

Net Zero and Electrified Buildings: Establishing a New Nomenclature for World-Wide Use

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ABSTRACT

To help achieve net zero emissions (NZ) targets by 2050, current studies and policy documents highlight the importance of shifting to Electrification with Renewables (ER) in buildings. However, there are barriers to quantifying ER and verifying NZ in buildings. Multiple definitions of NZ exist today which confuse the reporting of progress in this area and a need exists to expand Net Zero's definition to communicate progress in achieving NZ. This research proposes an approach to simplify and communicate building electrification and NZ by establishing a new nomenclature of (NZX%(ORG)-E%), where the "X%" defines the percentage of total energy use that is covered by renewables, "ORG" is the specific organization's NZ definition, and E% represents the percentage of total electricity use in the building. By applying this approach to a monitored single-family building in Georgia, the results showed that an 80% electrified building with renewables could become NZ by 65%, while a 100% ER building was projected to achieve 81% NZ. The objective of this research is to create an adaptable NZ nomenclature and methods that communicate to major agencies that are responsible for collecting data as potential climate solutions. This research addresses three challenges: (1) providing structured approaches to quantify ER's energy performance in a building; (2) extending a previously proposed NZ method to simulate the fraction of electrification and NZ status in a monitored residential case study; and (3) highlighting health impacts of ER by replacing combustion appliances and related governmental policies.

Introduction

Electrification and Renewables

In response to the Paris Agreement (United Nations (UN), 2015, 2019), 197 countries committed to reducing their Greenhouse Gas (GHG) emissions by 2050. Approaching the 26th UN climate change conference (COP26), 80 countries submitted new or updated Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC), covering 40% of global CO₂ emissions, shown in Figure 1.

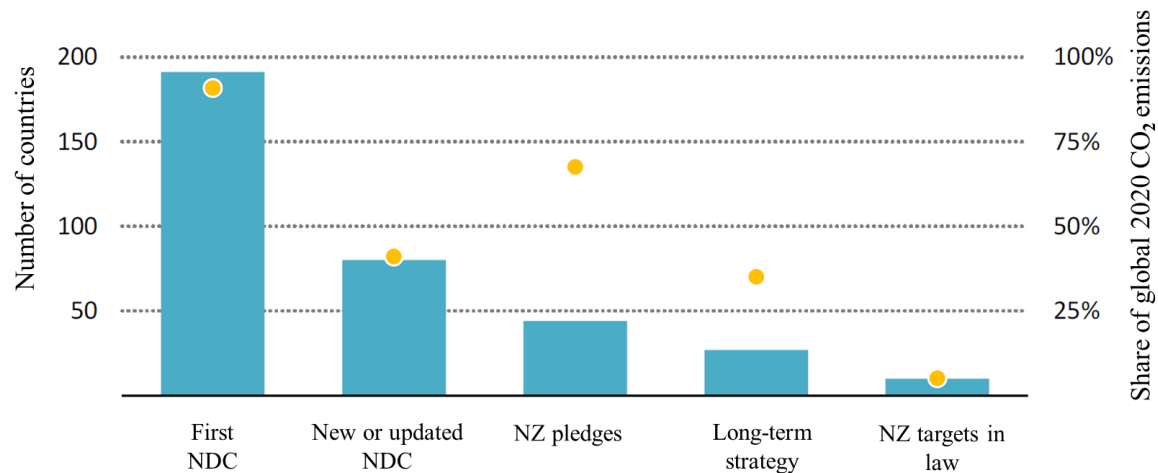
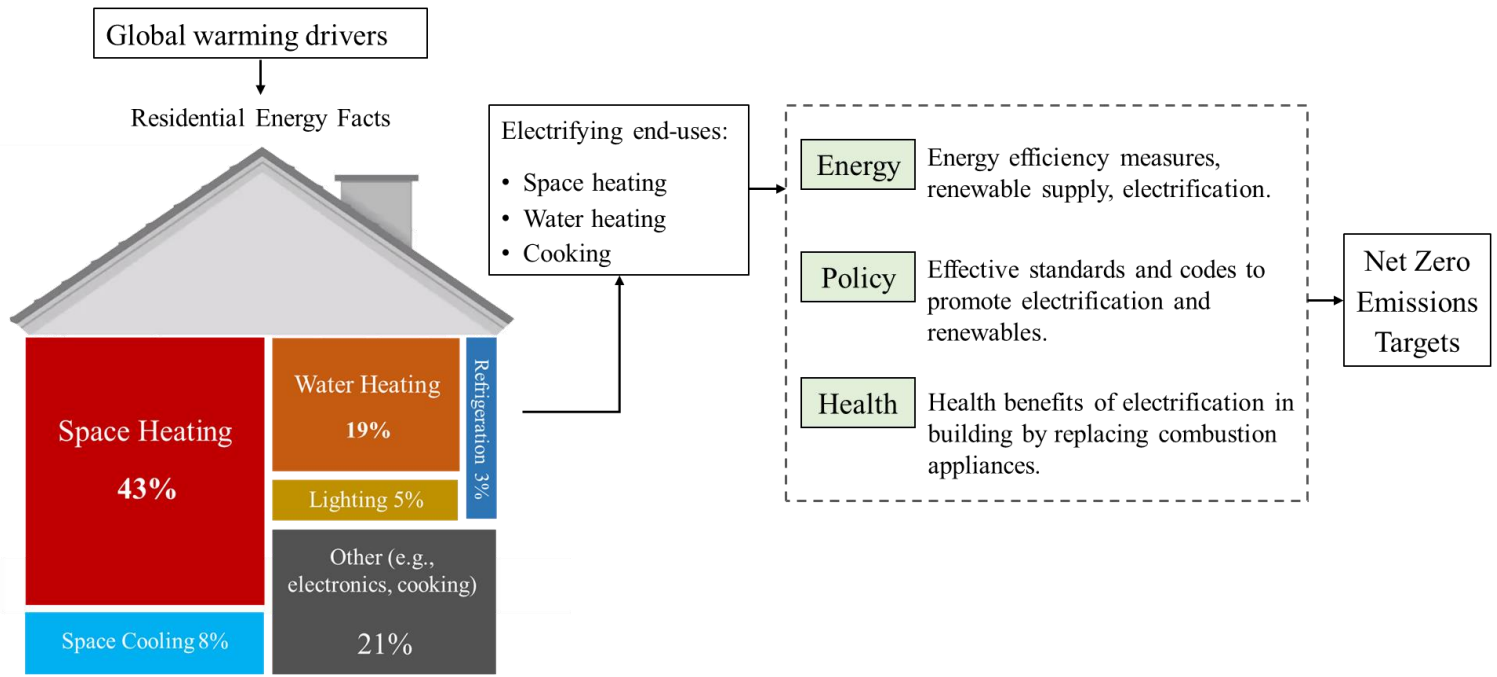


