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Minimizing Operational Carbon within Whole Life Carbon for New Construction

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Abstract

This study investigates a 28-year approach to minimize a building's operational carbon emissions while also including its embodied and transportation emissions. It delves into the complexities of operational emissions, encompassing electricity, natural gas, refrigerants, and energy tied to water usage. The findings reveal that in regions with carbon-intensive grids, heat pumps show potential for significant reductions in operational carbon emissions. However, incorporating embodied carbon emissions from construction materials mitigates the relative impacts, and including transportation emissions significantly impacts the building's overall carbon footprint. Comparing standards ASHRAE 240P and ASHRAE 228-2023 highlights their differences, with 240P's forward-looking approach considering more categories of emission contributions and 228 relying on historical emissions data. The research underscores regional variations, refrigerants' significance, and the potential of solar photovoltaic systems, battery storage and heat pumps in emissions reductions. This provides insights for architects, builders, and policymakers striving to reduce emissions to reach climate goals.

Introduction

The construction industry is placing greater importance on sustainable practices and carbon neutrality. Reducing operational carbon emissions, which include energy, water, and refrigerant leakage, is crucial for minimizing a building's overall carbon footprint. This paper examines challenges and solutions to lower a building's life cycle carbon or Whole Life Carbon (WLC) and aims to guide the steps toward a low-carbon future.

The assessment of WLC emissions, including embodied, operational, and transportation aspects, requires a careful examination of existing standards. This review acknowledges contributions from standards like EN 15978:2011, ASHRAE Standards 228 and 240P, and ISO 50010. However, limitations exist as these standards often omit crucial emission categories (Fig. 1) related to construction, transportation, and extended life cycles. Notably, EN 15643:2021 addresses transportation emissions (B8). In building design and construction, prioritizing sustainability and carbon footprint reduction is paramount. Existing literature emphasizes the need for a comprehensive approach to assess and mitigate carbon emissions throughout a building's entire life cycle.

In 2019, Atelier Ten challenged the assumption that Net Zero Energy (NZE) results in carbon neutrality in the built environment. Their research highlighted temporal and grid location variations impacting carbon neutrality, even with on-site photovoltaics. To address this, they proposed a paradigm shift, urging the incorporation of hourly greenhouse gas (GHG) emissions data in building design. Their five-step approach involves using hourly energy use and GHG data, selecting the grid region, distinguishing between average and marginal emissions, translating historical grid data, and integrating profiles into energy analysis. Atelier Ten's approach emphasizes the importance of hourly data for precise GHG predictions and advocates for carbon metrics in building design to reduce operational GHG emissions (DiStefano & Richardson, 2019).

NRDC challenged that NZE buildings were responsible as the prevailing definitions excluded significant perhaps the biggest carbon emissions resulting from their WLC emissions. Their work illustrated the need for an all-encompassing accounting of a building's GHGs to avoid suboptimization (Goldstein & Bacchus, 2012).

McConahey echoes Goldstein & Bacchus in advocating for a paradigm shift in the industry with her paper, "Why Whole Life Carbon Assessment is Important," stressing the importance of considering a building's entire lifespan. She calls on professionals to take proactive steps, educate clients, and prioritize the reduction of whole-life carbon as a fundamental aspect of sustainable building practices (McConahey, 2022).

Multiple studies emphasize the critical role of precise emissions factors and accounting in mitigating greenhouse gas emissions from the building sector, particularly in evaluating the impact of energy efficiency and electrification. Three types of emissions factors—average, consequential marginal, and short-run/long-run marginal—are discussed, underscoring their significance in diverse carbon reduction analyses. The choice of emissions factor is crucial, influencing outcomes significantly. Present, E et al compare these factors across energy efficiency measures, illustrating how different factors lead to varying conclusions on emissions reductions. The study emphasizes the need to carefully select emissions factors to accurately assess the carbon footprint of energy-saving initiatives. Additionally, Schrama et al stress the importance of using marginal emission factors, considering the actual contribution of renewable energy and reflecting market dynamics. Vader N. draws attention to the complexities of carbon emission factors in building design, highlighting the fragmented approach in the United States. His work recommends that building design professionals consider various variables when selecting emission factors for their projects (Present, E et al 2022; Schrama et al, 2019; Vader, 2022).

The US Department of Energy's Building Technologies Office offers tools and frameworks for informed decision-making by building owners. The choice of emission factors, varying temporally and regionally, is crucial, with carbon offsets used to balance remaining emissions. Recommended tools include ENERGY STAR Portfolio Manager and GHG Protocol Corporate Accounting and Reporting Standard. Adhering to best practices is essential for effective emissions reduction (Goetsch & Deru, 2022).

In addressing the environmental impact of refrigerants, studies advocate for lower Global Warming Potential (GWP) refrigerants and reduced refrigerant volume to minimize leakage. An Integral Group study highlights the urgent need for improved refrigerant management in the construction sector. The study estimates a potential 89.7 gigatons of CO_2e reduction over 30 years if refrigerant leakage is limited to 0.4%. The study encourages early consideration of systems during design stages and strategies for reducing volume, mitigating leakage, and enhancing end-of-life recovery (Hamot et al, 2020).

Pistochini T. et al highlight the potential of electrification and heat pumps to reduce GHG from residential space heating in the United States (Pistochini et al, 2022).

Dixit, et al introduce a holistic assessment model for embodied energy and water in construction materials, emphasizing the need to consider both energy and water consumption for sustainable building materials (Dixit & Kumar, 2022).

Fang et al explore the energy and emissions footprint of water supply sources, underlining the importance of localized emissions factors for electricity generation and upstream emissions consideration (Fang, et al, 2016).

Overall, the literature promotes a shift towards environmentally responsible practices, making WLC assessment a primary performance metric. Despite industry efforts, fragmented approaches to carbon emission assessment hinder the identification of effective strategies for minimizing operational carbon. Compartmentalization creates a disconnect between Whole Life Carbon's holistic approach and the more limited perspectives of existing standards. These omissions raise concerns about the efficacy of these standards. The paper calls for combining diverse perspectives into a comprehensive framework to address significant greenhouse gas emissions sources omitted in current standards.

