Meeting A Community's Emissions Reduction Targets Using Urban Building Energy Modeling

by

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Submitted to the Department of Architecture
in partial fulfillment of the requirements for the degree of

Master of Science in Building Technology

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2021

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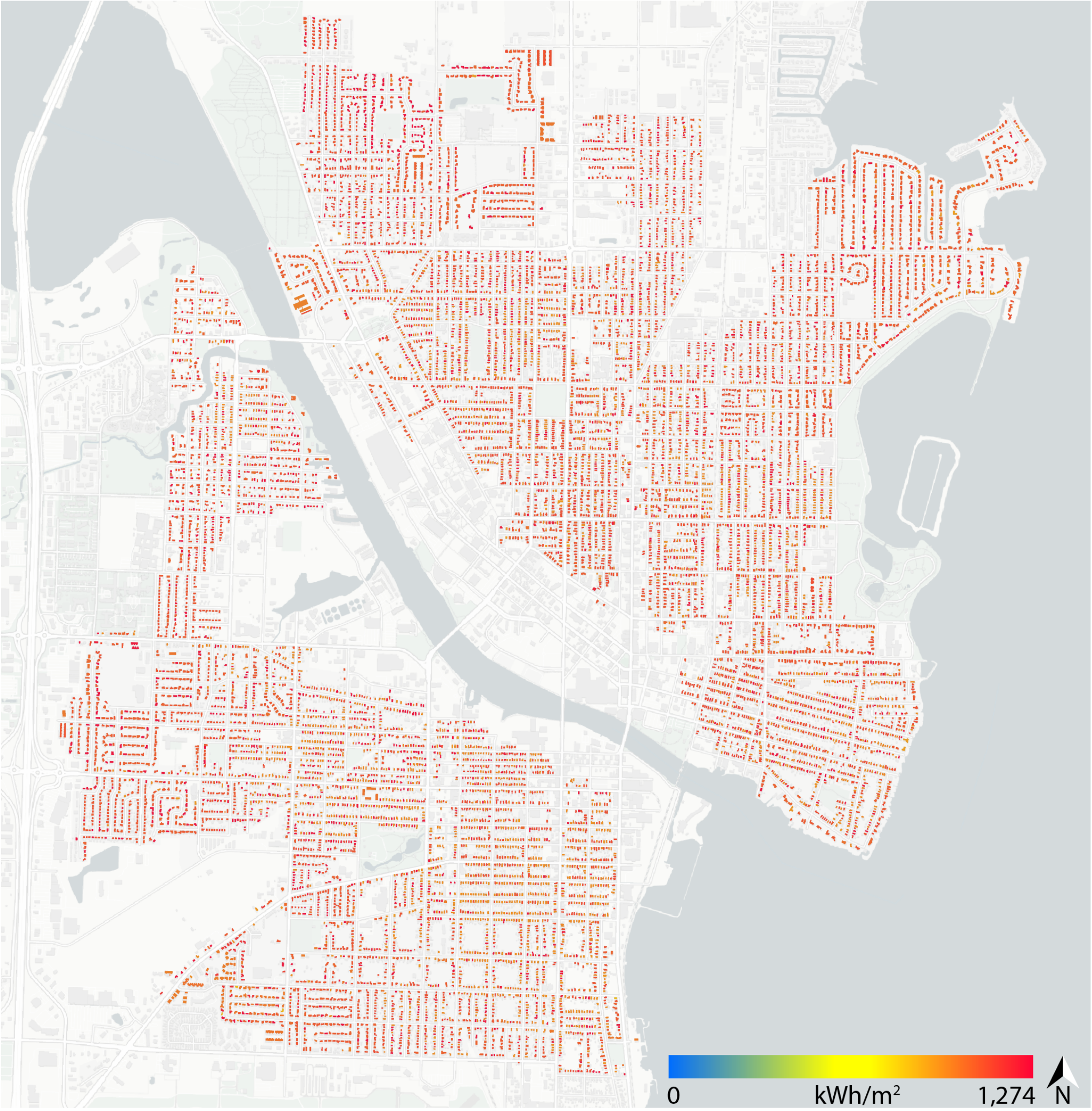

Figure 1: An urban building energy model showing the energy use intensity of the building stock. This model is the baseline results from a case study of Oshkosh, Wisconsin.

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Abstract

Communities around the world are striving to meet aggressive emissions reduction targets in a short time frame. This paper lays out a six-step process using urban building energy modeling to identify a combination of building energy efficiency upgrades and renewable energy deployment strategies that meet emissions goals. The process involves key decision makers in each municipality working with an energy modeling consultant to build up a model of their building stock and simulate various scenarios to meet the desired emissions reduction goals. Through a case study of Oshkosh, Wisconsin, the six-step process is tested, and a concrete action plan to meet their 80% emissions reduction goals by 2050 is presented. The final recommended solution involves upgrading all residences in Oshkosh to ENERGY STAR certified home standards, installing cold climate heat pumps to displace fossil-fuel based heating, and deploying photovoltaics over an area equivalent to 50% of all rooftops. To aid in the final step of the process, implementation, the city-wide strategies were broken down into actions individual homeowners could take and what the cost and payback periods for these actions would be. In order to meet global emissions reduction goals, the six-step process presented in this paper will need to be carried out in communities around the world. The approach has been shown to be flexible and applicable to anywhere with emissions goals and access to building footprint and characteristic data.

Thesis Supervisor: Christoph F. Reinhart
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Acknowledgments

I would like to express my deep gratitude to my advisor, Christoph Reinhart, for his support and guidance throughout this process. I also wish to thank the City of Oshkosh, WI for providing data for the case study. Specifically, Brandon Nielsen was indispensable in making the case study possible. I am appreciative of the support provided by members of the MIT Sustainable Design Lab, especially Yu Qian Ang and Samuel Letellier-Duchesne. Without their technical expertise, this research would not have been possible. Finally, to my family and friends, thank you for everything that got me to this milestone. The material presented in this paper is based in part upon work supported by Shell (project number 6942292) under the MIT Energy Initiative.

Contents

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Acronyms

ACH air changes per hour. 23

DOE Department of Energy. 15

GIS Geographic Information System. 13, 14

IPCC Intergovernmental Panel on Climate Change. 10

kWh kilowatt-hour. 33

MW megawatt. 33

PV photovoltaic. 22, 26

SFH single family home. 23

UBEMs Urban Building Energy Models. 11

UMI Urban Modeling Interface. 16

Chapter 1

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), global temperature rise must be kept under 1.5°C to limit the most catastrophic impacts of climate change [2]. To meet this challenge, the nations of the world will need to reach net zero emissions by 2050 and can only release 500 Gt of carbon dioxide from now until then [3]. Cities around the world have set aggressive emissions reduction targets aligning with the IPCC's findings, but few have crafted implementation plans to meet these targets [4]. With buildings accounting for approximately 40% of global greenhouse gas emissions, cutting emissions from the building stock is critical to meeting these emissions reduction goals [5]. Consequently, all new buildings from 2030 onward will need to be built to be very energy efficient and use renewables to offset any remaining emissions [6]. Yet focusing only on new buildings alone will not be enough. Most of today's buildings will still be in use in 2050, necessitating the retrofit of much of the existing building stock [7]. Current retrofitting rates hover at around one percent a year but will need to reach five percent a year by 2030 to put all existing buildings on a path to net zero by 2050 [8]. The central question is thus how to spur an increase in retrofits around the world to meet emissions reduction goals.