Figure 1: The number of countries with NDCs, long-term strategies and net zero pledges, and their shares of 2020 global CO₂ emissions. *Source:* Modified from (International Energy Agency (IEA), 2021). All rights reserved.

As Figure 1 shows, the EU and 44 countries, covering 70% of global CO₂ emissions, agreed to pledge to achieve net zero (NZ) emissions by 2050 (International Energy Agency (IEA), 2021). However, based on IEA's report, most of these net zero commitments vary in the scope and requirements, and lack "detailed policies and firm routes to implementation." The authors have done a comprehensive review analysis of NZ variations and requirements (Moghaddasi, Culp, Vanegas, et al., 2021). They also recommended that buildings need to follow a zero carbon policy and effective strategies for energy efficiency and electrification with renewables (Moghaddasi, Culp, & Vanegas, 2021). According to the IEA (2021), the fastest way to achieve NZ emissions targets is to use electrification with renewables (ER), which requires updated code language to include ER, innovative technologies, cost-effective solutions, equitable transition, long-term investment in clean energy, stronger policy and regulations on energy efficiency (EE) (Alexi Miller and Cathy Higgins, January 2021; International Energy Agency (IEA), 2021; Nadel & Ungar, 2019; U.S. Department of Energy (DOE), 2021b, 2021c).

In buildings (residential and commercial), most end-uses are electrified with the main exceptions in water heating, space heating, and cooking services (Jeff Deason et al., 2018). Studies by the National Renewable Energy Laboratory (NREL) showed that electrification could provide 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 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." However, the literature showed that electrification of end-uses might be challenging due to the higher initial cost and occupants' lack of interest. To accelerate the adoption of building electrification by people's choice, recognizing the health benefits of converting from gas appliances to ER is necessary and therefore demands further investigation and dissemination. As described in Figure 2, health impacts awareness and governmental supports that promote the use of ER in buildings would speed up achieving climate NZ emissions targets.



Source: Modified from DOE (2020)

Figure 2. A systematic diagram to expedite adapting electrified end-uses in residential buildings into the application of NZ.