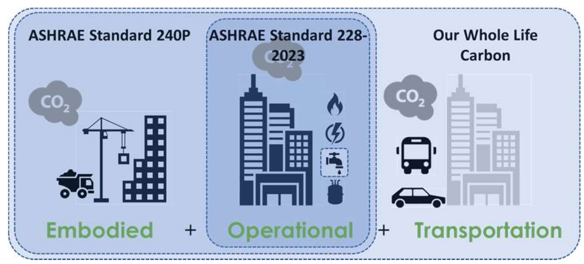

Figure 1: Total Carbon: System Boundaries

Problem Statement

The primary research question this paper seeks to ask is: How can operational carbon emissions within the WLC framework be minimized in new construction projects?

To delve deeper into this overarching question, the study will consider the following sub-questions:

- Which specific contributing factors of operational carbon emissions, such as energy usage, water and wastewater, and refrigerant leakage, significantly contribute to the building's 28-yr carbon footprint?
- How do operational carbon emissions align with, or differ from, the carbon emissions generated during the construction of the building?
- Which factors and strategies demonstrate the most success in reducing operational GHG emissions for new construction projects in various climate zones?

Background

The construction industry has shifted its focus from quantifying embodied carbon during the construction phase to addressing operational carbon emissions across a building's entire life cycle. EN 15978:2011 provides a nomenclature for assigning carbon emissions, and this paper uses its module and number designations (Fig. 2).

Operational carbon encompasses energy usage (B6), water and wastewater emissions (B7), operational (B1), and end-of-life refrigerant leakage (C1). Transportation, considered operational module (B8) by EN 15643:2021.

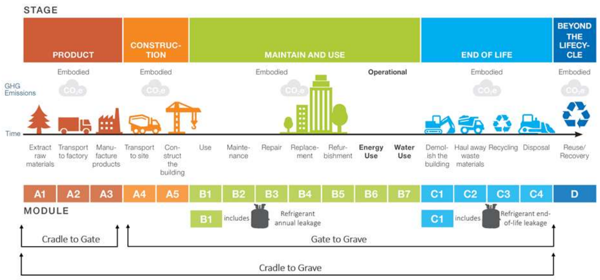

Figure 2: Whole Life Carbon: BS EN 15978:2011

To comprehensively address operational carbon emissions, it is essential to establish a common lexicon. Understanding the following concepts is crucial for assessing the environmental impact of different emissions sources, such as energy use, water consumption, and refrigerant leakage.

Whole Life Carbon Assessment: Our Whole Life Carbon Assessment adheres to the standards of BS EN 15978:2011, titled "Sustainability of construction works. Assessment of the environmental performance of buildings. Calculation method." This standard forms the basis for our assessment, offering a structured methodology for evaluating the environmental performance of buildings throughout their life cycle, emphasizing both construction-related and ongoing operational emissions.

Our comprehensive approach considers various emissions aspects, including Material and Construction Emissions (A1-A5) and Operational Emissions such as Refrigerant Leakage (B1), Refrigerant End of Life (C1), Energy Use (B6), Water Use (B7), and User Transportation Emissions (B8). Our focus is on operational carbon emissions in the context of WLC. We classify C1 as operational due to the frequent installation and decommissioning of refrigerant-containing mechanical equipment throughout a building's life, not just during demolition.

Refrigerants: A Crucial Consideration

Recent legislative developments have brought refrigerants into the spotlight. The legislative framework, notably the American Innovation and Manufacturing (AIM) Act, directs attention to hydrofluorocarbons (HFCs) and their role in GHG emissions. HFCs are found in many cooling and refrigeration systems and have a substantial impact on the environment due to their high Global Warming Potential (GWP).

Assessing B1 & C1 Refrigerant GHG Emissions: One focus of this paper is the assessment of B1 and C1 emissions. These emissions categories are of particular interest due to their potential for emissions reduction and the need for comprehensive data to support mitigation efforts.

Embedded Energy in Water: A Hidden Component

Water, essential for life, carries embedded energy through the entire water cycle, influencing energy consumption at various stages. The energy embedded in water is evident in extraction, treatment, conveyance, distribution, end-user consumption, wastewater disposal, collection and treatment, and the return to its source. On average, the entire water cycle results in an embedded energy consumption range of 1.8 to 6.8 kWh/m³. The U.S. water and wastewater sector's energy-intensive operations, especially in water treatment and desalination, result in a significant carbon footprint, releasing an average of 3 kg of CO_2e/m^3 of water. For the average household, this translates to ~1 ton of CO_2e emissions annually, highlighting the substantial carbon emissions within the context of the WLC assessment.

Methodology

This section presents a detailed methodology employed in this research, which estimates a building's GHG emissions over a 28-year study period. We establish emissions baselines using DOE PNNL prototypes as the foundation, providing a starting point for office and residential buildings. These baseline building prototypes comply with ASHRAE Standard 90.1-2019 for each of the climate zones studied. The baseline buildings feature a gas-fired heating system. Then we explore various energy conservation measures, including all-electric versions of the buildings, on-site PVs and batteries.

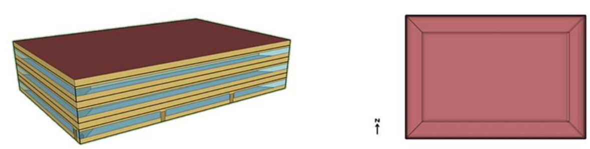

Figure 3: Mid-Rise Office Model Prototype

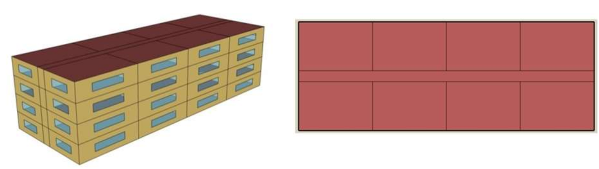

Figure 4: Mid-Rise Multifamily Model Prototype

These building prototypes exhibit distinct energy usage profiles (Fig. 5). Office buildings experience energy peaks during the day, while apartment buildings peak in the morning, drop during the day, and a have second peak in the evening. Our analysis involves overlaying hourly grid carbon emissions on these energy profiles to assess the impact of intervention measures. Certain strategies may be better suited to one building type over the other due to differences in grid carbon emissions during occupied and unoccupied periods.

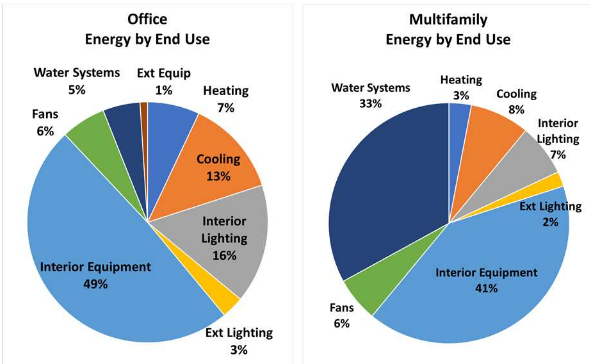

Figure 5: Office vs. Multifamily: Energy Use Comparison

In 2023, we began to include A1-A5 (embodied GHG) emissions in our study based on data from Walter P Moore, Greenbuild 2020.

