).

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 (Alexi Miller and Cathy Higgins, January 2021; Cheslak, October 2021; Cheslak et al., January 2021; New Building Institute (NBI), 2021). NBI (New Building Institute (NBI), 2021b) 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 (Alexi Miller and Cathy Higgins, January 2021; Cheslak, October 2021; Cheslak et al., January 2021; New Building Institute (NBI), 2021). 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.

2.8. 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 (Newburger, 2021). 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 2.2.

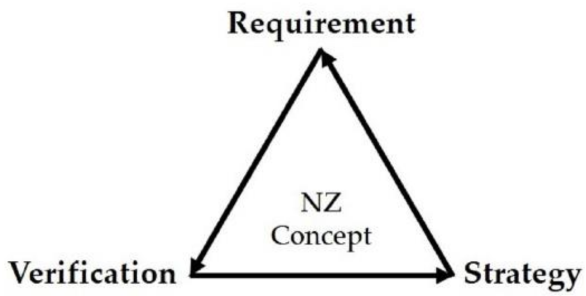


Figure 2.2: Schematic net zero clarification diagram.

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. presented four renewable energy supply options that a building can utilize, shown in Table 3.1.

Table 2.4: Net zero renewable energy supply options, (Torcellini et al., 2006).

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." The source and site energy were defined in Table 2.2

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, shown in Figure 2.3.

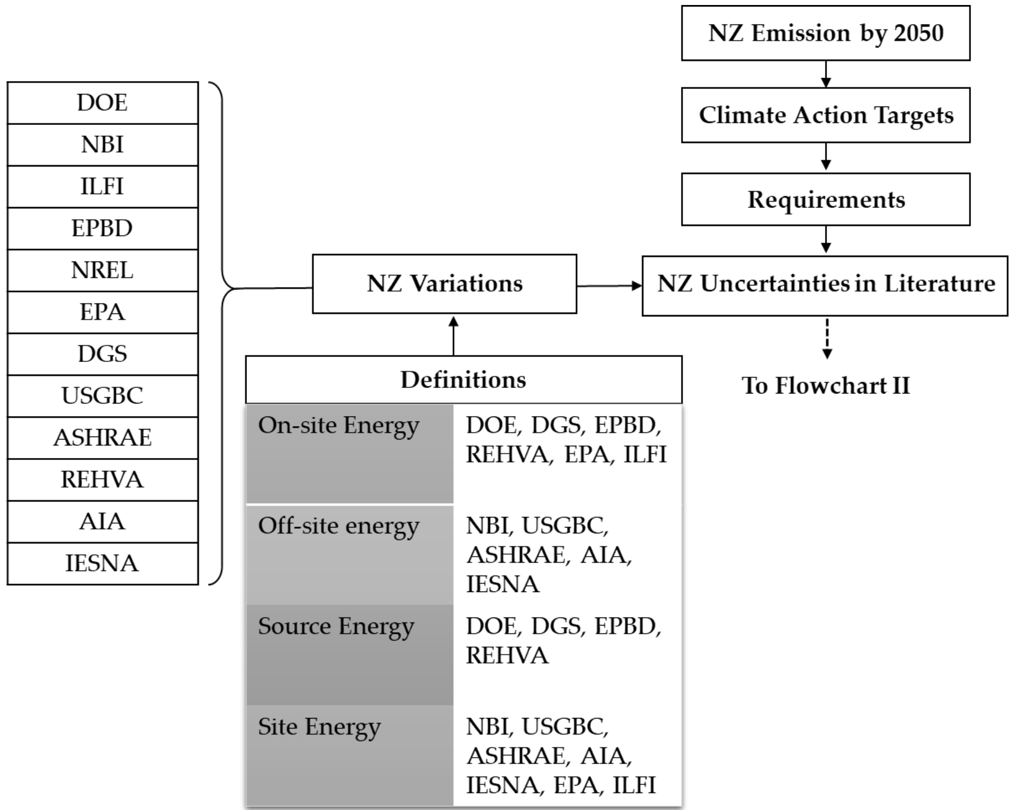


Figure 2.3: Flowchart I, supply and source requirements variation in net zero definitions.

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.

Flowchart II highlights parameters that vary in different NZ definitions and require verifications in defining a common concept, including period, metric, energy type, balance type, infrastructure connection, and requirements from review, as shown in Figure 2.4.

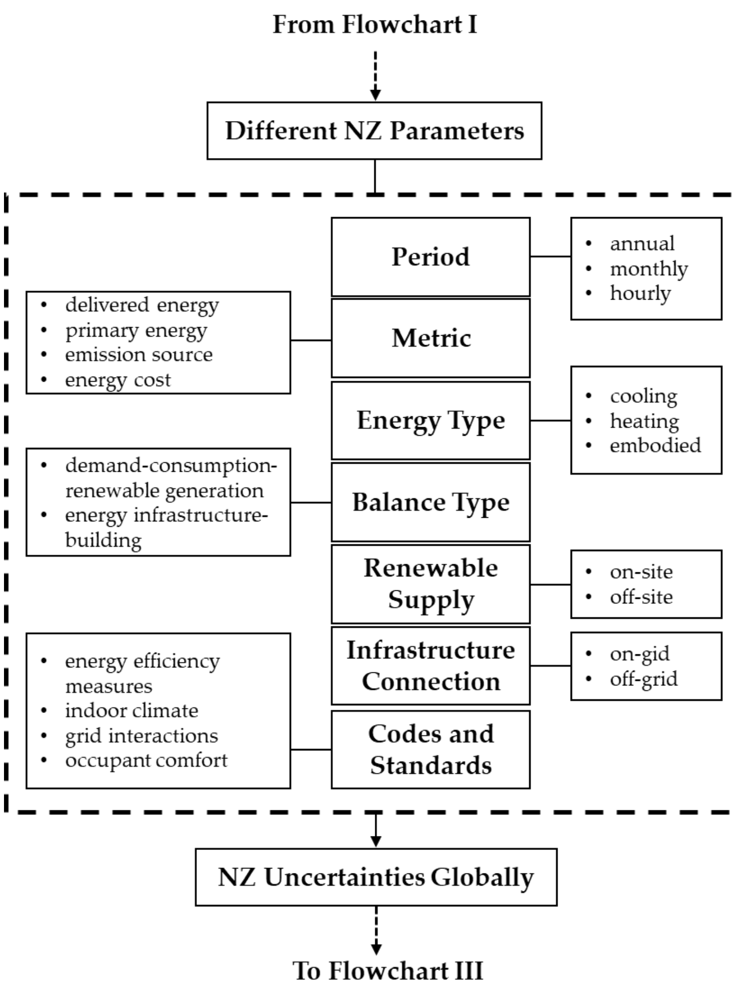


Figure 2.4: Flowchart II, net zero variable parameters in energy balance.

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 2.5.

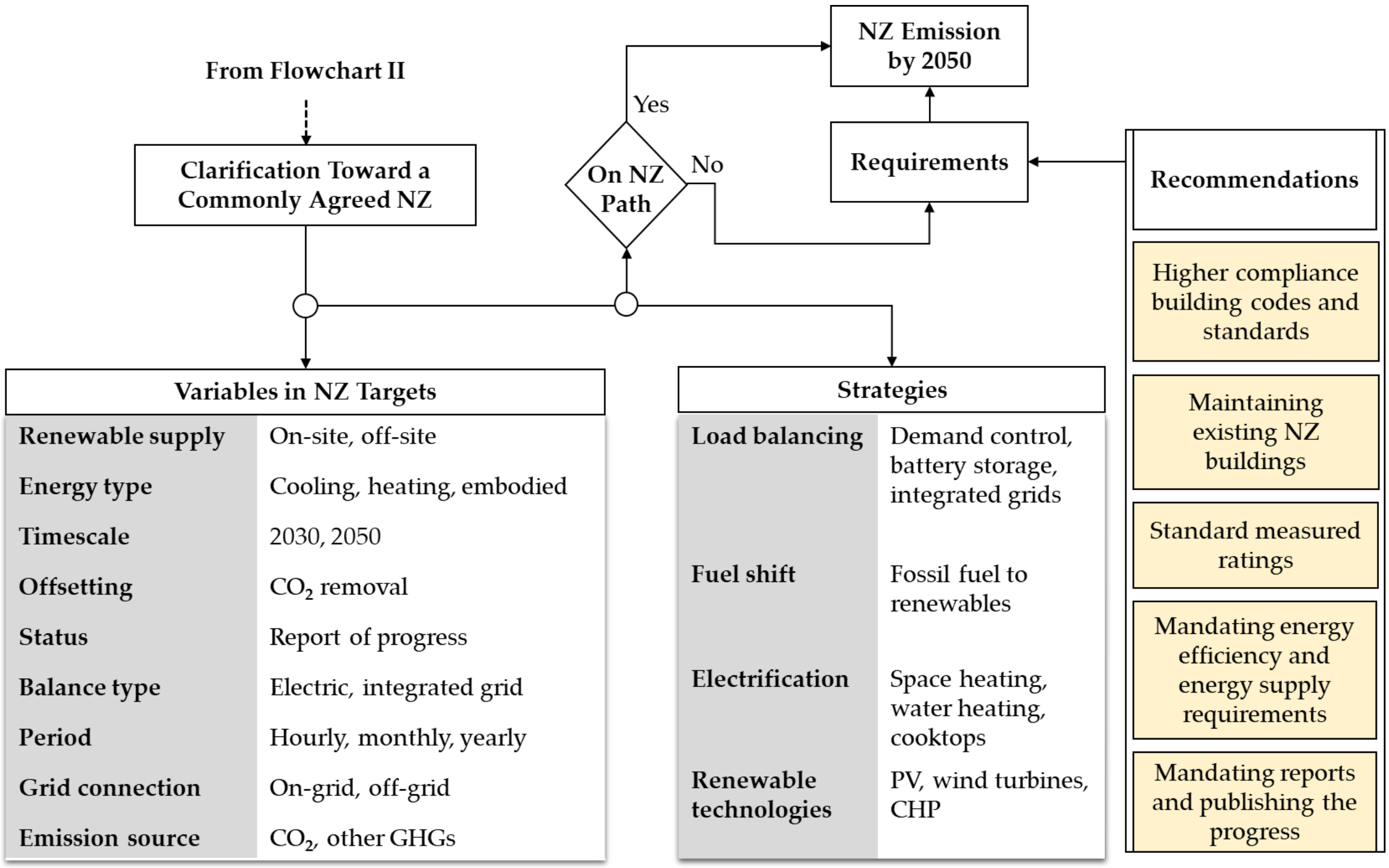


Figure 2.5: Flowchart III, hierarchical proposed Process for Clarification to Accelerate Net Zero (PC-A-NZ) through variations, strategies, and requirements.

2.9. 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 de-creasing 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 are 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.

The article presented in Chapter Two covered the dissertation's initial research question to verify the main contributors that cause the concept of the NZ broad. This article was published in Energies Journal, special issue "Environmental and Sustainable Built Environments." While this Chapter's main focus was investigating NZ at the building level, the following Chapters extend the NZ concept and methods to quantify energy performance and verify NZ achievements to a larger scale of communities.

3. NET ZERO ENERGY COMMUNITIES: INTEGRATED POWER SYSTEM, BUILDING AND TRANSPORT SECTORS*[4]

3.1. Overview

A Net Zero Community (NZC) concept and its energy characteristics are presented in this paper. NZC is an emerging topic with multiple variations in the scope and calculated methods, which complicates quantifying its performance. This paper covers three key barriers in achieving the NZC targets: (1) the main focus of current definitions on buildings and disregarding the community power systems and energy use in the 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 due to the in-creased savings in primary energy and greenhouse gas emissions related to the three main energy sectors – power systems, building, and transportation (PBT). To clarify the NZC, this paper reviews: (1) variations in the existing definitions and criteria from peer-reviewed publications; (2) systematic review of the latest climate projection models by policymakers to achieve net zero by 2050; (3) literature of renewable-based power systems; and (4) three planned NZC cases in inter-national locations to study their NZC targets, energy performances, and the challenges. The outcome delivers NZC design

*[4] Reprinted from "Net Zero Energy Communities: Integrated Power System, Building and Transport Sectors" by Moghaddasi, H., Culp, C., Vanegas, J., 2021. Energies, 14(21), 7065. Open Access Journal.

guidelines, including the energy efficiency measures, electrification, and renewables in PBT sectors to help stakeholders, including policymakers, developers, designers, and engineers speed up achieving their NZC targets.

3.2. 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 (United Nations (UN), 2020b). In cities, electricity or "power", building and transport sectors are the main consumers of primary energy and emitters of Greenhouse gases (GHG) (International Energy Agency (IEA), 2020b, 2021a; Masson-Delmotte, 2019; Nejat et al., 2015; Pablo-Romero et al., 2017; Ritchie, 2020, October 06, 2020; U.S. Energy Information Administration (EIA), 2016; U.S. Environmental Protection Agency (EPA), March 25, 2021). Buildings are accountable for a third of the global final energy use and around 40% of GHG emissions (International Energy Agency (IEA), 2020b, 2021a). The residential building sector is responsible for 25% of global energy consumption and 17% of carbon dioxide (CO_2) emissions (Nejat et al., 2015; Pablo-Romero et al., 2017). The transport sector accounts for 25% of the world's total delivered energy consumption and 24% of global CO_2 emissions (Ritchie, October 06, 2020; U.S. Energy Information Administration (EIA), 2016). Although beyond one-third (36.7%) of the global electricity comes from low-carbon sources (renewables, nuclear, and hydropower), they account only for a 15.7% share of the total global energy mix (U.S. Environmental Protection Agency (EPA), March 25, 2021). The rest of 84.3% (electricity, transport, heating) is sourced from fossil fuels (Ritchie, 2020). According to the Intergovernmental Panel on Climate Change (IPCC), electricity and heat production accounts for 25% of global CO_2 emissions (Masson-Delmotte, 2019; U.S. Environmental Protection Agency (EPA), March 25, 2021). This rate of fossil fuel-based energy consumption increases GHG emissions and causes environmental problems such as health issues, natural disasters, and global warming (Buis, 2019; Intergovernmental Panel on Climate Change (IPCC), 2019b). Therefore, a need exists to study climate change mitigation solutions at the larger scales and the existing challenges.

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

According to (Intergovernmental Panel on Climate Change (IPCC), 2019a), 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 (Intergovernmental Panel on Climate Change (IPCC), 2019a).” On 09 August 2021, (Intergovernmental Panel on Climate Change (IPCC), 9 August 2021) released a “faster warning” on the global temperature rise that without immediate reductions in GHG emissions, it would be impossible to limit the global warming to “close to 1.5°C or even 2°C.” In response to the Paris Agreement (United Nations (UN), 2015, 2019), 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 (International Energy Agency (IEA), 2021c; Rogelj et al., 2015). The result from 2020 reports showed a 5.8% reduction in CO_2 emissions as an outcome of the Covid-19 pandemic. Yet, 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(International Energy Agency (IEA), 2021b, 2021c). Thereby, in March 2021, IEA hosted a net zero summit to focus on the necessary actions that countries and companies who pledged for net zero emissions need to take to transform the goals into practice.

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 (International Energy Agency (IEA), 2021c). IEA report shows that ten (10) of these countries made their net zero target commitments as a "legal obligation", eight (8) countries proposed to make it a legal obligation, and the rest pledged through "official policy documents". Based on IEA, most of these net zero commitments lack "detailed policies and firm routes to implementation," and they vary in scope and timescale.

3.2.2. 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 (Attia, 2018; International Energy Agency (IEA), October 2020; Moghaddasi, Culp, Vanegas, et al., 2021). For example, Chen et al. 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" (Chen et al., 2017). Previous literature reviewed the NZ as the primary solution to achieving GHG emission reduction targets by 2050 (Aelenei & Gonçalves, 2014; Gupta, 2019; International Energy Agency & United Nations Environment Programme (UNEP), 2018; International Energy Agency (IEA), 2021c; Lucon et al., 2014; Sun et al., 2015). By conducting a comprehensive NZ literature review at the building level in (Moghaddasi, Culp, Vanegas, et al., 2021), the authors extended their analyses to the 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 that leave out community power systems and energy use in transportation; (2) the existing definitions 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 the current NZ knowledge applied to communities by including the application of three main global energy sectors: power systems, building, and transportation (PBT) in the following sections:

Section 2: Reviews existing NZC requirements and categorizes the variation criteria from the selected publications.

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

Section 4: Presents a systematic review of the 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 EEMs in building and transport sectors.

Section 7: Recommends NZC design guidelines to minimize energy demand through applying energy efficiency measures in PBT sectors and maximizing renewable supplies in communities.

3.3. Net Zero Community Definition

Existing NZC definitions have differing requirements that complicate the achievement of NZC objectives (Carlisle et al., 2009; Hammon, 2010; Kallushi et al., 2012; Leibowicz et al., 2018; Vera & Langlois, 2007). Table 3.1 shows variations in supply and source in the selected publications.

Table 3.1: 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)	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)	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	(Kari Sørnes, 2014)	IVL Swedish Environmental Research Institute
On a source energy basis, the actual annual delivered energy is less or equal to the onsite renewable exported energy.	Zero Energy Community (ZEC)	On-site	Source	(Peterson et al., 2015)	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 a district scale.	Zero Energy Districts	On-site	Site	(Pless et al., 2018)	US National Renewable Energy Laboratory (NREL)
The 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)	Sustainable Cities and Society Journal
100% 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	(International Living Future Institute (ILFI), 2019)	International Living Future Institute (ILFI) US

Table 3.1: Variations in the current net zero community concept.