The authors have investigated the existing NZ concepts and concluded that a modification is needed to clarify the NZ performance in a project (Moghaddasi, Culp, & Vanegas, 2021; Moghaddasi, Culp, Vanegas, et al., 2021). They have proposed a new adaptable nomenclature for NZ ($NZX\%_{(ORG)}$), where the “X%” was defined as the percentage of total energy use that is covered by renewables, and “ORG” is the specific organization’s NZ definition that is used by a project (Moghaddasi et al., 2022). In this paper, the authors extend the proposed ($NZX\%_{(ORG)}$) to ($NZX\%_{(ORG)-E}$), where “E” represents the percentage of electricity use to total energy use in the building. (Eq. 1-4).

$$X\% = \frac{\text{Energy}_{\text{Renewable}}}{\text{Energy}_{\text{Renewable}} + \text{Energy}_{\text{Nonrenewable}}} = \frac{\text{Energy}_{\text{Re}}}{\text{Energy}_{\text{Re}} + \text{Electricity}_{\text{NRe}} + \text{Energy}_{\text{Combustion}}} \quad \text{Eq. 1}$$

$$\text{Where: } \text{Energy}_{\text{Re}} = \text{OnSiteEnergy}_{\text{Re}} + \text{OffSiteEnergy}_{\text{Re}} \quad \text{Eq. 2}$$

$$\text{Energy}_{\text{NRe}} = \text{Electricity}_{\text{NRe}} + \text{Energy}_{\text{Combustion}} \quad \text{Eq. 3}$$

$$E\% = \frac{\text{Energy}_{\text{Electricity}}}{\text{Energy}_{\text{Re}} + \text{Energy}_{\text{NRe}}} = \frac{\text{Energy}_{\text{E}}}{\text{Energy}_{\text{Re}} + \text{Electricity}_{\text{NRe}} + \text{Energy}_{\text{Combustion}}} \quad \text{Eq. 4}$$

From Eq. 1 and Eq. 4, it is concluded that with a higher percentage of electrification (E%), renewables will provide a higher fraction of total energy use (X%), which accelerates the process of achieving NZ in the building. As shown in Eq. 1-4 the denominator can be configured to include all sources of energy used, where:

If $\text{Energy}_{(\text{NRe})} = 0$ or when the building is 100% ER, then $NZX\%_{(ORG)}$ rate maximizes;

If $\text{Energy}_{(\text{NRe})} > 0$, then $NZX\%_{(ORG)}$ could never reach 100%.

To clarify the source and supply requirements that are used in the NZX%(ORG)-E%, the ORG needs to be specified. Table 1 shows NZ variations in source and supply requirements defined by different organizations.

Table 1. Variations in NZ requirements. Source: modified from (Moghaddasi et al., 2022).

Organizations		On-site/Off-site Energy	Source Energy	Site Energy
New Buildings Institute	NBI	Both		•
ASHRAE*		Both		•
American Institute of Architects	AIA	Both		•
International Living Future Institute	ILFL	Both		•
Environmental Protection Agency	EPA	On-site		•
Department of Energy	DOE	On-site	•	
Department of General Services	DGS	On-site	•	
European Performance of Build. Directive	EPBD	On-site	•	

* In 2012, as part of a rebranding, ASHRAE began doing business as “ASHRAE” vs. using its full legal name of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2022).

The proposed NZX%(ORG)-E% is a measurable solution that includes all the current NZ concepts and is adaptable to different projects while integrating the use of ER into the NZ calculations.

Methodology

Case Study

Given the need for a measurable solution to track the energy performance of the planned NZ projects, this paper demonstrates the proposed NZX%(ORG)-E% via a case study of a monitored single-family building with two stories and a conditioned basement. The building is 2,450 SF (228 m²), located in Serenbe, a sustainable community in Atlanta, Georgia (Moghaddasi et al., 2020; Tabb, 2020). The project used efficient lighting, double-glazing windows, a ground source heat pump for space heating and cooling, and high-standard insulation (EarthCraft, 2021) as shown in Table 2.

Table 2. Existing energy efficiency measures in the case study

Lighting	50% LED and 50% incandescent (a total of 66 light bulbs)
Insulation	Wall, 2x6, R-19 (open-cell spray foam) Ceiling, Cathedral Attic, R-30 (open-cell spray foam) underside the attic
HVAC System	GSHP, water source heat pump/SM036-1VTC (ENERGY STAR, 2021) 4 COP (13.7 HSPF) 26 EER (30 SEER)
Window Glazing	0.60 (SHGC)- 1.80 (U-Value)
Hot Water efficiency	Domestic with gas storage water heater
Solar PV	4.7 kW (10% of the roof space)

As summarized in Table 3, to optimize the NZX%(ORG) in the case study, (1) energy efficiency (EE) was further improved through simulation in lighting, window glazing, and air sealing measures (other systems are fairly efficient); (2) on-site solar PV was increased from 10% of the roof space to 25% to cover a fraction of total energy use; and (3) NZ status was calculated for the project.

