Traversing the Winter Heat Island to a more efficient heat pump landscape: An exploration of urban microclimate analysis to inform city-scale system downsizing

Lino Sanchez, UC Berkeley
Stefano Schiavon, Center for the Built Environment, UC Berkeley

ABSTRACT

Oversizing heat pumps for winter heating in cold climates leads to excess capacity for summer cooling, which can compromise thermal comfort and increase energy use. These issues are compounded by an intensified urban heat island (UHI) effect that disproportionately impacts vulnerable communities living in densely developed inner-city cores. There is an opportunity to identify heat pump downsizing potential by mapping the winter context of the UHI effect, where localized pockets of stored urban heat can serve to lower heating loads for surrounding buildings. This study explores whether these warmer ambient temperatures can affect heat pump performance to locate where within a city equipment can be downsized for new construction. We focus on New York City for its pronounced UHI effect and building electrification goals. We used geospatial analysis to adjust regional weather data to microclimate-resolution through an urban energy balance model, subsequently fed into EnergyPlus building performance simulation software to model energy usage for apartment buildings fitted with single-zone window unit heat pumps (DOE 2024). Heating capacities were lowered stepwise from an oversized baseline setting to find the lowest market-available sizes suitable for apartment building units across city "Community Districts" (CDs) before comfort was compromised. We showed that all CDs could lower equipment capacity by one size, with 54 CDs able to downsize by two steps, leading to mean annual energy savings of 4.4% and a maximum 19.8%. Findings underscored the potential of heat pumps to be downsized by location within a city to guide strategic heat pump rollouts.

Introduction

An increasing greenhouse effect is heavily impacting building cooling needs in large cities by compounding already severe heat produced by the urban heat island (UHI) effect. This phenomenon involves higher densities of low-reflectivity surfaces in urban cores causing solar radiation to be absorbed and released at rates much higher relative to surrounding rural areas (Bornstein 1968; Gaffin et al. 2008), most heavily pronounced during summer nights when heat absorbed during the day by high-thermal capacity surfaces is gradually released to the outdoor air through radiative heat transfer. This physical process is driven by the temperature differential between the warmer surfaces of buildings, roads, and sidewalks, and the cooler outdoor air as stored heat flows into the cooler outdoor air per an urban surface energy balance (Oke 1982; Grimmon and Oke 1999). The absence of denser vegetation in urban cores further raises outdoor temperatures by eliminating any ambient cooling provided by evapotranspiration, the physiological process by which soil moisture transpires through plants and is released by the stomata to the local environment as vapor through evaporation (Yan et al. 2020).

The ensuing increases in building cooling loads caused by the UHI effect are leading to levels of energy consumption that only exacerbate our collective dependence on energy sourced from fossil fuels and place undue strain on regional electric grids. Natural gas consumption for indoor heating purposes remains a significant culprit for these increasing outdoor temperatures, as the direct onsite combustion of natural gas in furnaces for heating still contributes to the same greenhouse effects that will cause higher temperatures during the summer, with effects amplified by methane leaks. Still, equipping more homes with sufficient air conditioning, while providing needed relief, can further worsen the situation by contributing consequential waste heat to the outdoor environment. This further raises local temperatures and starts a feedback loop that only increases the need for more cooling, particularly in densely paved urban cores.

Building electrification, primarily facilitated through widespread heat pump adoption, is hailed as a key long-term strategy for urban heat adaptation. By way of the reserving valve, heat pumps allow for the bidirectional flow of refrigerant to facilitate both heating and cooling. Where cooling is provided through the same physics of conventional air conditioning, the reversed flow of refrigerant, switching the roles of the indoor evaporator coil and outdoor condenser coil, allows for heat to be extracted from the outdoor environment by convective heat transfer and delivered indoors. This process allows buildings to reduce their dependence on gas combustion without compromising on winter thermal safety and comfort, providing heat at much higher efficiencies than gas heating (Gram-Hanssen, Christensen, and Petersen 2012).

The technical sensitivities of heat pumps to fluctuating climatic conditions can make heat pump planning a challenge. Where heat pumps are known to thrive in more temperature climates, the design of heat pump systems to suit more severe climates remains an ongoing area of research.

