Developing a Building-by-Building Estimate of City-wide Electricity Savings Potential: An Early Trial for the City of Wilmington, Delaware

Final Report June 2021

3D LIDAR overview of downtown Wilmington.

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Executive Summary

The research outputs of the 2020-2021 "Wilmington as a Savings City" project, conducted jointly by the Center for Energy and Environmental Policy (CEEP) and the Foundation for Renewable Energy and Environment (FREE), provide a methodological framework that can be directly relevant to the City of Wilmington and other cities in Delaware. Using high-resolution and comprehensive data, the research effort pursues a detailed inventory of the Wilmington building stock with which we estimate building-level electricity consumption and possible energy-saving opportunities.

As the title of this report indicates, we apply an early trial of the methodological framework that we have developed for the purposes of describing how a new analysis might better serve the purpose of estimating 'savings city' potential. We call it an 'early trial' to underscore that the model described and applied in this report is part of an ongoing development process. The methodological framework will be refined in order to have practical value to urban planning. The results illustrated in this report should, therefore, be seen as an assessment of the overall value of the methodological framework brings to the table and not firm estimates to be used in planning. Currently, methods to estimate building energy savings potential for a city relies on technology potential for 'typical buildings'. As discussed below, our team is investigating a method that uses all buildings in a city and is sensitive to the range of differences in building stocks from one city to the next. The promise of this approach is that it can offer estimates derived from actual city building inventories, not 'typical' building stocks. The accuracy of estimates produced by this method should be greater and more useful to cities. We recommend its use by the reader to gain familiarity with the tool and its potential.

The 'Savings City' concept encourages an inquiry into city-wide energy use patterns and spatial and temporal energy use reduction options. Our purpose is to pursue a method that can model each building in a city. Urban building energy savings are often estimated at sectoral or end-use levels and do not examine the diversity of saving profiles. The method introduced here and applied in an early trial for the City of Wilmington applies building-level characteristics to identify specific savings profiles. We consider this to be a unique contribution of the tool worthy of further development. Once completed and validated, the tool can provide strategic insights for planners and decision-makers regarding the energy use profile of the city and the contributions of various strategies for savings that lower costs for individuals and a city as a whole. Such an insight is not typically accessible to city planners, policy makers, or community stakeholders.

The 'early trial' provided in this report offers guidance on how accurate, useful cost reduction strategies can be identified. We have placed the 'early trial' in the context of Wilmington's 2028 Comprehensive Plan for Wilmington, especially regarding the energy and sustainability sections of this plan. Results of the early trial down to the neighborhood planning level illustrates how a completed tool can be highly useful to the City of Wilmington.

ANNUAL CITY-WIDE ELECTRICITY CONSUMPTION ESTIMATE

Using our methodological framework, we arrive at an early, incomplete estimate of city-wide annual electricity use at ~1 TWh. This estimate relies on the entire city's building stock and estimates electricity consumption for each building. The research team did not have access to electricity use data at the scale and scope needed for full validation of this estimate. We are working on data development to enable validation. Still, we can use this estimate as a hypothetical benchmark for the purposes of showing how savings potential can be methodically estimated building-by-building.

ANNUAL CITY-WIDE ELECTRICITY USE REDUCTION ESTIMATE

With a hypothetical baseline consumption for Wilmington in place, the analytical model enables identification of possible energy saving measures. We include a limited bundle of building energy efficiency interventions to determine electricity reduction opportunities. The savings estimate depends heavily on the selection of energy conservation measures. Additional savings measures can be introduced that might deliver greater savings but such a portfolio might come at greater cost. At this stage, until the model can be further calibrated, we have limited our estimate of savings to measures that are relatively uncomplicated.

A preliminary estimate of 18.9% citywide electricity savings represents a site-level result and depends on only a few conservation measures. Even so, the value of building-by-building analysis can be seen. In the early trial, electricity-related losses propagate through the electricity grid. Site energy can be easily converted to source energy using a site-to-source ratio for a given fuel. We use a ratio from the U.S. Energy Information Administration's (EIA) State Energy Data System (SEDS) data to estimate the electricity-related losses ratio for Delaware (city-level data are not available) (EIA, 2021b). Using EIA electricity-related losses for the residential and commercial sectors for Delaware, we calculate the site-to-source ratio at 2.543, meaning the avoided electricity is double the savings at the site.

The savings at the source would be roughly equal to 50% of the estimated pre-retrofit city-wide electricity consumption values. This type of contribution could enable significant environmental and climate benefits for the area. Using the emission factors provided by U.S. Environmental Protection Agency (EPA) Emissions & Generation Resource Integrated Database (eGRID) eGRID2018, we can calculate the carbon dioxide ($CO2$), methane ($CH4$), nitrous oxide ($N2O$), and carbon dioxide-equivalent ($CO2{-}eq$) values that are associated with the roughly 50% city-wide electricity sourced reduction. We estimate that the avoided electricity demand resulting from the city-wide electricity savings intervention could reduce $CO2{-}eq$ by 416 million pounds during the first year of program operation. These first-year savings would continue each year that the energy efficiency measures are in effect.

In Figure ES- 1 below, the total savings estimate is illustrated as well as the average savings estimate per building type. The illustration suggests that residential facilities may be a promising focus for high electricity savings opportunities relative to other building types. Single-family households reach almost 25% savings across all buildings in this category. Several commercial building types also appear to promise high city-wide savings.

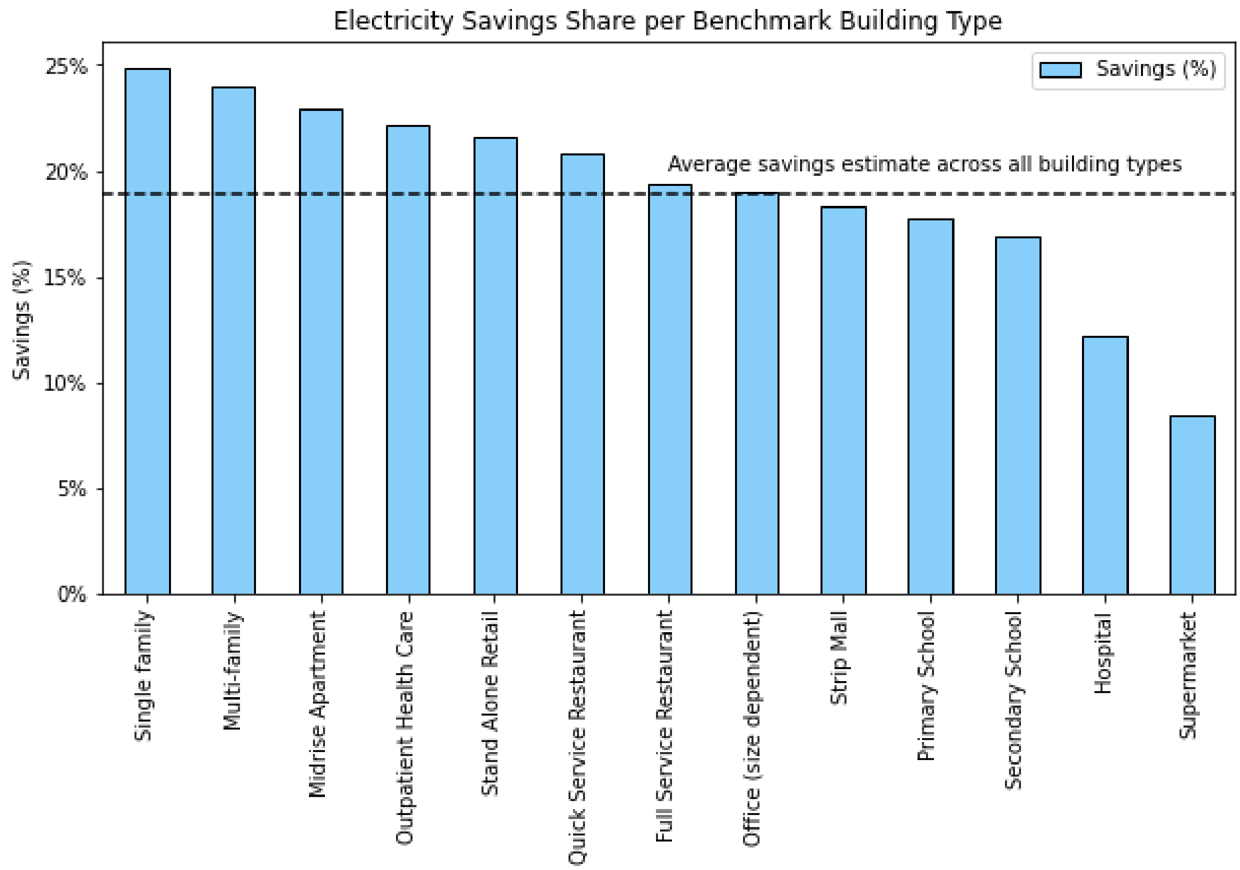

Figure ES- 1 Electricity savings (est.) per building benchmark category, sorted highest to lowest. Horizontal line indicates city-wide savings estimate.

Again, the pattern of savings illustrated in Figure ES- 1 depends on the electricity savings measures that are entered into the analysis. The limited set of electricity savings measures applied in this research include several measures that more often apply to residential buildings (see Byrne et al., 2020) leading to higher overall savings from these buildings. A different set of measures would generate a different overview.

In addition, several building types have unique circumstances that require additional specification of the energy savings measures. For example, hospital buildings have building zones that have unique functionality and energy demands (e.g. an operating room has unique demands for lighting, air conditioning, etc.). This research does not include energy conservation measures for these elements of the building, and this may lead to a lower overall estimate of the savings opportunity. However, specialized energy conservation measures might be available for these building types that can extract a higher overall savings opportunity. This will be explored in future study.

CITY-WIDE MONTHLY ELECTRICITY CONSUMPTION PATTERN (ESTIMATED)

The savings potential illustrated in Figure ES- 1 means that the City of Wilmington can possibly produce annual bill savings for citizens and business of ~$20 million (assuming the average retail rate of 10.52 cents per kWh as reported by the U.S. EIA (EIA, 2021a)) over the 15-year life of most upgrades that we have examined. The city's summer months represent a peak in electricity consumption, with a smaller peak occurring in the winter months. In future research, we intend to investigate intervention measures that can deliver larger savings, possibly at different times of the year. Monthly peak electricity consumption, according to the early trial's results, is reduced from an approximate 100 GWh to under 80 GWh for the peak month of August. Actual savings will depend upon our ability in future research to include data that can allow validation of the building-by-building consumption estimates of our model and the consumption-by-end-use estimates within buildings.

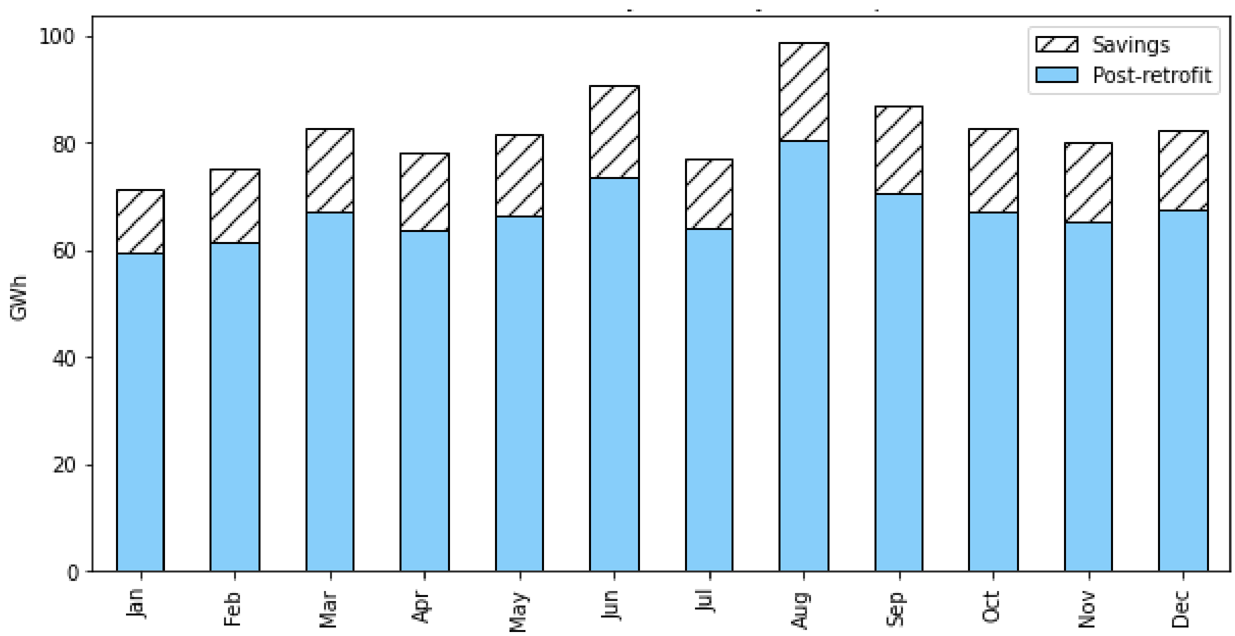

Figure ES- 2 Monthly electricity consumption and electricity use reduction estimates for the entire City of Wilmington.

NEIGHBORHOOD AREA ENERGY SAVINGS OPPORTUNITY (ESTIMATED)

The 2028 Comprehensive Plan for Wilmington divides the city into 11 neighborhood areas for planning purposes. We used these boundaries in an effort to make the results as useful as possible for the City. We have an early estimate from the early trial that savings in each planning district could be significant (above 16%). Downtown 'Midtown/Brandywine/Central' could have the highest pre- and post-retrofit electricity consumption. This would be unsurprising as this area contains Wilmington's downtown core and that typically is electricity-intensive. This district is a fairly high density area with significant new development. Baynard Boulevard could represent an area of the city that would see large decreases between its estimated pre-retrofit and post-retrofit electricity use level. This is a residential neighborhood just north of the Brandywine Creek and Park with commercial activity along N. Market Street. Since our approach yields higher saving estimates for residential buildings, it is expected that a neighborhood like Baynard Boulevard could realize large differences between their pre- and post-retrofit conditions.[1]

REDUCING THE ENERGY BURDEN THROUGH ENERGY CONSERVATION

In Figure ES- 3 below, we illustrate estimated electricity savings by neighborhood planning area as a percentage of income. This pattern is for residential buildings only. Using the neighborhood planning areas in this way yields valuable insights into the potential for residential electricity efficiency interventions across the City. In particular, the early trial shows further study of the effect of a city-wide energy efficiency strategy on those families in the city that spend the largest share of their income on electricity is warranted. Addressing energy poverty through energy conservation can deliver meaningful impact to families and households in need as it substantially reduces the burden their electricity bill represents.

For instance, Figure ES- 3 shows that in a early trial of the tool, single family households could reduce their electricity costs by as much as 5% of their income. This share of income is then free to be dedicated to other pressing needs. Considering low- and moderate income households can spend as much as 20% of their income on energy (including but not limited to electricity), freeing up 5% of income for other purposes is an important share of the family budget (Department of Energy, 2021; Ma et al., 2019).

[1] Note, this does not mean that this neighborhood planning district delivers the largest savings in an absolute sense. Figure ES- 3 reflects only the savings between pre- and post-retrofit conditions in percentage terms.