To assess operational emissions over the 2024-2050 period, we utilized NREL 2022 Cambium Mid-Case hourly average emissions factors with pre-combustion emissions based on the site's Balancing Area (BA) in 100-yr GWP (Fig. 6). Data from the NREL website may require some cleaning and preparation for analysis. Matching timestamps between energy model results and the Cambium data set is necessary.

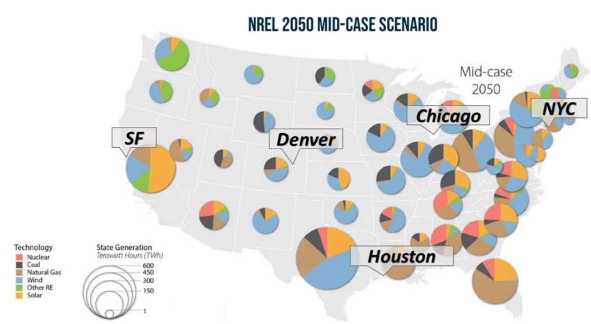

Figure 6: Forecast Electricity Generation Mix (Source:NREL)

Natural gas emissions are calculated using ASHRAE 189.1-2020 addendum m emissions factors but adjusted to a 100-year Global Warming Potential (GWP) to match the Cambium data and include upstream CH_4 emissions.

To account for water and wastewater emissions, we rely on data related to indoor water use and air-cooled equipment, as sourced from ME and DAR, Greenbuild 2022 which is similar to a LEED indoor water use calculator with assumptions for cooking and cleaning. Our methodology incorporates refrigerant leakage data from our BPAC 2022 study and transportation-related emissions (B8) are pulling information presented at Greenbuild 2020.

Building energy consumption are generated at an hourly granularity (8,760 data points per year). Emission factors are applied to the energy consumption data, multiplying the hourly results to estimate the total (B6) emissions. Water-related B7 emissions are not computed hourly given that the upstream and downstream municipal plants' hourly data isn't known. An annualized emissions factor derived from the Cambium data are applied to these. Natural gas is also assumed to have a fixed emissions factor but this factor is constant for the entire study period with no decarbonization from upstream leakage or downstream. Emissions are calculated not only for the present day but also projected through consecutive years from 2024 to 2050. This approach provides insights into emission trends over time. The B1 and C1 refrigerant leakage assumes an annualized rate and a separate end of life occurrence. We also assume that after the first end of life period that a newer next generation refrigerant is used which will have a lower GWP than the HFCs being phased out today.

The study employs a specific carbon accounting methodology to evaluate the impact of exporting surplus electricity to the grid per the CA ZERO Code. This method considers the cleanliness of the grid as a determining factor. If surplus electricity is fed back into a relatively dirty grid, it yields substantial carbon credits, while in cleaner grids, the credits are minimal. This methodology captures the dynamic nature of emissions based on the grid's decarbonization rate over time.

The research involves different scenarios and building prototypes, which serve as reference points for evaluation. Specifically, it explores:

All-Electric Versions: Modifications to the prototypes that rely solely on electricity for all energy needs.

Photovoltaic Systems (PV): Roof-mounted PV systems are added to evaluate solar energy generation.

Cold Climate Heat Pumps and Heat Pump Water Heaters: These interventions are added to the all-electric models to assess their impact on emissions.

Batteries: Batteries or energy storage systems (ESS) are examined for their potential to optimize energy demands and reduce GHG emissions, particularly when excess electricity is generated at times the grid is also clean.

The methodology extends to various locations, each with its grid characteristics and emissions profile:

Denver: Due to its relatively dirty grid, Denver serves as a case study for locations with high emissions today. CZ 5B has high heating and cooling loads with ample solar.

San Francisco: Characterized by a cleaner grid, San Francisco is a contrasting case with lower emissions due to its solar and wind. CZ 3C has muted heating and cooling.

Chicago: A location with a diverse energy generation profile, showing variations in emissions. CZ 5A has muggy summers and cold winters.

New York City: Similar to San Francisco, it has a clean grid but is mostly hydro with smaller diurnal amplitude. CZ 4A is close to Chicago with heating and cooling.

Houston: With the lowest heating use in our study, Houston's steady decline in emissions is of interest. CZ 2A has limited heating season and hot muggy summers.

The research conducts cumulative GHG emissions assessments for each run, applying measures such as cold climate heat pumps, heat pump water heaters, PV systems, and batteries to maximize building emissions reductions. The methodology offers a comprehensive approach, focusing on location-specific variables, energy system design, and carbon reduction strategies. The study will present findings, interpretations, and discussions on potential pathways to reduce operational GHG emissions, considering grid characteristics and evolving emissions profiles over time. A comparison against ASHRAE Standard 228-2023 and ASHRAE Standard 240P's first public draft is included, evaluating compliance and variations. ASHRAE 240P relies on forecasted data from Cambium, while ASHRAE 228 uses static historical data from eGRID 2018, emphasizing the importance of understanding distinctions and similarities between these standards in assessing building carbon emissions methodologies.

Discussion

Office Building Optimization: NYC

This analysis optimizes carbon emissions for a New York City office building, considering annual and cumulative emissions (Fig. 7 and 8), including gas and electric baselines, transportation, and materials. Materials have a notable impact, allocated to 2023, including refurbishment carbon for replacements from 2024-2050. Transportation's ongoing impact is represented based on a 2020 Greenbuild study. Focusing on operational cumulative emissions, excluding materials and transportation, (Fig. 9) the study assesses the building's lifetime operational carbon emissions. Switching to an all-electric system on a relatively clean grid in New York City (Fig. 14) immediately reduces carbon emissions (Fig. 10). Adding a PV system on the roof further reduces emissions, correlating with decreased energy consumption (Fig. 11).