Heat Pumps in Cold Climates

In cold climates, heat pump users might find electrical bills drastically increase during the heating season, even with specialized “cold climate” heat pumps (CCHPs) (Mendon et al. 2025). This is often caused by a sudden drop in operational efficiency as outdoor temperatures drop, requiring the system to expend more energy to pull heat out of the air and rely on backup auxiliary electrical heating to supplement heat supply and satisfy comfort needs (Francisco et al., 2004). Additionally, frost that accumulates on the outdoor coil can significantly compromise operational efficiency and requires frequent “defrost cycles” that involve temporarily reversing the flow of refrigerant to siphon heat from indoors to melt the ice, both compromising comfort and driving up heating costs (Konrad and MacDonald 2023; Ikram et al. 2025). Without proper configuration, systems can become oversized and succumb to operational efficiencies that cause equipment damage and compromise comfort.

CCHPs have demonstrated the ability to provide space heating in climates as cold as -30 °C (-22 °F) and even lower by taking advantage of inverter-driven variable speed compressor technology (Winkler and Shoukas 2024). As the evaporator temperature must drop to continue extracting heat from the outdoor air through convective heat transfer, the drop in refrigerant pressure causes a decrease in the mass flow rate of refrigerant (Konrad and Macdonald 2023). This lowers the coefficient of performance (COP) for conventional fixed-speed heat pumps and increases energy expenditure as the compressor must run longer. CCHPs handle this by modulating compressor speeds to maintain a steady flow of refrigerant during harsher cold spells and slow down when temperatures become mild. While CCHPs have demonstrated suitable performance in cold climates with COPs greater than 1, compressor energy is still substantial, and on top of the operational shortcomings of defrost cycling and reliance on auxiliary resistance heating, can make the prospect of a furnace that much more appealing, as heat will be reliably produced regardless of how cold it gets.

Still, for colder climates, like New York City, heating energy consumption often dwarfs cooling energy consumption, seeing annual citywide building space heating energy consumption (36% of total annual citywide building energy consumption) at roughly four times annual citywide building space cooling energy consumption (9% of total annual citywide building energy consumption) (Urban Green Council 2017). This creates ample opportunity for heat pumps to shine in terms of sustainability, given avoided onsite gas combustion.

The "Winter" Heat Island Effect

During the winter, the UHI effect remains physically present, but becomes fundamentally flipped in its thermal context through the "winter heat island" effect, where the same pockets of heat created through the UHI effect during the summer experience slightly warmer localized temperatures throughout the heating season. These pockets, comprised of those same high-thermal capacity urban surfaces, can see local wintertime temperatures raised by up to 2 °C relative to reference rural boundary areas (Macintyre et al. 2021). The same dark paved surfaces that intensify summer heat by absorbing and releasing solar energy can now act as a form of thermal storage during the winter, absorbing and gradually releasing the same solar energy to the surrounding nighttime air when heating is most needed. This could significantly lower heating loads and improve heat pump efficiency and performance as less heat is required to be extracted from the outdoor air to achieve indoor comfort (Vocale, Morini, and Spiga 2014). These slightly elevated temperatures can now serve as a means of thermal relief during the winter months, contrasting the more dire consequences seen during the summer (Yang and Bou-Zeid 2018).

Efforts to properly size heat pumps could take advantage of the winter heat island landscape to identify those same UHI-inflected locations where the local setting is a bit warmer, facilitated by the inherent sensitivity of heat pumps to slight fluctuations in outdoor temperatures. Where the winter heat island effect does not cause the same thermal vulnerabilities that mark the urgency of the UHI effect seen during the summer, these heat pockets could still hold operational performance implications for proper equipment sizing that could affect heat pumps that may have been sized to work in lower expected temperatures. Observing the microclimate variability created through the winter heat island landscape can show where any operationally damaging and energy inefficient system oversizing could be avoided and reveal opportunities for system capacity downsizing, as reduced capacity is compensated for by relatively higher localized temperatures.

Weather Data and System Sizing

Heat pump installers often base capacity needs on directly meeting the 1% cooling and 99% heating "design" temperatures prescribed through standard sizing methodologies like Manual J load calculation, sourcing relevant climate data from ASHRAE Standard 169 Climate Data for Building Design Standards (ACCA 2019). This protocol, leveraging these "ASHRAE Design Conditions", asserts that any system, whether a conventional HVAC system or a heat pump, must be equipped with enough installed heating and cooling capacity to meet conditioning needs for all hours of the year, except those highest 1% outdoor dry bulb temperatures and lowest 1% of outdoor dry bulb temperatures. However, where these peak conditions are unusually extreme, these systems may run the compressor harder than is necessary and leave the system oversized, particularly in terms of heating capacity (NYSERDA 2025), as more dense inner-city urban environments can often be noticeably hotter than surrounding rural weather reference points (Bourikas et al. 2016; Yang et al. 2020).