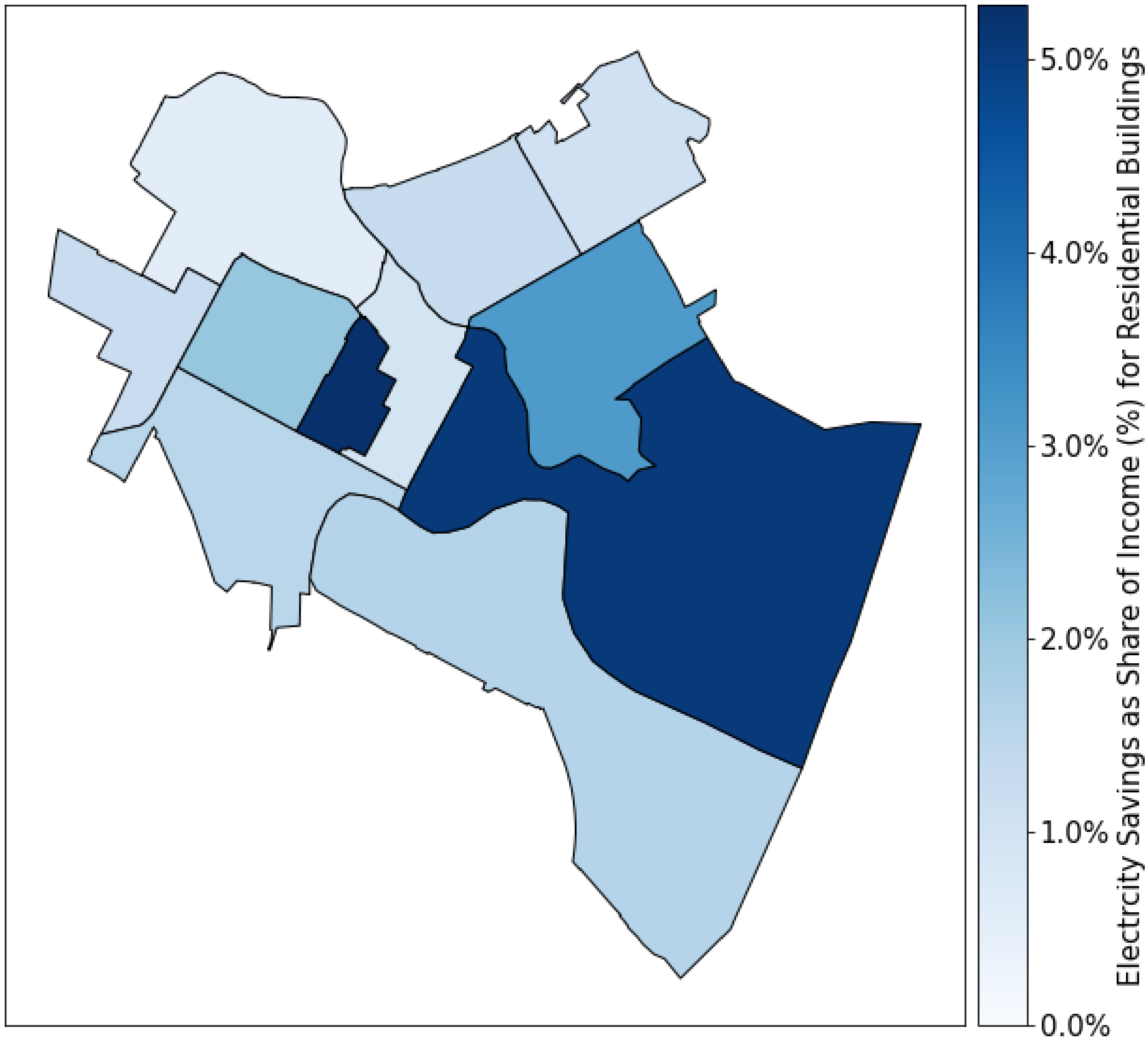

Figure ES- 3 Electricity savings as a share of income (%) for Wilmington's single family housing stock.

GENERAL

The tool we are developing can estimate building-level electricity consumption for an entire city. The tool needs additional specification and data development and further investigation of the sensitivity of estimated savings to the number and types of savings measures analyzed. One important aspect, emphasized in this report, is that urban energy planning can have equity consequences as energy poverty conditions can be improved through targeted and strategic energy efficiency efforts. We find that there are areas of the city with high energy burdens (i.e.

high expenditures as a share of income) due to the distribution of socio-economic status across the city. These areas could benefit in particular from an area-focused electricity efficiency effort as is documented in this report.

1.0. Introduction

Energy efficiency assessments that are conducted at scale – for towns, cities, counties, or states – typically rely on aggregated datasets such as provided through sectoral or technology-based overviews. The aggregated datasets in question prevent assessment at smaller scales such as the building or neighborhood analysis level. In contrast, energy efficiency assessments that are conducted at the building (or even neighborhood) level often face difficulties in the scale-up to the town or city level: designed for the evaluation of individual buildings, these strategies are often too time-consuming to be performed for a broad selection of different buildings and building types. The approach introduced and tested in this report aims to evaluate building-level performance at city-scales.

As discussed in this report, our team is investigating a method that uses all buildings in a city and is sensitive to the range of differences in building stocks from one city to the next. The promise of this approach is that it can offer estimates derived from actual city building inventories, not 'typical' building stocks. The accuracy of estimates produced by this method should be greater and more useful to cities.

We recommend its use by the reader to gain familiarity with the tool and its potential. For that purpose, we have previously applied an earlier version of the model for the City of Newark to illustrate the model's ability to operate at that scale (Byrne et al., 2020). In the present research, we test our current iteration of the model for Delaware's largest city: Wilmington. The early trial applied here illustrates the method's ability to calculate building-level performance at this scale.

1.1. The Value of an 'Early Trial' for Methodological Development

The research makes use of a model developed jointly by FREE and CEEP. This model can comprehensively estimate building-level electricity (and other energy) use patterns and evaluate the contribution of energy conservation measures (ECMs). This model was developed with the express purpose of evaluating city-wide energy performance in a manner that can facilitate urban planning department efforts to address growing demands for city economic development using sustainable energy strategies. Essentially, the model represents a *virtual audit* of the entire building stock of the city, relying on building attributes, geometric shape, and use case data to deliver an estimate of electricity consumption per building and likely savings from a designated portfolio of ECMs.. In this report, a preliminary application of the model is tested for the City of Wilmington. Further refinement of the model is planned.

The research identifies the assessment workflow, parameters, and data needed to calculate city-wide energy efficiency potential bassed on 3D modeling of each building in a city's boundary. The 'early trial', i.e. a preliminary application of an unfinished model, generates insights with the caveat that further work and development is needed that will produce different results than presented in this report. The model outputs documented in this report, as such, should not be seen as definitive assessment results but, rather, should be treated as indicators of the methodological framework's potential. Importantly, the eearly trial reveals model components that need further refinement and development as well as identifies possible data gaps.

1.2. Research Contribution to Wilmington's Sustainability Planning

The 2028 Comprehensive Plan for Wilmington, Delaware describes the city's ambitions and objectives, including five goals to become a sustainable and resilient city (City of Wilmington, 2019). Among other efforts, the city has pursued sustainable street lighting through a recent $2,294,883 light emitting diode (LED) retrofit of the 1,732 city-owned streetlights, reducing energy consumption by an estimated 70% and saving $154,038 per year for an overall cost savings between $3 -$4 million for the project (City of Wilmington, 2020). A similar effort is envisioned in this report for the city's building stock: to comprehensively retrofit the city-wide building stock to advance energy efficiency, save on electricity costs, deliver environmental benefits, and reduce existing inequalities and improve energy poverty conditions.

The model is applied here in a 'early trial' in order to preliminarily establish the City of Wilmington's potential to become a 'savings city'. To that end, the results of the model are presented at the planning levels used in the 2028 Comprehensive Plan. More specifically, the results are aggregated to the neighborhood area analysis planning level that separates the city into 11 neighborhoods. Alternative aggregations are available as well. For instance, while not included in this report, the results could be combined at the smaller community level or even at the street or city block level.

The model can provide understanding of the city's building stock that will be directly useful to the City of Wilmington once lessons from the early trial are processed and identified data needs are addressed. Considering that the model could provide: a) a virtual audit of the entire building stock of the city, b) estimates of the electricity consumption patterns of the city, and c) estimates of the electricity savings opportunities that might be present in the city, we are confident the eventual tool produced by the research team will have practical use for Wilmington in meeting its sustainability objectives outlined in the 2018 Comprehensive Plan (including Goal 5), but as well, that the tool will help cities throughout the State of Delaware in creating substantial bill savings while serving sustainability goals.

1.3. Case Study Area and Neighborhood Focus

The research is restricted to the municipal boundary of Wilmington. The project makes use of the municipal boundary 'shapefile' (a filetype used in geospatial analysis) that is publicly available via FirstMap Delaware, a public platform for geographic information system (GIS) data. [2]This GIS file contains the municipal boundary for all municipalities in Delaware. We extract the municipal

[2] The municipal boundary layer used can be found at: https://firstmap-delaware.opendata.arcgis.com/datasets/municipalities.

boundary for Wilmington for the purposes of this project. Figure 1 provides an overview of the municipal boundary. As is visible in Figure 1, the municipal boundary of Wilmington has an idiosyncratic profile. The profile covers the main parts of the city as well as several areas, like the Wilmington harbor area and the Cherry Hill waste treatment facilities.

To support the planning strategies of the city, the research outputs are aggregated to the relevant planning scales of the city. In particular, the research outputs are aggregated to the neighborhood planning council level. In other words, the estimated electricity consumption pattern for each neighborhood planning council - what can be considered a 'baseline' profile - is generated by aggregating building-level electricity consumption estimates for each building in each planning council's jurisdiction. In a similar fashion, the savings potential is aggregated to the planning council level in order to help planning and sustainable development efforts of the city.

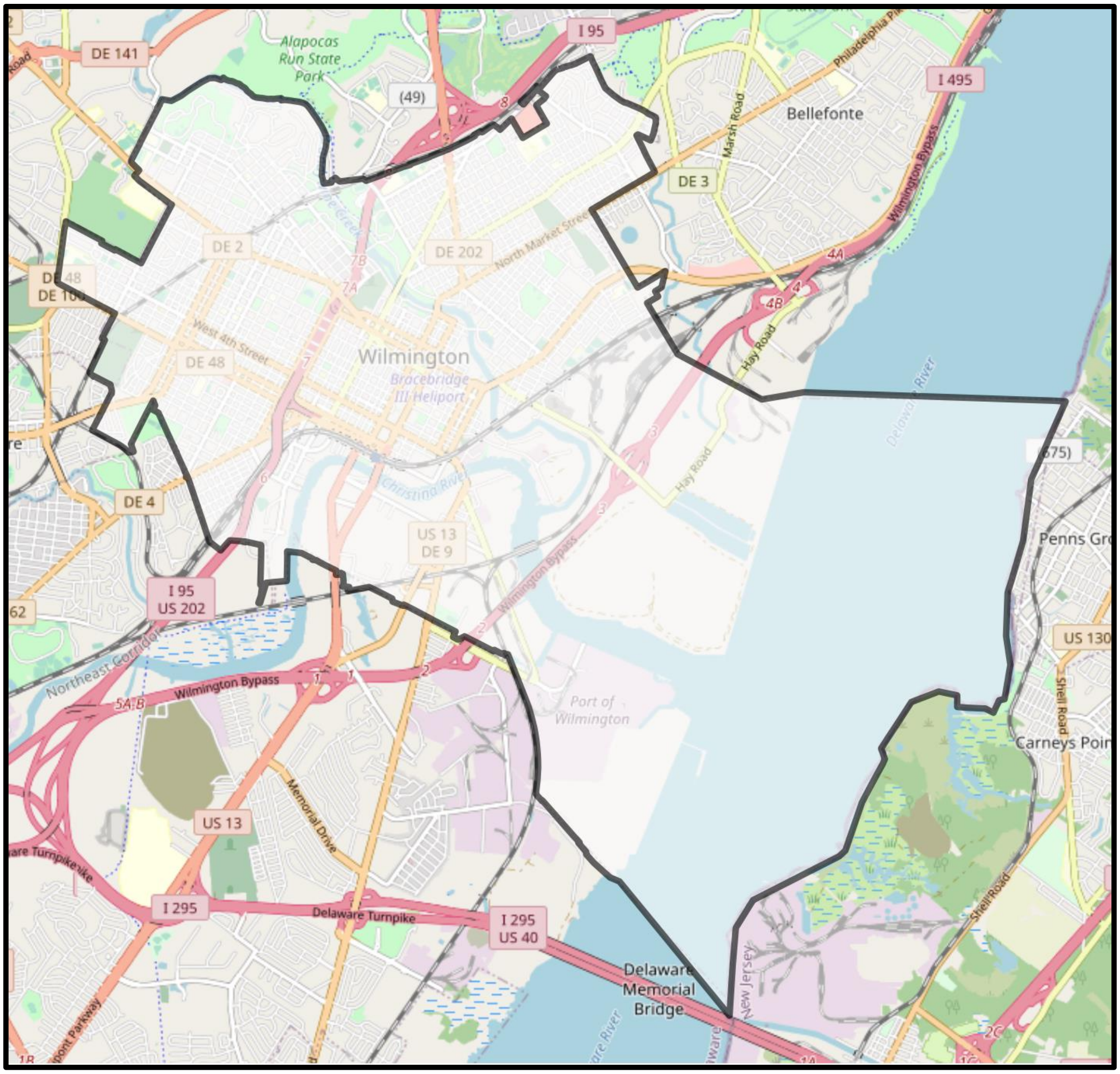

Figure 1. ***Municipal Boundary of Wilmington, Delaware.*** *The project is limited to the area encapsulated by the municipal boundary, i.e. this is our 'area of interest'.*

Since it has particular importance throughout the research as the main unit of measurement for electricity consumption and savings potential, the neighborhoods of Wilmington are described here in a bit more detail. The 2028 Comprehensive Plan for Wilmington divides the city into 11 neighborhoods (Figure 2). The 11 neighborhoods are included in the Comprehensive Plan to enable downscaling of city-wide goals and objectives into neighborhood-level recommendations. The 11 neighborhoods are, in alphabetical order:

1. Bancroft Parkway / Delaware Avenue: the neighborhood is home to a varied housing stock that includes single family homes, row houses and apartment buildings. The area includes the well-known commercial center of Trolley Square.
2. Baynard Boulevard: residential neighborhood just north of the Brandywine Creek and Park with commercial activity along N. Market Street.
3. Browntown-Hedgeville: The area includes a dense, older residential neighborhood as well as newer waterfront development. A key feature is that the neighborhood is split in half by I-95.
4. East Side: The area is mainly residential with a mix of medium and high density housing in close proximity to downtown and with riverfronts on both the Christina River and the Brandywine Creek.
5. Midtown Brandywine/Central: includes Wilmington's downtown core as well as the residential neighborhood of Midtown Brandywine. The area is home to a lot of new development.
6. Northwest: The Northwest is a residential neighborhood along the boundary with New Castle County.
7. Price's Run/Riverside/11th Street: The area includes a series of unique neighborhoods, commercial corridors and gateways located just north of Wilmington's downtown core and the Brandywine Creek and just west of the Amtrak Northeast Corridor.
8. Southwest: a far west neighborhood bisected by a rail line home to low density and medium residential, as well as commercial areas focused around Lancaster and Greenhill Avenues.
9. South Wilmington: a residential and industrial waterfront neighborhood on the south side of the Christina River.
10. West Center City: The area is mainly residential predominantly consisting of rowhouses, that is adjacent to the downtown core.
11. West Side: The area is mainly residential and consists mostly of rowhouses, as well as some single-family detached homes and apartment buildings.

Figure 2. **The 11 Planning Neighborhoods of the City of Wilmington (City of Wilmington, 2019).**

1.4. Structure of the Report

The report presents a novel building-by-building method to analyze energy efficiency opportunities urban building stock. We provide an early trial of the method's use in a case study of Wilmington's estimated building electricity consumption and savings profile. To that end, the report is structured as follows:

Section 2: Urban Sustainable Energy Potential Evaluation. Establishing city-wide sustainable energy potential is an active area of investigation. This section introduces the FREE-CEEP model and describes its main functionality as an urban planning tool.

Section 3: 3D Model of Wilmington. One of the primary inputs to the tool's operations is a description of the external shape and size of each building. As part of the research effort, a three-dimensional model of the city of Wilmington is constructed using available Light Detection and Ranging (LIDAR) data. This section reviews how such a model is created and outlines key characteristics and relevant insights. The section consists of the following two subsections:

- Building a 3D model: methods and data;
- Extracting useful dimensional data from the 3D model.

Section 4: Electricity Use in Wilmington. Available data for the City of Wilmington and its municipal government operations are reviewed. This review is performed to set initial boundary conditions on the possible electricity consumption of the city. While not suitable for model validation due to the unavailability of specific data components, this initial consumption review sets a possible boundary range of pre-retrofit consumption levels – if the output of our model generates a pre-retrofit baseline wildly different from these data overviews, it might suggest the presence of unknown limitations of our strategy.