In all scenarios where we studied a PV system, we have sized it to the building's roof size while allowing for aisles and space for rooftop equipment. The introduction of batteries, while possibly beneficial for operational carbon reductions, slightly increases energy usage due to inherent battery inefficiencies (Fig. 12 and 13). In regions with clean grids like New York City, operational carbon emissions are less impactful, and the addition of batteries may not fully offset their embodied carbon increase. We added 100 kg of CO_2e/kWh for batteries' embodied carbon and kg of 600 CO_2e/kWdc for the PVs based on a review of numerous sources. Our ESS has a 10% roundtrip loss which will always result in an increased EUI wherever they are used in the study. According to the Cambium data, the grid serving NYC does not have a sizable diurnal swing in carbon intensity during much of the year or in the future. Without this change in carbon amplitude, there is not much opportunity to employ batteries to shift grid usage to cleaner periods. This analysis underscores the nuanced relationship between batteries and carbon emissions reduction, emphasizing that the decision to incorporate batteries should consider factors beyond operational carbon reduction, such as resiliency, grid stewardship and cost arbitrage. The implications may vary depending on the grid's characteristics and regional needs.

By deploying these ECMs, RE and ESS, we were able to reduce the B1, B6 and B7 operational emissions by about two thirds from the initial value of nearly 1.2M kg of CO_2e. When adding back in the materials this percentage drops to less than 30% reduction from the baseline while still omitting (B8) transportation-related emissions.

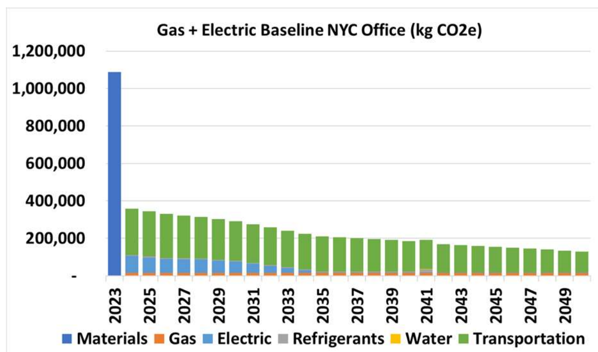

Figure 7: NYC Office: Annual Emissions

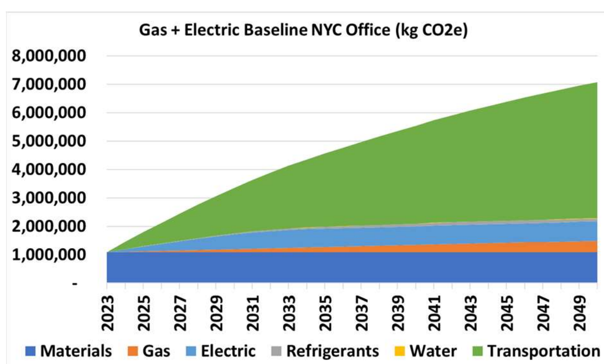

Figure 8: NYC Office: Cumulative Emissions

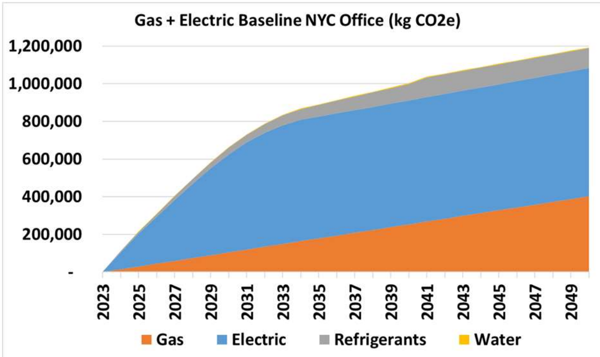

Figure 9: NYC Office: Cumulative Emissions- Excluding Materials and Transportation

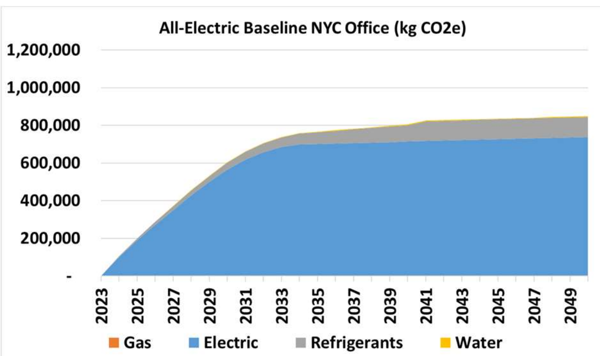

Figure 10: NYC Office: Cumulative Emissions- All Electric

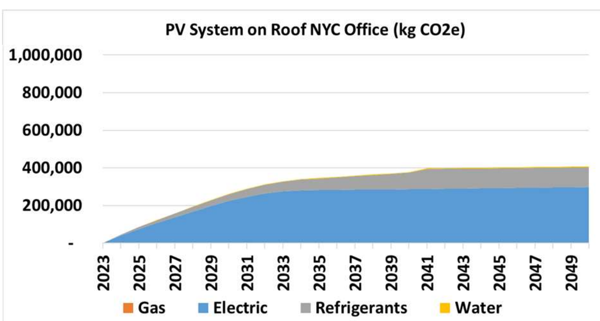

Figure 11: NYC Office: Cumulative Emissions- All Electric with Rooftop PV

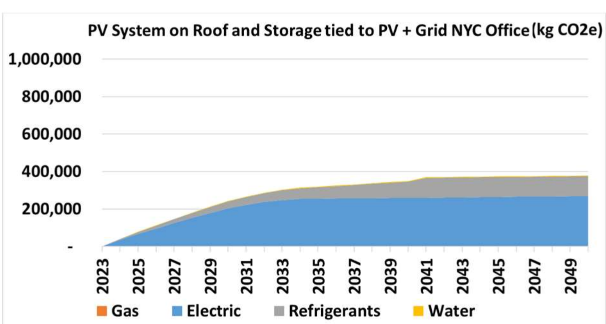

Figure 12: NYC Office: Cumulative emissions- All Electric with Rooftop PV and Battery Storage

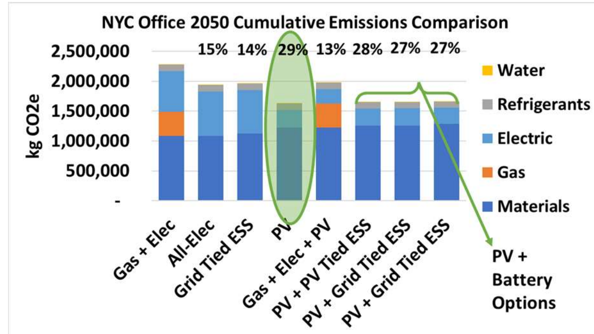

Figure 13: NYC Office: GHG Emissions Comparison

Office Building Optimization: Denver

In examining different locations, such as Denver, the impact of optimization strategies varies significantly due to the starting grid conditions (Fig. 15). In areas with dirtier grids and pronounced daily or seasonal swings in carbon emissions, the role of batteries becomes more viable. For instance, in Denver, batteries serve as a valuable tool to offset emissions throughout the day. Conversely, regions like San Francisco or New York City, which have cleaner grids (Fig. 14), they exhibit different outcomes based on their unique characteristics.