Table 3. Simulated improved energy efficiency measures and renewables in the case study.

Lighting	LED with linear control (100%)
Air Sealing	0.2 (air change/hour - ach)
Window Glazing	0.27 (SHGC)- 0.70 (U-Value)
Solar PV	4.7 kW (25% of the roof space)

The authors adapted simplified approaches suggested by ASHRAE Guideline 14-2014 to estimate the energy savings of the whole building (ASHRAE Guideline 14, 2014). The analysis of the house was conducted from January 1 through December 31 in 2020. The actual measured data (utility electricity plus solar PV generation) was collected to build and calibrate a base model of the building. Design Builder v7 (DB) and Energy Plus 9.4 (EPlus) programming tools were used to isolate the estimated energy savings of energy efficiency measures and to calculate the building's NZ status through three simulation phases: (1) baseline model; (2) calibrated model; (3) improved EEMs; and (4) increased rooftop PV coverage. Figure 3 shows snapshots of simulated base building in DB energy modeling software.

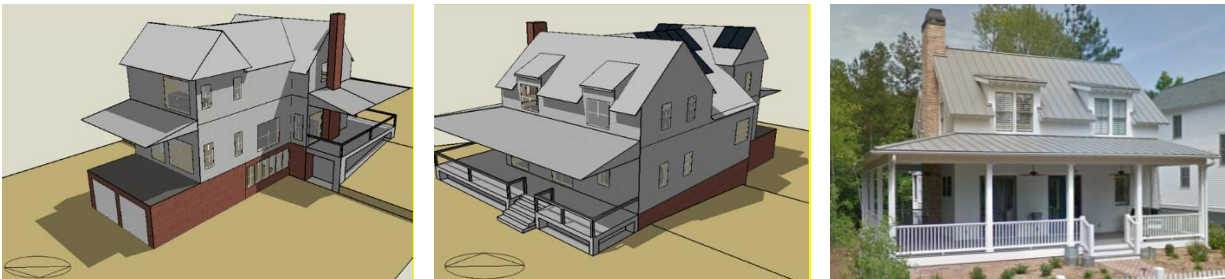
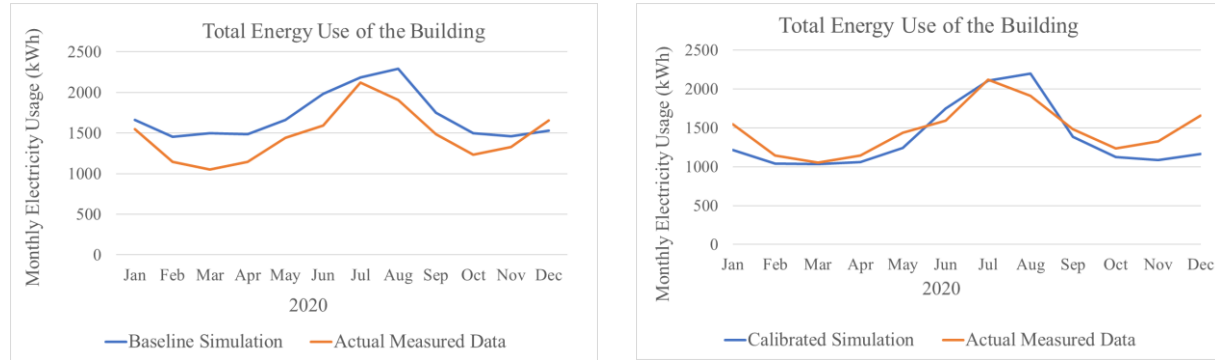


Figure 3: Simulated model of base building in Design Builder Software.

Phase 1: Calibrated Model. A simulation was conducted to create the baseline model which was then calibrated and used for quantifying the impact of the energy optimization phase. Figure 4A-B shows the baseline and the calibrated base case.