- Overview of available city-wide electricity use data, including residential and commercial electricity consumption. This part of the section reviews, in particular, the electricity consumption data reported by the incumbent utility, Delmarva Power.
- Overview of electricity consumption in service of municipal government operations.

Section 5: Electricity and Buildings. The buildings sector is a particularly relevant portion of the overall electricity consumption profile. We describe the building stock of Wilmington in detail. Section 3 can be divided into the following subsections:

- Review of the importance of the buildings sector within the electricity sector.
- Data on the building stock of the City of Wilmington as a whole.
- Description of relevant building stock characteristics.

Section 6: Application of our Consumption and Savings Model. To illustrate how to estimate the consumption and electricity savings profile of Wilmington, a 3D depiction of each building in the City is introduced. We then introduce energy conservation measures (ECMs) to estimate possible energy savings, relying on a classification scheme that simplifies the building stock of Wilmington into several possible building categories. These building categories are established by the U.S. Department of Energy (DOE). We estimate the potential savings that could be realized by implementation of the selected ECMs using a DOE simulation software in a specified trial case.

Section 7: Next Steps

2.0. Urban Sustainable Energy Potential

Urban centers are increasingly positioned as main decision-making partners regarding our common energy future. Large and small cities alike have taken up this responsibility by issuing ambitious energy targets that will transform urban energy economies across the nation. Targets of this kind are typically focused on deploying renewable energy generation. For example, many cities in the U.S. have introduced 100% renewable energy targets and several of these cities have actually already achieved this level of renewable energy sourcing (Adesanya et al., 2020). Performance evaluations of cities across the world suggests these types of efforts are resulting in significant greenhouse gas emission reductions (Kona et al., 2018, 2019; Kuramochi et al., 2017; Paolo Bertoldi et al., 2020; Roelfsema, 2017). In the U.S., the 25 largest cities have introduced energy targets and other policy measures that is estimated to reduce greenhouse gas emissions between 95 and 125 million metric tons of carbon dioxide equivalent by 2030 – a reduction of about 26%-35% against their business-as-usual scenario (Roelfsema, 2017). Similarly, another assessment of 54 U.S. cities estimates emission reduction of 70 MtCO2eq below their business-as-usual estimate by 2025 – equivalent to a 22% reduction against 2015 emissions of these cities (Kuramochi et al., 2017).

City targets for sustainable energy are now common but focus heavily on renewable energy. Consideration of city-wide energy reduction potentials typically achieves less attention as policy targets are phrased in terms of local government energy use reduction objectives, not city-wide targets (American Council for an Energy Efficient Economy, 2021). Any community-level efforts typically rely on incentives to motivate energy efficiency interventions on a one-by-one basis.

The modeling of urban sustainable energy potential has followed a similar trajectory: sustainable energy evaluations of cities are now relatively common but focus heavily on renewable energy, in particular rooftop solar (Taminiau & Byrne, 2020). Nevertheless, several city-wide evaluation methods for energy efficiency have been introduced and find energy saving potentials ranging from 20% to 40% (Byrne et al., 2020; Chen et al., 2017; Mastrucci et al., 2014; Pasichnyi et al., 2019;

Shahrokni et al., 2014; Tong et al., 2016). For instance, evaluation of Rotterdam, the Netherlands finds energy savings options as high as 70% for older dwellings and ranging from 24 to 61% for dwellings built post-1945 and before 1991 (Mastrucci et al., 2014). Citywide energy efficiency achievements of 13–14% are recorded for New York City through local energy disclosure practices (Meng et al., 2017).

The identification of city-wide energy efficiency potential increasingly depends on sophisticated and highly detailed catalogues of urban building and energy conditions. The rising availability of this type of data now enables an approach that goes beyond methods deployed in the past. Previous attempts at energy efficiency identification relied on more general perspectives of energy use, grouping for instance the built environment into sectors or technology levels. These sectoral or technology-based approaches had limited to no access to individual building-level conditions. With the emerging availability of high-resolution, low-cost geospatial databases that describe building conditions, layout, morphology, and other relevant parameters, it is now possible to evaluate entire cities on a building-by-building basis. Urban building energy models have been introduced to assess large-scale consumption patterns across tens to hundreds of thousands of buildings using advanced modeling and simulation techniques (Howard et al., 2012; Kontokosta & Tull, 2017; Reinhart & Cerezo Davila, 2016).

Under this new type of approach, all buildings in the city can be assessed without the need for an on-site audit. Essentially, through the use of remotely sensed data, known building-level conditions, and other databases, one can perform a "virtual audit" that can approximate the level of detail and value of an on-site energy audit for energy efficiency. This prospect could come with significant benefits:

- Low-cost estimation of city-wide energy efficiency potential that can be downscaled to the individual building level and every level in between.
- Confidence in energy efficiency estimates to the point where strategic policy decisions can be introduced and formalized. With sufficient levels of accuracy, validation, and

confidence, the approach could be used to extract financial commitments from external investors.

- Avoid the time-consuming and costly process of on-site audits that would simply take too much time and be too expensive to conduct at the city-scale. At minimum, the virtual audit assessment approach could be used to prioritize buildings and communities for on-site evaluation. If the accuracy of, and confidence in, the virtual audit is high enough, the approach could perhaps avoid the need for on-site audits entirely.

We developed an urban building energy modeling strategy that can capture these benefits. This section of the report introduces and describes the main components of the method. A previous iteration of this tool was applied for the City of Newark in Delaware and produced estimates within +/-2% of known consumption at the sectoral level (Byrne et al., 2020). The approach consists of two main steps:

1. Estimate the consumption patterns of each building in the city; and
2. Determine the effect of possible energy efficiency intervention measures.

2.1. Estimating City Scale Consumption using Building-level Analysis

The model used in this research relies on detailed, high-resolution, and sophisticated data. A main data component of the analysis is to rely on so-called Light Detection and Ranging (LIDAR) data that is increasingly used by cities to evaluate a broad range of different energy and non-energy matters (Taminiau & Byrne, 2020). Using this data, the model identifies the above-ground spatial dimensions of each and every building in the city. A GIS shapefile that provides the location, number, shape, and size of each building is used to identify every building.

Next, each building is categorized according to its alignment with U.S. Department of Energy (DOE) building benchmarks for commercial buildings and Pacific Northwest National

Laboratory (PNNL) building benchmarks for residential buildings. In total, we separate the Wilmington building stock into 18 different benchmark models.

Knowing each building's spatial characteristics, we inflate or deflate the associated benchmark model accordingly to extract an expected pattern of electricity consumption. In other words, the walls, floors, ceilings, windows and doors of each benchmark model are inflated or deflated based on the observed size of the building in question. The underlying thought is that a building's size, coupled with its use case, is a strong indicator for the overall electricity consumption pattern. In general terms, the larger the building or facility, the more electricity consumption takes place. A recurring computation is performed to process the entire building stock of Wilmington in this manner.

To calculate the various components of the analysis, we rely on several key software options. As mentioned, the spatial dimensions are derived from LIDAR data and are processed in ArcGIS software as well as Jupyter notebooks. We rely on a data processing software called KNIME for many of the calculations performed in this analysis as it enables scalability, reproducibility, and model development. A critical component in the analysis is the use of DOE Energy Plus software in conjunction with its companion software jEPlus in order to pursue repetitive calculation and building engineering calculations to establish performance profiles.

The model process is visualized in Figure 3. As documented in the Figure, the model's processing can be captured along the following steps:

1. We identify and extract all dimensional properties of the exterior spaces of the building benchmark (walls, roofs). These values are normalized by dividing the model by itself, leading to a normalized description of a building where, for instance, all walls range from a value 0 to 1.
2. We assign benchmark models to each 2D building footprint based on its use case (e.g. single family dwelling).
3. We identify the values of the exterior spaces in the 3D model created using the LIDAR data – all above-ground spaces that fall within the polygon footprints are extracted using ArcGIS software. For the roof height, we use the mean value as obtained from drawing

another footprint within the original building ground floor area that is 3 feet away from the original building ground floor footprint's edges. This is done to avoid edge effects.

4. We multiply the normalized building benchmark model by the dimensional values extracted from the 3-D model using KNIME software. The result is an individual building model equal in size to the observed building that can be modeled in Energy Plus software for its energy performance.
5. As given in the illustration, this process is done for each building, creating many individual building models that are each equal to the corresponding building observed in the LIDAR data. There are four such dimension sets illustrated below, but the analysis was performed for all 8,125 polygons.
6. Finally, using jEPlus – the companion software to Energy Plus – we insert each of these new building models into Energy Plus and calculate its energy performance profile. jEPlus enables iteration across many simulations allowing for the creation of 8,125 "input data files" (Energy Plus format).

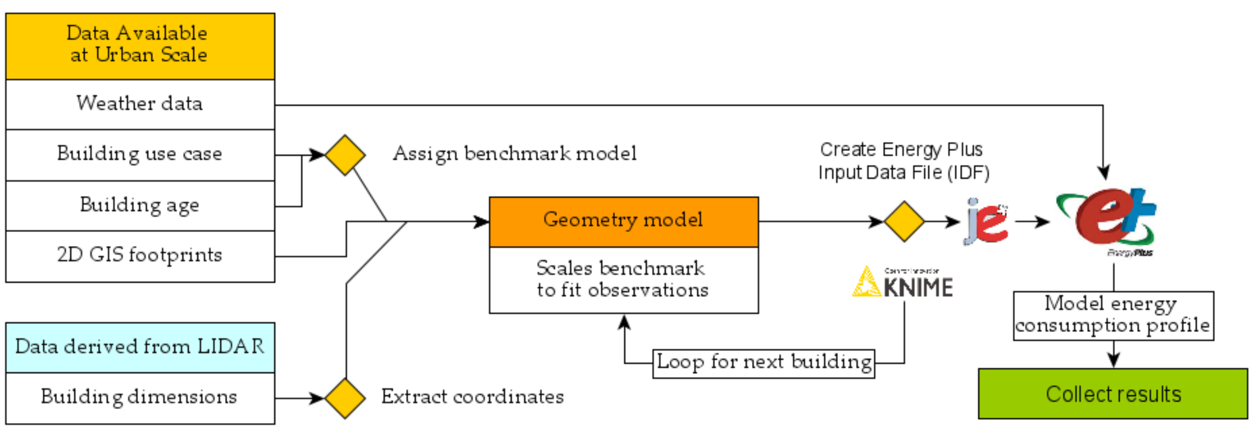

Figure 3 Illustration of the advanced building consumption model

The model essentially applies a relationship between the geometric characteristics of each building and its annual electricity consumption where this relationship is determined by the conditions provided in the benchmark model. In other words, the benchmark model dictates energy performance by specifying items such as material, insulation, zones, etc. but this performance is tested against different size buildings. Future iteration of the tool will go beyond the application of benchmark buildings as additional parameters and data are included in the assessment. For example, surveys of building-level performance, occupancy schedules, last known retrofit, etc. could provide insight that could be used to further specify a building-level model for that particular building. The model does not directly take into account the nature and diversity of human behaviors in buildings. Data on these variables is often anecdotal at this time. Research is expanding in this regard but it has not reached a level where we can include it in the project's model.

As it stands for this round of assessment, the approach has two key assumptions:

1. The buildings in Wilmington perform like a "typical" benchmark building of the corresponding class; and
2. Annual electricity consumption is dependent on the size of the building (in addition to the variables that remain unchanged, like material);

The first assumption will increasingly become less relevant as the approach develops as each building will be allowed to deviate further from 'typical' conditions as additional sources of data are incorporated.

The iterative process for each building generates a consumption profile of building engineering quality – it is based on U.S. Department of Energy software that, using the specified input parameters, calculates performance profiles that account for interactive effects. The end output of the process is an estimated energy consumption pattern for each building. This energy consumption pattern can be positioned as a pre-retrofit baseline in the context of a city-wide energy efficiency strategy. In addition, the tool can be used for scenario-building relative to, for instance, business-as-usual conditions.

2.2. Estimating Citywide Building Energy Savings

The next step in the assessment approach is to estimate the effect of possible energy efficiency intervention measures that reduce energy consumption. Figure 4 describes the approach taken to model the building electricity efficiency opportunity. The approach illustrates that, for each building, the analysis models the performance of that building based on its benchmark model and the suite of ECMs applied for that benchmark model. In effect, we revalue the energy consumption contribution of the building components by changing their characteristics to a post-retrofit condition. For example, for lighting, key metrics are Lighting Power Density (LPD), radiant fraction, and visible fraction. The pre-retrofit values for these metrics are determined by the benchmark model. Post-retrofit values for these cases are extracted from the literature and market surveys. We apply the same ECMs and post-retrofit values as was done for our previous research for Newark (Byrne et al. 2020).

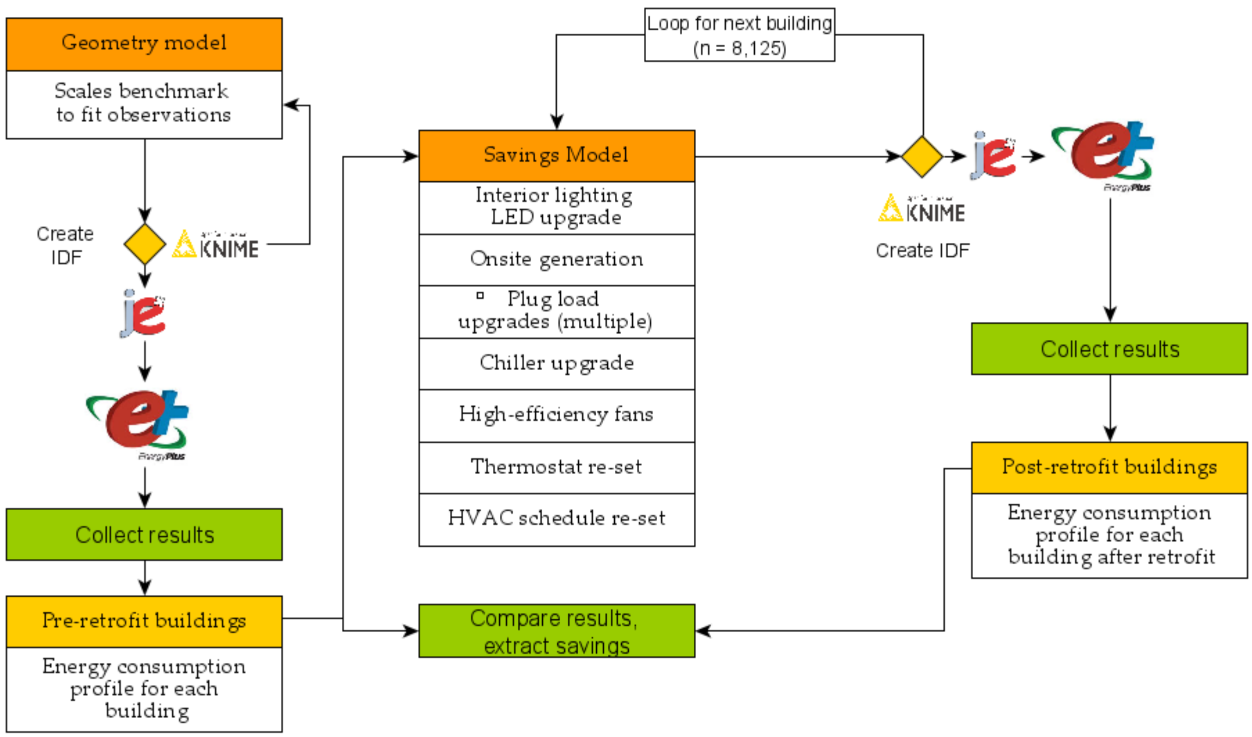

Figure 4 Illustration of the energy savings model

The second step of the approach provides a new energy consumption pattern for each building, the post-retrofit performance profile. The tool can model a broad range of possible energy efficiency interventions in this way and the various post-retrofit performance profiles can be compared and ranked based on pre-selected criteria. The post-retrofit performance profile is as such heavily dependent on the selection of measures. The post-retrofit performance profile can be contrasted against the pre-retrofit profile in order to estimate the available savings.