While there are currently no studies documenting the prevalence of improper equipment sizing in dense urban areas specifically attributed to the use of regional weather data instead of microclimate-informed weather data, simulation research has revealed markedly higher building cooling loads when incorporating microclimate-informed weather data over regional weather data that may not sufficiently capture localized UHI effects (Yang et al. 2024). Because designated climatic data collection “weather stations”, often situated at airport sites, will generally serve as the weather data sources for the design conditions used by practitioners implementing Manual J load calculations for sizing, systems may end up oversized, equipped to handle substantially higher heating peaks than are necessary (Hong et al. 2021). This excess heating and cooling capacity can be a problem for both the environment and consumer as increasingly frequent system cycling can result in both damaged equipment and a larger carbon footprint (UK DECC 2018; NYSERDA 2025). Systems experience an issue known as “short cycling”, where equipment is sized so large that selected thermostat setpoints are met too quickly, as the compressor becomes over-exerted and needs to frequently switch cycling on and off with each deviation from the setpoint, leading to equipment damage.

Simulation studies that have quantified the UHI energy effect are still often limited in their scope to improve guidance for equipment sizing because the regional reference weather data that measured microclimate temperatures are compared to are routinely based on Typical Meteorological Year Version 3 (TMY3) data. TMY3 is an annual time series data set of weather data aggregated across multiple years to represent “typical” weather across a representative year. TMY3 data sets, such as the EnergyPlus Weather File (EPW), are most commonly used for building energy simulation analyses projecting annual energy use, which typically falls outside the scope of work for contractors who generally size systems by ASHRAE Design Conditions. Still, because these peak conditions guiding system sizing are often informed by the same historic weather station data underlying TMY3, generally opting for weather data from the nearest site, these higher cooling loads could suggest an equipment sizing discrepancy seen for real buildings in major cities like NYC, whether systems be undersized for summer cooling or oversized for winter heating (Brown and Rajkovich 2020).

Objectives

Emerging urban energy modeling tools can help us understand the feasibility and sustainability impact of electrification interventions within a specific city district, but are often limited in their ability to reveal how well the same strategy would fare within another part of the city with a significantly different microclimate. The UHI effect and its influence on weather fluctuation and building energy performance can be hyper-localized and are often unevenly distributed throughout a city, meaning that certain communities will be more severely impacted than others. Optimal urban electrification and decarbonization planning relying on widespread heat pump adoption requires integrating microclimate as a system design variable alongside building envelope parameters. This ensures that hyperlocalized weather fluctuations caused by the UHI effect are accounted for in design conditions, else heat pumps may be sized improperly.

We propose a workflow for analyzing where heat pump installations for new construction can be downsized by iteratively simulating heat pump energy and comfort performance for a range of market-available model sizes across an entire city. We use New York City as a case study to apply this workflow for both its well-pronounced and documented UHI effect and for its position as a leading city in the building decarbonization movement. We focus on affordable housing complexes and the range of market-available sizes available for the typical window unit heat pump models offered by public assistance programs, acknowledging that studying one single building type will not be wholly representative of NYC's diverse building stock. While this study explores both the winter heating and summer cooling implications of the UHI effect, we pay particular attention to winter heat pump performance, given that summer performance is not uniquely diagnostic of heat pump suitability, compared with a conventional high-efficiency air conditioning system. Investigating the winter context hereby allows us to learn how urban heat pockets may directly affect the use of auxiliary electrical resistance heating and defrost cycling, heat pump energy consequences unique to the heating season.