NZC Definition	Net Zero Community/District	Onsite/Off-site Energy	Source/Site Energy	Reference	Organization/ Journal
A group of interconnected buildings with associated infrastructure, located within both a confined geographical area and a virtual boundary. A SPEN aims to reduce its direct and indirect energy use towards zero over adopted complete year and an increased use and production of renewable energy according to a normalization factor.	Sustainable Plus Energy Neighborhoods (SPEN)	Both	Site	(Salom & Tamm, 2020)	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	(Robert Hinterberger et al., 23 March 2020)	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)	Research Centre on Zero Emission Neighborhood s (ZEN) Norway
Note: The Key terms, on-site/off-site energy and source/site energy are defined at the US Department of Energy (2015) (Peterson et al., 2015)					

The existing variations in defining a community NZ presents a challenge to stakeholders such as developers and policymakers when attempting to implement NZC and track its progress. It was noted that “stakeholders face a lack of documented processes, tools, and best practices to assist them in achieving zero energy districts” (Polly et al., 2016). Koutra et al. 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" (Koutra et al., 2018). According to (Kennedy & Sgouridis, 2011), 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. 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" (Carlisle et al., 2009).

To adapt an NZC concept, it is important to clarify the existing variations in definitions and calculated methods. To do so, previous literature reviewed NZC variations, and the outcome presented different conclusions for each case (Amaral et al., 2018; Brozovsky et al., 2021; Carlisle et al., 2009; Marique & Reiter, 2014).

Torcellini's NZ classification (Torcellini et al., 2006) at the building level (NZB) from National Renewable Energy Laboratory (NREL) was analyzed in (Moghaddasi, Culp, Vanegas, et al., 2021). Carlisle et al. 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 3.2.

Table 3.2: Net zero community definition classifications. Modified from Carlisle et al. (Carlisle et al., 2009) 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 a building's and transportation total emissions, imported and exported energy is multiplied by the appropriate emission multipliers based on the utility's 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., 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.

However, Brozovsky et al. 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" (Brozovsky et al., 2021). The authors added that although the interest in scientific NZC is growing, a variety of "coexisting terminologies" and different methodologies have been developed. Brozovsky et al. 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 (Moghaddasi, Culp, Vanegas, et al., 2021). Table 3.3 summarizes the review publications on the NZC concept that presents main challenges, existing variations, and requirements for adopting the NZC.

Table 3.3: Review of NZC variation by selected publications.				
References	Review Focus	Challenges	Variations	Recommendations
(Marique & Reiter, 2014)	A simplified framework to assess the feasibility of 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)	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)	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 imbodied 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.

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

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

Many publications conducted energy analyses at the community level (Gjorgievski et al., 2020; Koutra et al., 2018; Moghaddasi et al., 2020; Neves et al., 2014; Palacios-Garcia et al., 2016; Parra et al., 2016; Parra et al., 2017; Petersen, 2016; Ravindra & Iyer, 2014; Vindel et al., 2019). 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 with the methodologies, system boundary, energy balance, climatic and geographic contexts, and infrastructure connections.

3.3.1. 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 (Bakhtavar et al., 2020; Xie, 2018). The authors included the application of life cycle assessment (LCA) and life cycle costing (LCC) as input data into their optimization model. The proposed model was applied to a case study in Canada (Table 3.4) to find the best renewable supply (RE) mix with the lowest undesirable outcomes.

Table 3.4: Proposed model for the case study, a medium-scale community in Okanagan Valley, BC, Canada. Modified from (Bakhtavar et al., 2020).

Building Types	Number of Dwellings	Area of units m^2	Average Energy Use (kWh)
Single-family detached house	40	210	2,259
Single-family attached house	2115	185	21,111
Senior congregate care Apartments	725	102	12,778

Grey-based and other different weighing energy planning approaches were set to find the optimal decisions, where the grey weighting program prioritizes environmental impact reduction (Bakhtavar et al., 2020). Figure 3.1 presents the result of five scenarios using different renewable technologies from the goal programming model.

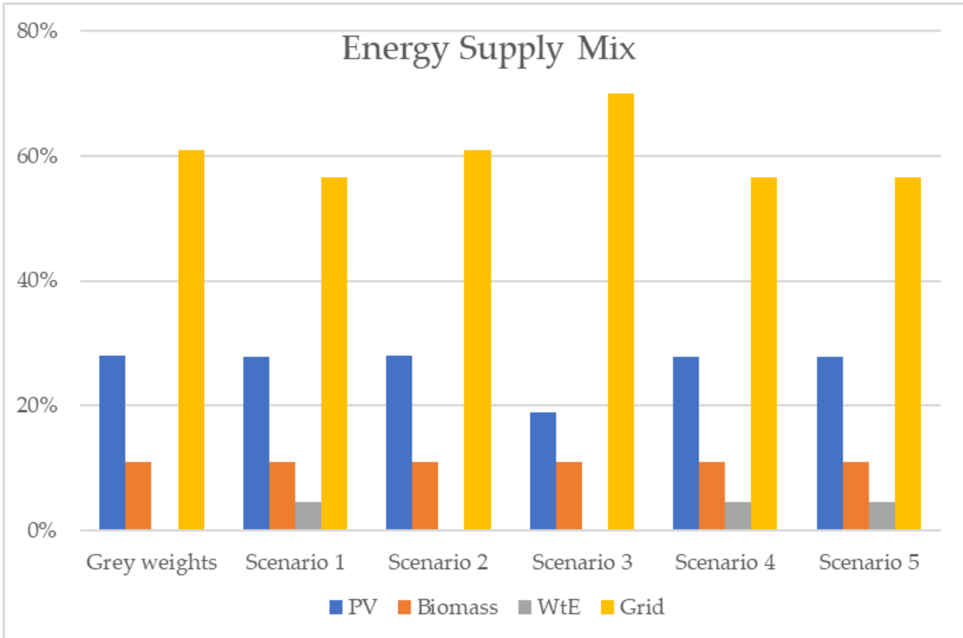


Figure 3.1: Optimal energy supply mix through different weighting scenarios, modified from (Bakhtavar et al., 2020).

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 (1) life cycle GHG emissions by 26.37%; (2) life cycle impacts by 24.9%; and (3) annual supply energy costs by 41.8% (Bakhtavar et al., 2020). However, the increased cost from the investment, operation and maintenance of integrated renewable energy led to a payback period of 30 years (Bakhtavar et al., 2020).

3.3.2. Techno-economic analysis of hybrid renewable energy system with solar district heating for NZC

Kim et al. 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 (Kim et al., 2019). A case study of Jincheon, an eco-friendly energy city in South Korea (area of 72,000 m^2), was selected and has 200 dwellings and six public buildings as shown in Table 3.5.

Table 3.5: Details on public buildings in a case study of Jincheon. Data modified from (Kim et al., 2019).

Public Buildings	Children Center	High School	Youth Center	Health Center	Library	Management Center
Gross floor area (m^2)	916	10,432	728	248	1986	386
Number of Stories	1	4	1	1	1	1

Kim et al. studied (1) the impact of the solar fraction on the Levelized cost of heat (LCoH); (2) shifting to renewables; and (3) economic analysis of integrating 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) gas-fired boiler and packaged air conditioning system; case (2) centralized heat pump system; and case (3) the proposed HERS system.

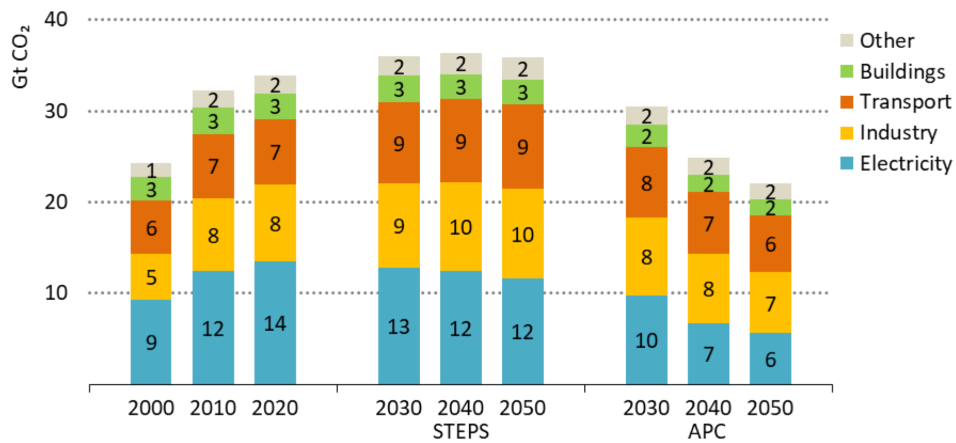
The result showed that with increasing the solar fraction of the proposed system from 42.8% to 91.8%, case (3) saved 73% and 61% of primary energy consumption compared to case (1) and case (2), respectively. Also, the calculated equivalent CO_2 emissions presented a reduction of 17% compared to case (1) and 61% compared to case (2). The result from 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 6-year payback period (Kim et al., 2019).

The above literature underlined the lack of a clear and common definition of the NZC terms. For example, both studies used 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 was not clarified. Bakhtavar et al. included LCA and LCC into their NZC optimization approaches, while Kim et al. have not. From the NZC study by Kim and Bakhtavar, it is concluded that supply-demand balancing optimization with renewables at a community level has positive outcomes but challenging solutions due to the renewable source accessibility, uncertainties and variabilities, programming tools, the source shift's economic feasibility, 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 and current NZC projects.

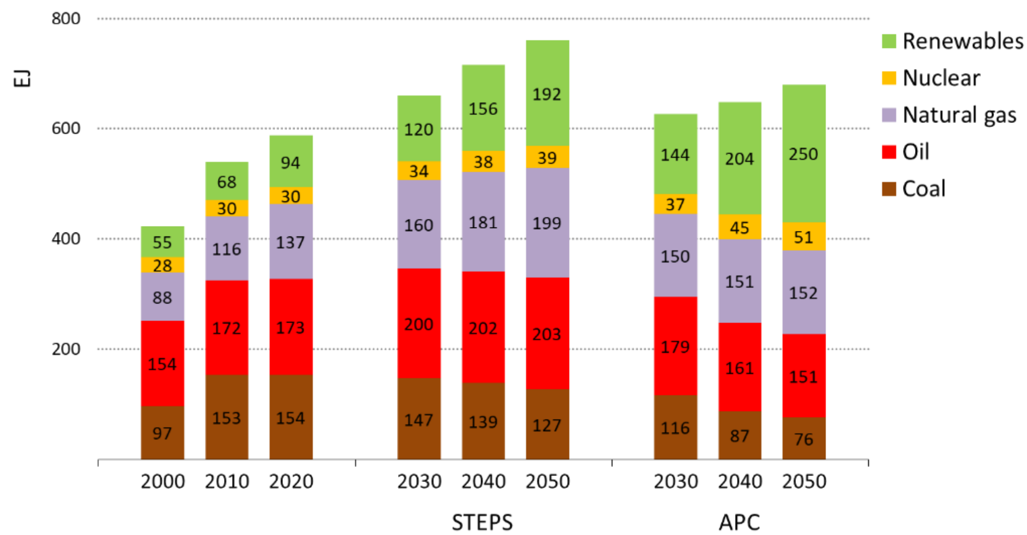
3.4. Global Climate Projection Model

The report of (International Energy Agency (IEA), 2021c) 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 (1) the increase in the world's population from 7.7 billion in 2020 to 9.7 billion in 2050 (United Nations (UN), 17 June 2019); and (2) the world's economic growth, which is projected to be two times larger by 2050 when compared to 2020 (International Energy Agency (IEA), 2021c). 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" (International Energy Agency (IEA), 2021c).

IEA categorized the NZ pledges into two groups: (1) 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 (2) 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 3.2 (a and b) presents IEA's projections of the global CO_2 emissions and energy supply by 2050 based on both APC and STEPS NZ pledges.



a. Global CO_2 emissions by sector.



b. Total energy supply by source.

Figure 3.2: IEA's analyses of global CO_2 emissions and total energy supply between "State Policy Scenario" and "Announced Pledges Case". Source: Modified from IEA (2021) Net Zero by 2050 (International Energy Agency (IEA), 2021c). All rights reserved.

According to Figure 3.2, 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. It results 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. Thereby, 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 (International Energy Agency (IEA), 2021c). EVs are around three times more efficient than combustion engine vehicles. IEA predicted 60% total passenger EV car sales by 2030 (compared to 5% in 2020) and 100% electric or hydrogen-powered by 2050 (International Energy Agency (IEA), 2021c). When Covid-19 and economic crisis lowered the car sales in 2021 (15% lower than in 2019) (Statista Research Department, Apr 8, 2021; U.S. Energy Information Administration (EIA), January 24, 2019), countries such as China, Italy, and France released subsidies for promoting EVs. The Global EV Outlook 2020 (U.S. Energy Information Administration (EIA), January 24, 2019) reported that the 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) (International Energy Agency (IEA), 2021c). This increasing rate of electricity demand requires demand-side management to stabilize the electricity supply through renewables and low-emission power productions such as bioenergy, hydropower, and battery storage (International Energy Agency (IEA), 31 May 2021, 2021c; Rogers et al., 2017). 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 renewable in global heating demand increases from 10% in 2020 to 40% in 2050, where the geothermal and solar thermal cover 75% of it (International Energy Agency (IEA), 2021c). 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, included as wind and solar power, hydropower, bioenergy, and geothermal (Global Wind Energy Council (GWEC), 25 March 2021; International Energy Agency (IEA), 2021c).

The statistic shows that the global gross domestic product (GDP) was about USD 85 trillion in 2020 and is projected to reach USD 122 trillion by 2026 (O'Neill, Jul 30, 2021). IEA reported the NZE’s projection on expanding the annual clean energy investments globally from USD 2 trillion (average over 2015-2020) to about USD 5 trillion by 2030 and USD 4.5 trillion by 2050 (International Energy Agency (IEA), 2021c, July 2021).

3.5. Decarbonization: Energy Efficiency, Electrification, and Renewables

According to the Organization for Economic Co-operation and Development (OECD) Environmental Outlook to 2050 (Pomázi, 2012), 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 (Meinshausen et al., 2011; Pomázi, 2012). This causes the global average temperature to increase from 3°C to 6°C higher by the end of the century (compared to pre-industrial times) (Pomázi, 2012). While the atmospheric CO_2 concentration is calculated at the monthly average of 419 ppm (in 2021), scientific analyses projected that with stabilizing GHG concentration at 450 ppm CO_{2e}, the possibility of limiting the global temperature rise below 2°C would be between 40% to 60% (Meinshausen et al., 2009; National Oceanic and Atmospheric Administration (NOAA), June 7, 2021; Pomázi, 2012; Rogelj et al., 2016; Rogelj et al., 2015; D. Van Vuuren et al., 2008; D. P. van Vuuren et al., 2008).

To address decarbonization strategies and requirements, Table 3.6 summarizes climate targets, improved energy efficiency measures (EEMs), electrification, renewables, and future requirements by three main emitters of the world China, EU, and US (Pomázi, 2012).

Table 3.6: Climate targets and approaches toward achieving net zero goals globally and by China, EU, and the US.					
Organization	Targets	Energy Efficiency Measures (EEMs)	Electrification	Renewables	Requirements
(International Energy Agency (IEA), 2020a) (International Energy Agency (IEA), 2021c; Schreurs, 2016)	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) (European Union (EU), 2021b; Potrč et al., 2021)	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 (Black et al., 2021; Global Wind Energy Council (GWEC), 25 March 2021; New Climate Institute & Data-Driven EnviroLab, 2020)	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, wind power, hydropower.	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 3.6: Climate targets and approaches toward achieving net zero goals globally and by China, EU, and the US.

Organization	Targets	Energy Efficiency Measures (EEMs)	Electrification	Renewables	Requirements
United States (US) (U.S. DEpartment of Energy (DOE), 2021b, MAY 17, 2021), New Building Institutes (NBI)(Alexi Miller and Cathy Higgins, January 2021), American Council for an Energy-Efficient Economy (ACEEE) (Nadel & Ungar, 2019)	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.

Table 3.6 highlighted variations in climate target plans extrapolated from policy documents, including timescale, emission source, political commitments, renewable accessibility, energy security, energy code 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 other emission sources are included. However, most of the policy documents globally addressed EEMs electrification, and renewable supplies as main approaches toward achieving NZ emissions by 2050.

According to (International Energy Agency (IEA), 2021c), the expansion of solar and wind power triples renewable generation by 2030 and eightfold it by 2050. Solar PV and wind powers account for 50% of the growth in RE supply, and bioenergy accounts for 30% (Global Wind Energy Council (GWEC), 25 March 2021; International Energy Agency (IEA), 2021c). Also, it is projected that the total battery capacity increase to 1,600 GW by 2050 (70% more than in STEPS) (International Energy Agency (IEA), 2021c). Accordingly, China's electricity-related coal consumption is predicted by IEA to decline by 85% between 2020 to 2050 (International Energy Agency (IEA), 2021c). Therefore, IEA recommended increasing the annual global investment in clean energy from USD 380 billion in 2020 to USD 1.6 trillion by 2030 (Global Wind Energy Council (GWEC), 25 March 2021).

At the community level, the first step is to create an energy efficient plan and design measures. EEMs reduce the energy use and demand to achieve a lower energy use for a community (Hammon, 2010; Leibowicz et al., 2018; Svensson et al., 2006;

Vera & Langlois, 2007). IEA 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 (International Energy Agency (IEA), 2021c). 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)."

The American Council for an Energy Efficient Economy (ACEEE) 2019 (Nadel & Ungar, 2019) 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 (U.S. Energy Information Administration (EIA), January 24, 2019), 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 3.3.

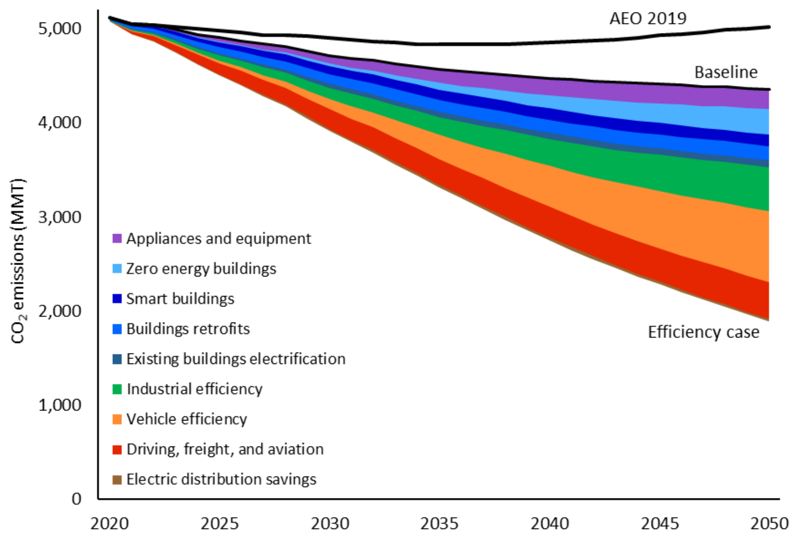


Figure 3.3: Energy-related carbon dioxide emissions in the reference and efficiency cases. Source: ACEEE (2019) (Nadel & Ungar, 2019).