Our analysis extended to the year 2050. Due to forecasted decarbonization, there are more hours with near zero carbon emissions, but there are some high swings, making certain strategies consistently relevant even with a decarbonized grid over the horizon.

For our Denver office building optimization, we utilized waterfall charts to present emissions reductions. Starting with the gas and electric baseline then transitioning to an all-electric baseline shows a reduction in emissions—even in a dirtier grid setting, thanks to grid decarbonization combined with the efficiency of heat pumps over combustion equipment. The addition of PV systems delivers substantial emission reductions, due in large part to the carbon intensity of the grid at the same time on-site solar provides energy. Incorporating batteries becomes a pivotal strategy, effectively addressing high daily swings with higher grid emissions after the sun goes down to facilitate cleaner energy utilization during these periods. We also added a new measure which assumes we can avoid higher GWP refrigerants like R-410a from day 1 and use next generation replacements with low Global Warming Potential (GWP) to further reduces emissions. These strategies combine to result in a 4-fold reduction of operational carbon B1, B6 and B7 over this 28-yr period without taking embodied carbon into account (Fig. 16).

However, when adding in the A1-A5 material carbon emissions, there is a notable increase, emphasizing the significance of materials in the overall emissions profile. Strategies, such as mass timber construction, can help mitigate embodied carbon in materials (Fig. 17), which was part of our Greenbuild 2020 and 2022 sessions but for SimBuild we are only including it here to illustrate how each measure relates to the Whole Life Carbon.

Transportation-related emissions also play a role, with an even higher impact compared to other emissions categories (Fig. 18).

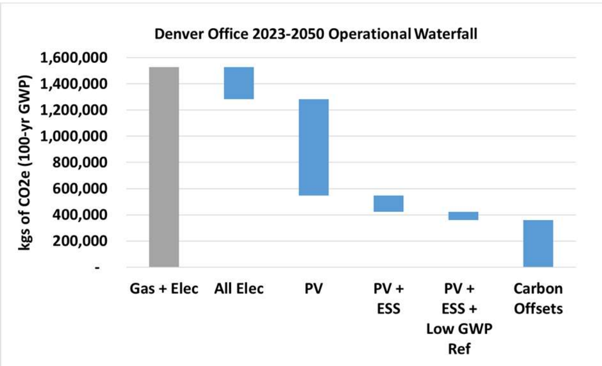

Figure 16: Denver Office 2024-2050 Operational Waterfall

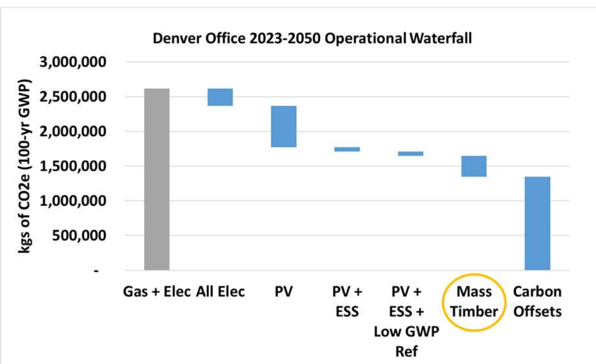

Figure 17: Denver office 2024-2050 Operational + Material Waterfall

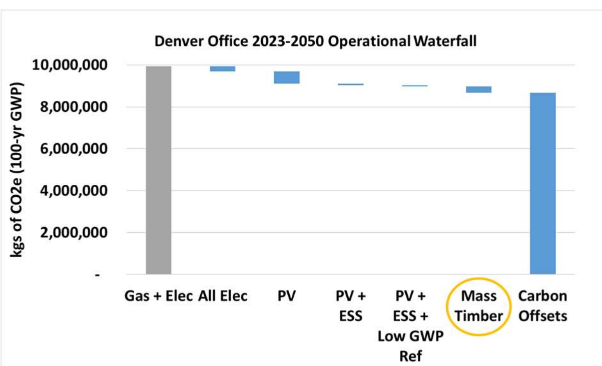

Figure 18: Denver office 2024-2050 Operational + Material + Transportation Waterfall

Multifamily Residential Building Optimization: Denver and San Francisco

For multifamily buildings, a wider range of strategies was explored: PV systems, batteries, heat pump water heaters (HPWH), and cold climate heat pumps (CCHP). These strategies were considered as viable options in multifamily buildings due to greater heating needs and larger domestic water loads.

The analysis included annual operational emissions (B1, B6, B7) and cumulative emissions, including the impact of transportation (B8) and embodied emissions (A1-A5). To gain insight into the lifetime emissions profile including C1 emissions, the focus was narrowed to operational emissions, excluding materials and transportation.

The examination of the Denver multifamily building first looked at transitioning from a gas and electric baseline to all-electric, which showed operational emissions significantly decreasing. This reduction was particularly notable due to the decarbonization of the electric grid along with the efficiency of heat pumps.

The addition of PV systems contributed to a further decline in emissions, as they offset electricity consumption from a not fully decarbonized grid. HPWHs emerged as a valuable strategy, particularly in multifamily buildings where domestic water heating played a substantial role. Importantly, the analysis revealed that water-related emissions (B7) held a more significant role in multifamily buildings due to increased water usage (Fig. 19).

Moving towards an optimized operational scenario, incorporating cold climate heat pumps, PV systems, and batteries yielded a remarkable reduction in emissions. Nevertheless, it is essential to note that these strategies did increase the significance of materials and transportation in the overall emissions profile. The introduction of mass timber construction demonstrated a reduction in embodied carbon (Fig. 20), although the multifamily context brought forward distinct challenges, notably related to water usage.

Exploring the San Francisco multifamily building, which started with a cleaner grid and milder climate, displayed similar trends in emissions reduction (Fig. 21). The analysis confirmed that cold climate heat pumps, heat pump water heaters, PV systems, and batteries continued to be viable strategies. CCHPs had little effect in SF due to there being almost no operating hours where its improved low-temp efficiency can operate. Even in Denver the overall annual impact of the improved efficiency at lower temps occurred at so few hours per year as to make it show minimal CO_2e reductions. This is not to say that CCHPs with no electric resistance backup are not valid measures for other reasons.