3.0. Creating a 3D Model of Wilmington

The LIDAR data is used to establish a 3D model of the built environment in Wilmington. This section, as such, covers the following:

1. A description of the LIDAR data.
2. The height profile that is established for the City of Wilmington using the LIDAR data.

3.1. LIDAR data for the City of Wilmington

To obtain height information for each building in Wilmington, we obtained Light Detection and Ranging (LIDAR) data covering and surrounding Wilmington from a data platform hosted by the National Oceanic and Atmospheric Administration (NOAA), available at: https://coast.noaa.gov/dataviewer/#/. [3] The LIDAR coverage is illustrated in Figure 5, showing the grid overlay of LIDAR coverage. The tiled grid overlay illustrated in Figure 5 is a common way of showing LIDAR coverage where each grid represents one datafile. From Figure 5, it is clear that the LIDAR coverage is sufficient: we have data for every area of the city.

[3] 2014 USGS CMGP Lidar: Post Sandy (DE & MD). Projection: State Plane 1983, Zone: Zone 0700 Delaware , Horizontal Datum: NAD83, Horizontal Units: Meters, Vertical Datum: NAVD88, Vertical Units: Meters, File Format: LAS, Data Classification: Unclassified, Ground, Low Point (noise), Model Key-point (mass point), Water Surface, Class 10 (see metadata), Class 15 (see metadata), Data Returns: Any Points, Ancillary Data: Intensity, Geoid Name: GEOID18.

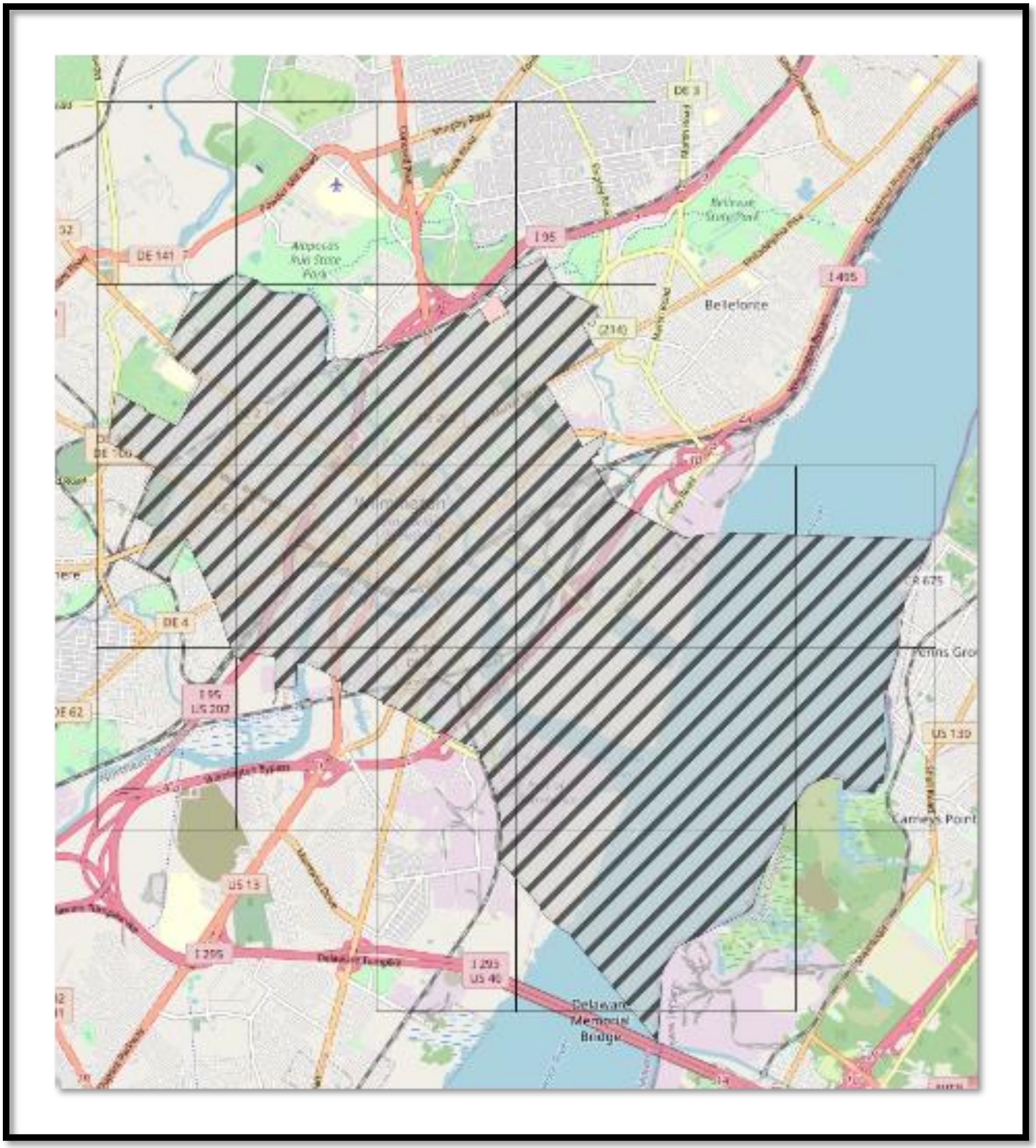

Figure 5. LIDAR coverage of the City of Wilmington, showing the grid pattern of LAS files.

We only show the data that intersects with the municipal boundary. Limiting the data to this coverage pattern reduces computational requirements. In total, these LIDAR files contain

236,922,756 XYZ data points. These ~237 million data points provide a profile of the city in three dimensions. For files associated with grid cells that are almost entirely outside of the municipal boundary, we further subset the data to only keep those X,Y,Z data points that intersect with the municipal boundary. The hatched area in Figure 5 is the area of interest – only the LIDAR data points that fall within this area are included in the results of this analysis. However, the data points that fall outside of the municipal boundary – i.e. the hatched area in Figure 5 – are still relevant as any edge effects need to be accounted. For instance, tall buildings or vegetation just outside of the municipal boundary still interact with the buildings inside of the hatched area, in particular through casting a shadow.

The LIDAR data can be used to establish a 3D representation of each building in the city. This is illustrated for an example building in Figure 6. We have selected a building in a residential neighborhood of Wilmington with fairly dense tree canopy coverage. As given in Figure 6, the building itself is clearly visible as are surrounding tree patterns, rooftop features, and the building's height above ground.

Figure 6 Example of a 3D representation of a building in Wilmington.

A similar representation can be shown for downtown Wilmington to further illustrate how the LIDAR data is used to capture the 3D overview of the city. The illustration in Figure 7 clearly describes the skyline of downtown Wilmington with the library in the middle right of the graphic. As can be seen in Figure 7, the LIDAR data enables a building-level overview that is aware of the surrounding features, specific morphological features of the building that may be relevant, as well as feature-to-building shading conditions.

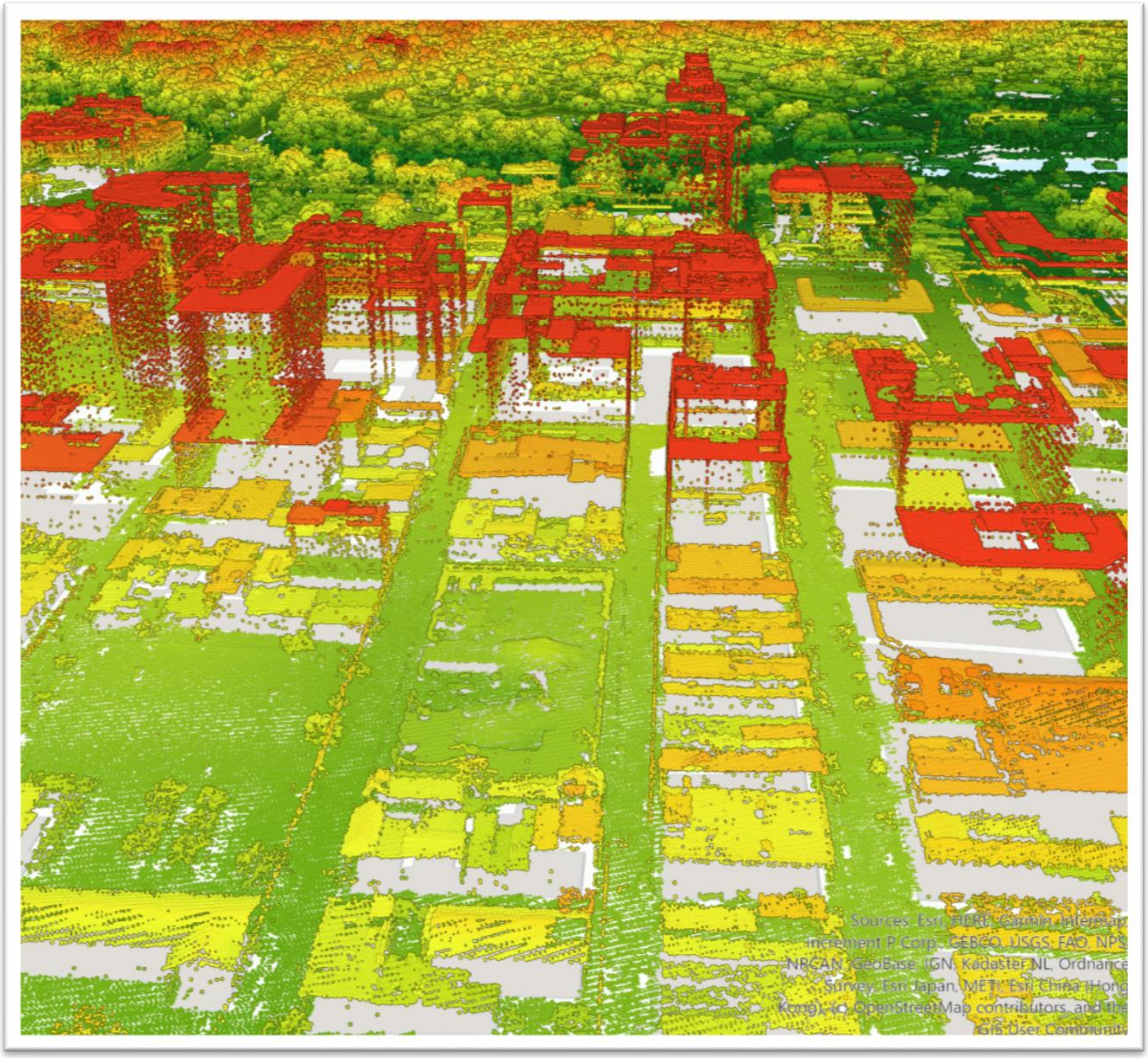

Figure 7 *3D representation of LIDAR point cloud for downtown Wilmington.*

3.2. Height Profile of the City of Wilmington

To determine physical dimensions of buildings such as volume, number of floors, or total square footage, it is necessary to understand the height profile of each building. The process to calculate the height profiles of each building are to, first, establish the ground elevation profile of Wilmington. This is also called the Digital Terrain Model (DTM). The DTM relies only on the

LIDAR data points that are classified as 'ground', all the other LIDAR data points are excluded from the visualization. [4] In other words, the DTM shows the ground elevation of the city. In a DTM, features that are especially visible include rivers and streams as they carve a path through the city. The DTM is used to establish the ground level elevation values for Wilmington.

A Digital Surface Model (DSM) can also be extracted from the LIDAR data. A DSM contains all the above-ground features and the ground-level data points. In a DSM, the outline of the buildings of Wilmington, trees, cars, and other above-ground features are visible. Using this data, the height of above-ground features can be calculated at high accuracy. However, considering the DSM contains both the ground level elevation values and the above-ground height values, an accurate determination of the rooftop height above ground level requires the creation of a third dataset, a so-called normalized Digital Surface Model (nDSM). This third dataset can be obtained by deducting the ground-level elevation values, as captured in the DTM, from the ground plus above ground values, as captured in the DSM. The nDSM for a portion of Wilmington is shown in Figure 8.

As shown in Figure 8, the above-ground features are easily identifiable. Buildings, especially, with their clear polygonal shapes, can be readily identified from the nDSM. In addition, we can use the building footprint data, which shows the location of each building for which we have available data, to filter the nDSM for only those locations that there is a building. Effectively, we mask the above ground features in order to only keep the data that overlaps with the building footprints as captured in the polygon shapefile. Our analysis is only interested in building-level physical dimensions, so any data external to the building footprint can be excluded. The result is a building-level overview of height information.

[4] The LIDAR data was processed for classification as per the metadata of the datafile. In other words, the LIDAR data downloaded from the NOAA data sharing platform was so-called classified LIDAR. The FREE research team did not need to classify the data.

Figure 8. nDSM for a portion of the City of Wilmington. The above-ground features are much more noticeable in the nDSM compared to the DTM and DSM. The buildings, but also trees and other above-ground features are easily identifiable. Each cell of the raster is now assigned its above-ground feature. If the cell of the raster is at ground level, it has been assigned the value 0. The white bright spots in the lower right are parts of the river: laser beams reflecting from the water can cause data discrepancies. Since we are interested in building-level features, this issue is irrelevant for our analysis.

The height and building-level overview generated from the LIDAR data can be used to calculate other geometric dimensions for each building such as perimeter, surface area, perimeter-to-area ratio, volume, and number of floors.

4.0. Electricity Use in Wilmington

Unlike for several other cities in Delaware that have municipal utilities and therefore have access to much more detailed electricity consumption data for the city as a whole as well as all of its individual customers, it is important to realize that no data was available that provides direct insight into the city-wide electricity use pattern. Instead, review of the available data regarding electricity consumption in Wilmington establishes the context for the research and identifies possible boundary conditions for electricity consumption ranges. These boundary ranges provide insight into the expected consumption range one might find in a city like Wilmington. Critically, the boundary range is not available as a validation tool – the data described in this section is too coarse. Additional data needs are discussed at the end of the report.

A helpful distinction in this matter is to separate electricity consumption data between, on the one hand, the municipal government of Wilmington's electricity consumption profile and data and, on the other hand, the entire city of Wilmington's consumption profile. This distinction is meaningful as it closely aligns with the available data sources: the City of Wilmington reports electricity consumption for its own operations and other data sources provide insight into consumption patterns of the rest of the city.

For a broader perspective than just the governmental operations in the city, we review several electricity-related data sources for the city as a whole. In particular, we take a close look at the following data sources:

1. City of Wilmington franchise revenues from electricity retail sales within city boundaries;
2. Estimated Delmarva Power customer counts within city limits;
3. Existing distributed renewable energy systems in the city to get a sense of scale;
4. Delmarva Power electricity sales data for the state of Delaware; and

For the municipal government of Wilmington, we cover the following data points:

1. Electricity consumption patterns of public buildings;

2. Ordinances and recent programs maintained by the City of Wilmington that relate to energy in general and electricity specifically;
3. City of Wilmington costs due to electricity use at public facilities and to operate city government.

Using this data, we identify boundary conditions on city-wide electricity consumption of ~800 GWh – 1,100 GWh. In addition, we identify a energy poverty overview of the ctiy which suggests portions of the city spend considerably more of their annual income on energy than other portions of the city.

4.1. Electricity Franchise Revenues

The City of Wilmington's annual budgets provide insight into the electricity franchise fees levied upon Delmarva Power for its retail electricity sales inside city boundaries. In particular, the City of Wilmington levies a 2% tax on the gross revenues from electricity retail sales in the city. Delmarva Power is the sole source of revenue in this category.

The City of Wilmington Local Franchise Tax levies 2% on all delivery and supply services, in the City of Wilmington. The Delaware electric tariff description reads: "In addition to the charges provided for in this Service Classification, City of Wilmington Local Franchise Tax shall apply to all services, rendered in the City of Wilmington" (Delmarva Power, 2018). From the levied franchise fees, we can determine Delmarva Power's total gross revenue from retail sales in the city (Table 1). Approximately $40-$50 million dollars in annual electric retail sales take place in Wilmington according to this data. The projection for FY2021 is substantially lower than figures for previous fiscal years. This is due to revisions in the Delmarva Power franchise agreement and a continued trend of lower electricity use. It is as of yet unclear whether or how any long-term effects from the COVID-19 pandemic will affect future city-wide electricity consumption.