A. Baseline Model.

B. Calibrated Model (base case).

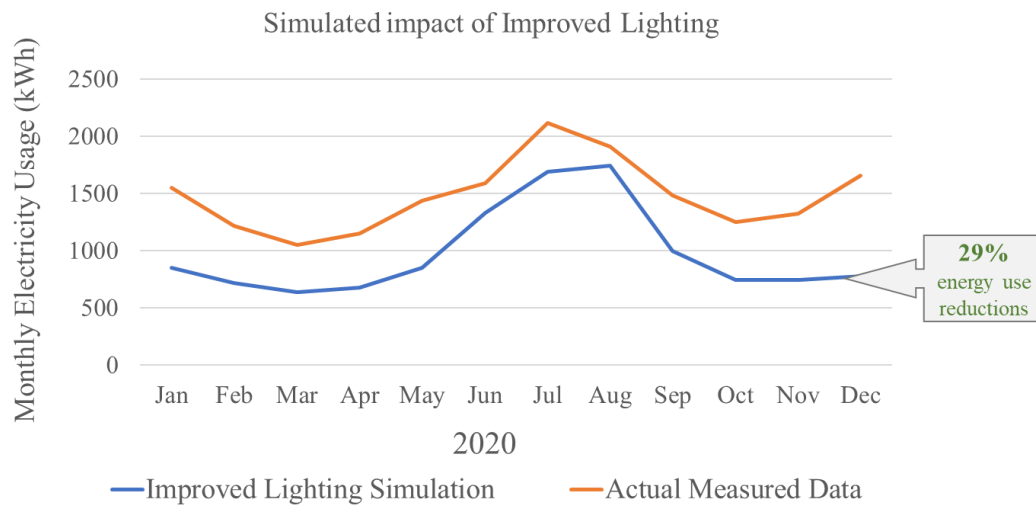
Figure 4: Actual measured energy data versus the simulated model.

In this paper, Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) were used to quantify the deviation between the actual measured data (A) and simulated data (S), as shown in eq. 5 and eq. 6.

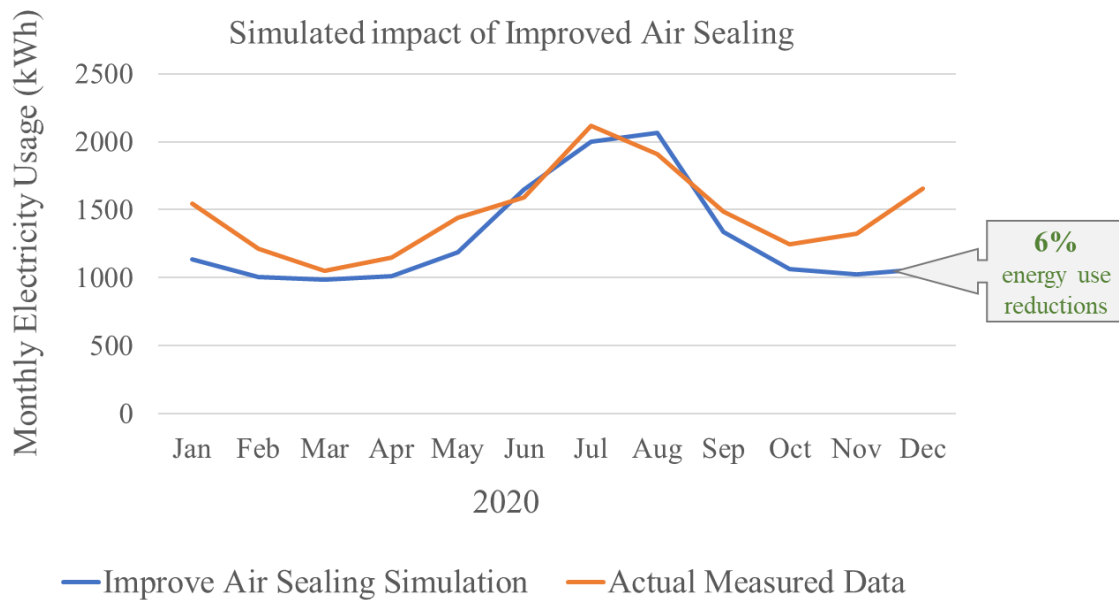
$$\text{NMBE} = \frac{\sum_{i=1}^n (A-S)}{n \times \bar{A}} \quad \text{Eq. 5} \quad \text{CV(RMSE)} = \frac{\sqrt{\frac{\sum_{i=1}^n (A-S)^2}{n}}}{\bar{A}} \quad \text{Eq. 6}$$

The calculated monthly NMBE and CV(RMSE) are 8% and 16% for the whole building calibration, respectively, slightly short of the ASHRAE 14 targets of 5% and 15% respectively (ASHRAE Guideline 14, 2014), nevertheless deemed fit for purpose by the authors.