3.6. Global Energy Transitions Toward achieving NZ by 2050

Three existing planned NZ communities were selected for this section as they (1) use community renewable energy systems; (2) incorporate energy efficiency measures; and (3) are growing their renewable portion of electric power, shown in Table 3.7.

Table 3.7: 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

As shown in Table 3.7, solar and wind power are the main renewable supplies in the precedent cases along with CHP plant as an energy efficient system to reduce the 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.

3.6.1. Solar Photovoltaic (PV)

According to the IEA, Photovoltaic Power Systems Programme (IEA-PVPS) (International Energy Agency (IEA), April 2021), solar PV covered 42% of the total renewable electricity production in 2020 - over 5% of the global electricity production (Our World in Data based on BP Statistical Review of World Energy & Ember, 2021). The location and size of the solar facility define whether it is a utility-scale or small-scale/distributed system (Hernandez et al., 2014). Total generation capacity in utility-scale generation facilities is more than 1MW unless multiple power technologies are available (Hernandez et al., 2014; U.S. Energy Information Administration (EIA), 2019). The small utility-scale facilities mainly depend on state-level practices, policies, and they function based on the independent grid in the form of rooftop PV and solar water heater systems (Dale et al., 2011; Hernandez et al., 2014; U.S. Energy Information Administration (EIA), 2019). 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 (U.S. Energy Information Administration (EIA), 2019), the consumers also can 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 (Hernandez et al., 2014). 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

(Hernandez et al., 2014; Pavlović et al., 2012; Sharma, 2011; Sharma et al., 2012; Zhang et al., 2012). The outcome of COVID-19 caused an increase in the PV capacity globally in 2020 (total 760 gigawatts), where the PV utilization covered about 3.7% of the world's electricity demand (6.2% China; 6% EU; 3.4% US), and saved around 875 million tons of CO_{2e} by the end of 2020 and is on the path of decarbonizing the energy mix (Feldman et al., June 22, 2021; International Energy Agency (IEA), April 2021).

3.6.2. 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 (Center for Climate and Energy Solutions (C2ES), Apr 29, 2021). With the pandemic, global new wind power installations exceeded a 53% yearly growth (90 GW), and 14% total growth (743 GW) in total installed capacity in 2020 compared to 2019, both onshore (86.9 GW) and offshore (6.1 GW) (Global Wind Energy Council (GWEC), 25 March 2021; U.S. Department of Energy (DOE), 2021a). To meet the IEA's NZE, 160 GW wind installation is needed by 2025 and 280 GW by 2030 (Global Wind Energy Council (GWEC), 25 March 2021). According to (Global Wind Energy Council (GWEC), 25 March 2021), the world's wind power installation will exceed 1TW by 2025, which estimates a 4% increasing compound annual growth rate (CAGR) for new installed wind capacity or adding 96 GW of new installations per year (total 469 GW) until 2025.

In this regard, China installed 93 GW of wind power by the end of 2020 and is aimed to yield 3,000 GW by 2060. North America (18.4%) and Europe (15.9%) become the second and third largest regional market for new wind installation in the world. Based on (U.S. Department of Energy (DOE), 2021a) the long-term growth in wind power capacity depends on (1) incentives from the government such as renewable electricity production tax credit (PTC) at the US's federal tax credit of 2.5 cents/kWh for generating from wind, biomass, and geothermal resources (2) economic improvements to make it competitive with solar power and natural gas; (3) clean energy demand and state-level policies to upgrade the transmission infrastructure (U.S. Environmental Protection Agency (EPA), July 14, 2021). While near-term growth is influenced by wind power's performance and cost improvements that reduce the power sale prices, wind energy purchases, and state-level renewable power policies (U.S. Department of Energy (DOE), 2021a).

3.6.3. Combined Heat and Power (CHP) Plant

CHP system, also known as cogeneration, is a clean approach to generating on-site electricity and thermal energy, which would otherwise be wasted (U.S. Department of Energy (DOE), March 2016, September 8-10, 2020). Based on the DOE, if properly designed and utilized, the overall efficiencies in CHP plants can exceed 80% (Gvozdenac et al., 2017; U.S. Department of Energy (DOE), November 2017). CHP saves utility costs by reducing the need to purchase electricity from the grid. Different sizes included: small-scale, which serves municipal or industrial users with less than 1MW capacity; and large-scale that serves cities (Beatley, 2012). CHP applies to places with hot water or steam requirements, with higher seasonal heat loads (Department of

Energy (DOE), 2016). 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 (Grand View Research (GWR), July, 2020). Although the CHP's high initial investment, maintenance costs, and harmful gas releases restricted its usage, renewable sources such as biomass fuels as well as wood, oil, and processed waste can be used (Grand View Research (GWR), July, 2020).

In 2019, the large-scale CHP plants gained a revenue share of 79.5%, and 20% for the small-scale plants, with an expected 5.5% growth rate from 2020 to 2027 (Grand View Research (GWR), July, 2020). Europe covered beyond 50% of the CHP installation demand in 2019. In the US, more than 4,600 CHP sites provided 81 GW, which covered 10% of its total electric generation capacity (Grand View Research (GWR), July, 2020). 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 (Grand View Research (GWR), July, 2020; U.S. Department of Energy (DOE), September 8-10, 2020). 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 (U.S. Department of Energy (DOE) office of Energy Efficiency and Renewable Energy, 2018).

The literature above showed that solar, wind, and CHP are major global energy transition strategies toward achieving NZ by 2050, where China was presented as the world's largest market for renewables (wind, solar) followed by the EU and US in 2020 (International Renewable Energy Agency (IRENA), 2021). It also highlighted the influence of the COVID-19 pandemic on global renewable energy capacity growth in 2020 and the challenges.

3.7. Planned NZC Precedent Cases

The cases are 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, passive strategies, etc. Yet, the communities have not achieved their NZ targets. The selected projects are the example of the world's NZC cases from the literature (Chance, 2009; Coates, 2013; Dunster, 2009; Eppinger, 2003; Fraker, 2013a, 2013b; Gaiser & Stroeve, 2014; Lovell, 2008; Raibley, 2011; Voss & Musall, 2012; Wheeler & Segar, 2013) with support resources and potentials to address their NZ targets. This section reviews NZC targets, energy strategies, savings, and challenges in each case.

The key challenge for data collection was the lack of (1) updated literature (last five years) on the existing communities with NZC targets; and (2) peer-reviewed publications to present the calculated measures and track the projects' NZ progress. Most of the available documents are either old (before 2016) or/and published as technical reports, white papers, webpage, and handbooks. In some cases, the presented data varies from different sources. For this review purpose, approximate values are used from the publications to present data, shown in Table 3.8.

Table 3.8: Planning characteristics at 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	4,350	1,006	~14 (4.5 du/acre)	2011
Kronsberg	1,200	15,00	6,000	47	2000

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

3.7.1. 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) (Zhu et al., 2015). The project's size is 1.7 hectares (ha), with 116 dwellings per hectare, including live/work units (Chance, 2009; Dunster, 2009; Hodge & Haltrecht, 2010; Saheb et al., 2018). BedZED includes 99 homes, with 220 residents and 100 office workers (Chance, 2009; Dunster, 2009). 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 (Hodge & Haltrecht, 2010). 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" (Dunster, 2009). The project aimed to cover emissions from office and local energy use embodied energy from construction, transport, food, and waste (Chance, 2009). 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 (Chance, 2009; Hodge & Haltrecht, 2010; Zhu et al., 2015).

The primarily utilized energy strategies were (1) solar PV to cover 20% of the electricity demand; and (2) a 130 kW-biomass CHP plant for the rest of the electricity and all the heating related to hot water (Chance, 2009; Hodge & Haltrecht, 2009, 2010; Twinn, 2003). Table 3.9 presents the total renewable energy cost breakdown (PV and CHP), which was 5.8% of the total construction cost of the community.

Table 3.9: Cost breakdown of the out-turn construction cost for BedZED, data from (Dunster, 2009)

BedZED	Out-turn construction costs (£)	Percentage of Total (%)
PV Cells	565,303	
CHP Plant	315,197	
Renewable Energy Total	880,500	5.8
Total Costs	15,250,000	100

The community included a six-plot terrace with 18 dwellings. Figure 3.4 shows that roofs are covered with 777 sqm of PV (Chance, 2009; Zhu et al., 2015).

Figure 3.4: 6-plot terrace BedZED, UK. Source: (Bioregional).

CHP system was planned based on a downdraft gasification method that converts woodchips into gas to produce electricity through a generator (Chance, 2009; Schoon, 2016). The local street tree surgery waste, certified by the Forest Stewardship Council, was used as a sustainable fuel for the CHP plant (Chance, 2009; Hodge & Haltrecht, 2010). When fully operational, the CHP plant required 20 tonnes/week of woodchip with a cost of $34/tonne (Lazarus, 2003).

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 (Hodge & Haltrecht, 2010). However, the restart programming caused complications with forming tars as a cool down for the system (Chance, 2009; Schoon, 2016). It was concluded that the CHP system operates more efficiently if it runs constantly for a community as small as BedZED (Chance, 2009; Schoon, 2016).

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) (Dunster, 2009; Lazarus, 2003). It was estimated that the CHP plant prevents about 326,000 kg of CO_2 emission per year from national grid electric production compared to the gas-fired power systems (Dunster, 2009). However, the CHP plant was decommissioned due to its maintenance complications and running costs (Chance, 2009; Hodge & Haltrecht, 2010; Lazarus, 2003). It was concluded that generating all energy on-site for a community as small as 2ha is a challenging solution (Chance, 2009). Chance recommended the use of CHP plant only with advanced consideration of proper management in selecting, installing, and maintaining energy equipment.

1. Regarding the transport sector, BedZED is committed to the Green Transport Plan (GTP) to reduce car energy use by 50% in 10 years by:
2. reducing parking space (less than 1/home compared to the UK's typical of 1.5/home);
3. car club (London's first one);
4. solar-electric PV systems to power 40 electric vehicles;
5. electric charging station (free - every two of the four parking spaces);
6. pedestrian and bike network (living streets);
7. public transport (bus stops, train stations);
8. mixes of use and internet delivery supermarkets (Chance, 2009; Dunster, 2009).

As an outcome, the residents drove an average of 2,318 kilometers per year, which was 64% less than the local average (Chance, 2009). 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" (Zhu et al., 2015). BedZED homes reduced their CO_2 emissions by 56% compared to the average UK home (Chance, 2009). It resulted that the community reduced its environmental impact by 20% to 30% by utilizing energy efficiency strategies at the construction stage (Dunster, 2009; Lazarus, 2003).

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.

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

West Village is the US's largest planned "zero net energy" residential development (Braun et al., 2012). It is a mixed-use community that was opened in 2011 and is located at the University of California at Davis Campus. The project was owned and operated by West Village Community Partnership (WVCP) and followed the principles of New Urbanism with linking walkability, sociability, and efficient transportation (Raibley, 2011; UC Davis West Village, 2013-2014). The community's size is 83 hectares, and it was planned for an ultimate capacity of 4,350 residents including 663 apartments and 343 homes (single-family) (Finkelor et al., 2010; Gaiser &

Stroeve, 2014; Marique & Reiter, 2014; UC Davis West Village, 2013-2014; Wheeler & Segar, 2013). 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 (Braun et al., 2012; England, June 2014). 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 generations and extensive use of energy efficiency measures (Braun, 2011; German et al., 2014; Wheeler & Segar, 2013). Based on DOE (Dakin et al., 2012), "Title 24 compliance savings were 31%–39% depending on building and orientation." The West Village Energy Initiative (WVEI) targeted to attain the NZ energy, where the WVEI Annual Report was a "snapshot of progress towards this goal" (UC Davis West Village, 2013-2014). According to the 2013-14 WVEI report (UC Davis West Village, 2013-2014), the supply met the demand at the community by 82%. The project was planned to reduce its energy use in single-family homes (65%); multiple-family homes (58%); commercial/mixed-use (45%); and common area lighting (50%) (Dakin et al., 2010; Wheeler & Segar, 2013).

The primary utilized on-site renewable energy at the community included (1) a centralized PV array; (2) a Renewable Energy Anaerobic Digester (READ) system; and (3) a 1MW battery (Dakin et al., 2010; Raibley, 2011). In 2012, 123 tonnes/day of waste was produced at UC Davis with more than 85% organic waste (England, June 2014). The READ project was utilized to convert organic waste to renewable energy (Raibley, 2011). 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 beyond 4 million gallons of fertilizer - enough to cover 56 ha of California's farmlands daily (Raibley, 2011). A 300-kW biogas fuel cell generator was utilized as a backup for the CHP plant (Dakin et al., 2010). 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 (Dakin et al., 2010; Wheeler & Segar, 2013). Regarding the transportation energy use, the West Village utilized:

1. integrated smart grid to support EV' charging stations;
2. method development to assess energy use from plug-in vehicles;
3. battery-coupled solar charging stations at single-family homes;
4. EV and solar-based activities;
5. street bicycle and pedestrian network;
6. bus transit stops in a 5-minute walk from residences;
7. parking controls and car sharing programs;
8. solar canopies for parking spaces; and
9. mixes of use and automated shuttles (Wheeler & Segar, 2013).

The NZC's energy use target in West Village was 9.2 million kWh (Dakin et al., 2010). According to (Hammer et al., 2014), "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)- the California Energy Efficiency Building Code (Title 24, 2008) (Dakin et al., 2012; Wheeler & Segar, 2013). The recommendations toward achieving NZC at West Village were highlighted as (1) the combination of aggressive EEMs, passive solar design, and renewable energy generation; (2) 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.

3.7.3. Kronsberg District, Germany

Kronsberg district in Hannover, Germany was planned as a future sustainable urban development model (Eppinger, 2003; Low, 2005). 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 with including 3000 units (Coates, 2009; Eppinger, 2003; Farr, 2011; Fraker, 2013a). Kronsberg is a mixed-use residential district located on 1,200 hectares, with 47 units per hectare and 68% of open space (Eppinger, 2003; Farr, 2011). The project was planned for an ultimate 6000 dwellings to accommodate 15,000 residents (Fraker, 2013a; Wang & Prominski, 2015). 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” (Farr, 2011; Low, 2005). The planning of Kronsberg was influenced by (1) ‘Agenda 21’, defined as a “vision for development that simultaneously promotes economic growth, improved quality of life and environmental protection” (2) the City of Hannover’s climate plan (1992) to reduce CO_2 emissions by 25% (from 1990 level) (Fraker, 2013a).

Hannover's vision for sustainable development led to a planning process with energy reduction, mixed-income residential zones, and transit-oriented design goals (Farr, 2011). Kronsberg’s main energy strategies included (1) EEMs; (2) CHP plants; and (3) 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 an additional 20% by using renewable energy (wind power). The result presented a 17% CO_2 reduction by applying the passive house (LEH) standard to all buildings (with providing subsidies) to use less than 55kWh/m^2/y energy for space heating; and 13% reductions by incentivizing high efficiency lighting and appliances (Fraker, 2013a; Granvik et al., 2003; Rumming, 2004).

The primarily utilized energy strategies 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 (Fraker, 2013a). The use of renewable technologies and CHP plants reduced CO_2 emissions by 45% compared to conventional systems (Anja Eckert, March 2004).

Three utilized wind turbines in 2001, generated 280 kW, 1.5 MW, and 1.8 MW, respectively (Fraker, 2013a; Low, 2005; Moghaddasi et al., 2020).

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 the residential planning;
2. bicycle and pedestrian networks;
3. a tramline that links Kronsberg with Hannover city center in 20-minute (with 8-12 minutes intervals and five stops at every 300-meter interval);
4. locating the dwellings within a 1/2 kilometer diameter from the stop stations;
5. parking enforcements (0.8 cars per unit allowance);
6. carpool program;
7. mixes of use included neighborhood parks and sports, community gardens, organic farms, a primary school, a community center, district arts, three children's daycare centers, a shopping center, a church, and a health center provided pedestrian friendly network (Eppinger, 2003; Farr, 2011; Fraker, 2013a; Low, 2005).

The result showed 71% carbon emissions reduction and 3.6 MW electricity supply from combined wind power (37kWh/m^2/y) and PV systems (0.04 kWh/m^2/y) by 2001 (Eppinger, 2003; Fraker, 2013a). Fraker 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 for energy use for heating exceeded the goal of 55 kWh/m²/y in 2001 (Fraker, 2013a; Rumming, 2004). 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/m²/y mainly from CHP line losses, excluding the solar (Fraker, 2013a; Rumming, 2004). It was concluded that energy efficiency strategies, even "aggressive standard of the passive house" are the most cost-effective carbon reduction approaches (Fraker, 2013a).

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.

3.7.4. NZC Analyzes in Precedent Cases

The analyses from precedent cases presented that the NZC definition, requirements, primary sources, savings, and challenges vary at each project regarding the demand reduction strategies and power production systems. One common NZC strategy in all the cases was balancing on-site energy demand through improved EEMs and renewable supply. Table 3.10 presents a comparative analysis of the energy performance of each case based on their planned targets by showing (1) the key drivers at the planning phase; (2) main requirements (emission source, site boundary, energy systems, renewable technologies); (3) planned energy saving targets; (4) published measured data to verify the energy performance and NZC achievements; (5) recommendations on the requirements, necessary to achieving NZC objectives by 2050.

Table 3.10: Analysis of NZC variation, strategy, and requirement from three precedent cases worldwide.