Building-level energy simulations were designed to study the energy savings from energy efficiency upgrades on homes and are well-suited for the kinds of analyses needed to bring buildings toward net zero [9]. However, creating energy models building-by-building is too time and labor-intensive to drive retrofit adoption to the requisite five percent level. To drive widespread adoption, these retrofits will need to be designed and modeled en-masse. Urban Building Energy Models (UBEMs) are designed for exactly this purpose.

UBEMs are a bottom-up, physics-based tool developed to simulate the energy use of buildings at the city scale. UBEMs can be used in multiple scenarios such as designing new neighborhoods, developing building-grid integration plans, providing building-level energy upgrade recommendations, and identifying carbon reduction plans at the building-stock level [10]. The lattermost use case is most relevant to municipalities. Policymakers can collaborate with an energy modeling consultant to create an UBEM and study the effects of implementing different energy efficiency measures across a city [8]. By predicting the resulting emissions reductions from the different measures, the team can find pathways to get from their baseline to their targeted emissions levels.

Building efficiency alone is not enough to reach the emissions reductions called for by many governments. Replacing heating systems with fossil fuel-free alternatives such as heat pumps and providing carbon-free electricity will also be required. Through an UBEM, policymakers can identify the most cost-effective combination of building energy efficiency upgrades, heating systems, and renewable energy deployment [11]. They can then leverage this knowledge to craft implementation plans and policies to support the necessary strategies. UBEMs have already been successfully developed to carry out these kinds of studies for cities in different countries and climate zones around the world [12].

Creating UBEMs to identify and test building upgrade strategies has traditionally been reserved for large cities. These cities have the resources to gather, clean, and streamline the input data and to hire experts to tailor the UBEM to their city. For widespread adoption, every town needs to be able to create an UBEM and use it to convince homeowners to conduct certain retrofits. Recent advances in big data and computational tools such as UBEM.io are now making this possible [13]. UBEM.io is a web app that streamlines the integration of widely available shapefiles with a building template library to create an UBEM. It enables any municipality to quickly and cheaply assemble an uncalibrated UBEM to guide their development of emissions reduction strategies [13]. This makes data-driven decision making for urban energy use issues much more accessible.

This paper lays out an innovative framework for communities around the world to use uncalibrated UBEMs to develop retrofitting programs to set and meet their emissions reduction goals. Furthermore, the author identifies ways to communicate the scenarios to government stakeholders and the retrofit requirements to individual homeowners to create the buy-in needed to increase retrofit adoption rates. Through a case study of Oshkosh, Wisconsin, a small American city with 13,100 buildings and 66,000 residents, the author shows how this approach is scalable and accessible to any community with building geometry and tax assessor data. In the U.S. alone, the approach used for Oshkosh opens the door to addressing emissions reductions in the 179 million housing units outside of major cities [14].

The paper is organized as follows: Chapter 2 presents the framework for communities to use an UBEM for emissions reduction planning; Chapter 3 discusses how this framework was applied to Oshkosh; Chapter 4 focuses on the takeaways for future studies in other communities, and Chapter 5 covers how these efforts can inform a community's policies to meet their emissions goals.

Chapter 2

Methods

The emissions reduction goals, local climate, building construction, and requirements of communities around the world vary widely. Yet despite their differences, every community, from a small farming town to a big metropolis, can follow the six step framework outlined in Figure 2.1. This framework lays out the necessary steps for communities to meet their greenhouse gas emissions reduction goals and help mitigate global climate change.

2.1 Step 1: Data Availability

The first step for any community looking to meet their emissions reduction goals is understanding the data they already have. Key data includes information on the building stock (e.g. tax assessor data, Geographic Information System (GIS) building footprints, energy use data, and emissions data), the current baseline emissions, and emissions reduction goals. To start off a municipality should conduct a carbon accounting to quantify current building-related carbon dioxide emissions. This is normally calculated using city-wide energy utility bills (e.g. gas and electricity) and carbon factors for these sources. The former can be provided by the local utility without infringing on individual's data privacy.

Figure 2.1: Six steps to meeting a community's emissions reduction goals.

2.2 Step 2: Scoping Consultation

The scoping consultation with the stakeholders and an energy modeling consultant is where the team formulates a series of questions they want to explore. These questions will vary but will generally fall into two categories: how to set emissions reduction goals or how to reach previously-determined emissions reduction goals. Many cities around the world have already set ambitious emissions reduction goals to align with Paris Agreement emissions reduction targets [4]. For communities that have yet to set emissions reduction goals, they can use an UBEM to identify technically feasible targets that are informed by global emissions reduction goals. In either scenario, once the key building-retrofit related questions have been identified, the local government stakeholders can work with consultants to transform these questions into strategies that can be studied with an UBEM. A case study of this framework applied to Oshkosh, Wisconsin, USA is provided in Chapter 3. At this stage, the team is ready to define the scope of the study - e.g. what building types to include - as well establish the boundary conditions - e.g. how the carbon emissions of the local power grid are going to evolve over the coming decades.

2.3 Step 3: Baseline Model

To create the baseline model, the consultant will draw on the input data identified in Section 2.1. GIS data such as shapefiles, geoJSONs, or CityGML is widely available and captures the geometry of the world's buildings in two or three-dimensional form [15]. These datasets are often maintained by city or state agencies but can also be retrieved from crowd-sourced collections such as OpenStreetMap [16]. If none of these data sources are available, it is infeasible to build an UBEM. To build the two-and-a-half-dimension block models used for energy simulations in UBEMs, additional non-geometric data is often required. At a minimum the building height or number of stories, the window to wall ratio, building use type, and construction properties must be specified or inferred [17]. Much of this information is found in tax assessor databases.

The non-geometric data, especially construction properties and usage schedules, has typically been the chokepoint in creating UBEMs [18]. Leveraging this data can require hundreds of hours of data pre-processing [18]. The use of standardized archetypes describing representative building construction and use properties has helped streamline this process [19]. Archetypes are created by segmenting the existing building stock based on climate zone, heating systems, construction year, and/or use type [20]. Creating archetypes used to require expert knowledge of the local building stock and a substantial amount of time, limiting the ability for small towns to afford UBEMs. The author used archetypal, a Python based conversion script developed by Letellier-Duchesne and Leroy that converts EnergyPlus models into an archetype library, a step that dramatically reduces the time required for creating an archetype [21]. Using this software, the author leveraged Department of Energy (DOE) EnergyPlus prototype building models to create a library of archetypes for different building ages, use types, and U.S. climate zones. [22][1]. The same approach can be used to create archetype libraries outside of the U.S. as well. For example, archetyping projects such as the TABULA initiative, which covers the building stock of 21 countries in Europe, are well suited for creating UBEM archetypes [23]. Crucially, these archetypes only need to be created once for each region and then they can be accessed and used by all communities. If standardized upgrades are co-developed, such as in the TABULA initiative, the process for studying upgrades becomes even easier.

Alternatively, many governments and NGOs such as the U.S. DOE, the Passivhaus Institut, and the International Living Future Institute offer prescriptive programs that detail required energy efficiency upgrades to meet certification standards [24][25][26]. These standards can be used to create a suite of upgraded building archetypes applicable across many different areas. Using these standards, the consultant can simulate retrofits in an UBEM without requiring the time or effort of developing one-off strategies. This greatly reduces study costs and opens UBEMs to every community. Uncalibrated UBEMs have been shown to yield close results (less than 20% error in energy use intensity) compared to actual energy use at the building stock level [27]. Thus, the predicted emissions from an uncalibrated UBEM should align with the emissions inventory data collected in Section 2.1. If the UBEM results are more than 20% off from the baseline inventory, then the emissions factor assumptions, building footprints, and templates need to be revisited.