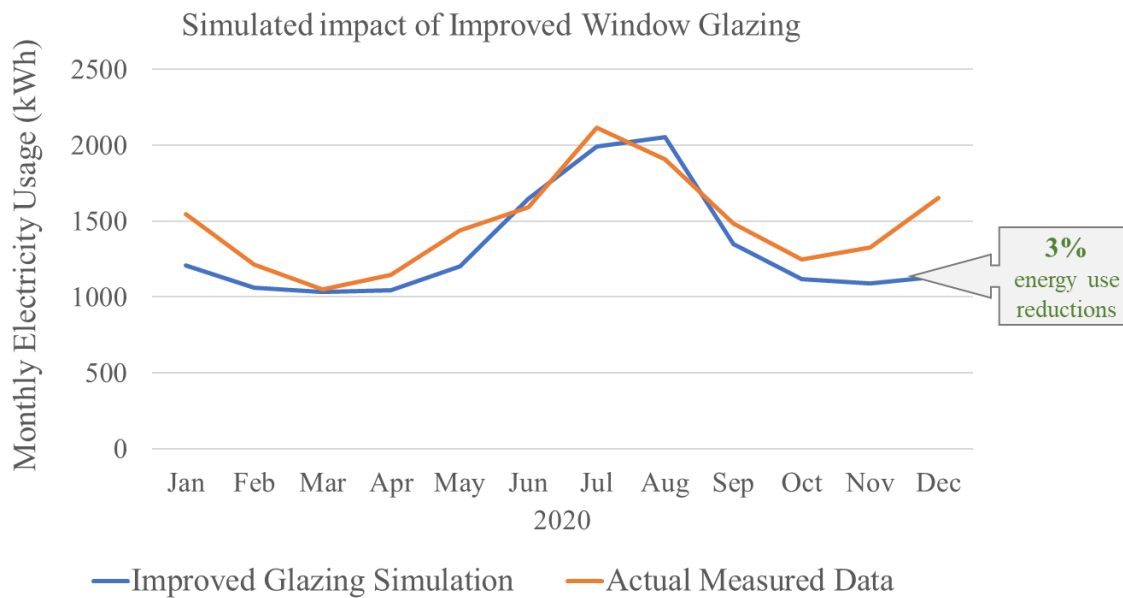
Phase 2: Improved Energy Efficiency (EE). The potential energy savings from three individual EE retrofits were simulated in the building. The existing building has a total of 66 light bulbs (half incandescent, half LED lights). Figure 5A shows that replacing all light bulbs with LEDs could reduce annual lighting energy use by 29%. Also, Figure 5B-C shows savings based on improved air sealing (6%) and window glass selection (3%) simulations.



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



B. Improved air sealing from 0.7ACH to 0.2ACH



C. Improved window glazing from 0.6 to 0.27 SHGC

Figure 5: Simulated utility electricity savings from the use of retrofit isolation approaches.

Residential LEDs use at least 75% less energy than incandescent lighting and last up to 25 times longer (Department of Energy (DOE), 2022). Although LED bulb sales have an increasing rate, 30% of light bulbs sold nationally in 2020 were still incandescent (American Council for Energy-Efficient Economy (ACEEE), 2021). As the results show, retrofitting the case study with all LEDs saved a significant amount of simulated energy use. Savings results from improved air sealing and window glazing showed that the existing measures used in the building are reasonably efficient. The retrofit building could reduce its total annual electricity use by 34%.

Phase 3: Increased Rooftop PV Coverage. Currently, 10% of the roof space in the building is covered with solar PV. The simulation results showed that by increasing the PV coverage to 25% of the roof space, the building could reduce its total utility electricity use by 88%, as shown in Figure 6.