Precedent Cases	NZC drivers	EEMs	Renewables	Main challenges	NZC outcome		Recommendations
					Planned	Measured (%)	
BedZED (Chance, 2009; Dunster, 2009; Forrest & Wiek, 2015; Hodge & Haltrecht, 2010; Lovell, 2008; Saheb et al., 2018; Twinn, 2003)	60% CO_2 emissions reduction by 2025 80% emission reductions by 2050	Passive strategies, energy efficient appliances, and lighting, smart energy meters, 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 (Dakin et al., 2012; Dakin et al., 2010; England, 2014; Wheeler & Segar, 2013)	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, LED	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, low tariffs for biogas electricity, lack of no-solar renewables incentives, 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, resident behavior; designing NZ strategies at early stages.

Table 3.10: Analysis of NZC variation, strategy, and requirement from three precedent cases worldwide.

Precedent Cases	NZC drivers	EEMs	Renewables	Main challenges	NZC outcome		Recommendations
					Planned	Measured (%)	
Kronsberg District (England, 2014; Eppinger, 2003; Fraker, 2013a; Rumming, 2004)	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 high efficiency appliances, high energy consumption than predicted, CHP line losses, building orientation regarding passive solar design	-Reducing electricity use by 30% -Total energy use (105 kWh/m²/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 refining tools over time; the need for broad NZ education; identifying regulatory and legislative barriers and solutions for adopting NZ.

Table 3.10 shows that although different NZC targets could improve savings in energy and CO_2 emissions, the projects encountered barriers in achieving their NZ goals. Precedent studies recommended the need for concrete regulations, incentives for renewables, planning for NZC strategies at early phases, and education on NZC and energy efficiency implementation to accelerate achieving its targets.

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 precedent cases highlighted the impacts of NZC planning at the early design phases on the 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 (Chance, 2009). The CHP plant was removed in 2005 due to maintenance complications (Schoon, 2016). 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 (Hodge & Haltrecht, 2010; Schoon, 2016). 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 plans (Saheb et al., 2018;

Schoon, 2016). It took BedZED over ten years to justify wind power as a proper system to fulfill its NZC goal (Schoon, 2016).

In the West Village community, initially (1) PV arrays generated more than 100% of the electricity used by buildings, which later was modified to combined solar thermal rooftop and PV systems; (2) solar arrays were planned to generate electricity off-site, but due to the financial and infrastructure complications PVs were placed on the rooftops and canopies; (3) biodigester system initially used anaerobic decomposition of liquid wastes to generate power, however, in 2006, professor Ruihong Zhang addressed the challenges in economics, speed digestions, and material processing to utilize and commercialize mixed wet and dry wastes (Wheeler & Segar, 2013).

The review of the precedent cases provided knowledge regarding improved EEMs, community power systems, efficient transportation for communities with different sizes, locations, and requirements in achieving energy efficiency plans. However, the precedent cases insufficiently reflected their commitments to NZC, mostly due to the (1) lack of updated measured data to track their progress; and (2) lack of peer-reviewed publications to document their performance and practices. To strengthen the projects as the world’s example of NZC, they need to provide publicly available published reports to track the performance of the ongoing NZC cases and their objectives.

3.8. Result and Recommendations

key finding of this review is the lack of quality data. As community organizations approach adopting an NZC, the need for support, standards, and published information on accessing the measured data is crucial for the success of a project to verify its NZC objectives. Precedent studies showed that the planned NZC communities with aggressive energy efficiency strategies and renewables have not met their NZC targets. The main challenges were (1) lack of policy documents that support their strategies; (2) lack of updated published measured data to report their savings. The communities need to upgrade their data based on the publicly available website 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 3.5 presents demand reduction strategies extrapolated from the global climate policy documents (Table 3.6) and the NZC performances in precedent cases (Table 3.10), which are emphasized and recommended by selected publications in NZC (Alexi Miller and Cathy Higgins, January 2021; Black et al., 2021; Chance, 2009; Dakin et al., 2012; Dakin et al., 2010; Dunster, 2009; England, 2014; Eppinger, 2003; European Union (EU), 2021b; Fraker, 2013a; Global Wind Energy Council (GWEC), 25 March 2021; Hodge & Haltrecht, 2010; International Energy Agency (IEA), 2020a, 2021c; Nadel & Ungar, 2019; New Climate Institute & Data-Driven EnviroLab, 2020;

Potrč et al., 2021; Rumming, 2004; Schreurs, 2016; U.S. DEpartment of Energy (DOE), 2021b, MAY 17, 2021; Wheeler & Segar, 2013).

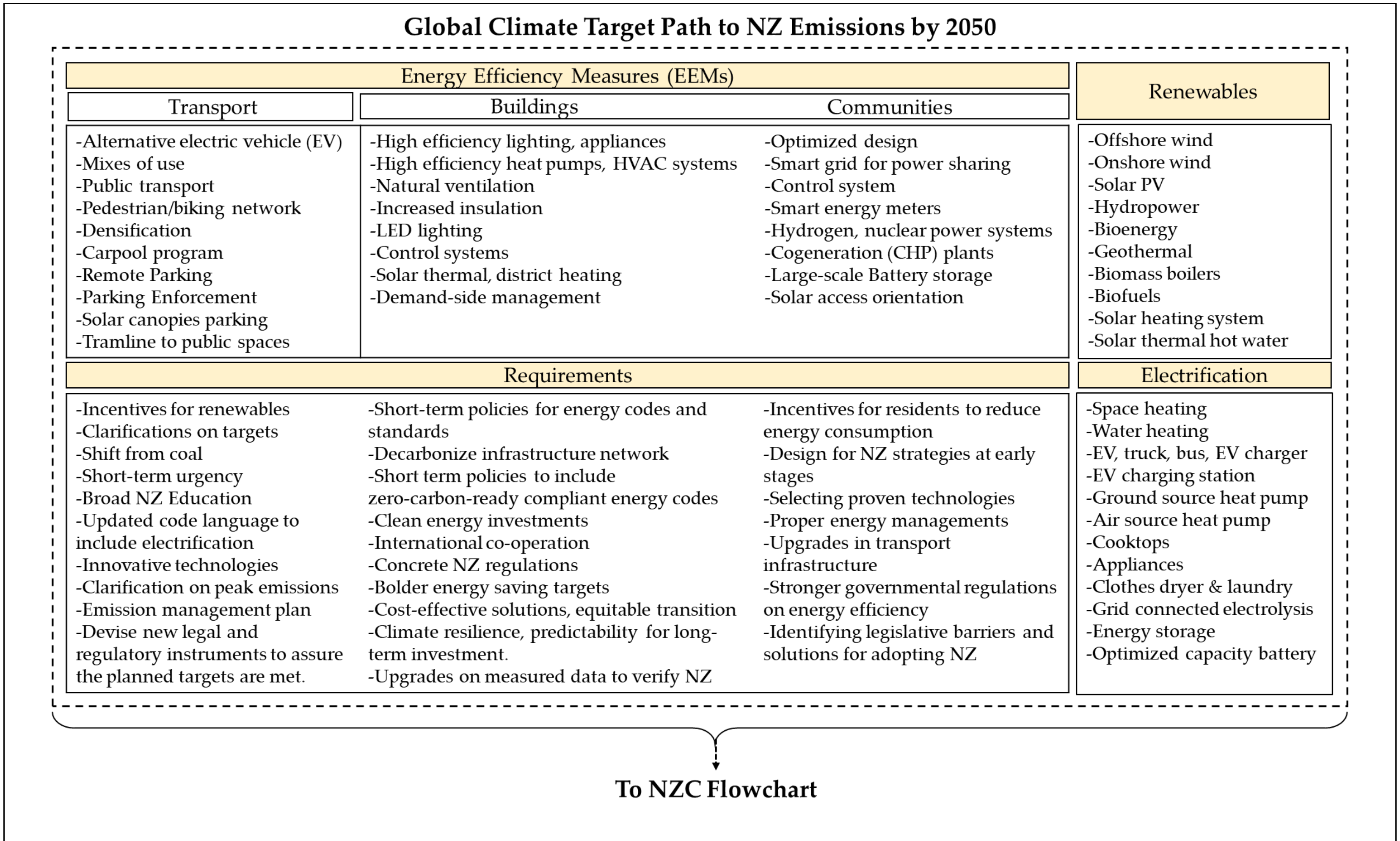


Figure 3.5: Highlighted climate mitigation strategies to accelerate achieving global NZ emission targets.

Figure 3.6 presents an NZC Flowchart as a design guideline applicable to communities to accelerate their NZ targets. 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 3.5). In this paper, the NZC path is considered based on Carlisle's near-zero community concept - when 75% of energy demand is generated from on-site renewable supplies. If a community is not on its NZC path, additional requirements are needed to support energy efficiency strategies through governmental legislation to help the community meet its NZC objectives.

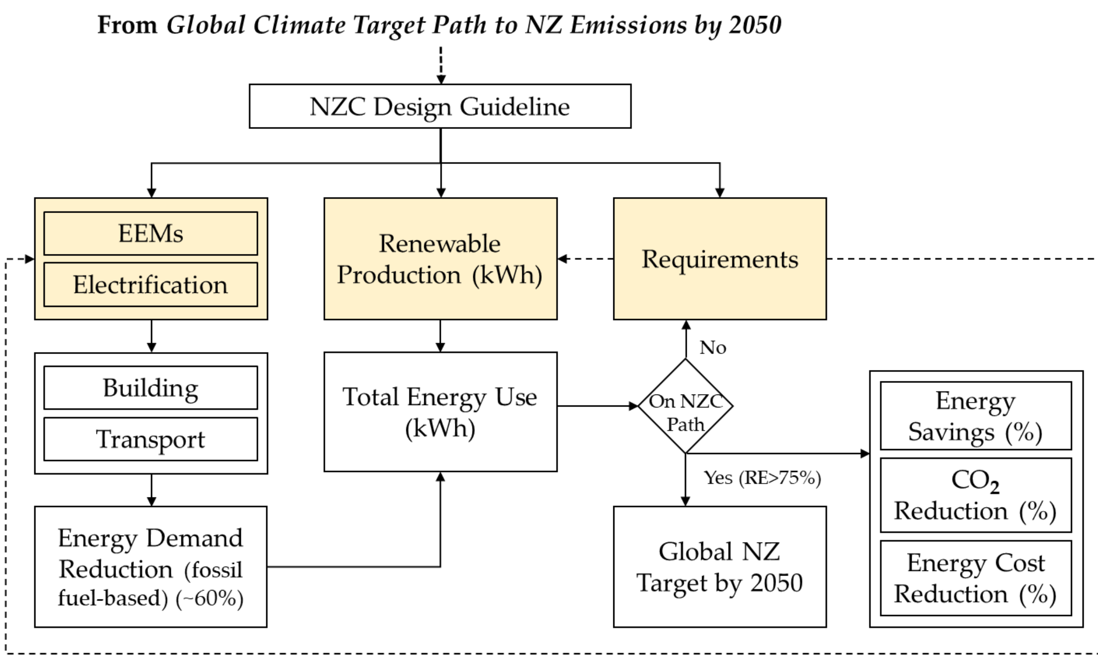


Figure 3.6: NZC Flowchart, energy balance in a community through EEMs, electrification, and renewable.

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

3.9. Conclusions and Future Work

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:

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

The literature showed that the existing NZC concepts vary in the definition of terms, emission sources, timescale, and energy source/supply requirements. These differences complicate tracking NZC successes. The current global climate mitigation solutions, although improving savings in energy and CO_2 reduction, are still insufficient to achieve the global NZ emission targets by 2050. Also, the precedent cases showed that most communities have not published updated measured data on their NZC success and 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 the NZC targets with specifying all the NZC requirements;
2. setting concrete regulations and policies to incorporate the use of EEMs, electrification, and renewables into the current energy codes and standards;
3. mandating public availability of the measured data of the projects' NZC performance.

Providing NZC energy design guidelines 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.

Chapter Three could be considered as a complementary study to Chapter Two by reviewing the Net Zero concept at the community scale. In this Chapter, energy use reduction approaches and renewable productions were studied through literature analyses and review of precedent cases. This article was published in the Journal of Energies, special issue "Energy Efficiency, Low Carbon Resources and Renewable Technology." The outcome of this Chapter delivered NZC design guidelines which were applied to a monitored case study in Chapter Four. In the following chapter, a reorganized Net Zero concept is proposed to enhance global understanding and standardize a definition that is measurable and adaptable to different regions and requirements.

4. AN ADAPTABLE NET ZERO MODEL: ENERGY ANALYSIS OF A MONITORED CASE STUDY

4.1. Overview

Increased efforts towards climate change mitigation and achieving Net Zero (NZ) are occurring globally and in the US. This research addresses three challenges to meeting the target goals: (1) quantifying energy use reduction approaches; (2) obtaining measured data to track the NZ progress; and (3) verifying NZ achievements. However, numerous definitions of NZ currently exist, and a modification is needed to clearly show which definition was used. To do so, a reorganized NZ concept (NZX%$_{\mathbf{ORG}}$) is presented that focuses on balancing on-site energy demands with renewable supplies in buildings at the community level. The 'X%' presents the fraction of renewable energy to the total energy used, and the "ORG" defines the organization's NZ definition that a project uses. As a project continues to improve, their rating increases toward NZ100%$_{\mathbf{(ORG)}}$. The Serenbe community, a monitored case study in Georgia is analyzed to quantify its NZ achievements. The results from the analysis showed that with improved energy efficiency measures, increased on-site solar power generation in buildings could provide 80% of the community's total energy use, which reduced utility electricity by 88%. Assuming Serenbe uses the Environmental Protection Agency (EPA)'s NZ definition, the community would become NZ80%$_{\mathbf{(EPA)}}$. The NZX%$_{\mathbf{(ORG)}}$ model is adaptable to different regions and requirements to enable projects to meaningfully achieve and communicate their NZ objectives.

4.2. Introduction

In 1988, the Internal Governmental Panel on Climate Change (IPCC) was formed by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide scientific evaluations on climate change to policymakers (The Intergovernmental Panel on Climate Change (IPCC), 2021). Accordingly, the US ratified the Montreal Protocol of 1987 in a 1990 amendment to the Clean Air Act (Pischke et al., 2018). In 2015, 196 Parties adopted the Paris Agreement to combat climate change through Greenhouse gas (GHG) mitigations with consistent finance fellow pathway (United Nations Framework Convention on Climate Change (UNFCCC), 2021a). On 3 August 2015, President Obama and the US Environmental Protection Agency (EPA) announced the Clean Power Plan to cut the carbon emissions from the US electrical power plants by 32% below 2005 levels by 2030 (Pischke et al., 2018; US Environmental Protection Agency (EPA), 2017). Further, on 22 April 2021, President Biden pledged that the US would cut its GHG emissions by at least 50% from the 2005 level by 2030 (Newburger, 2021). Teske stated two objectives in response to the Paris Agreement: energy efficiency measures and transition to 100% renewables (Teske, 2019). Studies presented Net Zero Energy (NZ) or Carbon-Free adoptions as the primary solution to GHG reduction goals (Aelenei & Gonçalves, 2014; Gupta, 2019; International Energy Agency & United Nations Environment Programme (UNEP), 2018; Lucon et al., 2014; Sun et al., 2015). On 23 April 2021, the European Union and 44 countries pledged to accomplish the NZ emissions reduction targets by 2050, with individual commitments varying in scope and timescale (International Energy Agency (IEA), 2021c). There are barriers in achieving the NZ targets that need to be addressed by providing: (1) consensus definition; (2) firm regulations for NZ implementation and quantifying energy performance; and (3) publicly available measured data to track the progress. Table 4.1 presents variations in NZ targets between different states in the US.

Table 4.1: States with net zero targets. Source: modified from (Clean Energy States Alliance, 2021).

Status	Net zero Goal	Year	Status
Arizona	100% Carbon-free electricity	2070	Order
California	100% Carbon-free electricity	2045	Legislation
Colorado	100% Carbon-free electricity	2050	Law
Connecticut	100% Carbon-free electricity	2040	Order
District of Columbia	100% Renewable energy	2032	Law
Hawaii	100% Renewable energy	2045	Legislation
Louisiana	Net zero greenhouse gas emissions	2050	Order
Maine	100% clean energy	2050	Legislation
Massachusetts	Net zero greenhouse gas emissions	2050	Order
Michigan	Economy-wide carbon neutrality	2050	Legislation
Nevada	100% Carbon-free electricity	2050	Order
New Jersey	100% Carbon-free electricity	2050	Order
New Mexico	100% Carbon-free electricity	2045	Legislation
New York	100% Carbon-free electricity	2040	Legislation
Oregon	Greenhouse gas emissions reduced 100% below baseline emissions	2040	Legislation
Puerto Rico	100% Renewable energy	2050	Legislation
Rhode Island	100% Renewable energy	2030	Order
Virginia	100% Carbon-free electricity	2045-2050	Law
Washington	100% zero-emissions electricity	2045	Law
Wisconsin	100% Carbon-free electricity	2050	Order

The NZ variations and differing source and supply requirements from multiple organizations were identified in (Moghaddasi, Culp, Vanegas, et al., 2021). Further analysis showed that the lack of scientific publications reporting on measured energy data contributed to the failure of validating the Net Zero Community (NZC) performance (Moghaddasi, Culp, & Vanegas, 2021). Other studies also concluded the importance of utility energy data to track the NZ progress and achieve its objectives

(Chen et al., 2017; Dorotić et al., 2019; International Energy Agency (IEA), 2021c; Klein & Coffey, 2016). To meet NZ emission targets, buildings need to follow zero carbon policies and strategies such as energy efficiency measures (EEMs), renewables, and electrification of end uses. However, the existing building codes and regulations are either insufficient to address the current NZ targets or lack firm routes for implementations. According to Kumar and Alok, codes and regulations need to promote electrification and renewables into buildings and transport sectors (Kumar & Alok, 2020). Economidou et al. reviewed the impact of European Union (EU) policies on the buildings' energy efficiency improvements and recommended additional policies with higher energy performance requirements; extension from building level to district level; use of electrification and smart technologies; and targeted financial mechanisms on energy efficiency in addressing decarbonization targets (Economidou et al., 2020).