2.4 Step 4: Scenario Development

Scenario development is where the energy modeling consultant carries out the urban-scale energy analysis. There are myriad tools to run an urban building energy model. For stock-level analysis, physics-based models that use a building energy modeling software such as EnergyPlus are most common and are more accurate than other model types such as regression-based statistical or reduced order models [28]. Through simulations, the consultant can study different building upgrade strategies to identify the best-performing options. Rapid iteration in this stage is critical. The author used the Urban Modeling Interface (UMI) to run the case study UBEMs [17]. UMI is a versatile tool for urban-scale simulations and its Shoeboxer algorithm speeds up the simulation time for large-scale energy models [29]. Using UMI, teams can simulate the energy use of tens of thousands of buildings in a day.

2.5 Step 5: Recommendations

From the options studied in Step 4, the team can narrow their recommended approach down to a handful of impactful upgrade strategies. This is a crucial step as too many options can overwhelm decision makers and lead to unproductive meetings. The consultant then takes these final strategies and meets with the local government representatives to present the proposed strategies.

2.6 Step 6: Implementation

With approval from the key decision makers, the sixth and final step of implementation can proceed. This is where the municipality must take the lead in gathering partner organizations to communicate the study results within the community and create a streamlined process for homeowners to carry out the necessary upgrades. To meet emissions reduction goals, local leaders will need to convince as many homeowners as possible to carry out the proposed upgrades. Consequently, it is critical to frame the benefits and costs of the upgrade packages for the individual homeowner and convince them to invest in their home.

A well-publicized demonstration project and streamlined financing and implementation process can make a big difference in this stage. Nolan et al. showed that messages about neighbors' energy conservation behavior spurred people to conserve more energy than other emotional or economic arguments [30]. Jachimowicz et al. showed that people will save energy if they think other people in their area care about saving energy [31]. Furthermore, Alcott and Rogers showed that long-term reductions in energy consumption require repeated communication efforts in order to create lasting change [32]. Thus to catalyze homeowner action, governments need to widely publicize their programs and show that members of the community are retrofitting their homes. Establishing social norms that upgrading a home to be more energy efficient is both desirable and necessary to community goals should spur further uptake of the retrofit program [33].

Finally, implementation needs to be accessible to all. This is where straightforward financing options through local banks or on-bill financing in collaboration with the local utility can make a big difference. If homeowners have easy access to capital and quick payback periods, they will be more inclined to carry out retrofits [34][35]. Ultimately, successfully encouraging widespread program adoption will require a multi-pronged approach that makes building upgrades a simple and financially attractive process.

Chapter 3

Results

The author tested the above described emissions reduction framework in the town of Oshkosh, Wisconsin. Oshkosh is a midwestern U.S. city with 66,000 residents in climate zone 6A. In many respects it is typical of any small American city, with an actively-engaged volunteer sustainability advisory board and a small paid planning department that is also tasked with keeping track of emissions targets. Like most other communities, Oshkosh does not have the resources to commission a consultant to build a traditional UBEM model from the ground up. Yet using the aforementioned six-step process, the author was able to easily create and use an Oshkosh UBEM in a matter of tens of hours, a timeframe that would make the cost of hiring a consultant feasible.

3.1 Step 1: Oshkosh Data Availability

The author found that Oshkosh has access to all the necessary data to build an UBEM. Their planning department has a GIS shapefile with building footprints for the entire city and tax assessor data with building use type and age. Through ICLEI – Local Governments for Sustainability (a coalition of over 1,700 city and state governments around the world), Oshkosh conducted a baseline greenhouse gas emissions inventory using 2007 measured gas and electricity consumption data from the local utility [36]. In 2016, Oshkosh and ICLEI used the 2007 emissions inventory to inform a series of emissions reduction targets: 25% by 2025, 40% by 2035, and 80% by 2050, as shown in Figure 3.1 [37]. Additionally, the author was able to obtain 2019 electricity and natural gas data from the local utility to create an updated baseline. As seen in Figure 3.1, this data showed that there was a substantial increase in emissions from 2007 to 2019.

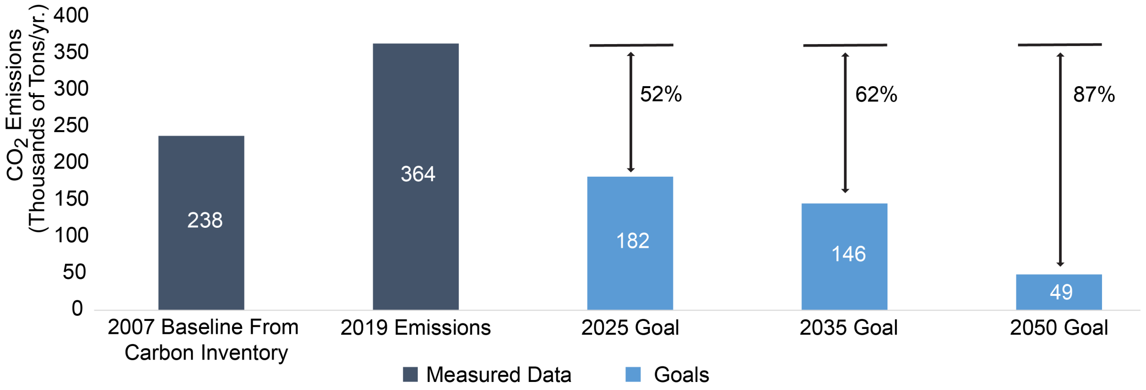

Figure 3.1: Note that because emissions increased substantially from 2007 to 2019, achieving Oshkosh's goals became much harder. The 25% reduction target for 2025 is instead 41%, the 40% target for 2035 is 53%, and the 80% by 2050 is 84%.