Methods

This study built off existing building energy modeling tools and frameworks to estimate the effect of microclimate variation on heat pump sensitivity and performance across an entire city. We used a geospatial approach to extrapolate energy performance findings into system sizing recommendations across a map of NYC Community Districts (CDs) to provide a spatial context that can support urban planners in deciding where downsizing efforts should be targeted. CDs were chosen as an appropriate resolution to capture the delineation of NYC's diverse communities by local government. Our analysis was accomplished by collecting microclimate data specific to each CD, serving as boundaries for data collection, and using these data as input to inform a unique urban weather simulation for each CD. These urban microclimate-adjusted weather data were fed into an established energy modeling workflow using EnergyPlus (Version 24.2) (DOE 2024) building energy simulation software to simulate performance across a range of installed equipment capacities to explore downsizing potential.

Energy consumption seen from lower capacities was compared to a regional weather base case to distinguish where energy savings could be attributed to downsizing, compared with simply the shorter system runtime caused by either warmer or cooler air, acknowledging possibilities for worsening efficiencies when systems become undersized. How much more equipment can be downsized for each CD explicitly by leveraging microclimate data, compared to the minimum size achievable when relying on the default regional reference weather data, is distinguished as "downsizing potential".

Setting up the building energy models

The modeling configurations of this study were intended to best match the context of the NYSERDA "Clean Heat for All Challenge" (CH4A), which focuses on distributing packaged terminal air conditioners (PTACs) to affordable housing units across New York State (NYSERDA 2025). Because the CH4A program has focused its measurement and verification efforts on six-story apartment complexes, each containing eight apartment units, we chose the DOE midrise apartment prototype building as a best modeling representation of these multifamily affordable housing complexes (Deru et al. 2011; NYSERDA 2025). This model takes up 3,130.8 total square meters (33,700 square feet), with 31 housing units distributed across four stories. This prototype was equipped with a conventional unitary HVAC system installed for each dwelling unit, consisting of a typical gas combustion furnace for heating and air conditioning system operated by means of a single direct expansion (DX) coil. Because

PTACs are essentially described as unitary heat pump window units, providing both heating and cooling with only electricity by means of the reversing valve, we swapped the existing HVAC in each unit for the modeled unitary heat pump system available within EnergyPlus.

We configured a sizing range to represent a typical market-available PTAC product line, consisting of 2.30 tons (T) heating/1.87T cooling, and downsized configurations of 1.80T heating/1.43T cooling, 1.50T heating/1.17T cooling, 1.20T heating/1.00T cooling, 0.91T heating/0.75T cooling, and 0.60T heating/0.50T cooling (Mitsubishi 2019) The 2.30T system, the largest model in this line, represents an "oversized" upper-bound baseline scenario, reflecting conservative contractor sizing practices intended to avoid risking winter discomfort from undersizing, from which progressive capacity reductions are evaluated on the basis of comfort and energy (Viera et al. 1996). This workflow, facilitated all within the Python programming language (Version 3.12.7), is portrayed in Figure 1.

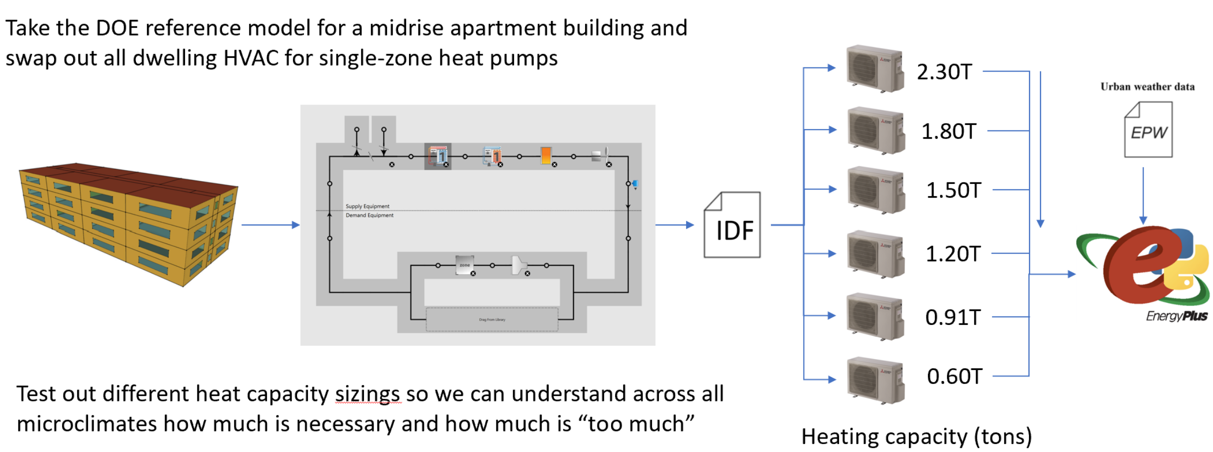


Figure 1. Workflow portraying the building model setup with window unit heat pumps at evaluated capacity sizes, each a unique Input Data File (IDF) to be run with a unique CD weather file in EnergyPlus within Python.