The relevance of batteries in multifamily buildings was evident, with a notable reduction in operational carbon emissions. However, once the analysis expanded to include materials including the batteries', the prominence of batteries slightly diminished, yet they still contributed to an overall reduction in emissions.

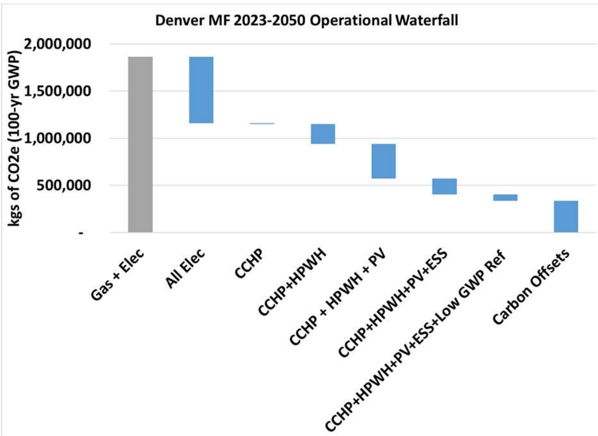

Figure 19: Denver Multifamily 2024-2050 Operational Waterfall

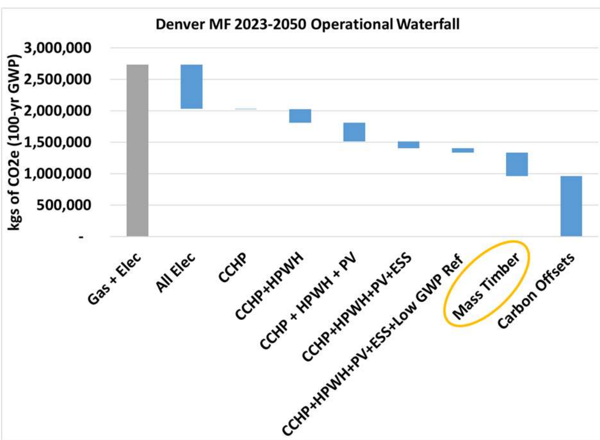

Figure 20: Denver Office 2024-2050 Operational + Material Waterfall

The multifamily building scenario underscores the need for a diverse range of optimization techniques for comprehensive emissions reduction. While PV systems and batteries in the operational phase had a substantial effect, emissions reduction involves various factors, including materials, transportation, and unique building attributes. Strategies to reduce operational carbon (B1, B6, B7, and C1) significantly outperformed baseline gas + electric hybrid versions in the same locations. Although no single strategy was sufficient to eliminate all operational carbon emissions, they notably reduced the starting point. In the final optimized operational emissions, B1, B7, and C1 emissions became more prominent. The focus on reducing operational CO2e emissions emphasizes the importance of upfront embodied carbon emitted before any B1, B6, or B7 emissions occur, while also highlighting the impact of B8 transportation emissions overshadowing other emissions reductions.

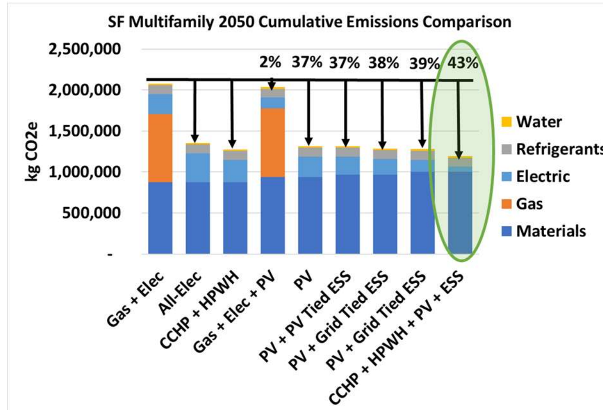

Figure 21: SF Multifamily: Cumulative Comparison, Including Materials

Comparing Methodologies: Our Methodology vs. ASHRAE Standards 240P and 228

In our analysis, we delved into two key standards, 240P and 228-2023, which serve as lenses to evaluate building carbon emissions. A few notable differences between these standards were noted. First, 228 focuses on a single year of analysis, while 240P uses a default 60-yr reference study period. Both review electrical grid emissions using the relatively large spatial eGRID subregions, in contrast to our approach using smaller balancing areas (BA). It is important to highlight this variation as it can lead to substantial differences, particularly in specific regions. Both standards encompass operational electric and gas emissions; however, it is crucial to recognize that both rely on annualized data. While there may be arguments to review grid emissions at a larger level such as eGRID subregions, the same cannot be said for substituting annual values in lieu of hourly granularity. PNNL's research for ASHRAE 189.1-2020 addendum aj looked at the loss in fidelity when reviewing 1 annualized value all the way to a full 8760 hourly file. PNNL recommended and the final version was approved with a 12x24 matrix of values which uses a single 24-hour period for each month in the year, which was easier to reprint within the standard and maintained much of the seasonal and daily granularity as the 8760 hourly file. Std 228 relies on historical 2018 eGRID data which discounts any decarbonization that has taken place during the past six years and any future decarbonization. Draft standard 240P uses the same NREL Cambium data as our studies but reduces the granularity to a single number for each year now through 2050 and at a larger spatial region. These differences, as we will demonstrate, can have a significant impact on results.

Our methodology encompassed transportation, which 240P does not cover. The effect of this difference is particularly evident when we compare Chicago under both lenses (Fig. 22). This was due to the BA data having more nuclear generation and the broader eGRID/GEA region having more fossil fuel electric generation in the BAs surrounding Chicago which change its grid emissions factors at the eGRID subregion to something much dirtier. This was also observed when looking at Seattle's BA vs GEA/eGRID-level emissions factors. The choice between balancing areas and eGRID subregions can significantly influence the emissions profile. Depending on the region, this difference can either be more pronounced or less so, but it is crucial to consider it, especially when exploring strategies such as purchasing carbon offsets. Balancing areas, despite their non-isolated nature, offer a localized perspective that may be beneficial for capitalizing on localized PV projects.

Our analysis also accounted for embodied carbon emissions, which 240P includes. However, one key difference lies in the consideration of refrigerants. In our approach, we considered the replacement of refrigerants with lower GWP options and eventually zero GWP refrigerants, leading to a reduction in emissions. In contrast, 240P in its first public draft does not consider this reduction (Fig. 23).