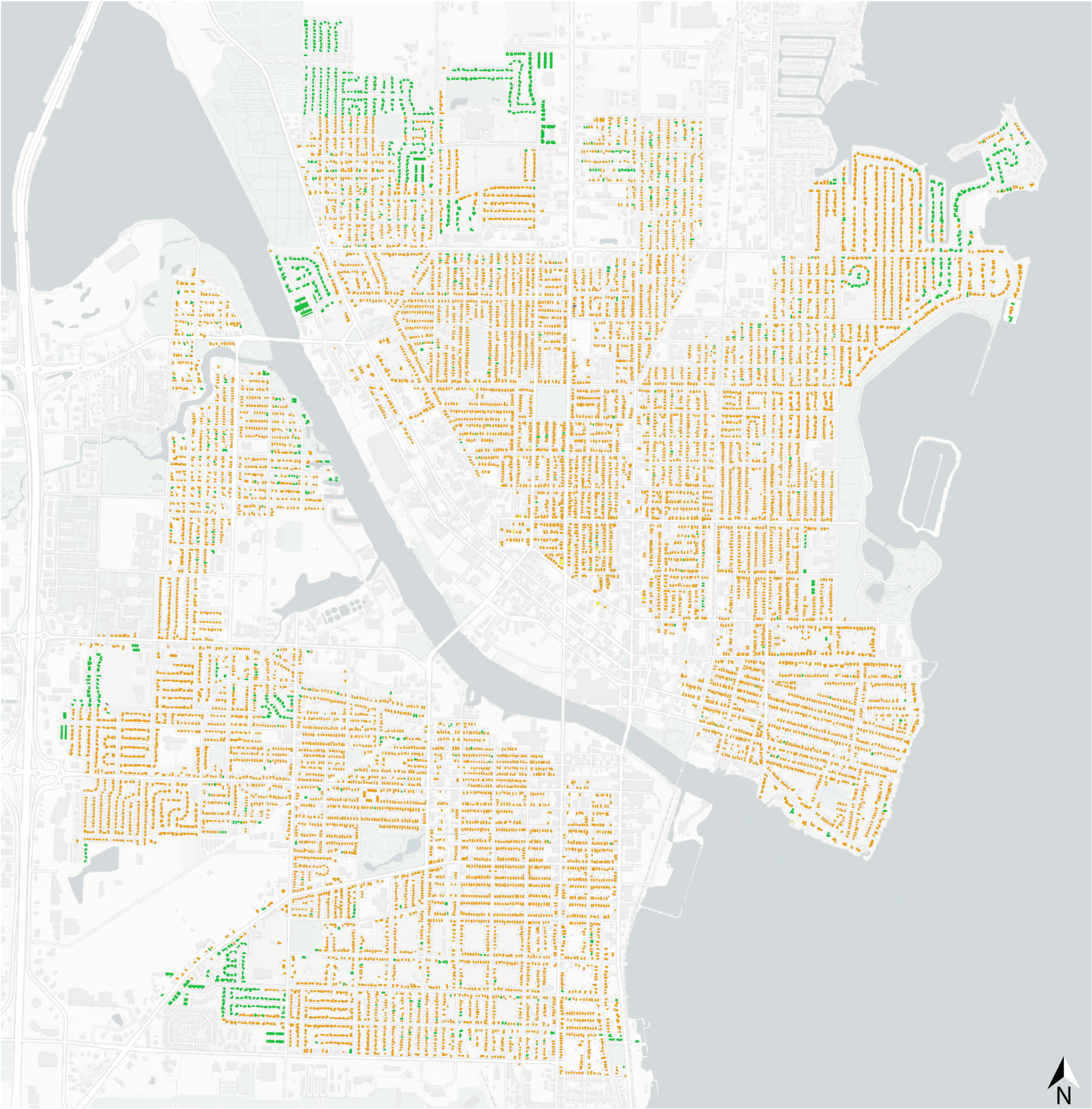

Figure 3.2: Overview of Oshkosh. Using tax assessor data and GIS footprints, the buildings in Oshkosh are categorized by age and use-type. Orange buildings are pre-1980 single family homes, green are post-1980 SFHs, grey are post-2004 SFHs, and yellow are commercial buildings. A few commercial buildings are included to account for shading while most commercial and industrial buildings (including a large number downtown owned by the University of Wisconsin) are excluded.

3.2 Step 2: Scoping Consultation

With the baseline data in place, the author met with Oshkosh city planners. The team developed a list of questions that the stakeholders in Oshkosh wanted to explore. The questions and their refinements in scope for the study are detailed in Table 3.1.

Table 3.1: Case study questions developed by Oshkosh stakeholders (initial) and revised by the author to reflect current UBEM capabilities (revised).

Initial Questions	**Revised Questions**
What area(s) in Oshkosh need to be addressed first?	What building types in Oshkosh need to be addressed first?
What is the most cost effective retrofit that can reduce CO_2 emissions?	What is the most cost effective retrofit to reduce CO_2 emissions for residential properties?
Life cycle emissions: how does retrofitting old commercial buildings compare to new commercial buildings?	Should Oshkosh retrofit old buildings or construct new ones? How do their life-cycle emissions compare?
Should oshkosh install photovoltaic (PV), wind, or both?	What renewable energy resources should Oshkosh use to power the community?

To be conservative, in this study the team assumed the emissions for electricity purchased from the power grid would remain constant. The grid emissions used for the study are thus based on the 2019 emissions factor (1.19 lbs. CO_2/kWh) from the local utility, Wisconsin Public Service [38]. The author also assumed that all new buildings built in Oshkosh will not impact emissions – i.e. all new buildings will have net zero carbon emissions. Through this consultation, the city narrowed the scope of the study to only residential buildings as single family residences are the predominant building type in Oshkosh.

3.3 Step 3: Baseline Oshkosh Model

With the study scope defined the author used the UBEM.io web app to create the baseline model. UBEM.io is designed to streamline the creation of UBEMs from GIS data [13]. It currently outputs UMI files but support for additional UBEM simulation tools are planned for the future [13]. Creating the Oshkosh UBEM involved some pre-processing, namely removing the geometry for all auxiliary structures such as garages and sheds (a process automated using GIS software) and matching the non-geometric properties to the geometry. The latter task can be time intensive, as there is often a mismatch between the two datasets [18]. However, this is strictly the responsibility of a municipality's GIS department and the author believes it will become more streamlined as conventions are established and best modeling practices are enforced.

The final UBEM shown in Figure 3.2 included 13,101 single family homes. The study included 16 commercial buildings only insofar as they shade other buildings and affect their energy use. Oshkosh was broken down into three archetypes for energy simulations (shown in Figure 3.2): pre-1980 single family home (SFH), post-1980 SFH, and new SFH (anything built after 2004, of which there were only five in the dataset). Each building in the city was modeled using the DOE's age-appropriate residential prototype buildings with characteristics documented in Table 3.2 [1].

Table 3.2: Oshkosh baseline building archetype characteristics. These values are based on the U.S. DOE residential prototype buildings [1].

Archetype	Furnace Efficiency	Equipment Power Density	Lighting Power Density	Infiltration	Wall Insulation	Attic Insulation	Floor Insulation	Window Conductivity
		(W/m^2)		(ACH)	(m^{2}K/W)			(W/m^{2}K)
Pre-1980	80%	2.6	2.6	0.75	0.53	6.34	None	1.99
Post-1980	80%	2.6	2.6	0.75	2.29	6.34	0.70	1.99
New	95%	2.5	1.5	0.20	4.4	8.63	0.70	1.99

The author used UMI to simulate the full model of Oshkosh in about five hours on a standard Windows desktop with 8 cores and 32 GB of RAM. The author used 2019 utility data on the aggregate gas and electricity consumption of Oshkosh residences to validate the baseline model results. After calculating the emissions associated with this measured energy use data, the results were compared to the emissions from the UBEM simulation and found to be within 1% of the measured data, as shown in Figure 3.3. This showed that using DOE templates to create archetypes predicts the energy use and emissions of Oshkosh's buildings well.

With a thus "validated" baseline model, the author focused on how to meet Oshkosh's emissions reduction goals. It is worthwhile noting that in Figure 3.3 the 2019 baseline emissions data represents a 16% increase in emissions from Oshkosh's 2007 baseline. While this is in line with Oshkosh's Milestone 2 reports of rising city-wide emissions, it is nonetheless concerning [37]. Beyond showing emissions growth of over 1% a year, it also makes reaching Oshkosh's emissions reduction targets that much harder. It is also key to note in Figure 3.3 that natural gas is the predominant source of residential emissions. Consequently, even if the electric grid decarbonizes, Oshkosh will not be able to meet its emissions goals without transitioning away from fossil fuels for heating and hot water.