Collecting and processing microclimate weather data

The Urban Weather Generator (UWG) is a physics-based modeling application that estimates urban microclimate weather data by adjusting input EnergyPlus Weather File (EPW) weather data per a framework of microclimate parameters and energy balance equations that capture the influence of the surrounding urban environment on localized heat and moisture exchange (Mao and Norford 2021). A sequence of sub-models, consisting of a rural model, vertical diffusion model, urban boundary layer model, and urban canopy model, adjust hourly values of outdoor temperature and relative humidity by capturing the vertical flow of heat and moisture. This is facilitated by the physical processes of sensible heat flux through radiative absorption and storage, latent heat flux cooling through evapotranspiration, and its turbulent mixing driven by wind patterns shaped by urban geometry.

We used the UWG to adjust default TMY3 regional weather station EPWs for Central Park, JFK International Airport, and LaGuardia Airport, to capture microclimate variation around NYC, keeping these EPWs as our base case "reference" weather data by which to compare subsequently generated microclimate-adjusted weather data. To best resemble contractor system sizing practice, we assumed that design conditions informing system sizing would be sourced from simply the nearest weather station. Unique microclimate boundaries were defined by NYC's 59 CD political boundaries (and 12 "Joint Interest Areas"), applied to this study as vector polygons (NYC Planning 2025). Accordingly, any input environmental data fed into the UWG was extracted spatially within the boundaries of each CD, thereby allowing for a unique microclimate-adjusted EPW file to be created for each CD. Essential urban environmental data inputs to the UWG consisted of building footprint polygons (NYC OpenData 2025) augmented with building audit data, land cover classification raster data (NYC OpenData 2017), and surface albedo raster data derived from surface reflectance imagery retrieved from Sentinel-2 (Liang 2001; European Commission and European Space Agency 2025). The workflow for processing these data is portrayed in Figure 2.