The existing variety in optimization strategies and challenges in addressing net zero building (NZB) and net zero community (NZC) targets complicate achieving its objectives. Zhang et al. presented a systematic methodology to assess and optimize the economic performance of NZBs by including the application of life cycle cost, benefit-cost analysis, and building performance simulation (Zhang et al., 2021). Wills et al. proposed a hybrid statistical and engineering-based model to retrofit a community with improved envelope, mechanical and district renewable energy systems to achieve NZC (Wills et al., 2021). Ceglia et al. examined the concept of “smart energy community” and concluded control strategies, sustainable renewable systems, and storage systems as important factors for exploiting economically efficient sources (Ceglia et al., 2020). Fournier et al. summarized that a building's peak load and energy costs need to be managed by disincentivizing energy use during peak loads, time balancing between energy usage and delivered energy, and policy plans for decarbonization (Daniel Fournier et al., 2020). Kelly et al. showed that load shifting with thermal storage could add flexibility to the energy demand to meet the supply and suggested heat pumps as responsive options to variations of electrified heating systems (Kelly et al., 2021). Guillen et al. presented the "design significance" of occupant settings, construction, and HVAC settings in energy modeling on the variations in thermal comfort, energy use, and payback periods of design upgrades (Estrella Guillen et al., 2021). variations and differing source and supply requirements from multiple organizations were identified in (Moghaddasi, Culp, Vanegas, & Ehsani, 2021). Further analysis showed that the lack of scientific publications reporting on measured energy data contributed to the failure of validating the Net Zero Community (NZC) performance (Moghaddasi, Culp, & Vanegas, 2021). Other studies also concluded the importance of utility energy data to track the NZ progress and achieve its objectives (Chen, Hong, & Piette, 2017; Dorotić et al., 2019; International Energy Agency (IEA), 2021; Klein & Coffey, 2016).

In this paper, the NZ concept is reorganized such that the ability to understand the assumptions made would be clear for all. The proposed concept is trackable, measurable, and adaptable to different regions and requirements, shown in Table 4.2.

Table 4.2: Variations in NZ requirements.

Organizations		On-site/Off-site Renewable Supply	Source Energy	Site Energy
US Green Building Council	USGBC	Both		•
Illumination Engineering Society of North America	IESNA	Both		•
New Buildings Institute	NBI	Both		•
ASHRAE		Both		•
American Institute of Architects	AIA	Both		•
Environmental Protection Agency	EPA	On-site		•
International Living Future Institute	ILFL	On-site		•
European Performance of Buildings Directive	EPBD	On-site	•	
Fed. of European Ventilation and Air-conditioning	REHVA	On-site	•	
Department of Energy	DOE	On-site	•	
Department of General Services	DGS	On-site	•	

The outcome of this research will provide stakeholders with design guidelines and systematic approaches to estimate the expected savings in energy and CO_2 emissions and verify NZ achievements on a project. With this plan, the projects are required to have publicly available reports to show committed NZ plans, measured utility energy performance, and renewable generation.

This paper covers:

1. An adaptable Net Zero model;

2. A comparative energy analysis of a monitored building's total electrical use versus two (2) simulated models (improved EEMs and improved EEMs plus increased PV);

3. A comparative energy analysis of a monitored community's total electrical use versus two (2) simulated models (improved EEMs and improved EEMs plus increased PV);

4. A comparative analysis of the community solar field versus rooftop PV systems in regard to the design limitations and installation cost.

4.3. Proposed Model

An adaptable NZX%**(ORG)** concept is proposed with 'X%' representing the percentage of total energy use met by renewables in a project over a year, and 'ORG' indicating the organization's NZ definition and requirements that a project chooses to follow. A monitored case study of Serenbe, a sustainable community in Atlanta, Georgia is analyzed to quantify its energy performance and verify its NZC achievements. The main energy indicators used for the analysis include (1) energy efficiency measures (EEMs), and (2) renewable power production.

The state of Georgia has targeted to reduce its GHG emissions by 80% below the 2001 level by 2050. According to Nygren, Serenbe's founder and developer, the project aim to become NZC by reducing the fossil fuel-based energy use in buildings by 50% for the existing buildings and by 70% in the newer sections (Nygren et al., August 2021). If Serenbe uses the US Environmental Protection Agency (EPA)'s NZ definition and generates 50% of its total energy from renewables, then the model becomes NZ50%**(EPA).** The improved EEMs will be analyzed to estimate the long-term energy savings and CO_2 emissions reductions for the community. Figure 4.1 presents a systematic approach for the proposed NZX%$_{\textbf{(ORG)}}$ model applicable to different projects.

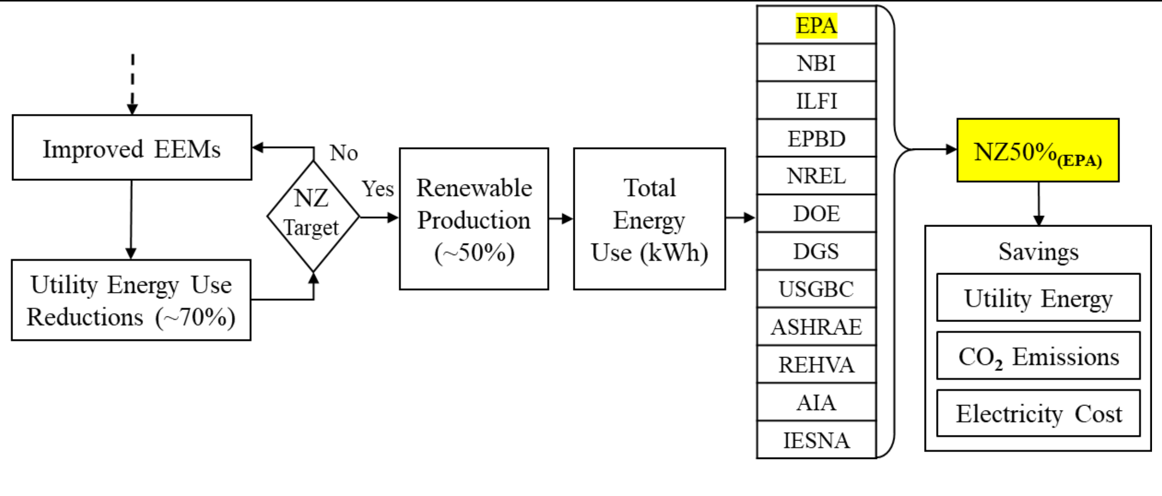


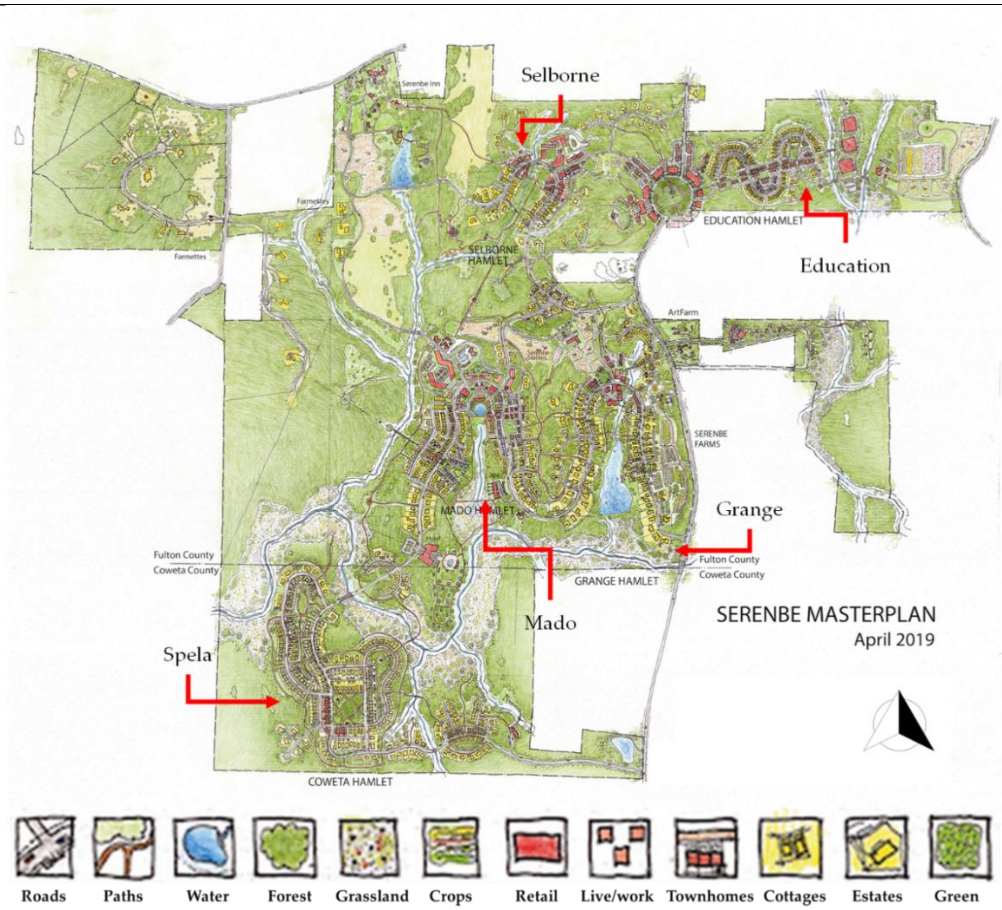
Figure 4.1: NZX%$_{\textbf{(ORG)}}$, adaptable to different regions with different requirements.

4.4. Monitored Case Study

The Serenbe community, located 30 miles southwest of Atlanta, Georgia, US, is a sustainable project with NZC plans. Serenbe was initially planned in 2001 and construction began in 2004. The project is a 486-hectare, mixed-use residential community with 70% open space (natural reserve area). Serenbe is designed for an eventual 1800 dwellings and a population of 3000. The average density is 12 dwellings per hectare (varies between 6 to 50) - the open space is excluded from the density (Tabb, 2020). Serenbe's land plan is composed of five omega "Ω" shape hamlets, which are about 30% complete and occupied, shown in Figure 4.2 (Moghaddasi et al., 2020).

Figure 4.2: Arial view of Selborne hamlet in the Serenbe community. Source: Serenbe Development.

Primary energy strategies in buildings in Serenbe included (1) rooftop solar PV systems; (2) mandated geothermal heating and cooling systems to save electrical energy use and reduce utility costs; and (3) mandated Earth-Craft certification - a green building program that "[saves] homeowners a projected 30 percent on their energy bills, relative to comparable buildings that use standard construction methods" (EarthCraft, 2021). EarthCraft is a regional efficient-homes certification program that is developed and supervised by the DOE Building America research partner Southface Energy Institute. EarthCraft focuses on energy and resource-efficient criteria, including ENERGY STAR Certified Homes Version 3.0 for its gold and platinum levels (Department of Energy (DOE), 2014). Further energy strategies in the Serenbe community include passive solar heating, natural ventilation, efficient lighting/HVAC/windows/appliances, and agricultural activities. Regarding transportation energy use, Serenbe encourages pedestrian and biking networks, use of electric golf carts, and mixes of use for daily requirements. Figure 4.3 summarizes Serenbe's planning characteristics.



Serenbe Community Masterplan (2019). Source: Serenbe Development; modified from Phillip Tabb's Masterplan (April 2019)

Serenbe	**Area** (ha)	**Population**	**Dwellings**	**Density*** (du/ha)	**Year** (Project opened)
Ultimate plan	486	3,000	1,800	~12 (average)	2004
Status (2020)		~850	~600	~4 (average)	

Figure 4.3: Planning characteristics at the case study of the Serenbe community.
* The open space (70% of the land) is excluded from the density (du/ha).
Note: ha = hectare; and du/ha = dwelling units/hectare

4.5. Methodology

To quantify the NZC performance of the case study of Serenbe, the energy analysis was conducted at two levels: (1) building, to minimize utility energy use with improved EEMs and rooftop PV systems; and (2) community, to optimize on-site renewable generations. A comparative analysis was conducted between three types of buildings in Serenbe as follows:

A. Nest Cottage, by DOE in 2012,

B. DOE Zero Energy Ready Home, by DOE in 2014,

C. A typical (average-size) single-family building in Serenbe, by the authors in 2020,

- Baseline: total building electrical use (measured electricity data plus PV generation)
- Simulated models: calibrated base case; improved EEMs; improved EEMs plus increased PV

DesignBuilder v7 (DB), an energy modeling software that works with EnergyPlus 9.4 (EPlus) was used to evaluate the building's energy performance. The built-in EEMs were used from building A and B, and then they were improved in building C. A comparative analysis was conducted in three steps: (1) calibrate a base case with simulating the total building electrical use; (2) simulate the improved EEMs to estimate the energy savings; and (3) increase rooftop PV coverage to lower the utility energy consumption in building C in 2020. Next, an analysis extrapolated the single home (building C) to estimate the energy savings of total buildings in the Serenbe community in 2020. The results are presented as savings in utility energy, electricity bills, and CO_2 emissions at the community level. The calculated savings will be approximate and can be used to estimate the planned reductions and planned NZC level. Monitoring and reporting will provide the actual NZC levels achieved year by year.

4.5.1. Building A: Nest Cottage by DOE (2012)

The Nest Cottage subdivision in Selborne Hamlet was built as a new construction test house (NCTH) by DOE's Building America (BA), Southface, and Martin Dodson Builders (Butler et al., 2012). There are 15 cottage-style buildings with an average size of 120 m^2. The buildings are targeted to meet the DOE BA's 30% energy saving goal compared to constructions that meet the 2009 IECC (Butler et al., 2012). The main EEMs used in Nest Cottages were a ground source heat pump (GSHP) and improved insulation (wall and roof) using open-cell spray foam (Butler et al., 2012). In the Nest Cottages, building A was selected for the DOE's energy analysis purposes. Figure 4.4 summarizes the characteristics of building A.

Site	Atlanta, GA, climate zone IECC 3A (mixed-humid)
Construction year	Completed 2011
Total area (conditioned)	157 m^2
Type/stories	Single family, 2 stories and 1 basement

Figure 4.4: Planning characteristics of building A. Source: (Butler et al., 2012).

The design goal for the Nest Cottage was saving energy use while minimizing cost increases and maintaining metrics of comfort, durability, and indoor air quality. The specification for building A is detailed in Table 4.3.

Table 4.3: Nest Cottage, Building A Specifications. Data From DOE, (Butler et al., 2012).

Measure	**Nest Cottage**
Foundation	Basement
Foundation insulation	R-10 (exterior drainage mat)
Wall Construction	2x6
Wall Insulation	R-20 (open cell spray foam)
Ceiling Construction	Cathedral Attic
Ceiling Insulation	R-26 (open cell spray foam)
Window Ratings	U-0.35, SHGC-0.31
Infiltration	$ACH_{50} \leq 5$[a]
Heating Efficiency	5.5 COP at full load and 6.3 COP at part load
Cooling Efficiency	16 EER at full load and 18.6 EER at part load[b]
Ventilation	Central fan integrated supply[c] that meet ASHRAE 62.2 ventilation rates when outside air ventilation is used
Hot Water Efficiency	0.67 EF[d], gas storage water heater
Lighting	20% incandescent, 80% CFL
Appliances	ENERGY STAR

Table 4.3: Nest Cottage, Building A Specifications. Data From DOE, (Butler et al., 2012).

a: Includes ACH going to the fan intel.
b: For water loop applications per AHRI/ISO 13256-1 (Butler et al., 2012) (Air-Conditioning, Heating, and Refrigeration Institute, 1998).
c: Consists of a ducted outside air intake connected directly to the return plenum of the central HVAC system that ensures adequate ventilation when the central system is not calling for heating or cooling (Butler et al., 2012).
d: The energy factor (EF) indicates a water heater's overall energy efficiency based on the amount of hot water produced per unit of fuel consumed over a typical day (Department of Energy (DOE), 2021a).

As shown in Table 4.3, the main EEMs were improved in envelope measures and HVAC systems (GSHPs). In addition, air sealing measures and insulation installation followed the EarthCraft and ENERGY STAR programs’ requirements. High-performance glazing windows with 0.31 solar heat gain coefficients (SHGC) were utilized. The building includes a lighting package of 80% compact fluorescent lamp (CFL) and 20% incandescent bulbs with ENERGY STAR appliances. The efficient GSHPs are used with a rating of 16 energy efficiency ratio (EER) at full load and 18.6 EER at part load, and 5.5 coefficient of performance (COP) at full load, and 6.3 COP at part load (Butler et al., 2012). A gas storage water heater was utilized with an energy factor (EF) of 0.67, which meets the ENERGY STAR Requirements (Department of Energy (DOE), 2021a, 2021b; ENERGYSTAR, 2021).

4.5.2. Building B: Zero Energy Ready Home by DOE (2014)

The Proud Green Home is the first DOE Zero Energy Ready Home certified by the Georgia Department of Energy in 2014. The building is a 261 m^2 single-family house, constructed in 2013. Figure 5 summarizes the planning characteristics of building B.

Site	Atlanta, GA, climate zone IECC 3A (mixed-humid)
Construction year	Completed 2013
Total area (conditioned)	261m^2
Type/stories	Single family, 2 stories

Figure 4.5: Planning characteristics of building B. Source:(Department of Energy (DOE), 2014).

Building B meets the requirements of EarthCraft, the EPA's Indoor airPlus, the EPA's WaterSense guidelines on the hot water distribution criteria, high insulation level (beyond the 2012 IECC), and efficient lighting/construction/window performance. As a result, the building improved energy savings by 60% when compared to a conventional building in Georgia that meets the 2009 IECC (Department of Energy (DOE), 2014). Table 4.4 details building B's specifications.

Table 4.4: Zero Energy Ready Home specifications. Data From (Department of Energy (DOE), 2014).