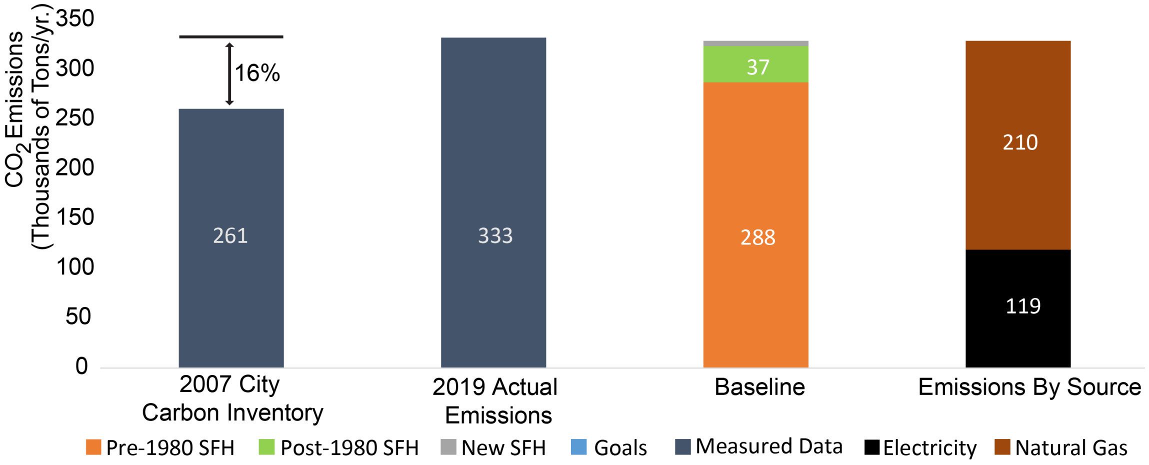

Figure 3.3: Baseline Oshkosh-wide emissions from simulations compared to measured utility data. Note that pre-1980 single family homes are the biggest contributors to Oshkosh's emissions. In this study, due to the lack of additional data, all on-site combustion of fossil fuels is assumed to be natural gas.

3.4 Step 4: Scenario Development

Accounting for 99% of all homes in Oshkosh, the pre- and post-1980 single family homes became the focus of the investigation. The energy efficiency upgrade strategies investigated are based on the DOE's ENERGY STAR certified home program [22]. This nationwide program defines prescriptive insulation and airtightness goals by climate zone for new construction that greatly decrease a building's energy consumption but do not rise to passive house standards. This means homes could be further upgraded if desired, but the goal is to use strategies that are low-cost and scalable. The insulation upgrades (listed in Table 3.3) generally require a layer of continuous external insulation that would coincide with siding replacement and adding insulation in wall cavities if they are un-insulated. They further specify air sealing all cracks, adding further insulation in the roof, and installing some underfloor insulation between the basement and first floor. The program also requires all lighting to be LEDs and all appliances to be ENERGY STAR certified. Finally, the furnace needs to be upgraded to an ENERGY STAR certified 95%+ efficient condensing unit when the current one wears out.

After simulating upgrades to all the pre- and post-1980 homes in Oshkosh to the ENERGY STAR standard through the UBEM, there was a 31% emissions reduction potential from the baseline. With the emissions growth from the 2007 baseline, the ENERGY STAR upgrades by themselves are not enough to meet even the 2025 goals. The author thus looked for additional means to reduce emissions across Oshkosh's buildings.

Table 3.3: Oshkosh upgrade requirements by archetype. Note the windows were not upgraded because their payback period is lengthy.

Archetype	Furnace Efficiency	Equipment Power Density	Lighting Power Density	Infiltration	Wall Insulation	Attic Insulation	Floor Insulation	Window Conductivity
		(W/m^2)		(ACH)		(m^{2}K/W)		(W/m^{2}K)
Pre-1980 SFH	95%	2.50	1.50	0.15	4.40	8.63	5.28	1.99
Post-1980 SFH	95%	2.50	1.50	0.15	4.40	8.63	5.28	1.99

Electrifying the heating system using a cold climate heat pump in addition to the energy efficiency upgrade package enables Oshkosh to achieve additional emissions reductions. In this scenario, when the existing gas furnace wears out, it is replaced by a cold climate air source heat pump. Air source heat pumps are highly efficient at supplying heating and cooling using only electricity and cold climate versions can efficiently supply heating at outside air temperatures down to −20 °F (−29 °C) [39]. This scenario is focused on moving away from on-site combustion of fossil fuels, a step to eliminate the natural gas consumption in Figure 3.3 that will be required to meet stringent emissions targets. A big challenge with air source heat pumps is that their emissions reduction potential is tied to the carbon-intensity of their electricity supply. Even with the higher-than average grid emissions in Oshkosh today (25% above the national average), electrified heating leads to a 28% additional reduction in emissions from the energy efficiency scenario [40]. Through a combination of energy efficiency and heat electrification upgrades across all single-family homes, Oshkosh can reduce its emissions 59%. This is enough to meet Oshkosh's 2025 and 2035 emissions goals. However it would be infeasible to renovate enough of Oshkosh's homes in time to meet the 2025 targets. In light of this, the 2025 goal is infeasible, the study focused in on Oshkosh's 2035 and 2050 goals.

While the energy efficiency and heat electrification scenario achieves Oshkosh's 2035 goal, meeting the 2050 goal will require further emissions reductions. To that end, the team studied rooftop photovoltaic (PV) deployment on Oshkosh homes. The approach used in Oshkosh (and that should be replicated elsewhere) is to reduce energy consumption as much as possible through energy efficiency and heat pump upgrades and then supplement with renewables for the remaining emissions reductions needed. It would take PV covering the equivalent of 50% of Oshkosh's rooftop area to achieve the additional emissions reductions to meet Oshkosh's 2050 goal. This translates to approximately 130 MW of installed PV capacity. This PV could be installed on a mixture of rooftops and fields but either way it will need to be a substantial investment. At the current residential cost of $2,710/kW of PV installed, the total cost would be $260 million after the 26% federal tax credit [41]. Given the PV capacity Oshkosh requires, it would be feasible to aggregate residential installations at the commercial scale of hundreds of kWs. Through aggregation, the installed price of PV systems in Oshkosh could approach today's commercial cost $1,720/kW [41].

This 37% savings per kW would mean the total PV capacity Oshkosh requires would only cost $165 million after the federal investment tax credit.

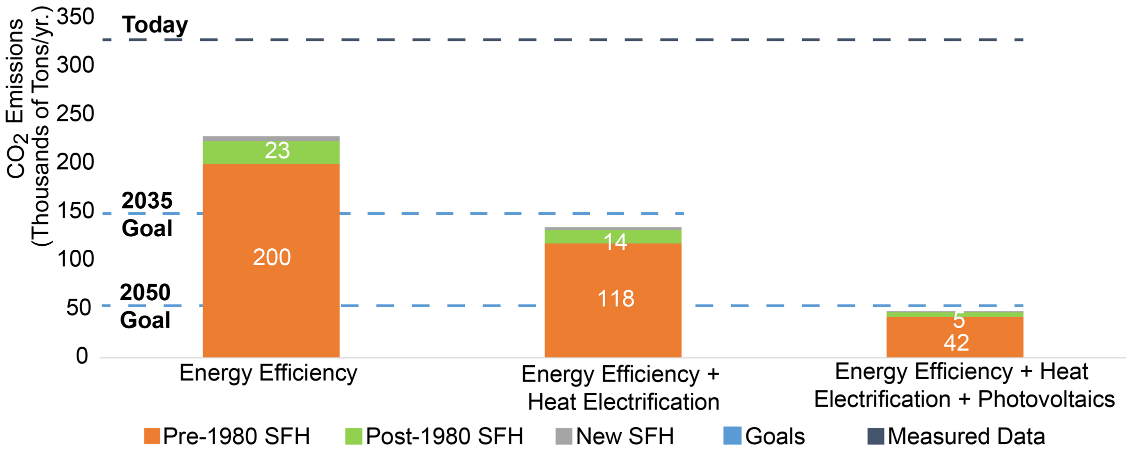

Figure 3.4: The three strategies for Oshkosh to meet its emissions reduction goals. It is only through a combination of all three (energy efficiency, heat electrification, and photovoltaics) that Oshkosh can meet its 2050 goal.