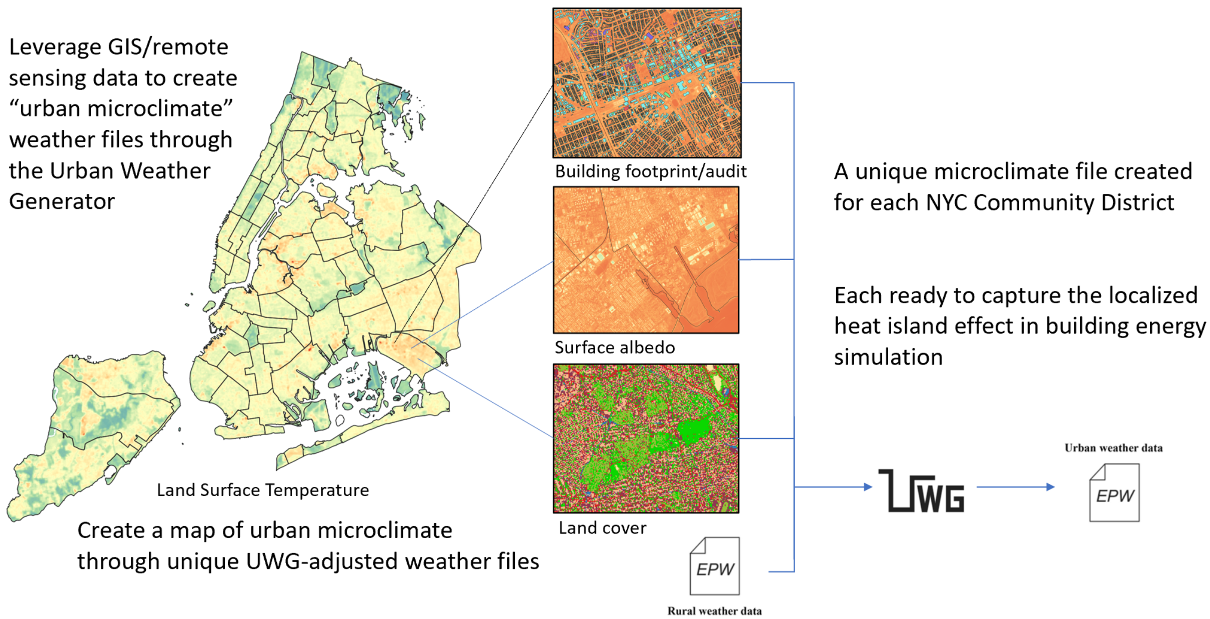


Figure 2. Workflow for processing urban microclimate-adjusted EPW files through the Urban Weather Generator (UWG), highlighting the extraction of urban environmental data statistical inputs derived from within each Community District, together with the backdrop of land surface temperature.

These inputs were entered into the UWG as numerical ratios and averages, consisting of the 'vertical-to-horizontal urban area ratio' (ratio of vertical surface area to flat surface area), building density (fraction of total surface area developed), average building height, grass coverage, tree coverage, and building stock, along with the designated ASHRAE climate zone of 4A for NYC. Building footprint data described the urban geometries of each CD and informed anthropogenic heat sources based on unique building types and programs (NYC OpenData 2025). This involved merging the building footprint data with detailed building attributes obtained from the New York City LL87 building audit data set, listing primary building types and programs attributed to specific building sites between 2019 and 2024 (NYC 2025). Land coverage and albedo layers described the thermal conductivity of urban surfaces, with regions of denser vegetation allowing for the modeling of cooling from resultant evapotranspiration and latent heat flux.

Processed microclimate-adjusted weather files served as the input weather data required for EnergyPlus simulation, with six separate Input Data Files (IDFs), each representing a unique heat pump system sizing configuration, run for each CD. 426 total simulations revealed annual and seasonal heating and cooling energy expenditure, along with thermal comfort unmet hours, at each sizing configuration for each CD. These results were used to test how far down a heat pump system can be downsized from an oversized baseline configuration for each CD, with downsizing marked as acceptable when the next lower downsizing “step” both lowered energy use and did not render the space thermally uncomfortable, defined as causing no more than 300 unmet heating hours per ASHRAE Standard 90.1 (Ruya and Augenbro 2018; ASHRAE 2022).

Quantifying short cycling

In EnergyPlus short cycling, termed "cycling loss", is implicitly quantified through a fixed "degradation coefficient" that adjusts the partial load fraction (PLF), the drop in system efficiency attributed to increasingly frequent on/off cycling (Cutler et al. 2013). Multiplying the system COP by the *PLF* raises energy expenditure to account for short cycling efficiency loss as a penalty for running the compressor at relatively low loads, whether for heating or cooling.

In EnergyPlus the *PLF* is calculated at each timestep as a function of the Part Load Ratio (*PLR*), the fraction of total equipment capacity utilized, multiplied the degradation coefficient C_d. This term is then multiplied by the energy quantity consumed by the heating and cooling coil E_{coil} to produce an energy penalty attributed to short cycling at each timestep. To aggregate total short cycling energy loss for both winter and summer, we summed cycling energy losses across all seasonal time steps. We next divided these total seasonal energy losses by the “ideal” seasonal energy consumption, implying no cycling losses, to retrieve the fraction *F* of seasonal energy consumption specifically attributed to short cycling efficiency losses, described in eq 1.

$$F_{cycling,season} = \frac{\sum_{i \in season} E_{coil,i} C_d (1 - PLR_i)}{\sum_{i \in season} E_{coil,i}} \quad (1)$$

While this equation mathematically describes the PLF, we instead relied on the quadratic “part-load performance curve” EnergyPlus uses to retrieve an output PLF for any input PLR, meaning the degradation coefficient used in eq 1 was implied, rather than explicitly derived.