Our findings reveal consistent optimization strategies across various scenarios, emphasizing the advantages of electrification, particularly with the addition of heat pumps, even in dirtier grids. The inclusion of PV systems consistently shows improvements. A notable distinction is observed in the advantage of adding batteries, evident in our approach analyzing hourly data, whereas 240P's annualized data does not reflect this advantage. This highlights the importance of considering the lens through which these strategies are examined. Real-world storage systems, with some energy losses in each cycle, may show higher energy usage than systems without storage. Granular data analysis, such as hourly assessments, is crucial for accurate carbon arbitrage, as annualized grid factors may not fully capture the benefits of energy storage.

Moving on to 228, the use of historical 2018 data was a noteworthy factor. In some cases, it did not support electrification as much as our approach, which includes decarbonization trends. However, adding heat pumps to multifamily buildings continued to demonstrate emissions reductions (Fig. 24). Similar to 240P, batteries did not appear advantageous in 228 due to the use of annualized data (Fig. 25) for the same reasons as stated above for 240P. Standard 228 is intended for either new construction or existing buildings and only looks at a single year of operational use. Because it ignores embodied carbon from materials and leverages outdated grid factors, it is less suited to new construction in the authors' opinions as it skews the only carbon worth tallying is B1 and B6 while devaluing anything which could be done in the A1-A5 materials emissions.

In both standards, operational emissions were considered, but the broader picture, including materials, and transportation is significant. Transportation, although a placeholder in our current analysis, is anticipated to play a substantial role in carbon emissions, making it a crucial factor to consider (Fig. 26).

To summarize, 228 may discourage electrification due to its historical data and annualized perspective. Nonetheless, strategies such as heat pumps and PV systems continue to demonstrate carbon emissions reductions. Batteries may not appear advantageous under either lens due to the annualized approach. The critical takeaway is that the perspective and boundaries set by these standards are essential to consider in developing a comprehensive whole-life carbon assessment, especially as we aim to reduce carbon emissions in building design.

Conclusion

The quest to optimize operational carbon emissions in building design is a multifaceted journey, influenced by grid cleanliness, material choices, transportation, and ASHRAE standards. The analysis reveals key insights:

- Building materials significantly contribute to a building's carbon footprint. Embodied carbon emissions may dwarf the impacts of emissions reductions from operational carbon optimization.
- Transportation emission play a substantial role, necessitating their integration into holistic carbon reduction strategies.
- The choice between ASHRAE 240P and ASHRAE 228 depends on assessment goals. ASHRAE 240P provides a forward-looking, comprehensive view, while ASHRAE 228 relies on historical data and omits some emissions.
- Regional variations affect GHG emissions, requiring region-specific strategies.
- Refrigerants can have significant impact, especially with grid decarbonization.
- Photovoltaics transform high-emission grids, reducing the building's carbon footprint.
- Heat pumps are valuable for lowering operational carbon emissions.

- 240P in its current version will never support use of storage (thermal or electrical) due to its use of annualized emissions rates.
- Whole Building Life Cycle Assessment (WBLCA) is increasingly relevant, accounting for all building emissions.

In conclusion, mitigating operational carbon emissions is a vital but intricate challenge. The construction industry can chart a path toward sustainability by choosing the appropriate ASHRAE standard, accounting for regional disparities, and addressing refrigerants. This journey is further underscored by the decarbonizing electricity grid, the increasing significance of material selections, and the substantial impact of transportation emissions, emphasizing the need for a multifaceted strategy to achieve a greener and more environmentally responsible future.

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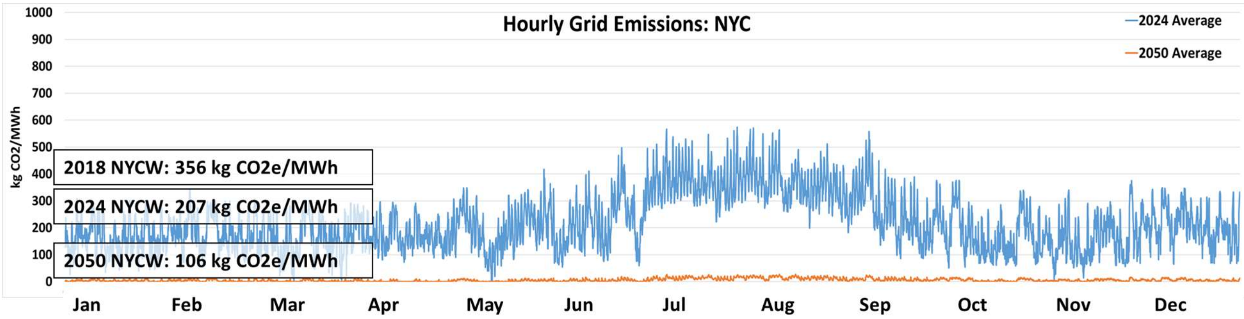


Figure 14: Hourly Grid Emissions: NYC-2024 and 2050 Average Emissions (Source: NREL)

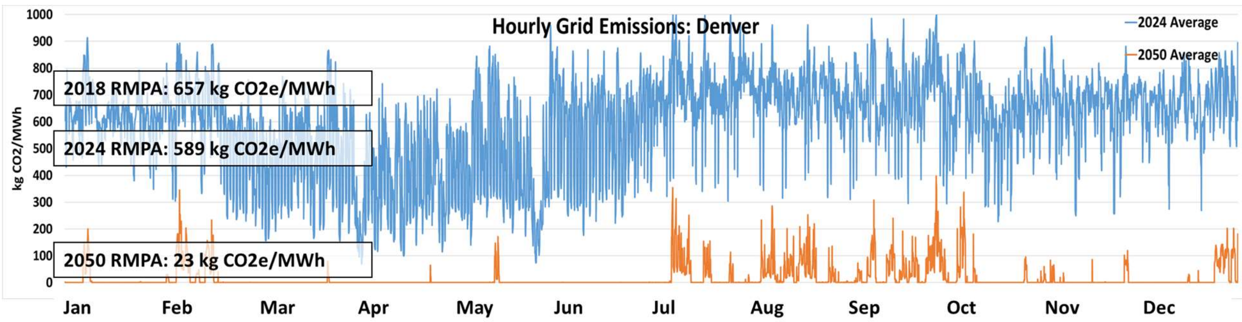
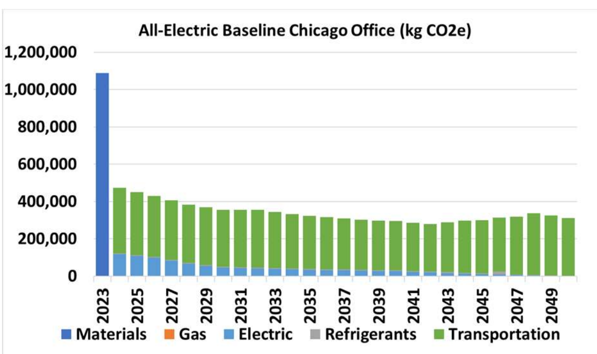