An alternative strategy to installing local PV would be to procure the necessary carbon-free energy through a power purchase agreement for local off-site renewable generation such as wind, utility-scale solar, or biogas.

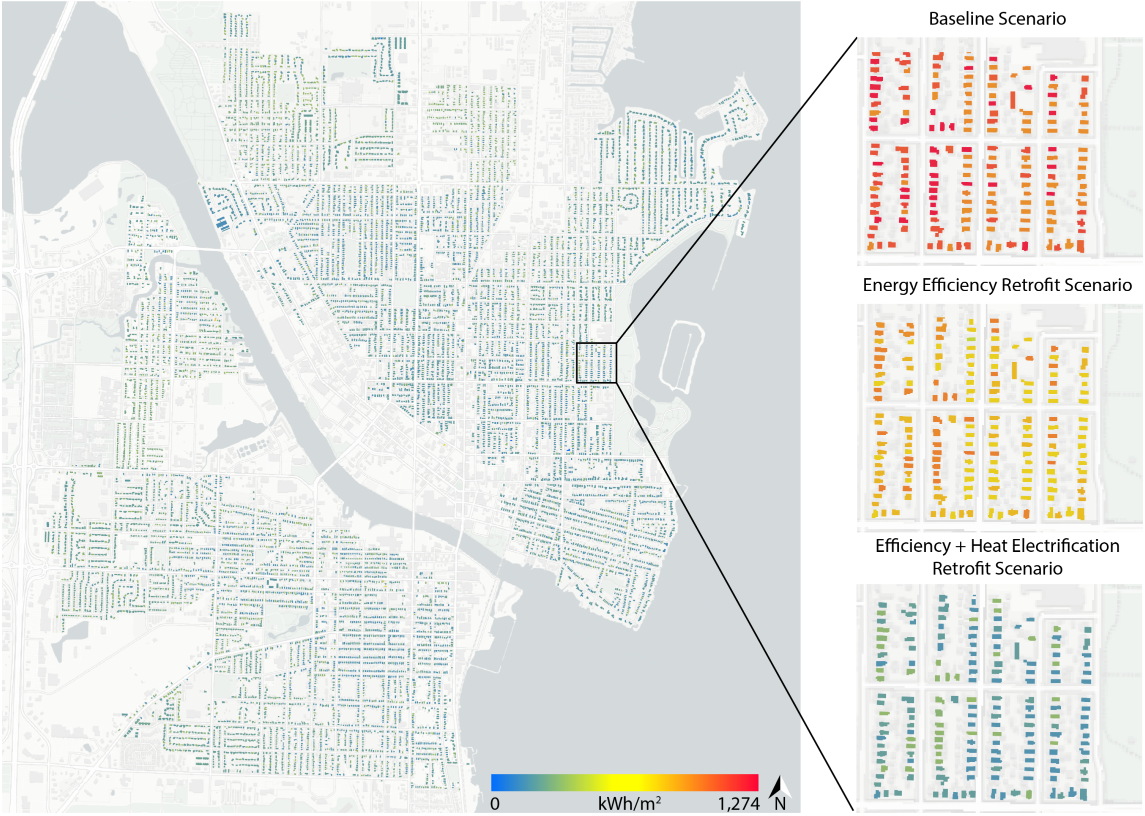

Figure 3.5: Overview of Oshkosh energy use intensity (kWh/m^2) simulation results. The large map shows the energy efficiency and heat electrification scenario. The inset neighborhood shows the three major scenarios studied and is representative of the results for the rest of Oshkosh.

3.5 Step 5: Recommendations to Oshkosh

While there are multiple pathways to achieve Oshkosh's emissions reduction goals, it is important to present a simple set of the best options to the city's stakeholders in Step 5. The final combination of strategies presented to Oshkosh are shown in Figure 3.4. The author focused in on the energy efficiency and heat electrification upgrade to meet Oshkosh's 2035 goal and the energy efficiency, heat electrification, and photovoltaics scenario to meet Oshkosh's 2050 goal. These strategies empower Oshkosh to take charge of achieving its goals without relying on broader efforts to decarbonize the grid. Achieving the 2035 goal on-time would require an average of 7.5% of Oshkosh's homes be retrofitted to the ENERGY STAR standard with heat pumps each year for the next 13.5 years. While this goal is possible, current retrofitting rates hover around 1% a year, making it unlikely [7].

The 2050 goal is the ultimate objective. If the Oshkosh-wide retrofitting rate reaches 5% before 2035, the rest of Oshkosh can easily be fully retrofitted to ENERGY STAR standards with a heat pump by 2050. Installing 130 MW of PV across Oshkosh is sizeable but not out of the question given the timeline, as less than 5 MW would need to be installed each year for the next 28 years. The key for Oshkosh will thus be motivating homeowners to partake in these upgrades. The answers to the questions asked by Oshkosh stakeholders (Table 3.4) sum up the results of the study. A clear takeaway is that Oshkosh can meet its emissions reduction goals through retrofits and photovoltaics alone. Finally, while new construction will also need to be built to zero carbon standards, it does not make sense to knock down an otherwise functional home to reach emissions goals.

Table 3.4: Case study questions and their answers based on simulation results.

Questions	**Answers**
What building types in Oshkosh need to be addressed first?	Pre-1980 single family homes.
What is the most cost effective retrofit to reduce CO_2 emissions for residential properties?	A combination of energy efficiency upgrades to the ENERGY STAR standard and cold climate heat pumps.
Should Oshkosh retrofit older buildings or construct new ones? How do their lifecycle emissions compare?	Retrofits have lower lifecycle emissions. Since Oshkosh's goals can be achieved by retrofitting, this should be the city's focus.
What renewable energy resources should Oshkosh use to power the community?	Oshkosh has the rooftop area to deploy enough PV to meet its goals when buildings are also retrofitted to be more efficient and use heat pumps. Purchasing off-site renewables is also a possibility.

3.6 Step 6: Implementation From A Homeowners Perspective

Persuading homeowners to upgrade their homes will require a combination of economic and social capital. On the economic side, the author calculated the costs, savings, and payback periods for the different upgrade packages that each homeowner can choose from. These "back of the envelope" calculations are meant to show homeowners that their individual contribution matters and makes economic sense. For the energy efficiency upgrade, pre-1980 homeowners would need to spend, on average, \$10,250 on upgrades. The improved insulation, infiltration, and lower equipment energy use leads to lower energy bills, resulting in a payback time of ten years. Post-1980 homeowners would only need to spend \$8,700 and would have a five-and-a-half-year payback period. These slow payback periods could be improved through additional utility, state, or federal incentives for energy efficiency upgrades.

To meet Oshkosh's emissions goals, homeowners will also need to install heat pumps and photovoltaics. If Oshkosh can aggregate installation of its PV systems at the commercial scale, the systems would, on average, cost each homeowner \$12,600. When combined with the energy efficiency upgrades, the package would have a payback time of 7.5 years for a post-1980 home and 10 years for a pre-1980 home. Additionally, the use of fossil fuels for heating will need to be replaced with electric heat pumps. These heat pumps should be installed when the existing furnace reaches the end of its life. The costs of heat pumps is rapidly dropping and their premium over existing high-efficiency furnaces is relatively insignificant. When accounting for the additional benefit of heat pumps providing cooling in the summer, they can be cheaper than purchasing a separate heating and cooling system. The combined energy efficiency, heat pump, and PV upgrade would have a payback time of 10.5 years for post-1980 homes and 15 years for pre-1980 homes. The current high cost of electricity compared to the cost of natural gas in Oshkosh leads to the slow payback period for heat electrification. That being said, the cost of electricity from PV over its lifetime is often lower than the cost of retail electricity and it is fixed, unlike the cost of natural gas. Therefore, the heat electrification upgrade will likely perform better financially in the future. Furthermore, the costs of upgrades and PV systems are expected to drop precipitously as they become more widespread. Finally, at the community level it is critical that the installation of PV panels is tied to the installation of heat pumps. If PV adoption is high yet heating systems still burn fossil fuels, there will be a substantial mismatch in electricity supply and demand on the grid. Additionally, emissions from electricity consumption will drop but the overall emissions will remain high because of the onsite combustion.