Measure	Building B
Wall Insulation	Above-grade, 2x6 advanced frame R-20 open cell spray foam plus R-6.6 rigid foam, fiber cement, and corrugated siding
Roof Insulation	ENERGY STAR 24 gauge aluminum standing seam metal roof R-32 open cell spray foam plus R-5 rigid foam, sealed attic
Window Ratings	Coated aluminum clad, dual pane, low-E, U-0.29, SHGC-0.20
Infiltration	0.21 ACH_{50} [a]
HVAC System Heating Efficiency Cooling Efficiency	Mini-split heat pump with 1 exterior unit, 3 interior units ducted to rooms 8.20 HSPF (2.40 COP) [b] 14.30 SEER (12.51 EER) [b]
Ventilation	90% efficient energy/heat recovery ventilators (ERV)
Hot Water Efficiency	Solar thermal, with 80 gallon tank and electric backup, 0.95 efficient.
Lighting	63% LED and 32% CFL, with lighting controls
Appliances	ENERGY STAR

a: Air changes per hour at 50 Pascals pressure (ACH_{50}) (Department of Energy (DOE), 2014).
b: The heating/cooling requirements meet the ENERGY STAR Version 3 (ENERGY STAR, 2013).

The main utilized EEMs in building B included HVAC systems with heat recovery ventilator (HRV), solar thermal water heater, and improved air sealing. Mini-split heat pumps (with variable speed compressors and fans) were used to cover a total 6.5 kW (22,020 Btu/h) heating load of the building. Also, with the air sealing value of 0.21ACH50, energy recovery ventilators (ERVs) were required to exchange heat, fresh air, and humidity into the building. Further, a solar thermal heater was utilized to provide 100% of the building’s hot water demand.

4.5.3. Building C: Typical Building in the Serenbe Community (2020)

For the purpose of this study, building C with 228 m2 is selected as an average size building in Serenbe and a basis of design to estimate the community's energy performance. To do so, energy analysis was conducted to (1) calibrate the simulated utility electrical use with a base level of PV coverage (10% of the roof space) to create a base case model; (2) improve EEMs in the base case and determine EEM generated savings; and (3) in-crease PV coverage to 25% of the roof space with improved EEMs to calculate an NZC level. The building used double-glazing windows, LED lightings (50% of the total light bulbs), geothermal (heating/cooling) system, high-standard construction materials and insulation (Earth Craft Certified), and domestic hot water (standalone gas boiler). The building's baseline, with 12 PV solar panels (4.7 kW) on the roof, is shown in Figure 4.6.

Figure 4.6: Building C in the Serenbe Community. Source: Modified from Google Map 2021.

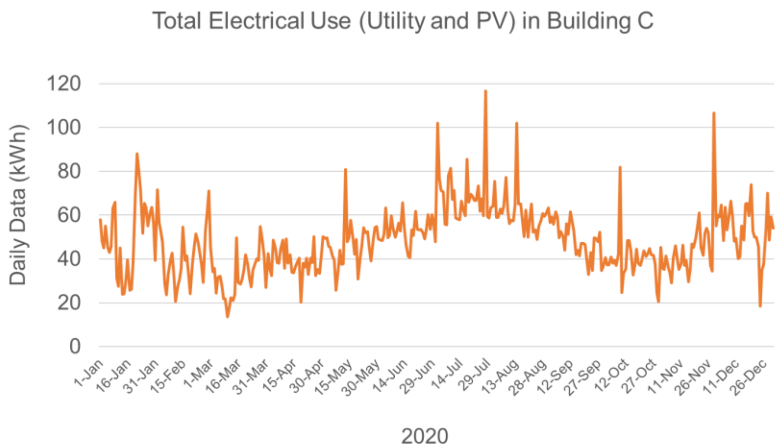
Four batteries are installed in building C. Each battery has a total energy capacity of 13.5 kWh with 11.4 kWh usable energy (Panasonic Corporation, 2017).

4.5.3.1. Measured Data plus Produced Solar PV (Base Case)

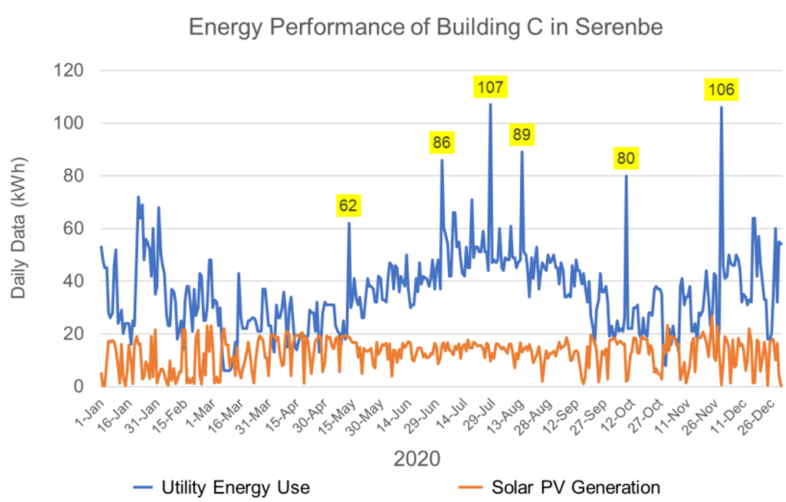
Building C is a single-family detached house. The building was constructed in 2016 and is EarthCraft certified. Table 4.5 shows the planning characteristics of building C.

Table 4.5: Planning characteristics of building C. Source: residents of the building (Juliet Culter et al., 2019-2021).	
Building Characteristics	
Site	Atlanta, GA, climate zone IECC 3A (mixed-humid)
Construction year	Completed 2016
Total area	228 M^2
Type/stories	Single family, 2 stories and 1 basement
Zones	3 - basement, main floor, upper floor
Wall Construction	2x6
Wall Insulation	R-19 (open cell spray foam)
Ceiling Construction	Cathedral Attic
Ceiling Insulation	R-30 (open cell spray foam) underside the attic

Figure 4.7 shows the daily electrical performance in building C from 01 Jan to 30 Dec 2020.



7A.



7B.

Figure 4.7: A. Daily electrical use (utility electricity data plus PV generation) in building C from Jan 1 to Dec 30 in 2020. B. Daily utility electricity use and solar PV generation from GreyStone Utility Power Corporation and Generac Power Systems in building C from 01 Jan 2020 to 30 Dec 2020.

The analysis showed that the rooftop PV systems provided 26% of the total electricity use in building C (17,641 kWh) in 2020. Figure 6B shows six dates with unusual energy peak loads that have occurred due to the occupant using a pottery kiln during the COVID-19 pandemic.

4.5.3.2. Improved EEMs Simulations

Buildings A and B showed that with improving EEMs in HVAC systems, building air sealing, lighting, and window glazing, energy savings could improve by 30% to 60% when compared to a similar construction that meets the 2009 IECC. These parameters were improved in building C to evaluate the energy savings, as shown in Figure 4.8.

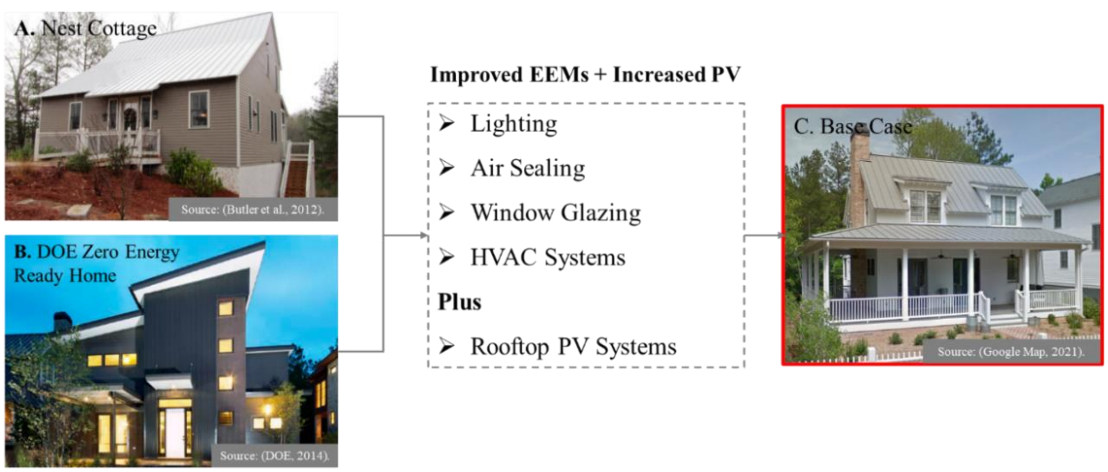


Figure 4.8: Main parameters in energy efficient buildings in Serenbe.

Table 4.6 presents specifications for the calibrated base case and improved EEMs used in the simulations in building C.

Table 4.6: Specification for building C and the improved EEMs used in the simulation.

EEMs	Base Case	Improved EEMs
1) Lighting	33 LED (50%) and 33 incandescent recessed lightings (50%)	LED with linear control (100%)
Normalized power density (W/m²-100 lux)[a]	7.5	3.50
2) Glazing	Double Low E (e2=.1) Clear 3mm/13mm Air	SageGlass Climatop Grey No Tint
Solar heat gain coefficient (SHGC)	0.60	0.27
U-Value (W/m²-K)	1.80	0.70
3) Air sealing Constant rate (air change/hour - ac/h)	0.7	0.2
4) HVAC	GSHP, water source heat pump SM036-1VTC	Same as the one used in the Base Case.
Heating Efficiency	4 COP (13.7 HSPF) (ENERGY STAR, 2021)	
Cooling Efficiency	26 EER (30 SEER) (ENERGY STAR, 2021)	
Hot Water Efficiency	Domestic with gas storage water heater	

Table 4.6: Specification for building C and the improved EEMs used in the simulation.

[a] In the DesignBuilder, the maximum lighting gains are defined as W/m²-100lux, and the actual lighting energy used for the zone in the simulation is based on this value plus floor area and illuminance requirements as follows:

Max Lighting power (W) = Lighting energy (W/m²-100lux) x Zone floor area (m²) x Zone Illuminance requirement / 100

Note: the templates in DesignBuilder were used and modified for the simulation base case and improved EEMs.

4.5.4. Optimization variables

The simulation was conducted to optimize (1) the loads (window, construction material, air sealing); (2) the systems (HVAC, lighting); and (3) the renewable generations (rooftop PV, solar field) to attain NZC. The primary EEMs that improved energy savings in building C are summarized as follows:

4.5.4.1. Lighting

In building B, 63% LED technology with lighting controls was utilized, while in building C, 50% LED and 50% incandescent lights were used. According to the DOE, residential LED lightings use 75% less energy than in-candescent lighting and last 25 times longer (Department of Energy (DOE), 2022). During the simulation analysis, LED with linear controls lighting technology was selected for all 66 lighting bulbs.

4.5.4.2. Window Glazing

Building B used coated aluminum clad, dual pane, and low-E glazing window. In the simulation analysis, the closest glazing type to the ones measured in buildings A and B (with SHGC-0.2-0.31) was selected with SHGC-0.27 in building C.

4.5.4.3. Air Sealing

In building B, the above-grade 2x6 walls were constructed with advanced framing techniques and were filled with R-20 open-cell spray foam. Also, the underside of the roof deck was covered with the R-32 open-cell spray foam (0.21ACH50). The closest parameters selected for building C resulted in air sealing of 0.2ACH50.

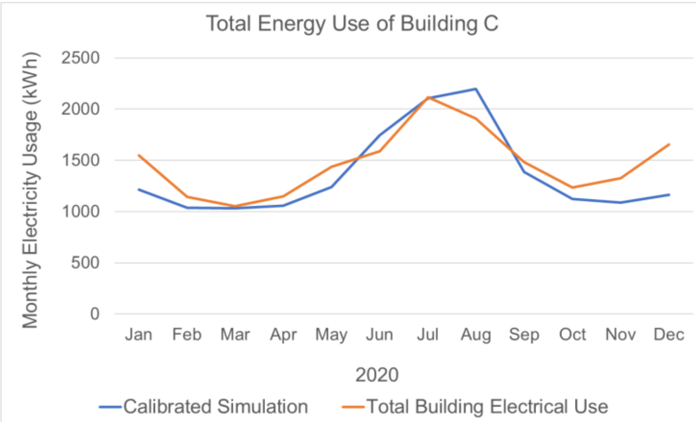
4.5.4.4. HVAC Systems

An important energy measure in both buildings A and B was the use of ground source heat pumps (GSHPs). Building C, also, used a GSHP with 13.7 heating seasonal performance factor (HSPF) and 30 seasonal energy efficiency ratio (SEER). As the current HVAC system is highly efficient, the same efficiency rate was used for the simulation. The SEER rating of the GSHP is improving steadily (International Energy Agency (IEA), 2020c). It is expected that with the updated efficiency rate for newer systems, the savings in source energy and CO_2 emissions increase above the estimated levels.

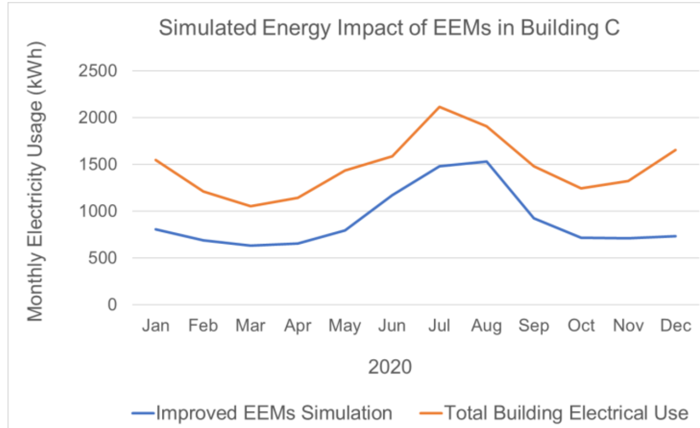
Also, it is recommended to shift the gas district water heater to a solar thermal water heater. According to IEA, energy-related building codes and retrofits need to be adjusted with renewables, where buildings with available roof space and solar insulation get equipped with solar thermal water heaters as they are energy efficient and cost-effective (International Energy Agency (IEA), 2021c).

4.5.5. Results from Energy Analysis of Building C

Building C is typical of other buildings that will be built in Serenbe. To analyze the energy performance of this building, calibration analysis was conducted using total building electrical use (utility electricity data and PV generation) versus simulated model in 2020, as shown in Figure 4.9A. The “calibrated simulation” acts as a base case for all simulation analyses, and “total building energy use” is the baseline that represents the actual energy use of buildings C. Two scenarios were analyzed and compared with the baseline: (1) improved EEMs, and (2) improved EEMs plus increased PV coverage from 10% ($24m^2$) to 25% ($58m^2$) of the roof space, as shown in Figures 4.9B-D. See the Appendix (Table 5.1 to Table 5.4) for simulated variables and their relationship to the measured data.

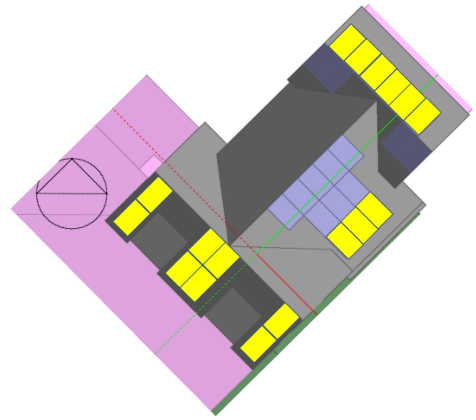


A. Calibrated base case Vs. measured baseline.



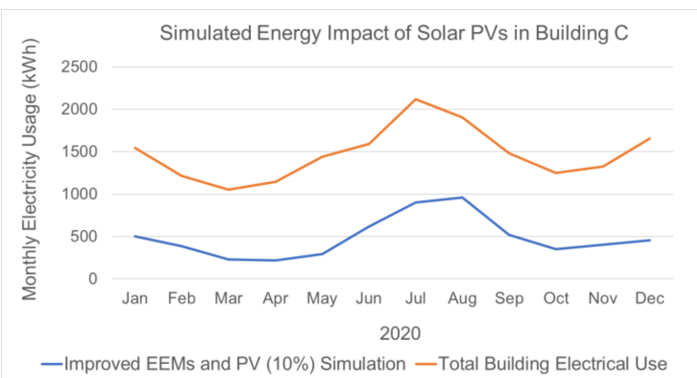
B. Energy use reductions from improved EEMs simulation Vs. measured baseline.

Figure 4.9: Systematic analysis to verify net zero in building C.

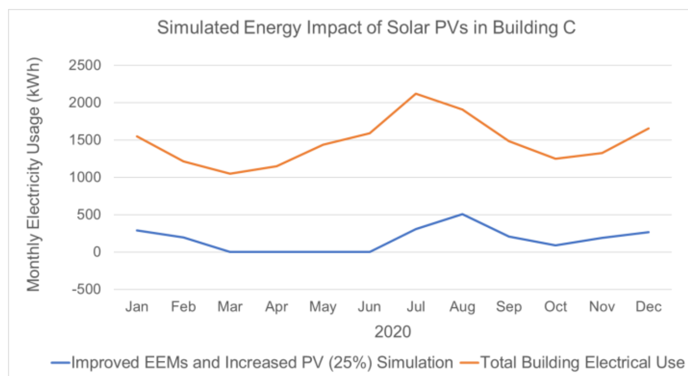


The existing rooftop PVs on 10% of the roof space (24m²).

The simulated model rooftop PVs on 25% of the roof space (58 m²). The yellow panels show the added PV systems.



C. Utility energy use reductions with improved EEMs & PV (10%) simulation Vs. measured baseline.



D. Utility energy use reductions with improved EEMs & PV (25%) simulation Vs. measured baseline.

Figure 4.9: Systematic analysis to verify net zero in building C.

Figures 4.9A-D summarize the monthly energy consumption of building C in each scenario. The results showed that improving EEMs could reduce the building's annual energy use by 34% (Figure 4.9B). The existing rooftop PV (10% of the roof space) could cover 46% of the rest of the energy demand and help the building become NZ46% (Figure 4.9C). With increasing rooftop PV to 25% of the roof space, the building would generate 80% of its total energy from the solar system and become NZ80% (Figure 4.9D). Table 4.7 summarizes the percentage of total energy covered by renewables and utility energy savings in each scenario.