According to the Exelon 2019 Annual Report, Delmarva Power and Light serves about half a million customers across its 5,400 square miles of service territory in Maryland and Delaware (Exelon, 2019). The main city served by Delmarva Power is Wilmington according to the Exelon

2019 Annual Report (Exelon, 2019). Total revenues reported by Delmarva Power for bundled electricity retail sales throughout the state are about $458 million in 2019, meaning that the estimated ~$46 million in retail sales in Wilmington in 2019 (Table 1) represents about 10% of Delmarva's total revenues.

Table 1. Overview of the Franchise Fees Levied by the City of Wilmington on Delmarva Power for its Retail Electric Sales inside City Boundaries. The estimated total gross revenue is likely an undercount as some customers to Delmarva Power are exempted from the local 2% tax. Sources: Annual Budgets of the City of Wilmington.

Fiscal year	2% Franchise Fee Revenues	Estimated total Delmarva Power gross revenue from electricity retail sales inside city boundaries
FY2016	$952,421	$47,621,050
FY2017	$916,631	$45,831,550
FY2018	$952,421	$47,621,050
FY2019	$921,140	$46,057,000
FY2020	$919,113	$45,955,650
FY2021 (Projected)	$764,123	$38,206,150

4.2. Delmarva Power Customers Per Zip Code

Additional insight is obtained from knowing how many customers Delmarva Power serves within Wilmington city boundaries. One path of discovery is to determine the number of customers per zip code. The number of customers per zip code is provided as part of Delmarva Power's outage reports. For the City of Wilmington, the relevant zip codes and customer counts are included in Table 2. The main relevant zip codes are 19801, 19802, 19805, and 19806. These four zip codes cover the city (and parts of surrounding areas - in particular 19805 covers most of Elsmere in addition to parts of Wilmington). As indicated in Table 2, Delmarva Power serves approximately 44,000 customers in the Wilmington area. This number includes customers served by competitive suppliers. [5]

Table 2. ***Number of Delmarva Power Customers per Zip Code.*** *Source: (Delmarva Power, 2020)*.

Zip code	Number of Delmarva Power customers
19801	9,057
19802	11,468
19805	18,236
19806	5,287
Total	44,048

Delmarva Power serves a total of 320,954 customers throughout its Delaware service territory. In other words, the approximately 44,000 customers in the Wilmington area represent about 13.7% of Delmarva Power's Delaware customer base by count. Considering the 44,000 customers is likely an over-count due to the coverage of the zip codes, it is reasonable to conclude this figure is of the same order of magnitude as the ~`10% of total revenues described in the previous sub-section.

4.3. Delmarva Power Electricity Sales Data

Delmarva Power doesn't report retail sales data that is specific to the boundaries of the City of Wilmington. Nevertheless, relevant insights can be obtained from the retail sales data that the utility company does report. The following data points are useful:

[5] According to retail choice statistics, approximately 13% of customers served by Delmarva Power were ascribed to competitive suppliers as of September 2020. A higher proportion of commercial customers have selected a competitive supplier (almost 33%) while only ~10% of residential customers make use of a competitive supplier.

- The monthly retail sales data provided by Delmarva Power delivers an insight into the overall load profile of the customer base across the state;
- A breakdown of electricity sales per customer end-user; and
- A breakdown of the electricity sales per end-use function.

4.3.1. Monthly Electricity Sales Data for Residential and Non-Residential Customers

A monthly load profile is available for the entire customer base of Delmarva for residential and non-residential customers. This monthly load profile can be used to evaluate the accuracy of the load inventory assessment. As illustrated in Figure 9, the monthly electric residential sales pattern has pronounced summer and winter month peaks with reduced consumption taking place in the shoulder months. The implication of Figure 9 is that heating and cooling needs increase electricity consumption across the residential customer base of Delmarva Power. In contrast, electricity consumption for non-residential customers has a less pronounced seasonality pattern. The COVID-19 pandemic does not appear to have a clear effect on the overall consumption pattern of Delmarva's customer base.

This information is useful as electricity consumption load profiles can be similar in Wilmington. Residential consumers of electricity likely have similar seasonal sensitivity as observed for the entire residential customer base of Delmarva Power and, likewise, the non-residential consumer base of Wilmington likely has a similarly lower sensitivity to the weather pattern.

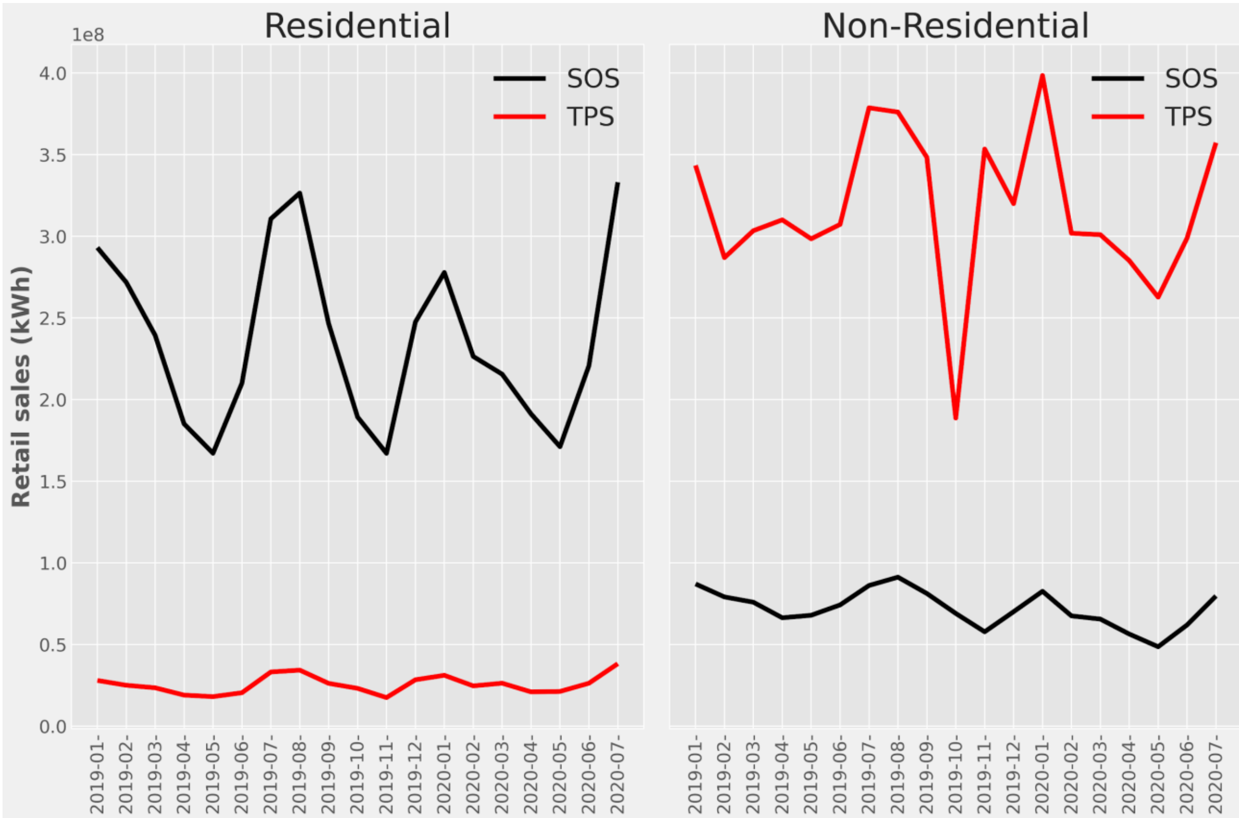

Figure 9. Monthly Electricity Consumption for Residential and Non-Residential Standard Offer Service (SOS) and Third-Party Suppliers (TPS). Data from Delaware Public Service Commission (PSC) Customer Choice website that lists the Delaware Electric Supply Choice Enrollment Information (available at: https://depsc.delaware.gov/electric-regulation/).

4.3.2. Delmarva Power Breakdown of 2019 Sales

Delmarva's Delaware state-wide retail sales are predominantly residential (Table 3). Most residential customers have remained with Delmarva's standard offer service (SOS) while commercial and industrial customers have switched to delivery-only services from Delmarva Power. Historical breakdowns of electricity consumption show that, out of the approximately 3 TWh in residential sales, about ⅔ is for non-space heating and ⅓ is for space heating purposes.

The information is useful as it provides insight into Delmarva Power's customer base breakdown. Combined with the other data sources reported in this interim report, a profile of electricity consumption can be extracted for the city of Wilmington. For instance, assuming a similarity to the statewide profile, most customers in Wilmington are residential customers that purchase electricity directly from Delmarva Power (i.e. do not rely on a third party supplier). Total electricity sales in 2019 throughout the state of Delaware was equal to just over 7.9 TWh. Assuming the 10%-14% relationship uncovered above holds true, the City of Wilmington may have an annual electricity consumption pattern that ranges between 792 GWh and 1.1 TWh.

Table 3. 2019 Electricity Retail Sales, Revenues, and Customer Counts per End-user for Delmarva Power in Delaware. Source: EIA 861 Annual Reports.

2019	Type	Residential	Commercial	Industrial	Total
Revenues (000s $)	**Bundled**	352,580.9	104,506	815.3	457,902.2
	Delivery	16,321.7	62,098.1	8,020	86,439.8
Customer Count	**Bundled**	260,007	24,419	61	284,487
	Delivery	26,562	11,374	101	38,037
Electricity Sales (MWh)	**Bundled**	2,853,406	904,380	9,796	3,767,582
	Delivery	295,839	2,758,309	1,105,607	4,159,755

4.4. City of Wilmington Municipal Government Electricity Costs

The municipal government of Wilmington annually publishes their budget. These budgets provide insight into the position of electricity consumption to serve public buildings and exterior lighting for buildings operated by the municipal government. As these reports provide, the local government of Wilmington spends over $1 million annually for electricity costs associated to the city's street- and traffic lights and another ~$1 million per year for other electricity costs (*Figure 10*). Overall, it shows that the electricity costs for buildings' operations are decreasing over time while the streetlight costs appear to be increasing.

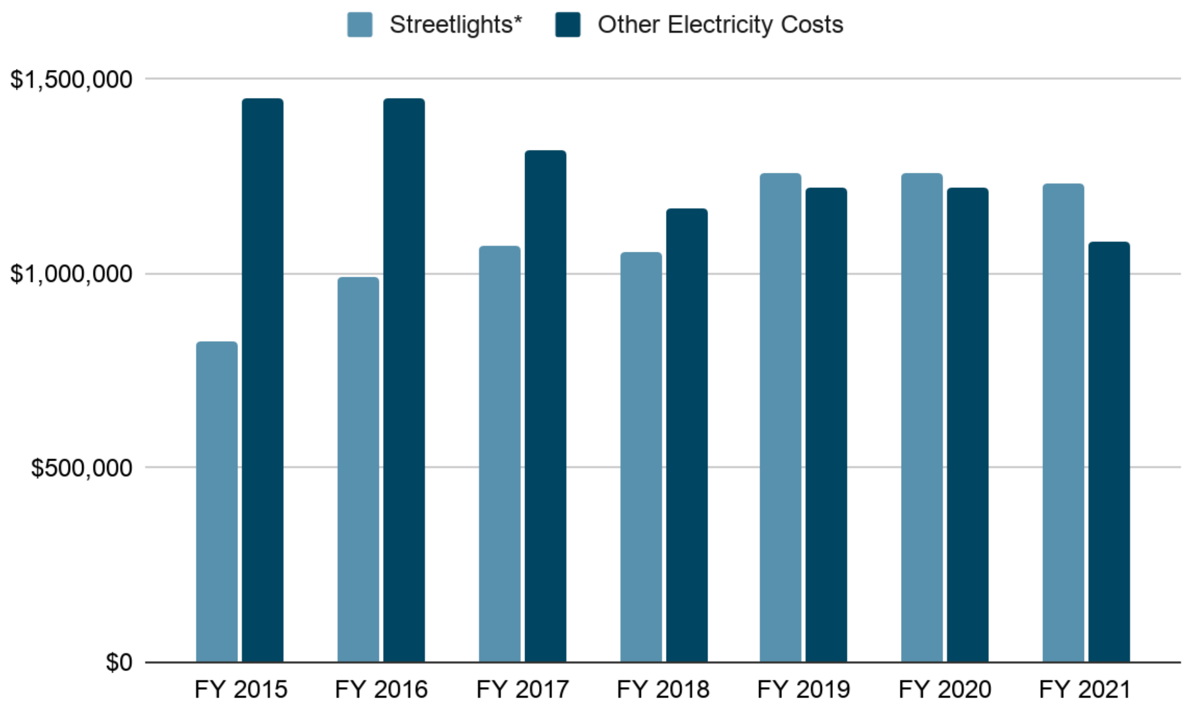

Figure 10. Municipal electricity costs associated with streetlights and other electricity services (including buildings). Data from annual budget reports published by the City.

The monthly electricity consumption data for the City of Wilmington to power local government operations can also be reviewed. This load profile is useful as it helps determine the assessment model's capability to accurately reflect monthly electric load for this selection of buildings. An overview of the monthly electricity consumption pattern for the City of Wilmington local government operations is illustrated below (Figure 11). The monthly electricity consumption pattern shows that the municipal government has a baseline monthly electricity consumption of around 450,000 kWh per month. Depending on the time of year, this electricity consumption pattern can reach as high as almost 600,000 kWh per month.

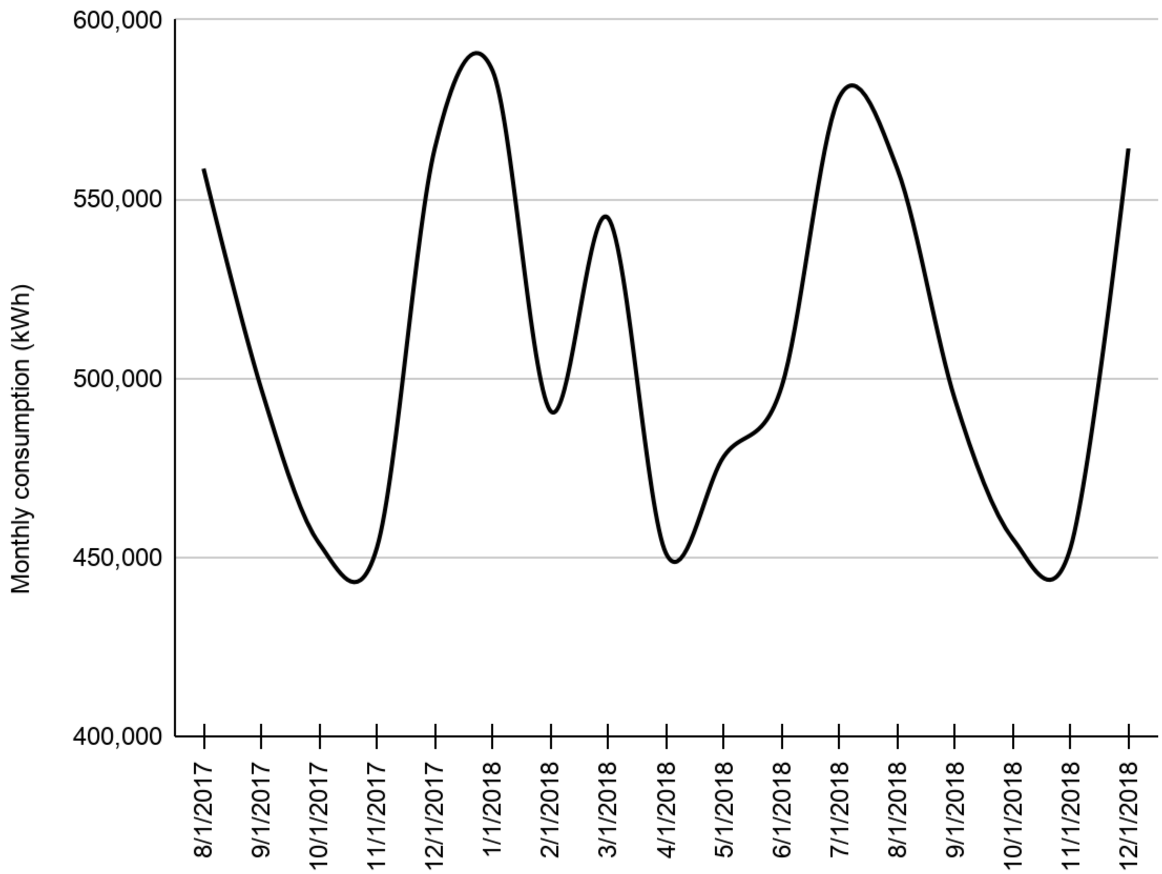

Figure 11. Monthly electricity consumption for Wilmington municipal government (2017-2018). Note: y-axis doesn't start at 0 to emphasize seasonal patterns of electricity consumption.