Results

Evaluating the validity of identified equipment downsizing potential across CDs first required confirming generated microclimate weather data was at all noticeably different than the reference weather. We compared temperature differences between the highest observed summer (June through August) temperature and lowest observed winter temperature (December through February) across each CD to the highest summer temperature and lowest winter temperature recorded within the reference weather data, shown in Figure 3. Observed summer high and winter low outdoor dry bulb temperatures were captured at 7pm when the UHI effect would be relatively more pronounced. All CDs saw winter minimum temperatures increase in the microclimate-adjusted weather, with a maximum temperature increase of 2.2 °C. Microclimate-adjusted weather data saw summer peak temperatures also increase as high as 2.2 °C, but also drop by as much as 0.6 °C. Wintertime outdoor temperature increases seen with the microclimate weather data were more visibly pronounced for CDs surrounding JFK Airport and Central Park, with CDs surrounding Central Park seeing the highest increases in summertime temperatures. In contrast, CDs surrounding JFK airport saw summertime peak temperatures drop, reflecting a more pronounced summertime UHI effect surrounding this weather station.

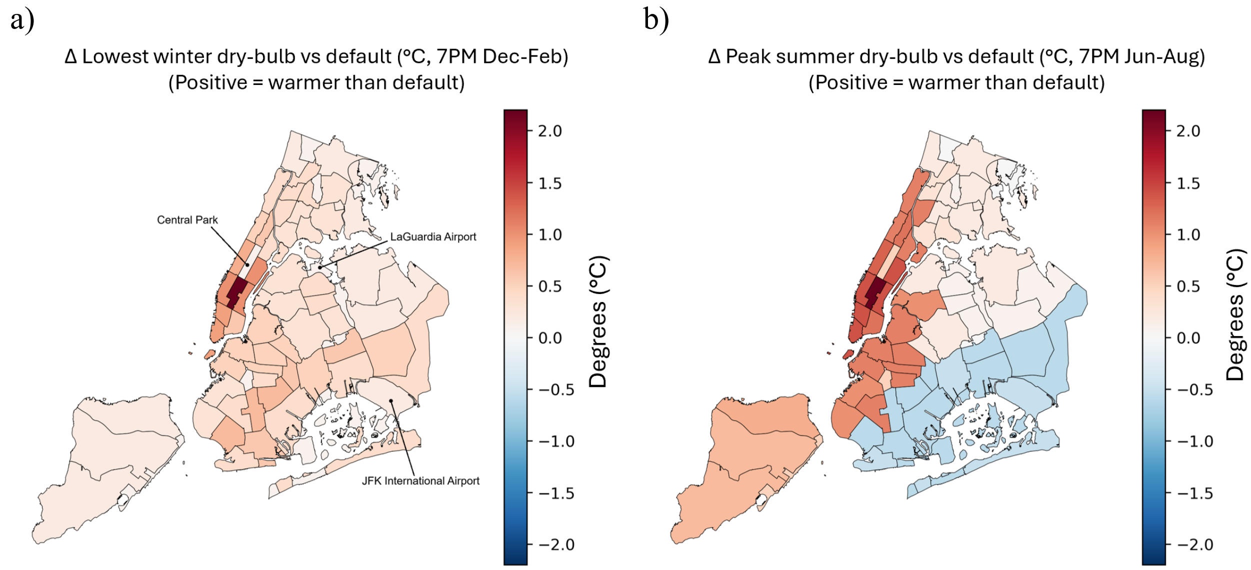


Figure 3. Outdoor dry-bulb summer peak and winter minimum temperature difference (°C) between default weather data and microclimate weather data across Community Districts, with respective weather stations indicated.

Final downsizing potentials were evaluated against two "base case" scenarios: 1) "oversized" (2.3T) equipment analyzed with reference weather data, and 2) minimum achievable equipment size achievable with reference weather data. A total of 426 simulation runs across 71 NYC CD weather files and six separate heat pump sizing models revealed that all of NYC can afford to downsize equipment by at least "one step" from the representatively "oversized" baseline, meaning 2.3T reduced to 1.8T heating capacity. 54 CDs could downsize by two steps, which included all of the Bronx and all but one CD in Queens. 12 of these 54 CDs, all located in Manhattan and Brooklyn, were new downsizing opportunities, only realized when running simulations with the microclimate-adjusted EPWs, and not the default regional EPWs, outlined in Figure 4 a). Most of NYC saw annual space conditioning expenditure reduced between 3 and 5% with microclimate-informed equipment downsizing relative to the oversized baseline with no microclimate effect, with several CDs showing 10 to 20% savings, shown in Figure 4 b).

a) b)