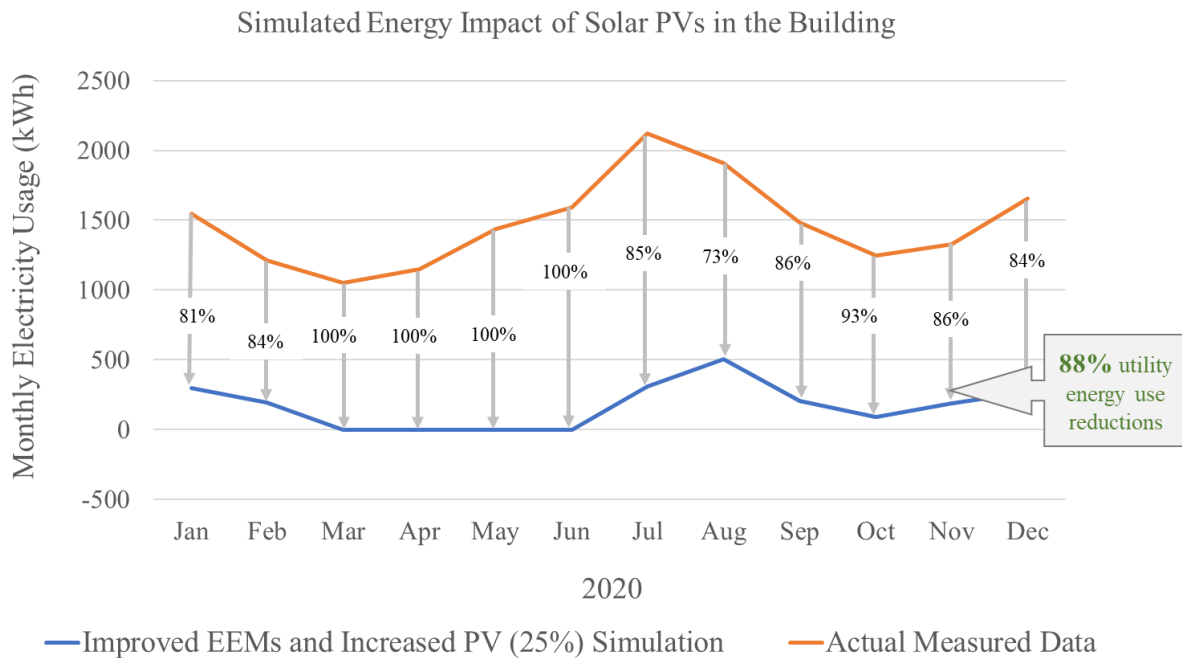


Figure 6: Simulated utility electricity savings from increased PV coverage to 25% of the roof space.

Proposed model. As the building uses on-site renewable generation and considers site energy for its energy calculation, ASHRAE’s NZ definition was used ($NZX\%_{(ASHRAE)-E\%}$). The ASHRAE specifies site energy in its NZ definition, other organizations may specify source energy. Based on Eq. 4, the current building is E80%, where electricity covers 80% of the building’s total energy use, with 20% non-renewables. Therefore, the retrofit building with increased PVs could become $NZ65\%_{(ASHRAE)-E80\%}$. However, if the building would be converted into E100%, it could achieve an $NZ81\%_{(ASHRAE)-E100\%}$, where renewables could provide 81% of the building’s total electricity use, as shown in Table 4.

Table 4. The process for estimating $NZ81\%_{(EPA)+E100\%}$ in the simulated building. Source: (Moghaddasi et al., 2022).

Simulated energy savings in the case study	Total electricity use [kWh]	Percentage of electricity covered by renewables	Percentage of utility electricity use reductions
Actual measured electricity data	17,641	26%	—
Simulations			
Retrofitted EEs and existing PV (10%) simulation	10,789	46%	65%
Retrofitted EEs and increased PV (25%) simulation	10,769	81%	88%

Given the average retail price of electricity in Georgia of 9.93 (cents/kWh) and the average CO₂ emissions factor of 680 grams/kWh (U.S. Department of Energy (DOE), 2021a),

the retrofit building is estimated to achieve savings in utility electricity, electricity cost, and CO₂ emissions, as shown in Table 5.

Table 5. Simulated savings from NZ81%(ASHRAE)+E100% in the case study.

Total Simulated Savings				
Year of Analysis	Building size (SF)	Annual electricity generations (kWh)	Annual electricity savings (\$)	Annual CO ₂ savings (tones)
2020	2,450 (228m ²)	8,767	870	4k

The calculated savings are approximate and practical for stakeholders to easily estimate the planned reductions and NZ level in their projects. Monitoring and reporting will provide the actual NZ levels achieved year by year.