Another breakdown is possible using monthly electricity consumption provided by Delmarva Power for municipal operations. This data covers 2016-2018 (not all months are available) at the street address level for a total of 3,362 observations. These observations can be separated into 14 different rate categories. Table 4 provides an overview of the 2016-2018 data. The monthly data is available at the street address level. As such, the data can be used to calibrate the electricity consumption model by comparing model outputs to the known building-level consumption data points.

Table 4. Overview of municipal electricity consumption per rate category (2016-2018). Data provided by City of Wilmington public officials. Original data source: Delmarva Power.

Rate Category	kWh	Gross revenue ($)
DPL DE Outdoor Lighting	12,222,816	$2,135,305
DPL DE General Service-Primary	6,089,975	$304,971
DPL DE Med Gen Svc-Secondary	3,958,566	$269,535
DPL DE Sm Gen Svc-Non Demand	411,487	$64,537
DPL DE Unmetered Sm Gen Svc-Non Demand	81,614	$26,265
DPL DE Lg General Service-Secondary	41,738	$5,756
DPL DE Residential Svc	20,615	$3,774
DPL DE Outdoor Recreational Lighting	13,640	$4,588
DPL DE Unmetered Med Gen Svc-Second	2,412	$3,059
TOTAL	22,842,863	$2,817,790

4.5. Socio-Economic and Energy Poverty Conditions

Wealthier households tend to spend a smaller proportion of their budget on energy. In contrast, households of lower average annual income tend to spend an outsized portion of their budget on energy costs. This 'energy burden', as such, is larger for poorer households compared to wealthier households. To identify the energy burden of Wilmington's households, therefore, it is first necessary to gain an understanding of the overall household income pattern of the city.

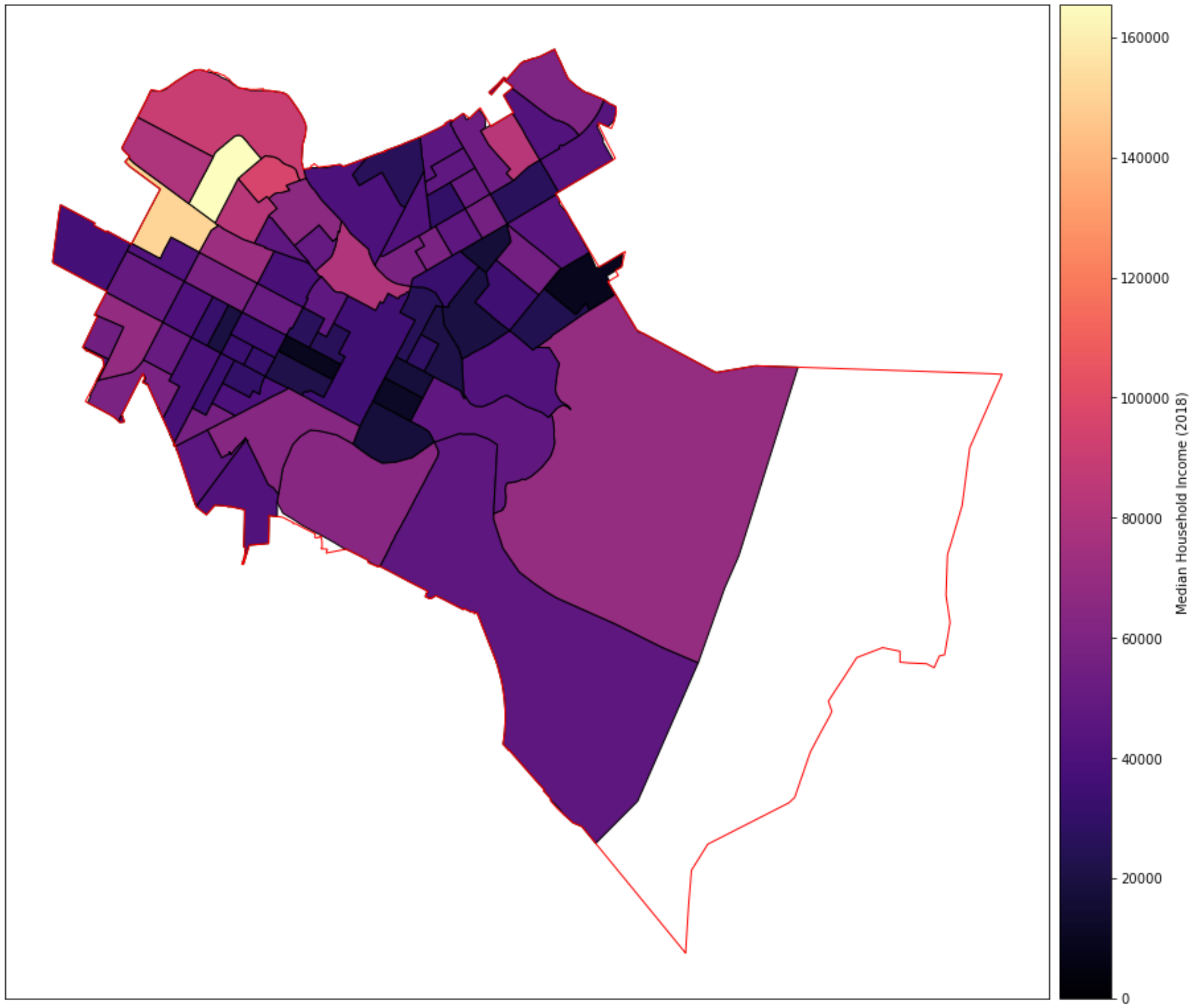

Figure 12 Median 2018 household income by U.S. Census block group.

As indicated in Figure 12, using U.S. Census Block Group data, there is a clear spatial layout to income throughout the city with higher-income families residing in the Trolley Square / Rockford Park area of the city. The darker areas, south and east from downtown, are among the areas of the city with the lowest median household income per year. In fact, the lowest median household income is reported by the U.S. Census at just over $9,000 per year while the highest median value is recorded at over $165,000 per year. This means that there are three orders of magnitude difference between the lowest median household income at the census block group level and the highest median household income at this spatial unit.

This spatial concentration of the socio-economic pattern means that saving one unit of electricity in a low-income block group is considerably more meaningful than saving one unit of electricity at a high-income block group, despite the fact that high-income areas typically use more electricity per unit of floor area. The disproportionate 'energy burden' results in a state of 'energy poverty' for certain households throughout the city. Using data from the Low Income Energy Affordability (LEAD) tool developed by the Office of Energy Efficiency and Renewable Energy from the U.S. Department of Energy, this pattern can be captured by comparing the actual energy expenditures with the energy expenditures as a share of household income (Figure 13). The Figure 13 shows that average annual energy expenditures increase at higher levels of annual income: households at over 400% of the Federal Poverty Level (FPL) spend ~17% more, on average, on energy per year than the households at 0%-100% FPL. As a share of income, however, the difference is much more significant: A household at 400%+ FPL spends on average about 2% of their income on energy costs while a household at 0%-100% stands at 22%. This means that a household at 0%-100%, on average, dedicates over one-fifth of their income to energy. Saving a unit of energy for these households, as such, frees up a much larger share of their budget.

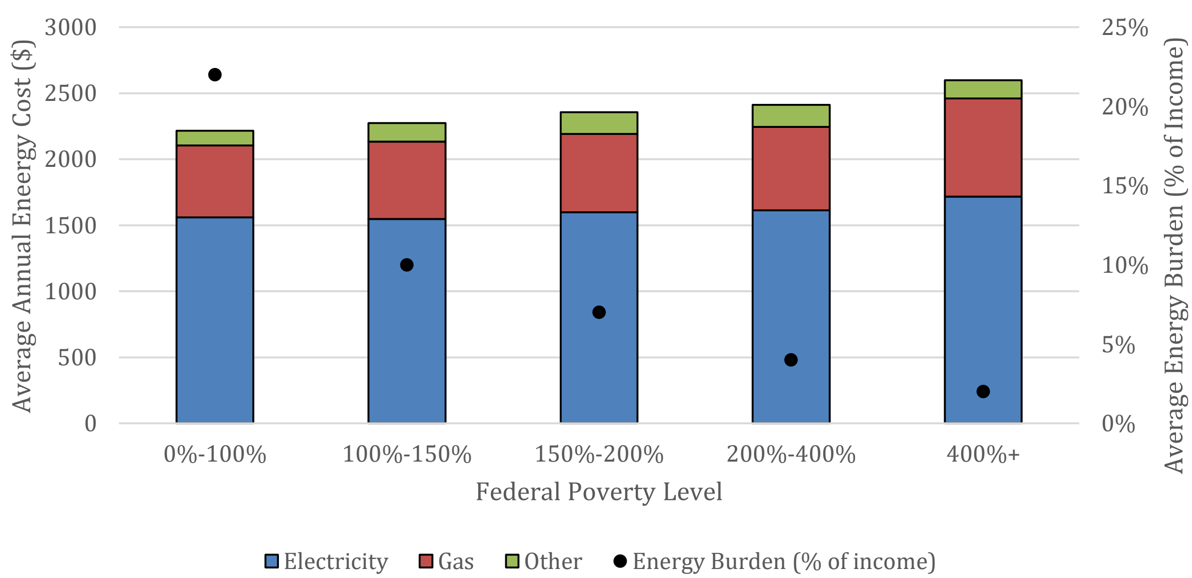

Figure 13 Annual Energy expenditures and energy burden for households in Delaware at different federal poverty levels.

5.0. Buildings as a Key Sector for Electricity Use

The City of Wilmington has a rich history with buildings dating back as far as the 1700s. The city is home to 17 historic districts and 48 buildings on the National Register of Historic Places (City of Wilmington, 2019). It is therefore no surprise that the buildings sector represents a key component of the 2028 Comprehensive Plan for Wilmington. Indeed, Goal 5 outlined in the comprehensive plan reserves a substantial portion of its work items for sustainability improvements for the built environment. Items included in this sustainability objective include a complete audit of the city's building stock, improvements to the energy performance of public buildings, and incentivizing energy efficiency interventions in the remaining building stock of the city (City of Wilmington, 2019).

A city's building stock is often a key contributor to the well-being and living environment of its citizens, both in terms of providing housing and meaningful social interactions but also in terms of a city's energy use and concomitant local air quality concerns and greenhouse gas emissions. In other words, buildings are a key sector for sustainability evaluations. In 2019, buildings, as a sector in the United States, were responsible for about 35% of the U.S. carbon dioxide emissions (EIA, 2019). Recent declines in emissions in the building sector stem primarily from the reduction in electricity-related CO_2 emissions (EIA, 2019)https://www.zotero.org/google-docs/?x9WLq8.

5.1. Building Stock of Wilmington

A useful starting point in the investigation of Wilmington's building stock, is to review the location, shape, size, and number of each building within the city. For that purpose, we rely on a publicly available dataset for the city's building 'footprints' - the ground floor area encapsulated by the exterior walls of each building, not counting the floors of each building, and represented as a 2-dimensional polygon. This dataset of building footprints captured 10,873 footprints that intersect with our area of interest, the municipal boundary of Wilmington. The total ground floor area of all these footprints combined is 4,031,908 square meters. The ground floor footprint of buildings in Wilmington is typically equal to or less than 1,000 square meters but there are several buildings in the database that exceed 5,000 square meters and some are even as large as 35,000 square meters in ground floor area. The distribution of building ground floor area for the 10,873 buildings in Wilmington is illustrated in Figure 14.

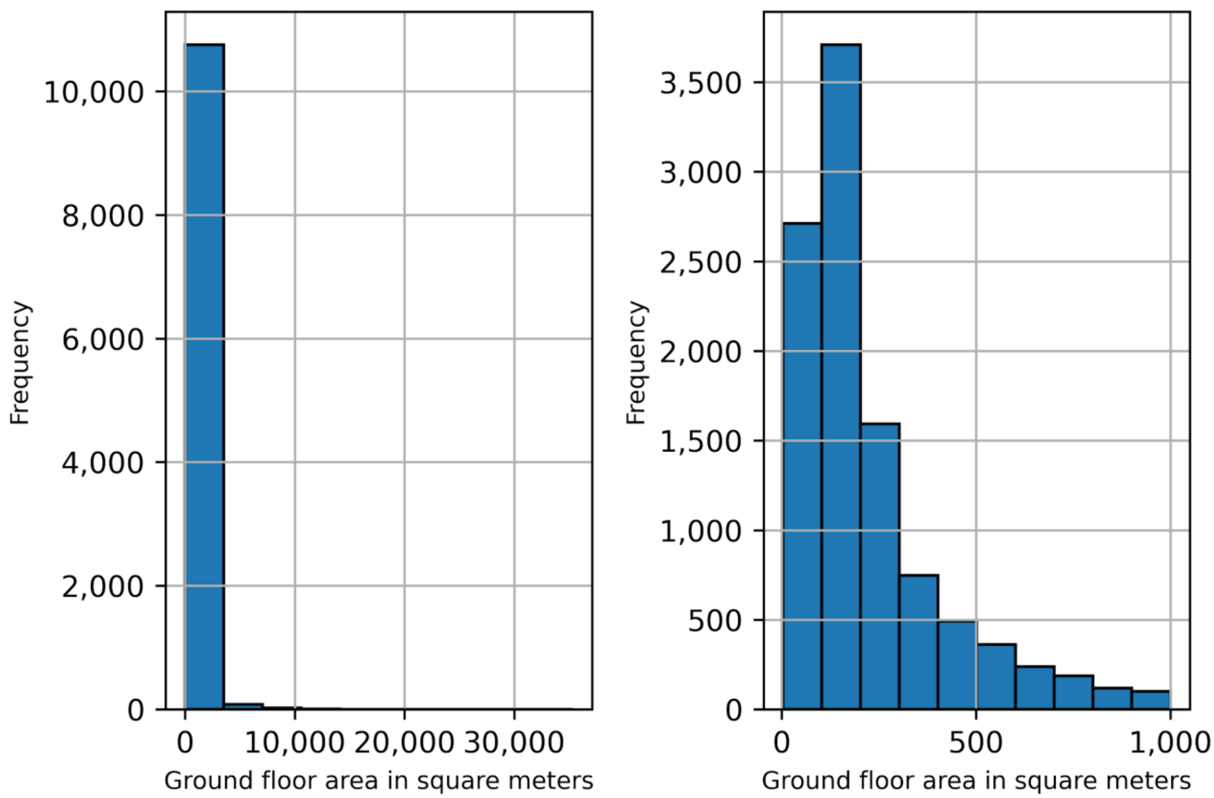

Figure 14. Distribution of footprint ground floor area in the City of Wilmington for all buildings in Wilmington (left) and for only those buildings that are less than 1,000 square meters (right). The vast majority of buildings has a ground floor area of less than 1000 square meters but several footprints have areas in excess of 5,000 square meters in ground floor area.

5.2. Building Use Case Information

An important aspect of the assessment of a building's energy use is to determine what energy is used for in a building (for example, lighting, changing indoor temperatures, cooking, washing, etc.). For this early trial, we rely on publicly available data that describes the typical functions and typical energy uses of typical buildings in Wilmington. However, it is critical to note that buildings differ in their multiple needs and energy uses. As a simple example, one can consider multiple row homes that are attached to each other: this effectively represents one building but has multiple addresses and each address in the structure can be assigned a different use case. Similarly, commercial buildings will differ in function and energy use among themselves (restaurants vs office towers) and between their needs and those of residences.

A publicly available dataset was found that provides building-level attributes for 28,714 records. For each record, the database provides several relevant attributes and features, including the parcel ID number, lot number, address, street number, street name, contact organization, owner's address, and other information. Of particular importance to the project are the contact organization details listed in the data. *Figure 15* provides an illustration of the database, separating the City of Wilmington into 28,714 unique polygons.