On the social capital side, the city can make it very clear: achieving Oshkosh's emissions reduction targets requires buy-in from every homeowner. Then, through a few targeted demonstration projects that implement the recommended upgrades, Oshkosh can build up the social norms that will encourage all residents to pursue these necessary upgrades. Through open houses and community aggregation programs, Oshkosh can encourage all residents to contribute to meeting the city-wide emissions reduction goals through their individual actions.

Chapter 4

Discussion

The case study of Oshkosh, WI highlighted a few key takeaways for applying the six step process in other municipalities. First, the goals need to be clearly set upfront to guide all decision making. Achieving these goals is the ultimate arbiter of success. Second, the boundary conditions must be agreed upon at the outset of the study. This includes what types of buildings to include, what emissions are counted, what baseline data set is used, and what the assumption will be for emissions from the power grid. All these factors can affect the outcome of the study. The grid emissions, in particular, have an outsized impact on the results. Projections for nationwide grid emissions vary widely and can change utility to utility. Current political events can also sway projections. One useful resource for future studies is the NREL Cambium dataset [42]. Using standard assumptions such as the ones found in Cambium are helpful when comparing emissions reduction plans across communities.

Another key takeaway from the Oshkosh case study is that as the grid becomes cleaner, certain strategies such as heat electrification make more sense. For instance, if the grid emissions in Oshkosh had been more in line with the regional grid average of 1.68 lbs. CO_2/MWh, heat electrification would not make sense as it would increase emissions compared to a natural gas furnace. On the opposite end of the spectrum, as the grid decarbonizes PV displaces fewer pounds of carbon dioxide per kWh generated. Whereas PV can currently be used to “zero out" emissions from fossil fuel consumption, a cleaner grid means a higher capacity of PV will need to be installed to achieve the same emissions reductions. The need to remove any on-site fossil fuel emissions is precisely why heat electrification must be part of any long-term retrofitting plan. Additionally, rooftop PV could potentially become (if it is not already) one of the cheapest sources of electricity, making it financially desirable from a homeowner's perspective. Furthermore, these distributed renewables will play a key part in meeting utilities' renewable energy goals.

The case study also highlighted how there are multiple ways to reduce Oshkosh's emissions. To capture the different combinations of photovoltaics and building upgrades that can be used to meet Oshkosh's emissions reduction goals, the author created Figure 4.1. This graph highlights the emissions target frontier between building retrofits and PV installations. For example, to meet the 2035 goal, if 25% of buildings have been retrofitted with the energy efficiency and heat electrification package, Oshkosh will need to install 140 MW of PV. Looking at emissions reductions this way provides stakeholders with more flexibility to meet their goals but could also result in an over-installation of PV. For example, in Oshkosh only 130 MW of PV is needed to meet the 2050 goal if 100% of buildings are retrofitted to the efficiency and heat electrification standard. So if 140 MW is installed by 2035 because building retrofits are lagging, there will be more PV than was necessary by 2050. Since energy efficiency upgrades are usually cheaper than PV installations on a per kWh basis, the total cost could be higher than necessary. Furthermore, in Figure 4.1 it is clear why the additional cost of the heat electrification upgrades makes sense: Oshkosh will require 40% less installed PV capacity to meet their 2050 goal than if they only carry out energy efficiency retrofits.

As retrofit programs get underway, local governments can plot their progress each year to track their success and adjust their implementation plans accordingly. An example of this is shown in Figure 4.2. In Figure 4.2, the author assumed adoption rates increase 1% every three years, rising to 5% by 2033. If the adoption rate remains at 5%, all buildings in Oshkosh will be retrofitted by 2046, in time for the 2050 goal. These adoption rates are an estimate and future work to better understand retrofit adoptions rates is necessary. It is key to note that any combination of PV capacity and

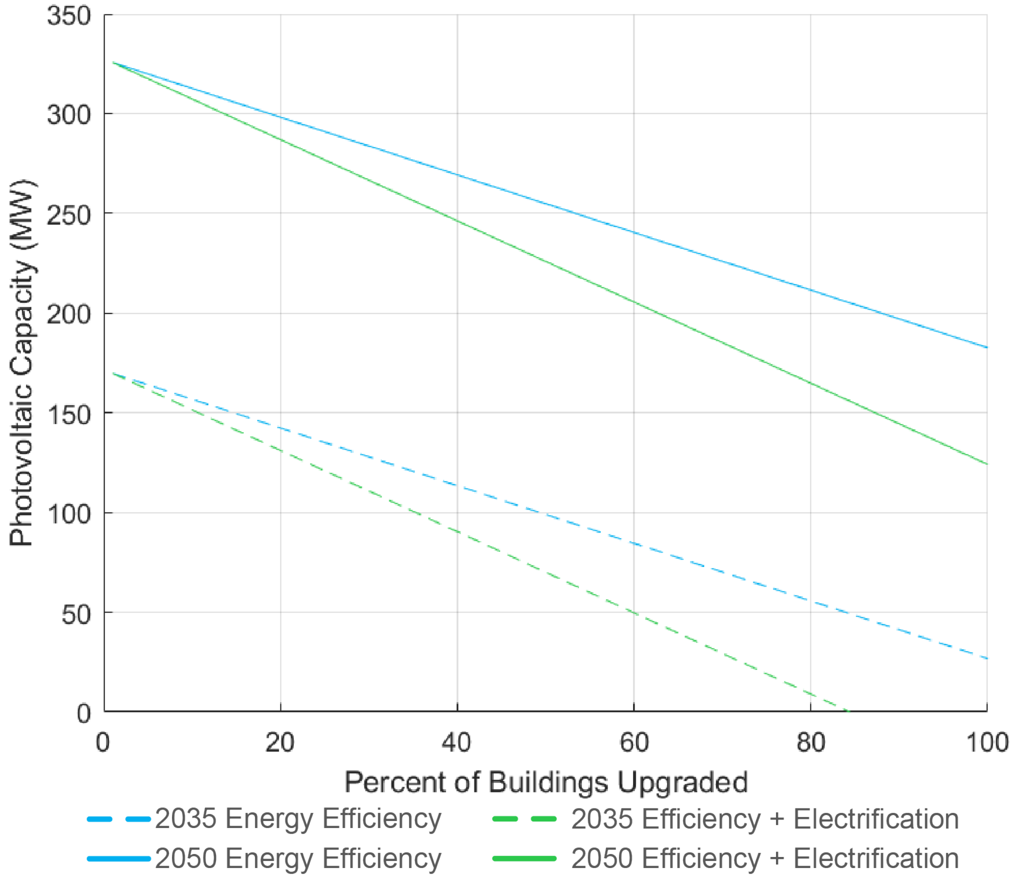

Figure 4.1: Emissions target frontier curves for Oshkosh, Wisconsin based on a grid emissions factor of 1.19 lbs. CO_2/MWh. Emissions reductions can come from a variety of strategies, this graph shows different combinations of building upgrades and PV deployment that will get Oshkosh to its goals. Anything above and to the right of a target line means Oshkosh succeeds at meeting the goal.

building upgrades that falls above and to the right of the emissions target frontier curves meets Oshkosh's goals. While the actual numbers will change from place to place, communities around the world are also likely to require a combination of these strategies to meet their emissions goals. For these communities, Figure 4.2 can lead to the most economic pathway to their emissions reduction goals. Finally, it is important to recognize that as the emissions associated with grid electricity changes, the emissions target curves in Figure 4.2 will shift. These curves will thus need to be periodically updated to account for the most recent shifts in grid emissions.