Table 4.7: Comparative analysis of the measured baseline and two simulated scenarios in building C in 2020.

Scenarios	Electricity use [kWh]	Percentage of electric power covered by PV	Utility energy savings compared to the baseline
Baseline: Utility electricity use and PV	17,641	26%	__
1- Improved EEMs and existing PV (10%) simulation	10,789	46%	65%
2- Improved EEMs and increased PV (25%) simulation	10,769	80%	88%

By analyzing building C, it is inferred that retrofitting buildings with improved EEMs and rooftop solar PV systems (25% of the roof space), the building's utility electrical use could reach zero in some months. It could be concluded that achieving NZ at the community level needs: (1) improvement in energy efficiency to minimize energy demand; (2) solar generation at the building level; and (3) an optimized NZ path for the community to achieve its objectives. Since Serenbe is at 30% completed construction (2020), using building C as a basis of design for the other 70% would further increase energy savings at the community level. Reducing energy use by around 34% in a community of 1800 dwellings allows for smaller size renewable power systems. Energy performance and savings in three energy-efficient buildings in the Serenbe community are summarized in Table 4.8.

Table 4.8: Energy analysis of the three types of energy-efficient, single-family buildings in Serenbe.

Buildings in Serenbe Community (Detached single-family)	**Construction completed**	**Year of analysis**	**Area (m^2)**	**PV (kW)**	**Calculation tools**	**Result**	**Type of Analysis**
A- Nest Cottages	2011	2012	157	__	Building Energy Optimization (BEopt)	Met the goal of 30% above the BA benchmark.	Calculated method.
B- DOE Zero Energy Ready Home	2013	2014	261	10	__	-60% less energy use compared to a similar building with the 2009 IECC. -Home Energy Rating System (HERS) Index of -10, NZ home.	Measured utility data.
C- Building C	2016	2021	228	4.7	DesignBuilder v7 EnergyPlus 9.4	39% savings with improved EEMs. 91% additional savings with increased solar PV.	Comparative analysis of the measured baseline data with simulated models.

As shown in Table 4.8, all three buildings improved their energy savings when compared to a conventional building in Georgia. However, the analyses for buildings A and B were conducted only one year after buildings' construction in 2012 and 2014, respectively. Also, the saving results in building A were reported based on calculated methods rather than measured data. Therefore, updated reports on the total electrical use (utility energy data and PV generation) are needed to be available for all buildings to the researcher to quantify and verify the projects' NZ progress.

4.5.6. Community Energy Analysis

The Serenbe community mandated EarthCraft certification for all buildings, use of geothermal for all new construction built after 2011, and rooftop PV systems for all buildings that are constructed after 2022. Figure 4.10 shows the total electrical use of the existing 600 buildings (residential and commercial) and the current solar PV generation (19 buildings with rooftop PVs) in the Serenbe community in 2020.

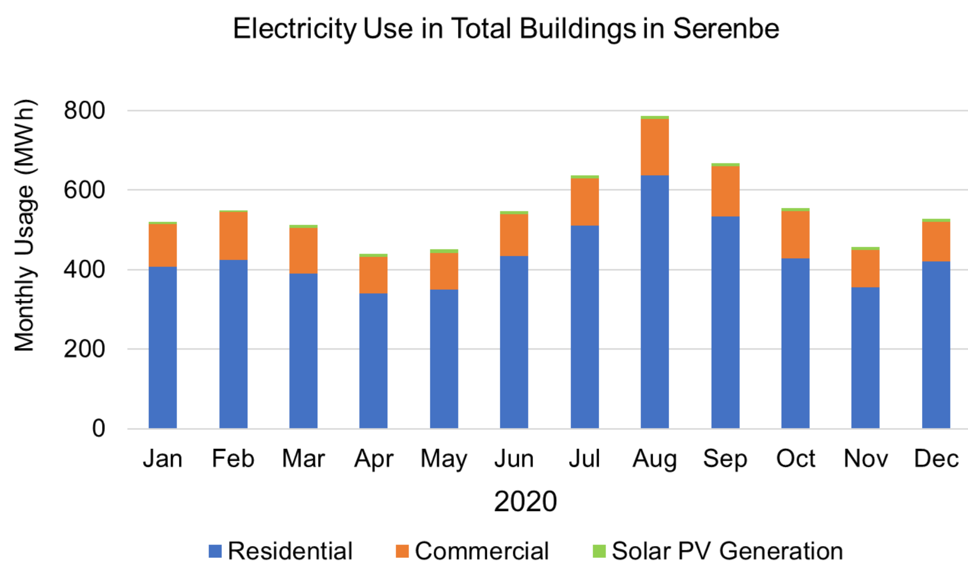


Figure 4.10: Utility electricity use and solar PV generations in buildings (residential and commercial) in the Serenbe community in 2020.

To become an NZC, Serenbe needs to further reduce fossil fuel-based energy use and increase renewable generations. Community design guidelines were previously developed by the authors to accelerate achieving NZC targets through improved EEMs, electrification, and renewables in power systems, buildings, and transport sectors (PBT) (Moghaddasi, Culp, & Vanegas, 2021). Applying these methods to the Serenbe community will reduce peak loads, where renewable technologies could generate the rest of the energy demands. Figure 4.11 highlights the parameters in PBT sectors in Serenbe that need to be improved or included to speed up the community's NZC achievements.

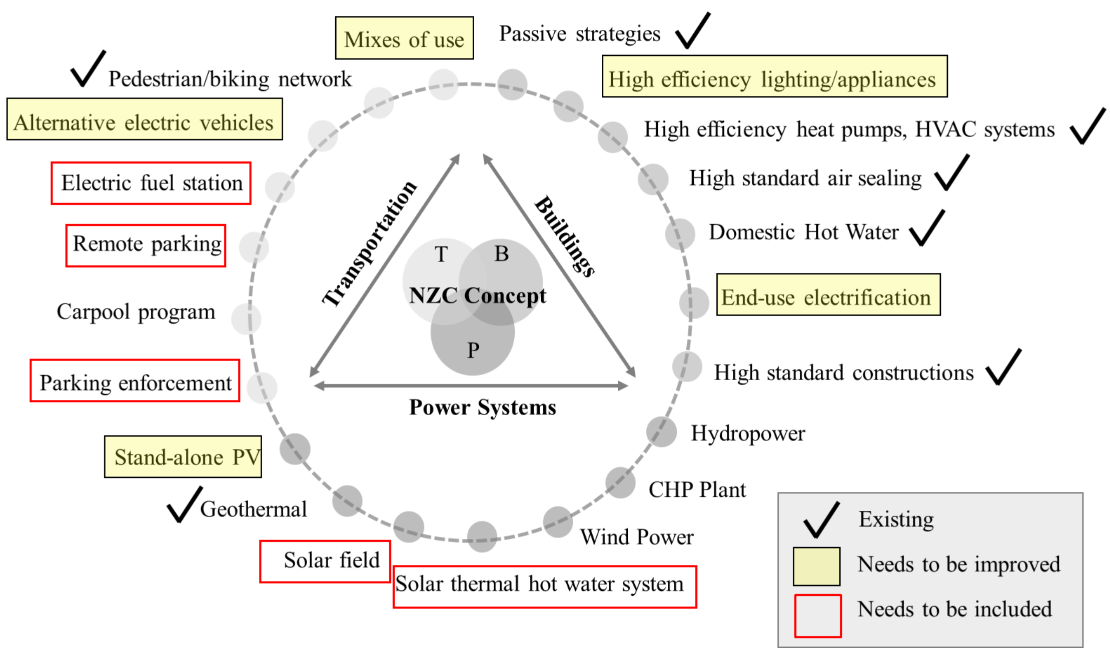
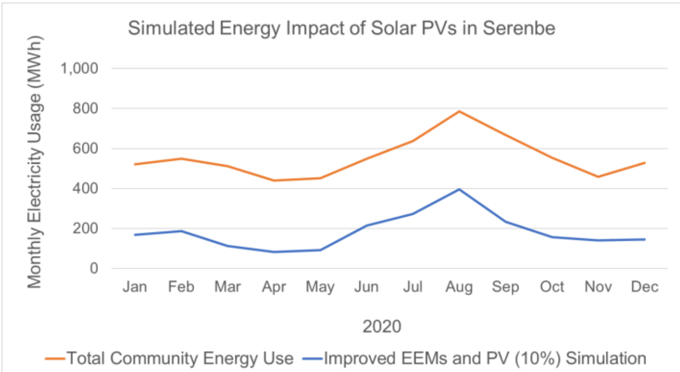


Figure 4.11: Energy parameters in power systems, buildings, and transport sectors in the Serenbe community that accelerate the community's NZC achievements.

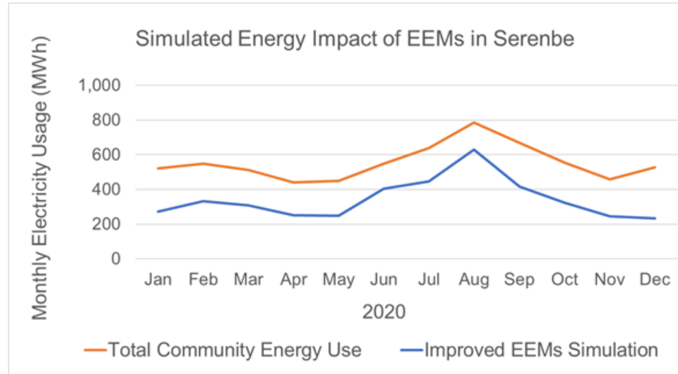
NZC Design Guidelines. Community energy balance through improved efficiency in PBT indicators.

Note: (P) community power production through renewable sources; (B) energy use in buildings; (T) energy use in transportations. Source: Modified from. (Moghaddasi, Culp, & Vanegas, 2021).

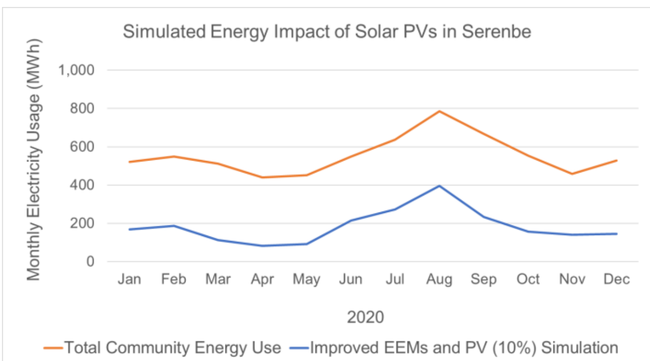
The community energy analysis was conducted on a square meter basis, as shown in Figure 4.12: (A) base case calibrated model with extending building C to the Serenbe scale (600 buildings) and use of the total community electrical use (utility energy use and PV generation); (B) improved EEMs simulation; (C) improved EEMs and increased rooftop PV (10% of the roof space) in all buildings, and (D) improved EEMs and increased rooftop PV (25% of the roof space) in all buildings. See the Appendix (Table 5.5 to 5.8) for simulated variables and their relationship to the measured data.



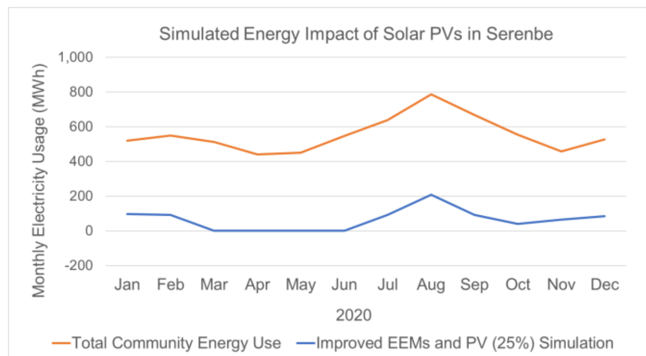
A. Calibrated base case Vs. measured baseline (utility and PV generation).



B. Improved EEMs simulation Vs. measured baseline.



C. Improved EEMs & PV (10%) sim. Vs. measured baseline.



D. Improved EEMs & PV (25%) sim. Vs. measured baseline.

Figure 4.12: Systematic energy analysis for the Serenbe community to become NZC.
Note: 1Megawatt hour (MWh)= 1,000 kilowatt hour (kWh).

Figure 4.12 shows 34% community energy saving as a result of improving EEMs compared to the baseline (measured data). The results show that the community could either become NZ46% and increase its utility energy savings by 65% by retrofitting the existing buildings with rooftop PV (10% of roof space), or it could be-come NZ80% with covering 88% of roof spaces with rooftop PV systems in all 600 buildings.

By reducing the total community's utility energy use (~30%-50%), a community power production system could generate the rest of the energy demand (~50%-80%) from renewables. Building C showed that 12 rooftop PV systems (4.7 kW) provided 26% of the total electricity use of the building. Considering the Serenbe's area, density, and available vacant land, a solar field would be a potential solution to generate on-site energy. Also, as Serenbe is in the woods with significant agricultural and farm-to-table activities, a CHP plant (combined heat and power plant) could be a solution for the community's energy backup. Wood and organic wastes, which otherwise go to landfills could be used as a source for the CHP plant.

4.6. Community Solar and Economic Analysis

According to IEA, as of 2021, on-site solar PVs are installed on 25 million rooftops worldwide and are projected to increase to 100 million by 2030 and 240 million by 2050 (International Energy Agency (IEA), 2021c). Community solar projects have become increasingly affordable in the US over the past years. Reduction in the cost of PV systems, consumer-friendly finance options, and increased consumer demand are the credited reasons. This presents an opportunity for multifamily houses or other structures to obtain solar-ready roofs. The National Renewable Energy Laboratory (NREL) predicts that appropriate and supportive regulatory frameworks set up by federal, state, or local governments could result in significant uptake of community solar to potentially cover all homes and businesses (Feldman et al., 2015).

According to Feldman et al., it is estimated that 49% of households are unable to install PV systems when accounting for renters, inability to access roofs in high rises and multi-unit houses, or insufficient roof space (Feldman et al., 2015). It is also estimated that 48% of businesses cannot accommodate PV systems due to similar exclusions as in the household sector such as insufficient roof space to install a PV system with an adequate capacity that meets the energy needs of the business. By catering to customers who meet the criterion, the share of community solar could reach between 32% and 49% of the distributed PV market (Feldman et al., 2015). This would imply an additional deployment of 5.5–11.0 GW of solar PV, representing $8.2–$16.3 billion in added investment (Feldman et al., 2015).

Savings to Investment Ratio (SIR) is a metric that is often used to investigate projects' affordability. The metric captures the ability to recover one’s investment in solar based on the utility bill savings resulting from the solar energy generated by a given solar energy system. After conducting SIR analysis for all 50 states with the assumption that individual residential PV systems cost between $3.00 to $3.50 per watt and have a life span between 25 to 35 years, NREL recommended a shift to solar as a cost-effective option for households in 12 to 25 states (Melius et al., 2013).

In contrast to individual solar, community solar projects are more significant, benefiting from the wholesale pricing and reducing the cost to commercial solar ($1.91

per $watt_{AC}$[5]) or utility solar ($1.35 per $watt_{AC}$) (Feldman et al., 2021). At that level, community solar projects will be a financially viable option in every state except Alaska (Melius et al., 2013). However, more houses moving to solar will reduce the grid's demand, which reduces the clearing prices in the grid. This would reduce the cost of electricity that solar would offset, thereby negatively impacting the SIR (Das et al., 2020). But the phenomenon would only take place at very high solar levels, and given the relatively small potential defined by NREL, we may never see a decline in the cost of electricity offset.

4.7. Results and Discussion

This paper estimated the potential for electricity generation and saving for the Serenbe case study. The area of the typical building C in Serenbe is 228 m^2 with a pitch roof surface area of 193 m^2. According to NREL, 25% of the total rooftop area in residential is suitable for PV (Melius et al., 2013), which provides 58 m^2 of PV per house (with average size) in Serenbe. Atlanta has a solar irradiance of 4.75KWh/m^2/day (National Renewable Energy Laboratory (NREL), 2018; Sengupta et al., 2018). Assuming a panel efficiency of 19%, common for home solar installations, solar panel installations in Serenbe can produce an average of 0.95 kWh/m^2/day or around 16.7MWh per house per year when it is fully developed (Solar Electric Supply, 2020).

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[5] $watt_{AC}$: watts alternating current

Given the average retail price of electricity in Georgia of 12c per KWh and average CO_2 emission of 680 grams/kWh (Das et al., 2020), this would imply an annual saving of $1,621 in electricity cost and 9.19 tonnes of CO_2 per building in Serenbe. As table 4.9 shows, Serenbe (1800 buildings) would generate a total of 24 GWh of electricity per year with an estimated CO_2 saving of 16.5k tonnes (equivalent to the annual emission of 3595 vehicles) (United States Environmental Protection Agency (EPA), March 2018). This implies that the solar installations in Serenbe could displace emissions for an average of two vehicles per household. Higher availability of roof area combined with higher efficiency panels could push this number higher.

Table 4.9: Cost analysis of the community solar (Serenbe)				
Specifications				
PV model (Watt)	PV efficiency	Solar irradiance in Ga ($kWh/m^2/day$)	Retail price of electricity in Ga (Cents per kWh)	Average CO_2 emission in Ga (grams/kWh)
390	19%	4.75-5	12	680
Total Savings from Community Solar				
Number of dwellings	Average area of solar PV (hectare)	Annual electricity generations (GWh)	Annual electricity savings ($)	Annual CO_2 savings (tonnes)
600 (2020)	3.5	8	~1million	5.5k
1800 (eventual)	10.4	24	~3million	16.5k
Note: Ga = Georgia Note: 1-gigawatt hour (GWh) = 10^6 kWh				

Table 4.10 shows three scenarios for community solar: (1) all 1800 buildings install rooftop PV; (2) half of the buildings (900) install rooftop PV and include 5ha of the solar field; and (3) 20% of the buildings (360) install rooftop PV and include 8ha of the solar field.