Figure 15. Use case information for the City of Wilmington. Data obtained from: https://data-nccde.opendata.arcgis.com/search?tags=boundaries

There are 21,125 unique contact organizations listed in the data. Contact organization information included in the dataset can be binned by the top-10 organizations most often named in the data (Table 5). The Wilmington Housing Authority, the City of Wilmington, the Wilmington Neighborhood Conservancy Land Bank Corp ("Land Bank") and the Woodlawn Trustees Inc [1] are each listed over 100 times in the database. Woodlawn Trustees is a 100-year old charitable foundation created by the Wilmington industrialist and philanthropist William Bancroft.

The contact organizations listed in Table 5 could represent an appropriate first target for 'pilot' operations of an energy use reduction strategy. For example, the City of Wilmington, according to the data, has at least 308 separate entries in the database – many of these entries could be buildings and structures that could have lower electricity bills after a post-retrofit intervention. A pilot program of this kind could support city objectives and, at the same time, establish an energy efficiency market that is ready for larger programs (e.g. city-wide programs for the residential sector).

Table 5. **Top 10 largest contact organizations.** City organizations, state of Delaware, and several LLCs together represent the largest organizations by count of entries in the database. Naturally, most buildings, not listed here, are owned by individual residents or companies.

Top 10 Largest Contact Organizations	Number of entries
Wilmington Housing Authority	349
City Of Wilmington	308
Wilmington Neighborhood Conservancy Land Bank Corp	178
Woodlawn Trustees Inc.	145
Short Sale LLC	87
State Of Delaware	83
Property Exchange LLC	73
Mcleen Company LLC	71
Habitat For Humanity Of New Castle County Inc.	66
Wilmington Housing Partnership Corporation	54

5.3. City of Wilmington Zoning

Zoning data is obtained from the New Castle County GIS Open Data platform (https://data-nccde.opendata.arcgis.com/search?tags=boundaries). The zoning data separates Wilmington into 283 distinct polygons that can be grouped based on their zoning code. Figure 16 color-codes the

283 zoning designations based on their zoning code. Based on its zoning, the city can be separated into distinct areas for distinct functions.

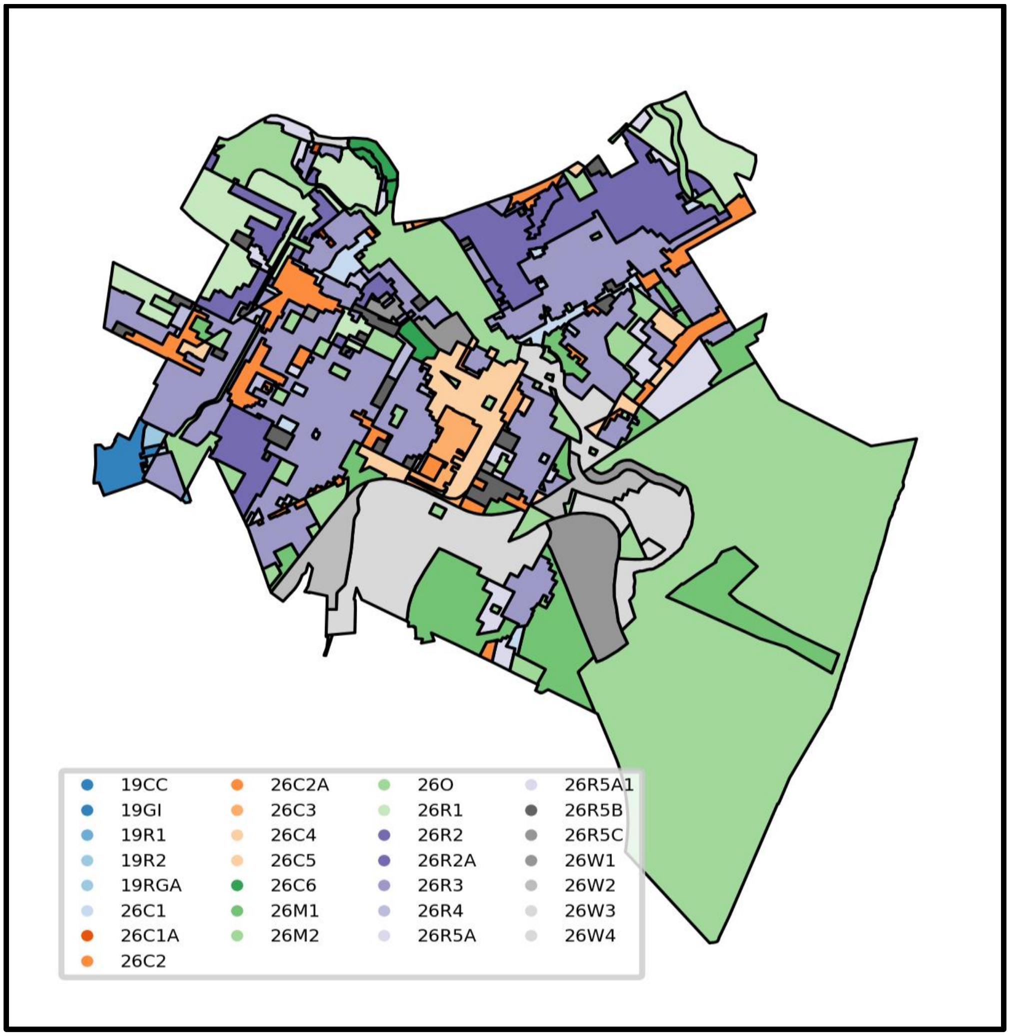

Figure 16. **Zoning overview of Wilmington by zoning code.** For a detailed overview of the zoning codes, see Table 6.

The zoning codes specify different zoning categories as given in *Table 6*. The table shows that there are categories like 'general industry', 'garden apartment', 'neighborhood shopping' and others that are included in the zoning codes. In terms of the total area represented by the different zoning categories, general manufacturing, one family row houses and open space represent the largest areas.

Table 6. Zoning code metadata, showing specific zone descriptions. Note that there are some zoning codes that are described with two different zoning descriptions.

Code	Zoning Description	Number of polygons	Ground Floor Area (sq. meters)
26M2	General Manufacturing	2	8,732,419
26R3	Single Family Row Houses	25	5,458,352
26O	Open Space	49	2,381,962
26M1	Light Manufacturing	14	2,132,432
26R2	Single Family Detached & Semi-detached Dwellings	14	2,032,928
26W4	Waterfront Residential / Commercial	5	1,929,647
26R1	Single Family Detached Dwellings	11	1,657,772
26C2	Secondary Business Center	28	1,021,600
26W1	Waterfront Manufacturing	2	735,189
26R5A	Apartment Houses Low Density	13	644,364
26C4	Central Office	3	589,605
26W2	Waterfront Manufacturing/Commercial	3	588,860
26W3	Waterfront Low Intensity Manufacturing/Com Recreation	1	466,905
26R5B	Apartment Houses Medium Density	24	433,368
26C1	Neighborhood Shopping	25	362,198
26C3	Central Retail	3	275,671
26C5	Heavy Commercial	10	272,248
19GI	General Industry	1	220,630
26R5C	Apartment Houses High Density	7	207,131
26R4	Row Houses W/Conversions	15	187,036

Continued from previous page.

Code	Zoning Description	Number of polygons	Area of Polygons (sq. meters)
26C6	Special Commercial	6	185,342
26R2A	One Family & Semi-detached Dwellings	4	168,443
26R5A1	Apartment Houses Low-medium Density	5	80,163
26C2A	Secondary Office Centers	1	48,018
19RGA	Garden Apartment	1	36,578
26C1A	Neighborhood Commercial	5	18,205
19CC	Community Commercial	1	13,744
19R2	One/Two Family Dwelling	1	9,721
19R1	One Family Dwelling	1	5,816
26R5A	Apartment Houses Medium Density	1	4,638
26O	Waterfront Residential /Commercial	1	3,040

6.0. Application of the Building-by-Building Estimation Model: An Early Trial

The primary contribution of this research is the application of the energy use and savings model. We have selected Wilmington as the case study candidate for this test. Previous sections have introduced relevant portions of the model as well as Wilmington-specific data and items. The preliminary insights reported here illustrate the tool's abilities and generated data overviews. A particular feature for further refinement is the use of differentiated energy savings measures that can be grouped together into specific energy savings packages for strategic understanding. This section documents the primary findings of the preliminary application of the model.

6.1. Annual City-wide Electricity Consumption

Using our methodological framework, we arrive at an early, incomplete estimate of city-wide annual electricity use at ~1 TWh. This estimate relies on the entire city's building stock and estimates electricity consumption for each building. The research team did not have access to electricity use data at the scale and scope needed for full validation of this estimate. We are working on data development to enable validation. Still, we can use this estimate as a hypothetical benchmark for the purposes of showing how savings potential can be methodically estimated building-by-building.

6.2. Annual City-wide Electricity Use Reduction Estimate

A preliminary estimate of 18.9% citywide electricity savings represents a site-level result and depends on only a few conservation measures. Even so, the value of building-by-building analysis can be seen. In the early trial, electricity-related losses propagate through the electricity grid. Site energy can be easily converted to source energy using a site-to-source ratio for a given fuel. We use a ratio from the U.S. Energy Information Administration's (EIA) State Energy Data

System (SEDS) data to estimate the electricity-related losses ratio for Delaware (city-level data are not available) (EIA, 2021b). Using EIA electricity-related losses for the residential and commercial sectors for Delaware, we calculate the site-to-source ratio at 2.543, meaning the avoided electricity is double the savings at the site.

The savings at the source would be roughly equal to 50% of the estimated pre-retrofit city-wide electricity consumption values. This type of contribution could enable significant environmental and climate benefits for the area. Using the emission factors provided by U.S. Environmental Protection Agency (EPA) Emissions & Generation Resource Integrated Database (eGRID) eGRID2018, we can calculate the carbon dioxide ($CO2$), methane ($CH4$), nitrous oxide ($N2O$), and carbon dioxide-equivalent ($CO2{-}eq$) values that are associated with the roughly 50% city-wide electricity sourced reduction. We estimate that the avoided electricity demand resulting from the city-wide electricity savings intervention could reduce $CO2{-}eq$ by 416 million pounds during the first year of program operation. These first-year savings would continue each year that the energy efficiency measures are in effect.

Table 7 City-wide savings at site and source

Electricity Estimates	Sites	Site-to-source conversion	Sources
Consumption (GWh)	~988	2.543	~2,512
Savings (GWh)	~181		~462

Table 8 State output emission rates (eGRID2018) and avoided emissions

Emissions	lb / MWh	Avoided emissions (lbs)
CO_2	898.3	415,014,600
CH_4	0.034	15,708
N_2O	0.004	1,848
$CO_2 - eq$	900.4	~416,000,000

In Figure 17 below, the total savings estimate is illustrated as well as the average savings estimate per building type. The illustration suggests that residential facilities may be a promising focus for high electricity savings opportunities relative to other building types. Single-family households reach almost 25% savings across all buildings in this category. Several commercial building types also appear to promise high city-wide savings.

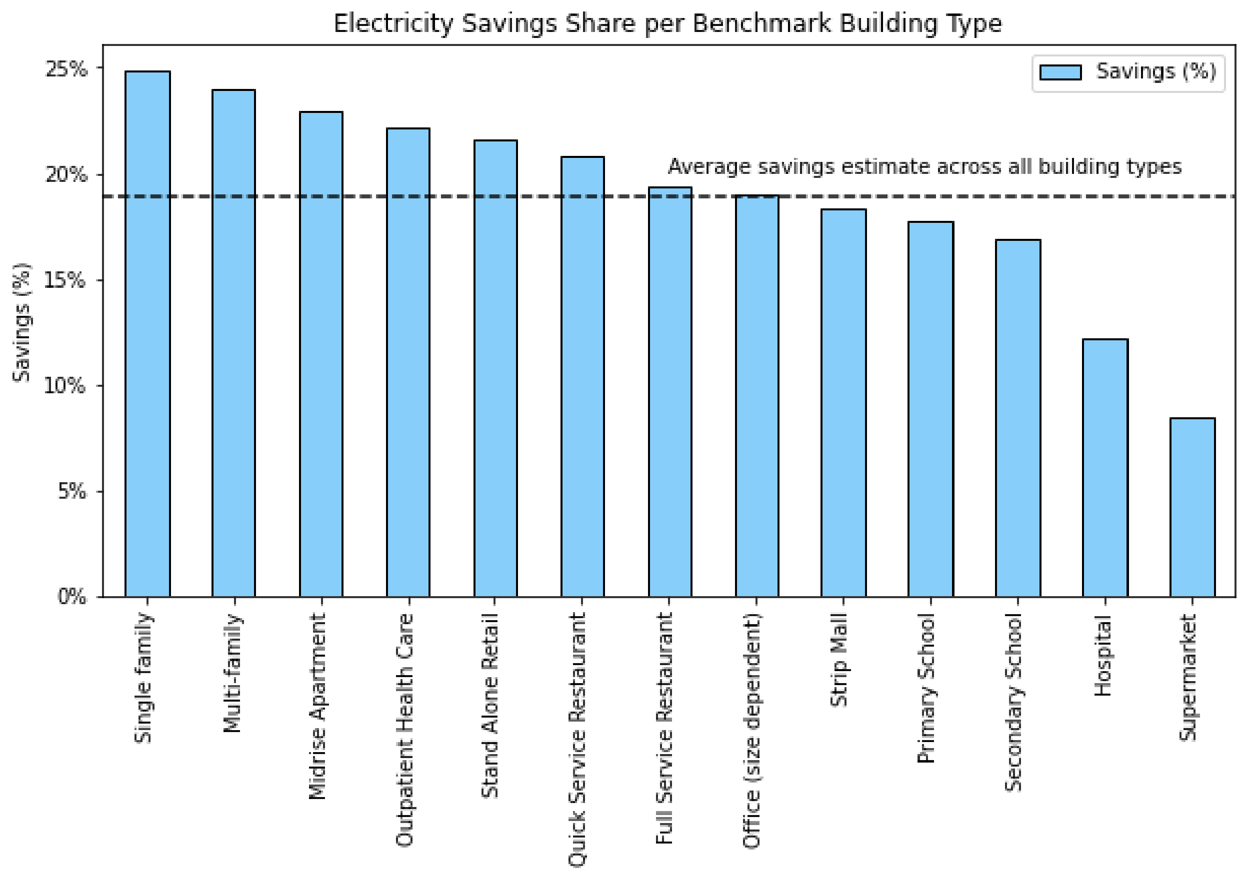

Figure 17 *Electricity savings (est.) per building benchmark category, sorted highest to lowest. Horizontal line indicates city-wide savings estimate.*

6.3. City-wide Monthly Electricity Savings Estimate

The savings potential illustrated in Figure 18 means that the City of Wilmington can possibly produce annual bill savings for citizens and business of ~$20 million (assuming the average retail rate of 10.52 cents per kWh as reported by the U.S. EIA (EIA, 2021a)) over the 15-year life of most upgrades that we have examined. The city's summer months represent a peak in electricity consumption, with a smaller peak occurring in the winter months. In future research, we intend to investigate intervention measures that can deliver larger savings, possibly at different times of the year. Monthly peak electricity consumption, according to the early trial's results, is reduced from an approximate 100 GWh to under 80 GWh for the peak month of August. Actual savings will depend upon our ability in future research to include data that can allow validation of the building-by-building consumption estimates of our model and the consumption-by-end-use estimates within buildings. It will also depend on the conservation measures we investigate and their costs.