Figure 15: Hourly Grid emissions: Denver-2024 and 2050 Average Emissions (Source: NREL)



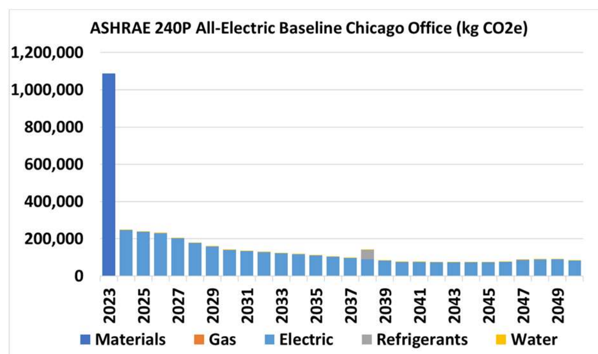
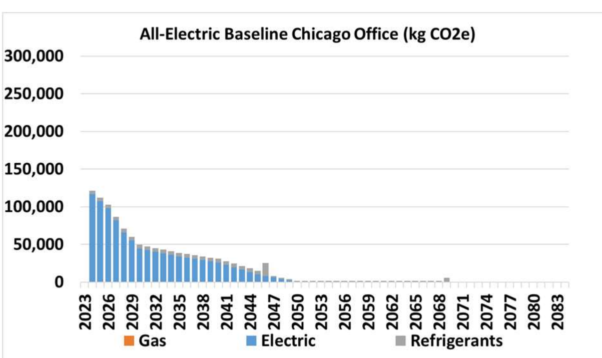


Figure 22: Our Methodology vs. ASHRAE 240P-Annual GHG emissions



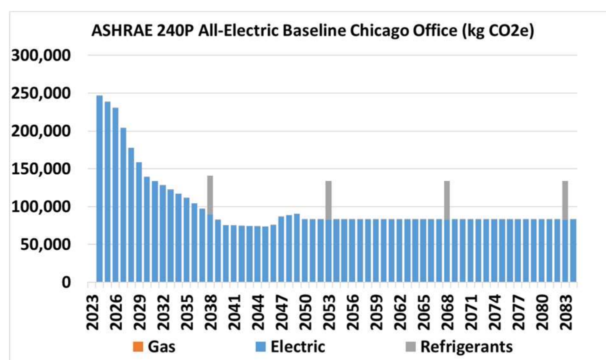
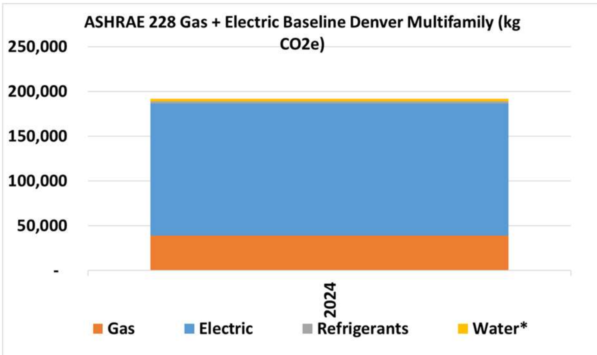


Figure 23: Our Methodology vs. ASHRAE 240P-Annual GHG Emissions-Using 240P's 60-yr Reference Study Period



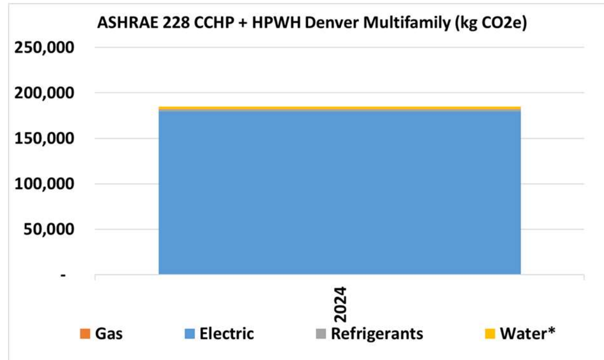


Figure 24: 228-2023 Results -left: Gas +Electric Baseline -right: Electric Baseline CCHP+HPWH Denver Multifamily

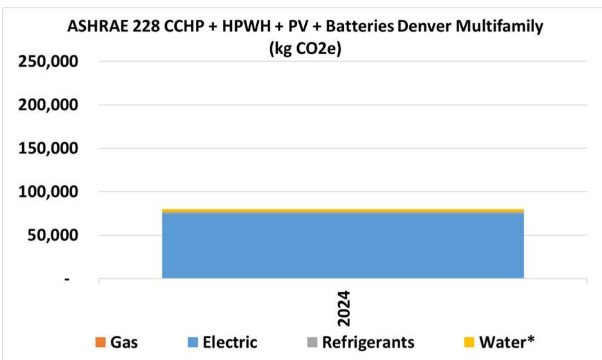


Figure 25: 228-2023 Results- Electric Baseline CCHP+HPWH+PV+ Batteries Denver Multifamily

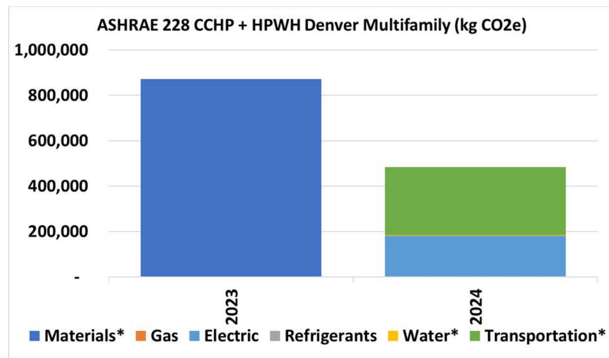


Figure 26: 228-2023 results- Electric Baseline CCHP+HPWH+PV+ Batteries + Materials + Transportation