Discussion

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), 2021). Yet, the World Energy Outlook 2020 reported a lack of consistency in the current NZ concept and strategies to achieve its targets (International Energy Agency (IEA), 2020). Therefore, there is a need for an adaptable nomenclature for NZ and effective methods to accelerate the actions in achieving global NZ emissions by 2050. In this paper, the NZX%(ORG)-E% was developed as a practical and measurable solution for stakeholders, policymakers, engineers, and architects to (1) estimate the buildings' NZ status; (2) promote the use of ER in the NZ application; and (3) provide a globally understandable NZ. The authors recommended metrics to describe the percentage of electrification and renewables used in buildings. According to the proposed NZ nomenclature, every building that uses a fraction of ER is an NZ by X%. The projected NZX%(ORG)-E% will guide and motivate stakeholders to take the first steps in terms of using the most effective measures to raise the NZ number higher, while highlighting the interrelationship between building performance and grid cleanliness in overall progress toward NZ goals. The actual NZX%(ORG)-E% will be published based on the metered data achieved from measurement. This method will help stakeholders to improve savings in utility energy use, energy cost, and CO₂ emissions in their projects. Also, the awareness of the health impacts of the ER would expedite its adaptability.

Further, the results showed that to optimize savings (energy, emission, energy cost)s in buildings we need to (1) reduce overall energy use through energy efficiency measures (i.e., HVAC systems, lighting, appliances) and passive strategies (i.e., efficient window glazing, coatings, airtightness, natural ventilation); (2) electrify end-uses, while conscientiously reducing and/or shifting peak loads (i.e., electric heat pumps, solar water heater, cooking systems); and (3) significantly increase renewable productions. However, there are limitations in using ER that need to be further studied:

1. Peak loads and energy cost increases without management of electrification;
2. The impacts of metrics of comfort, indoor air quality, and resiliency in the ER application;
3. Regulation and policies that promote electrification codes in buildings.

However, to accelerate the adoption of building electrification, recognizing the health benefits of converting from gas appliances to ER is necessary. For example, Salimifard et al. investigated the positive impacts of building electrification and grid decarbonization on premature deaths caused by building sectors (Salimifard et al., 2022). Buonocore et al. emphasized the significance of site-specific information and regulations in estimating the climate health benefits of the ER efforts (Buonocore et al., 2016). Ou et al. showed the health benefits of building electrification and concluded it as a cost-effective solution, compared to the sources with high particulate matter (PM_{2.5}) emission intensities (Ou et al., 2020). The conventional alternative to electric heating and cooking are combustion appliances, burning natural gas, for example, on-site which results in indoor air quality and health problems. Studies show that the primary pollutants from combustion appliances are carbon monoxide (CO) and nitrogen dioxide (NO₂) which cause serious health issues such as asthma in children, cough, wheezing, chest tightness, diabetes, cancer, and cardiovascular effects (Belanger et al., 2013; Lin et al., 2013; Seals & Krasner, 2020; U.S. Environmental Protection Agency (EPA), 2016).

Conclusion

The authors developed a modified Net Zero nomenclature using simplified approaches by combining actual measured data and simulated models that include electrification and all existing NZ concepts defined by different organizations. To show the process of this proposal, it was applied to a monitored single-family building in Atlanta, Georgia. A comparative analysis was conducted between the utility data and simulated models in balancing on-site energy demand with renewable supplies. The results showed that by retrofitting improved EE measures and the current PV coverage (10% of the roof space), the building could reduce its utility electricity use by 65%, which could increase to 88% by increasing the PV coverage to 25% of the roof space.

ASHRAE's NZ definition was used for the case study (NZX%(ASHRAE)-E%). ASHRAE specifies site energy, other organizations may specify source energy toward counting for NZ. The developed NZX%(ORG)-E% demonstrated that with a higher percentage of electrification in a building (E%), renewables could cover a higher fraction of total energy use (X%), therefore, the building could achieve a higher rate of NZ. By applying the results to the case study, the simulated retrofit building with increased PVs was projected to become NZ65%(ASHRAE)-E80%, as the building is 80% electrified, with 20% non-renewables. If the building becomes fully electrified (E100%), it could achieve an NZ81%(ASHRAE)-E100%. The proposed NZX%(ORG)-E% was demonstrated on the base building and is practical, measurable, and adaptable to different organizations' requirements and projects. The NZX%(ASHRAE)-E% is globally understandable as it is measurable; it respects every organization's NZ definition, requirements, and contributions by providing a translatable solution to the concept.

One of the main challenges in the NZ concept is that, to the best knowledge of the authors, there is no international committee on NZ. As an outcome, multiple definitions by different organizations exist worldwide which creates uncertainty in NZ concepts and methods that delay the climate actions Targets. The goal of this paper is to propose an early-stage unified concept and methods to stimulate other entities to apply it to their building projects and further develop it. Future work will be developing improved methods to estimate the final NZX%(ASHRAE)-E% in two steps (1) apply the application to different projects and publish the yearly results on their NZ performance; (2) communicate to major reporting agencies that are responsible to gather NZ data as a potential climate solution.

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