Table 4.10: Optimized community solar solution for Serenbe.					
Percentage of buildings with rooftop PV (25%) in a community of 1800 buildings	Average area of the solar field (Hectare)	Total area of the solar panel (Hectare)	Cost		Total installation cost (Million USD)
			PV on the roof (Million USD)	Solar field (Million USD)	
(1) 100%	-	10.44	11.8	-	11.8
(2) 50%	5.2		5.9	3.7	9.6
(3) 20%	8.3		2.4	6	8.3

It was assumed that the cost of rooftop PV to be $3 per Watt and that of the solar field to be $1.90 per Watt. With 19% PV efficiency and solar irradiance of

4.75KWh/m^2/day or 4.75/24KWh/m^2/h, the cost of rooftop PV was calculated to be \$3x4.75/24x0.19x1000/m^2 or \$112.8/m^2. Similarly, the cost of the solar field will be \$1.90x4.75/24x0.19x1000/m^2 or \$71.5/m^2. The total installation cost was calculated for the three scenarios described above as illustrated in table 4.10. As the Serenbe community is composed of five separate hamlets, the solar field could be distributed either in one or multiple locations depending on the available vacant land. Table 4.10 compares the price of three scenarios and given the lower cost of scenario 3 - 29% less than scenario 1 and 13% less than scenario 2 - shows a preference for a solar field after retrofitting 20% of the buildings (360 buildings) with rooftop PVs. Also, scenario 3 is a more practical solution due to the limitations in rooftop PV installations (i.e. design, orientation, space, accessibility).

4.7.1. NZX Model in Serenbe 2020

The results from energy analyses show that for Serenbe to become NZC, total peak loads need to be balanced with on-site renewable supplies. The analyses showed that with improved EEMs and increased PV systems on the roof, both building C and the community of 600 buildings could reduce its utility energy use by around 65-90%. Also, it was concluded that with providing a 7ha solar field, only 33% of the 600 buildings need to be covered with rooftop PVs for Serenbe to become NZ80%. As an outcome of this solution, the installation cost could be reduced by \$2.9 million compared to if all the 600 buildings have rooftop PV systems.

Also, with Serenbe generating from on-site sources; calculating site energy in quantifying its NZC practices; and allowing for combustion fuels, the NZ definition by EPA, NBI, AIA, ASHRAE, IESNA organization could be selected by the project. Assuming Serenbe uses EPA's NZ, the model projection will become NZ80%$_{\textbf{(EPA)}}$. Figure 4.13 summarizes the process of becoming NZ80%$_{\textbf{(EPA)}}$ in the Serenbe community in 2020.

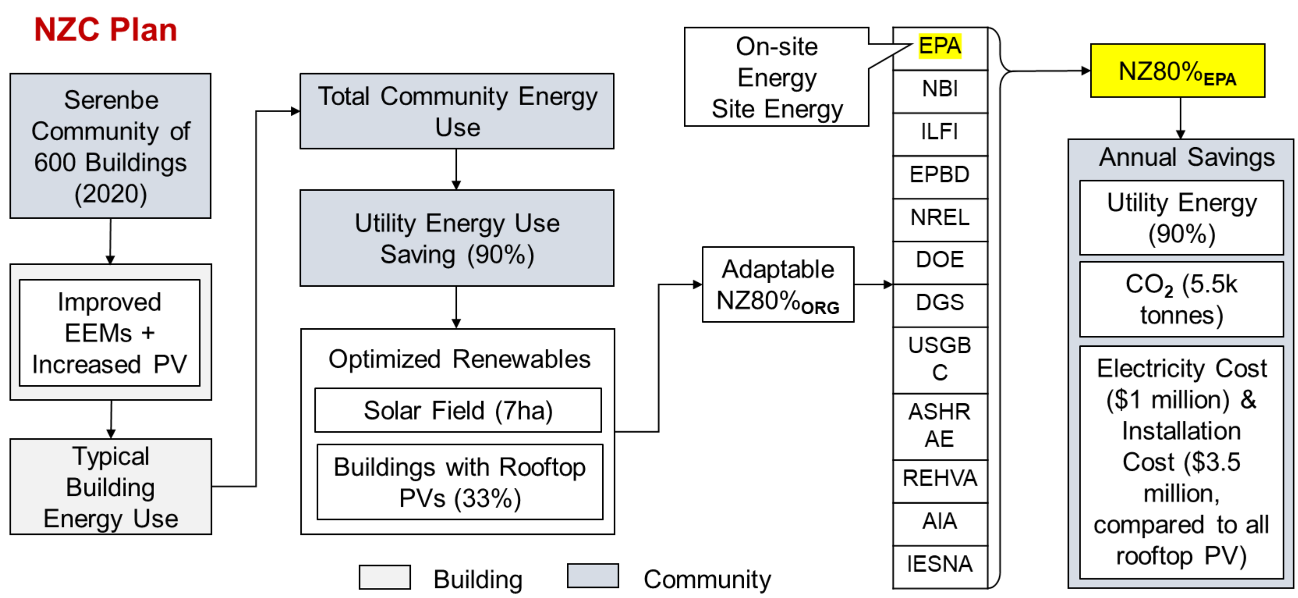

Figure 4.13: Adapting the NZX% model to the Serenbe community with 600 buildings in 2020.

Regarding transportation energy use, various mix-use options are accessible through pedestrian networks, including restaurants, cafés, community centers, stores, groceries, health centers, spa centers, and schools. Also, electric golf carts are used for between-place transportation. Yet, further improvements are needed, including:

1. providing solutions that reduce trip distances;
    - integration of mixes of use daily requirements (i.e. groceries, cultural center, library),
2. encouraging pedestrian movement;
    - comprehensive path system and sidewalks,
    - remote parking lots for the gasoline-powered vehicles at the site boundary,
    - parking enforcement,
3. promoting alternative electric vehicles;
    - solar-powered charging stations in individual buildings,
    - electric fuel stations,
    - autonomous electric shuttles (Hou et al., 2021).

Buildings in Serenbe are EarthCraft certified with a geothermal system (heating and cooling) and district hot water. Facilities are partially equipped with rooftop PVs, efficient lighting/HVAC systems/windows/appliances, and improved constructed standards. To accelerate achieving NZC, Serenbe needs to further (1) improve EEMs (i.e. retrofit existing buildings with LED lighting technology and mandate it for the new construction) (2) use solar thermal water heater and electrified end uses and stoves; (3) incorporate renewable energy power sources and renewable infrastructure systems; (4) promote/mandate electric vehicles and boost pedestrian/biking net-works for in-place transportation; and (5) provide remote parking lots at the site boundary and alternative electric vehicles (i.e. autonomous shuttles) for between-place transportation.

4.8. Conclusions

Net Zero Community modeling is an emerging field. This paper presents a reorganized Net Zero concept through a systematic methodology that combines measured data and simulated models. This method is adaptable to both buildings and communities in regions with different requirements. To test the validity of this proposal, it was applied to a monitored case study of the Serenbe community and a single-family building in Serenbe. The results from the analysis showed that with improving energy efficiency and increasing rooftop solar PV systems, the building could save around 65-90% in utility energy use compared to the baseline - total electrical use (utility electricity use and PV generation) in 2020. The EEMs with the highest impacts on energy savings included GSHP, lighting, building air sealing, and window glazing. By extending the results from building C to the community of 600 buildings, Serenbe could become 80% Net Zero by 80%, following the EPA’s NZ definition (NZ80%EPA). Considering the availability of vacant land in Serenbe and economic point of view, combined rooftop PV systems with a solar field were concluded as a practical solution (i.e. solar cost, design, orientation, space, solar access).

5. CONCLUSION

This dissertation presents a reorganized Net Zero concept through a systematic methodology that combines measured data and simulated models. This method is adaptable to both buildings and communities in regions with different requirements.

In Chapter Two, we concluded that NZ design principles can be realized at the building level, however, transforming a building to NZ requires clarifications and fully verified parameters and strategies. Further, the integration of energy efficient strategies, renewable technologies, and optimization approaches would cause a shift in source and consumption patterns.

In Chapter Three, we showed how NZ design principles can be achieved at the community level by addressing improved EEMs, electrification, and renewables into the PBT sectors; NZC requirements and structured approaches must be defined at the early phases of the planning; published measured data is needed to verify the NZC commitments by each project.

In Chapter Four, we proposed an adaptable concept along with systematic methods that enable key stakeholders, including developers, engineers, building and grid designers to accelerate achieving their projects' NZ objectives. Analyzing the case study of Serenbe showed that (1) the NZ energy practices can be quantified and verified at the community scale; (2) savings in energy and CO_2 emissions need foresight both in the early phase of design and planning with careful implementation of the strategies; (3) documented annual reports on the monitored hourly and monthly utility data is necessary to track the NZ progress; (4) the adaptable $NZX\%_{(ORG)}$ is a practical concept that motivates stakeholders to take the first steps and improve. This paper concludes that incorporating a community with improved EEMs and renewables are key elements in optimizing energy use and achieving NZC targets.

One problematic difference in NZ reporting is that some methods allow only on-site renewable generation and others allow for off-site renewable generation. Since the primary intent of all NZ methods is to reduce carbon in the atmosphere, it is recommended that all NZ processes allow both on-site and off-site renewable generation as counting toward the Net Zero. This will (1) motivate a higher use of solar and wind farms by a variety of communities that lack the land needed for renewable generations; and (2) accelerate achieving an NZ by enabling the growth of off-site renewable power. For example, achieving NZ would be difficult for cities without access to land for generation on-site renewables, unless remote generation is allowed to count for NZ.

The results from $NZX\%_{(ORG)}$ present a promising plan that Serenbe can apply and estimate its progress to NZC by 2050, which is measurable, trackable, and adaptable to different regions and requirements. This paper conducted calculations based on a monitored case study analysis, measured utility electricity data and PV generation, and simulated assumptions on a square meter basis.

5.1. Significance of the findings

The World Energy Outlook 2020 analyzed the global NZ target and reported the lack of consistency in the current NZ concept and strategies. Comprehensive NZ reviews in Chapters One and Two underlined the necessity for an upgraded NZ concept through clarifications, calculated methods, and documentation and track of the existing NZ progress. This research proposed an updated concept of $NZX\%_{(ORG)}$ that enables projects with different geographic contexts to achieve what they can achieve today and plan to achieve for the future. According to the $NZX\%_{(ORG)}$ model, projects are required to have a publicly available publication that shows the NZ progresses.

Currently, 121 countries released climate action targets to become NZ or carbon neutral along with 509 cities, and 2163 companies (United Nations Framework Convention on Climate Change (UNFCCC), 2021b). Advanced technology and scientific calculation methods are available to perform NZ, yet commitments on 2020 NZ targets have failed to achieve the goals. The results from this proposal showed that by improving energy efficiency in buildings, a community with an average size (500 hectares) could reduce its energy use by (30%-50%) and reduce its CO_2 pollution by (50%-70%). Community renewable power, then, could provide the rest of the energy demand and verify the percentage of NZ in a project. By applying the model to the Serenbe community and quantifying its targets, $NZ80\%_{(EPA)}$, the model has been verified and could significantly contribute to the latest releases on the global NZ targets by 2050.

5.2. Limitations of the research

1. access to the utility energy and PV generation data;

The community solar PV generation data was not available. The data was estimated based on the number of buildings covered with rooftop PV (19 buildings) and extending data from the base building C in 2020 to the community level.

2. sample size (one typical building) is relatively small;

We have gathered data on an average size, energy efficient building in Serenbe as a base design and extended our measured and simulated analyses to the entire community (600 buildings) in 2020.

3. transportation energy analysis has been ignored to simplify quantifying community energy performance.

5.3. Future work

Although building electrification currently dominates the discourse, electrification needs to occur in transportation to make cities livable. For instance, the total number of electric cars and the total miles driven in each state need to be measured and available by law and regulations. Ongoing metering of power used, purchased, and generated is another factor that must be done to validate NZ achievements.

Future studies are needed in (1) community level solutions to reducing energy/emissions in transportation sectors; (2) standardizing electrification systems so that a wider range of individual buildings and communities can move toward full electrification. A detailed energy analysis of a community with the calculation of total energy use in buildings and transport sectors will be developed with a formulated NZC model that includes the combined use of electrification and renewables.

APPENDIX

DATA ANALYSES OF THE MEASURED DATA AND RESULTS FROM DESIGN BUILDER AND ENERGY PLUS SOFTWARE

Table 5.1: Errors from calibrated simulation versus measured data (utility energy and solar PV) in Building C.

Year (2020)	**Calibrated Simulation (kWh)**	**Total Building Electrical Use (kWh)**	**Errors**
Jan	1213.03	1547.00	-28%
Feb	1037.24	1141.93	-10%
Mar	1031.49	1051.47	-2%
Apr	1057.97	1146.72	-8%
May	1238.25	1438.32	-16%
Jun	1747.19	1590.18	9%
Jul	2104.41	2118.42	-1%
Aug	2194.99	1908.55	13%
Sep	1386.87	1483.43	-7%
Oct	1126.02	1233.83	-10%
Nov	1088.25	1325.63	-22%
Dec	1161.92	1655.02	-42%

Table 5.2: Monthly energy savings from improved EEMs simulation versus measured data in Building C.

Year (2020)	Improved EEMs Simulation (kWh)	Total Building Electrical Use (kWh)	Monthly Energy Use Reductions
Jan	807.37	1547.00	48%
Feb	691.05	1213.02	43%
Mar	634.47	1051.47	40%
Apr	658.10	1146.72	43%
May	793.33	1438.32	45%
Jun	1171.91	1590.18	26%
Jul	1483.62	2118.42	30%
Aug	1530.75	1906.60	20%
Sep	922.71	1483.43	38%
Oct	718.72	1247.97	42%
Nov	710.93	1325.63	46%
Dec	731.74	1655.02	56%

Table 5.3: Monthly utility energy savings from improved EEMs and solar PV (10%) simulation versus measured data in Building C.

Year (2020)	Improved EEMs and PV (10%) Simulation (kWh)	Total Building Electrical Use (kWh)	Monthly Utility Energy Use Reductions
Jan	501.25	1547.00	68%
Feb	388.31	1213.02	68%
Mar	230.37	1051.47	78%
Apr	215.37	1146.72	81%
May	296.09	1438.32	79%
Jun	620.20	1590.18	61%
Jul	903.74	2118.42	57%
Aug	959.84	1906.60	50%
Sep	517.63	1483.43	65%
Oct	351.10	1247.97	72%
Nov	403.86	1325.63	70%
Dec	458.23	1655.02	72%

Table 5.4: Monthly utility energy savings from improved EEMs and increased rooftop PV (25%) simulation versus measured data in Building C.

Year (2020)	Improved EEMs and Increased PV (25%) Simulation (kWh)	Total Building Electrical Use (kWh)	Monthly Utility Energy Use Reductions
Jan	295.44	1547.00	81%
Feb	193.02	1213.02	84%
Mar	-0.14	1051.47	100%
Apr	-0.14	1146.72	100%
May	-0.22	1438.32	100%
Jun	-0.12	1590.18	100%
Jul	309.05	2118.42	85%
Aug	505.83	1906.60	73%
Sep	206.14	1483.43	86%
Oct	89.71	1247.97	93%
Nov	188.38	1325.63	86%
Dec	266.31	1655.02	84%

Table 5.5: Errors from calibrated simulation versus measured data (utility energy and solar PV) in buildings in Serenbe.

Year (2020)	Calibrated Simulation (MWh)	Total Community Energy Use (MWh)	Errors
Jan	408.08	520.43	22%
Feb	499.33	549.73	9%
Mar	502.22	511.95	2%
Apr	406.13	440.20	8%
May	388.05	450.75	14%
Jun	601.98	547.88	-10%
Jul	633.31	637.53	1%
Aug	903.89	785.94	-15%
Sep	623.79	667.22	7%
Oct	505.70	554.12	9%
Nov	375.94	457.94	18%
Dec	370.36	527.54	30%

Table 5.6: Monthly energy savings from improved EEMs simulation versus measured data in buildings in Serenbe.

Year (2020)	**Improved EEMs Simulation (MWh)**	**Total Community Energy Use (MWh)**	**Monthly Energy Use Reductions**
Jan	271.61	520.43	48%
Feb	332.67	549.73	39%
Mar	308.92	511.95	40%
Apr	252.63	440.20	43%
May	248.62	450.75	45%
Jun	403.77	547.88	26%
Jul	446.49	637.53	30%
Aug	630.36	785.94	20%
Sep	415.02	667.22	38%
Oct	322.79	554.12	42%
Nov	245.59	457.94	46%
Dec	233.24	527.54	56%

Table 5.7: Monthly utility energy savings from improved EEMs and solar PV (10%) simulation versus measured data in buildings in Serenbe.

Year (2020)	**Improved EEMs and PV (10%) Simulation (kWh)**	**Total Community Energy Use (kWh)**	**Monthly Utility Energy Use Reductions**
Jan	168.63	520.43	68%
Feb	186.93	549.73	66%
Mar	112.16	511.95	78%
Apr	82.67	440.20	81%
May	92.79	450.75	79%
Jun	213.68	547.88	61%
Jul	271.97	637.53	57%
Aug	395.26	785.94	50%
Sep	232.82	667.22	65%
Oct	157.68	554.12	72%
Nov	139.51	457.94	70%
Dec	146.06	527.54	72%

Table 5.8: Monthly utility energy savings from improved EEMs and increased rooftop PV (25%) simulation versus measured data in buildings in Serenbe.

Year (2020)	**Improved EEMs and PV (25%) Simulation (kWh)**	**Total Community Energy Use (kWh)**	**Monthly Utility Energy Use Reductions**
Jan	96.68	520.43	81%
Feb	92.92	549.73	83%
Mar	-0.07	511.95	100%
Apr	-0.05	440.20	100%
May	-0.07	450.75	100%
Jun	-0.04	547.88	100%
Jul	93.01	637.53	85%
Aug	208.30	785.94	73%
Sep	92.72	667.22	86%
Oct	40.29	554.12	93%
Nov	65.08	457.94	86%
Dec	84.89	527.54	84%

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