Going forward, the author hopes to carry out a demonstration project of the pro-

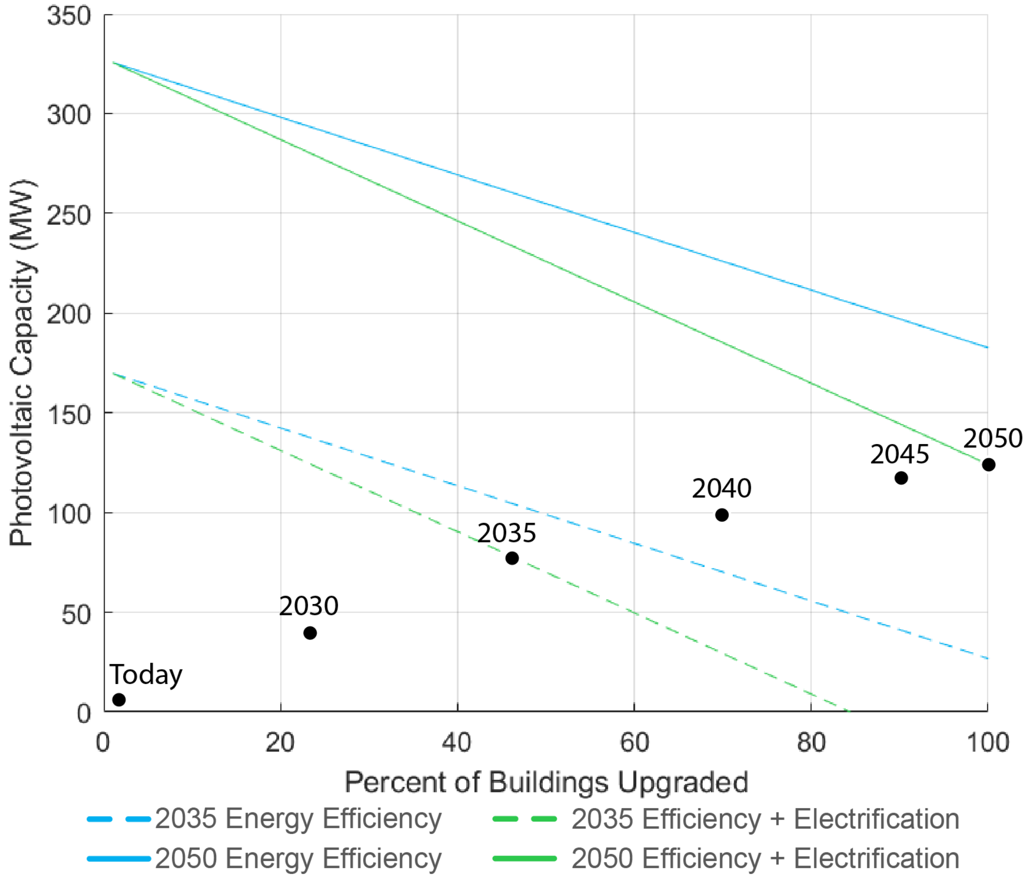

Figure 4.2: An example of using emissions target frontier curves to track progress towards emissions goals in Oshkosh. The curves are based on today's grid emissions of 1.19 lbs. CO_2/MWh. Any combination above and to the right of the relevant curves meets Oshkosh's emissions goals.

posed upgrade strategies in Oshkosh. Working in cooperation with the local weatherization organization and the city planning department, this project will upgrade a handful of Oshkosh homes to the standards set forth in this paper. These homes will serve as focal points for community action by showing residents the tangible steps they can take to help the city meet its emissions goals. The other benefit of a demonstration project will be to measure the actual costs and savings of the proposed upgrades for a real home in the community. The upgrade process will be extensively documented to benefit local contractors and other homeowners. Ultimately, the hope is that this project will kickstart a community aggregation program for building retrofits in Oshkosh.

The city planning department can further play a critical role in driving retrofit adoption rates. In discussions with planners in Oshkosh, they raised the potential for using the permitting process to educate homeowners on retrofit options. Every time a homeowner wants to do major work on their house, such as replacing siding, they must get a permit from the city. By flagging all permit requests that have the potential to include envelope upgrade measures, the planning department can ask homeowners to consider installing additional insulation and an air, water, and vapor barrier. By piggybacking off of existing work, the homeowners are educated about their options and the costs and hurdles to implement the more invasive envelope upgrades are greatly reduced. The short-term impact of educating owners every time they file a permit also has the potential to have a big impact on adoption rates. This voluntary education is a valid but temporary solution. The best way to ensure that envelope upgrades are carried out is to codify low energy building standards in the local building code. This way, whenever a building is upgraded, the codes will help Oshkosh get closer to its emissions goals.

Not studied here but relevant to municipalities going forward is how to best align the increasing electrical demand from heat pumps and electric vehicles with the variable production from renewables. The lack of low-cost storage necessitates co-optimizing these developments to reduce the strain on the grid and maximize the use of low-carbon energy sources. Demand-side management and other strategies will be needed to avoid costly power grid infrastructure improvements. Energy efficiency is once again crucial as it reduces overall energy demand to provide for future load growth potential. This aspect of emissions reduction plans can be studied using a buildings-to-grid UBEM and is worthy of a separate manuscript in and of itself.

Chapter 5

Conclusion

This paper outlined a six step process for jurisdictions to meet their emissions reduction goals using Urban Building Energy Modeling (UBEM). This process involves a collaboration between local stakeholders and an energy modeling consultant and includes: determining data availability, holding a scoping consultation, developing a baseline UBEM, identifying different upgrade scenarios, recommending the most effective upgrades, and implementing the upgrades across a municipality. The author has shown that this process works in a small midwestern city through the case study of Oshkosh, Wisconsin. The required upgrades to meet Oshkosh's emissions goals are extensive but feasible given today's technology. The six step process is repeatable and scalable to communities around the world looking to upgrade their buildings and deploy renewable energy resources to meet their emissions reduction goals. The necessary data is widely available and the major technical and cost barriers to building an UBEM have been overcome through advances such as UBEM.io, UMI, and open-source GIS data.

The policy implications are clear: jurisdictions now have the capability to identify science-backed strategies to meet their emissions reduction policy goals. These analyses are low-cost and low effort, meaning they are accessible to diverse communities, no matter the size. Furthermore, the case study of Oshkosh showed that city-wide efforts to upgrade nearly every building will be necessary to meet common emissions reduction targets. With 2050 getting closer every day, these retrofitting efforts will need to start sooner rather than later. The onus thus falls on local policymakers to commission UBEM studies to guide their efforts. Policymakers can use UBEM studies to design programs that implement the suggested strategies and drive retrofit adoption rates by engaging residents. The sooner these programs are developed and rolled out around the world, the more likely it is that emissions reduction goals can be met and the worst impacts of climate change can be mitigated.

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