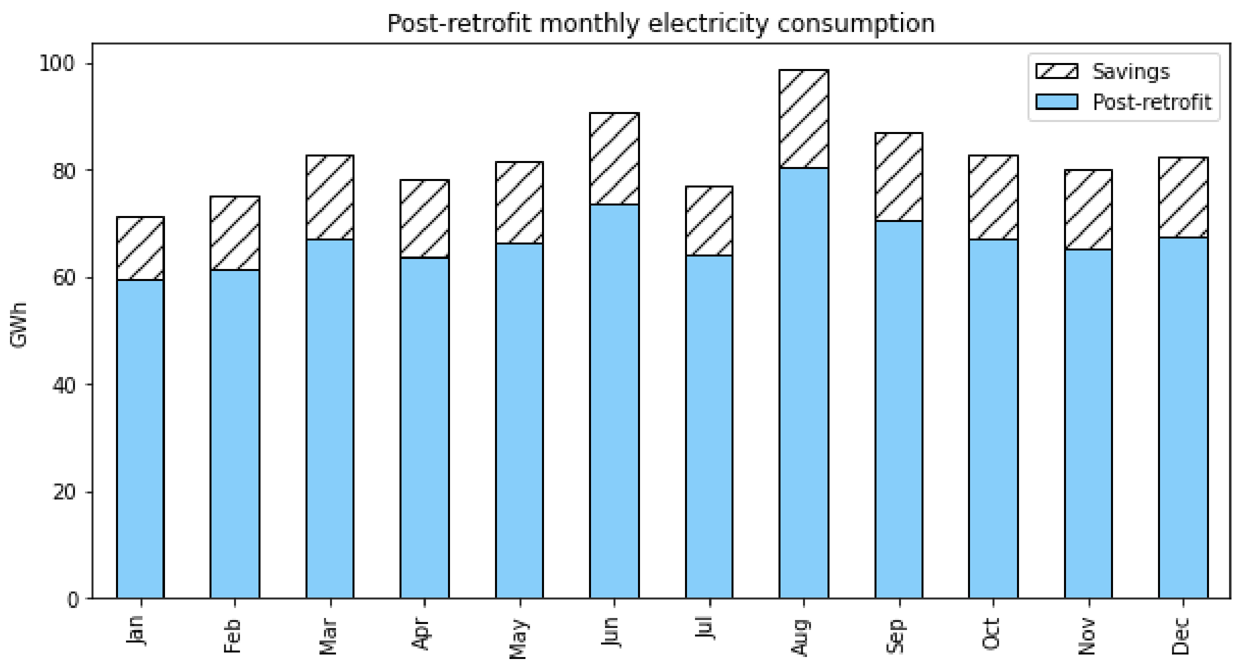

Figure 18 Monthly electricity consumption and electricity use reduction estimates for the entire City of Wilmington.

6.4. Neighborhood Area Energy Savings Opportunity

The 2028 Comprehensive Plan for Wilmington divides the city into 11 neighborhood areas for analysis. We follow that same distinction in this report in an effort to make the results as useful as possible for the city. The downtown neighborhood area ('Midtown/Brandywine/Central') appears to have the highest pre- and post-retrofit electricity consumption. This would be unsurprising as this area of the city contains Wilmington's downtown core and several residential neighborhoods. These are fairly high density areas with a substantial new development. Baynard

Boulevard's adjacent neighborhoods represent an area of the city that could see the largest decrease between its estimated pre-retrofit and post-retrofit electricity use level (as a result of the conservation measures we included in the early trail). This area is mostly populated by residential neighborhoods just north of the Brandywine Creek and Park with commercial activity along N. Market Street. Since our approach yields higher saving estimates for residential buildings, it is expected that a neighborhood area like Baynard Boulevard could realize the biggest difference between their pre- and post-retrofit conditions.[6]

Using the neighborhood areas in this way yields valuable insights into the potential for electricity efficiency interventions across the City. Each area, at minimum, could offer a savings opportunity of 16% or so based on our early trial (assuming the modest electricity retrofit package built for the trial).

6.5. Socio-Economic Profile of 'Savings City' Implementation

As documented before, Wilmington has a strongly concentrated spatial distribution of household income with areas south and east of downtown having among the lowest median household income. Lowering electricity consumption in an area of low to moderate average annual income is substantially more meaningful compared to lowering electricity consumption in an area of high annual income. We review this for the single-family building stock in the city.

Early trial estimates of savings as a portion of income for the single-family building stock are reported in Figure 19. On average, a household in East Side or West Center City could see electricity savings in excess of 5% of their annual income – this is a meaningful level of savings for these households. An intervention of this kind, when organized by the City or a public agency, can be seen as a 5%+ raise in income for the lowest-income households in the city. The total single family building stock could receive savings in excess of $4.6 million per year. These estimates a

[6] Note, this does not produce the conclusion that these areas deliver the largest savings in an absolute sense. The Figure ES- 3 reflects only the savings between pre- and post-retrofit conditions in percentage terms.

preliminary and more data are needed to accurately estimate annual savings. And the size of savings are sensitive to the retrofit package considered.

The results in Figure 19 calculate only the savings that occur in the single family building stock. Savings from other building categories (e.g. publicly owned buildings) can be dedicated to low- and moderate income households in the City, raising the impact even further. For instance, once initial costs for the intervention are recovered through bill savings, these buildings can enjoy a lower electricity bill for many years (if households do not increase energy use). A (portion) of these long-term savings could be dedicated to raising the quality of life for those most in need.

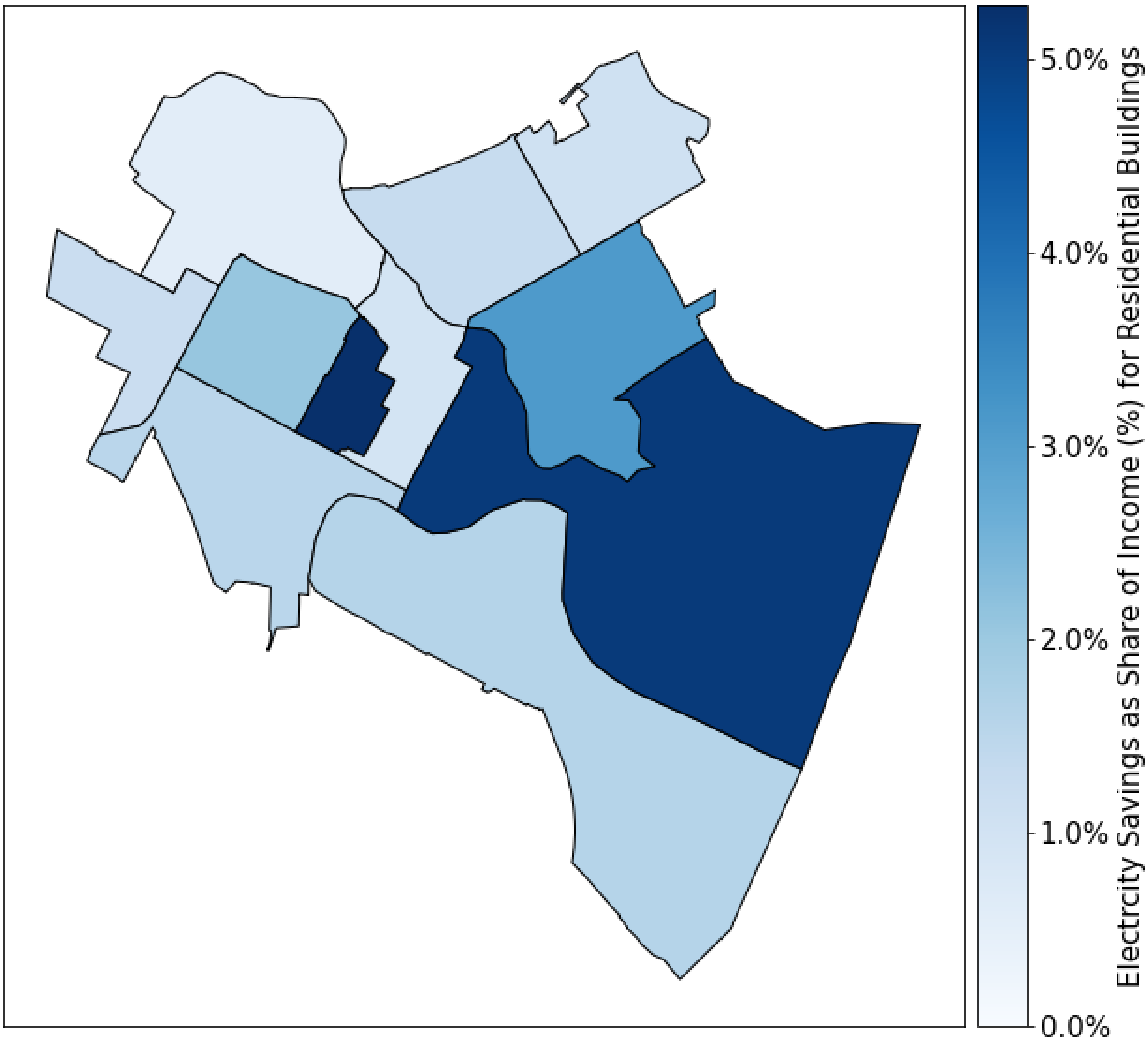

Figure 19 *Electricity savings as a share of income (%) for Wilmington's Single Family housing stock.*

6.6. Single Family Building Stock Savings Distribution

The model used to calculate electricity consumption and savings opportunities for the different benchmark buildings in a city can account for building geometry and use case. In a general sense, the model is constructed around the notion that, everything else being equal, larger buildings have larger total consumption compared to smaller buildings. Using benchmark models, we assume a typical characteristic to each building benchmark class that displays little variation from one building to the next.

There are, of course, many variables that influence the energy savings opportunity. Different occupancy schedules, differences in equipment performance and schedules, occupant preferences, family incomes, ages of members, etc. – all influence the electricity consumption pattern of a building. A deterministic approach can account for these variables when the data are available.

However, it is often the case that this data are not readily available for the needed entire case study area. In the past, we have introduced probabilistic approaches that account for this variability by modeling probability distributions for the relevant variables. While this accounts for possible variation, the probabilistic character can be distant from the actual consumption pattern when variation is applied randomly within a constrained feature range.

The approach covered in this report works because it is reviewing building portfolios of significant scale, even when downscaling the perspective to, for instance, the neighborhood analysis area. The neighborhood analysis areas still contain a significant number of building types, allowing for the use of 'typical' use cases. Still, assumptions in probabilistic models and the level of variation surrounding probability-produced estimates can be large and can prove unreliable for planning and for convincing investors to support conservation efforts.

To illustrate a more representative energy savings opportunity distribution – i.e. one that displays a higher level of variation – we can modify the model's outputs for the single family building stock based on the income level of the household occupying the building. Income determines a great deal of electricity consumption. In general terms, the higher the income, the higher the per unit area electricity consumption. A higher per unit area consumption raises the baseline against which the post-retrofit consumption profile is compared and, as such, raises the percentage of possible savings.

We can incorporate this effect into our model by reviewing the distribution of income across the City. Depending on the distance to the median income for the City, a consumption modifier is entered into the model that inflates or deflates the energy saving opportunities. The result of this pattern is provided in Figure 20. For the single-family building stock, we can model a distribution of possible savings ranging between ~15% to 38% depending on building size, shape, and income of the household. But it bears repeating that assumptions in probabilistic models and the level of variation surrounding probability-produced estimates can be large and can prove unreliable for planning and for convincing investors to support conservation efforts. At this stage, illustrating the method of assessment, rather than validating resulting estimates. This is an early trial of the model and estimates should not be assumed as ready for presentation to planners or investors.

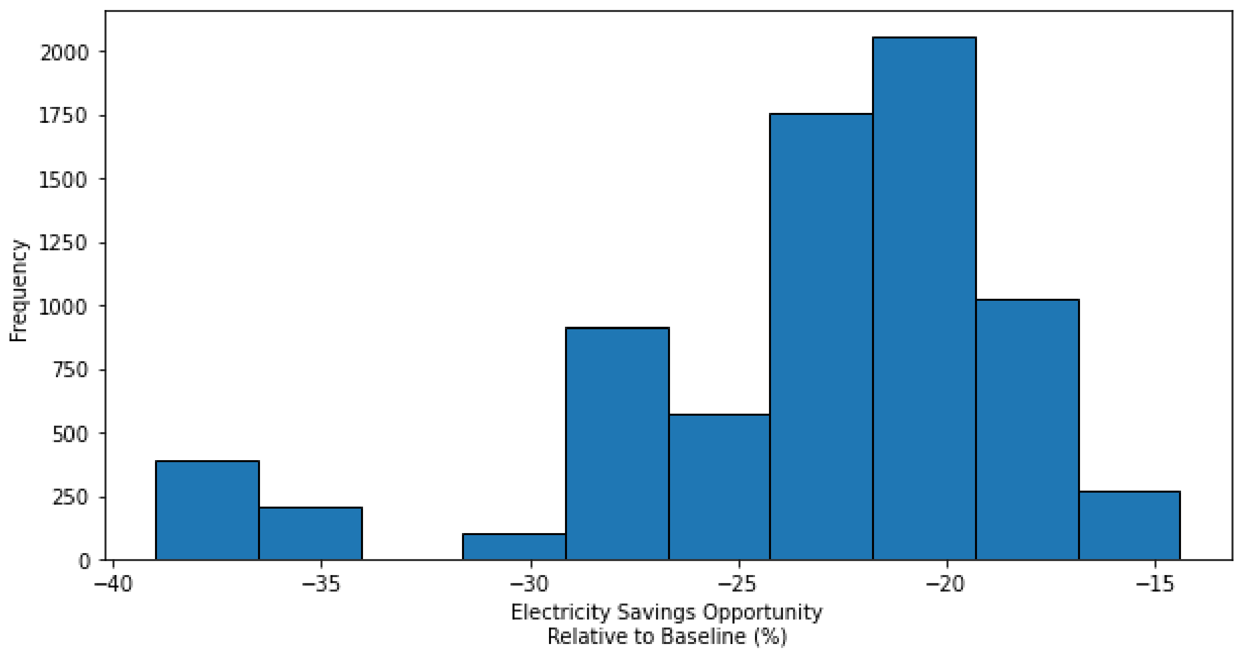

Figure 20 *Distribution of electricity savings within single family*

7.0. Next Steps

The focus of the research is the development of a tool that can: 1) estimate the annual energy consumption of each building in a city or region, using US Department of Energy benchmarking analytics and available city data; 2) estimate the effects of different portfolios of energy efficiency improvements for each building, using UD Department of Energy simulation software; and 3) estimate the aggregate impact of building energy efficiency improvements at the city scale.

At this stage, we can show that the new building-by-building approach has considerable promise. The early trial offers the reader an opportunity to see how the building-by-building approach operates. It cannot offer estimates that meet our validation standards. We recommend use of the early trial by the reader to gain familiarity with the tool and its potential.

The tool allows calculation of energy savings opportunities. We outline in the report how such an assessment can be conducted by showing a step-by-step case in our early trial regarding Wilmington's energy savings opportunity. The early trial illustrates an important step that can be taken in urban building energy analysis but is not found in research on building energy efficiency, namely, the potential eventually for city planning to specifically address the needs of low- and moderate-income income households and neighborhoods. Eventually, we hope that urban planners can use the tool to approach investors interested in addressing energy sustainability and energy for priority neighborhoods that are most burdened in meeting their building energy bills. More broadly, the tool promises to help us estimate city-scale potential to contribute significantly to decarbonization of the building stock.

Reliance on remote sensing data and geospatial information promises the opportunity to assess building energy potential through a city-wide 'virtual audit'. In contrast to on-site audits, a virtual audit can identify strategic priorities and consequences of energy efficiency strategies. Our research on the 'solar city' potential for Wilmington (Byrne et al., 2019) represented a virtual audit but for rooftop solar energy potential. Combined, these two assessments can form the beginnings of a citywide transition to a 'sustainable city'. For instance, one could envision similar virtual audits to explore

The 'early trial' provides insight into the direction of development for the model. In particular, based on the lessons learned as part of this year's investigation, the following aspects of the model require additional attention:

- Development of standardized and repeatable energy conservation measures that can be used for the development of scenario-based analysis (e.g. calculation of energy savings potential using limited, standard, or comprehensive energy efficiency interventions);
- Creating an assessment at the city-scale of urban building savings potential requires detailed information regarding individual buildings that can be challenging to come by. We plan to improve model operations so that it can more readily assess use conditions at the individual building-level scale. This means incorporating additional data that are available to create more specific building models. Needed data includes building-specific occupancy schedules, occupant behavior, energy end-uses, planned or existing renovation efforts, etc.
- The research effort is limited to the electricity profile of the city. As such, one available strand of future research could be to explore the natural gas profile and savings opportunities for the entire city.
- Similarly, the research could expand to include additional savings interventions for other resources such as water use.

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