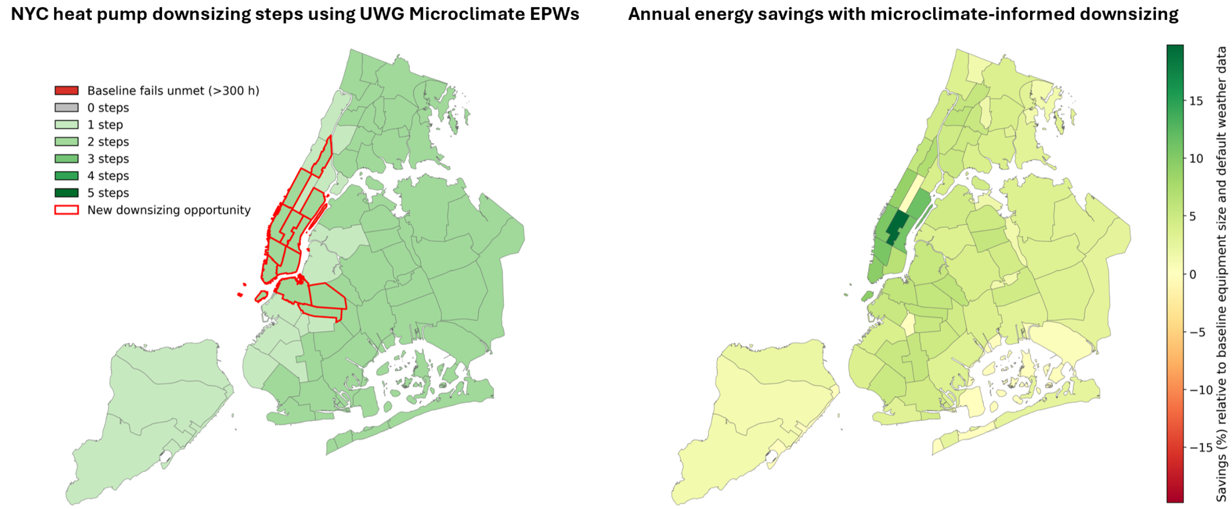
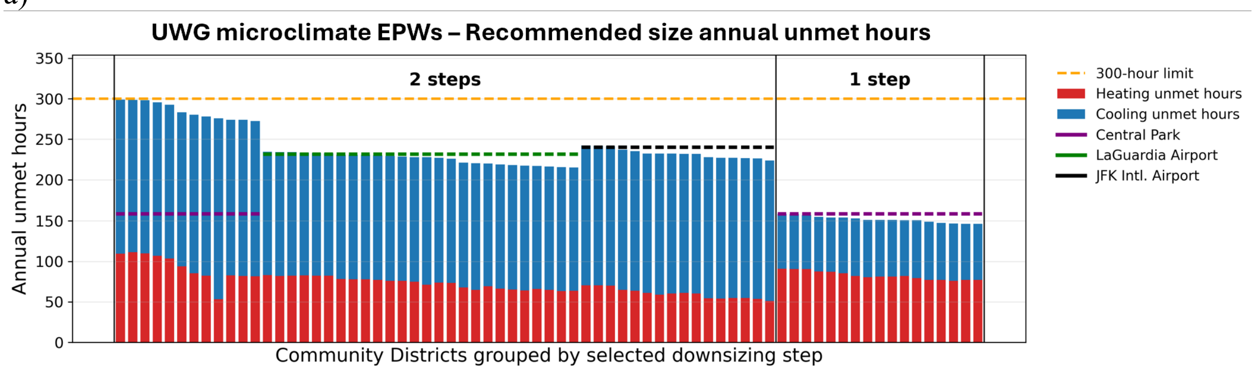


Figure 4. Energy implications of equipment downsizing across New York City Community Districts (CDs). a) Downsizing steps from no recommended downsizing to the maximum allowable. b) Energy savings resulting from recommended downsizing compared to the baseline oversized system modeled with the reference weather file.

Because the utilized 300 unmet hours limit left uncertainty over whether equipment downsizing limitations were either dominated by summer or winter unmet hours, we broke down the distribution of seasonal unmet hours and corresponding energy use across downsizing recommendations in Figure 5. Figure 5 a) depicts heating and cooling season unmet hours across CDs for each recommended equipment size informed by the microclimate-adjusted EPWs, positioned relative to annual unmet hours calculated if each CD's default regional weather data were analyzed. Similarly, Figure 5 b) depicts annual space conditioning energy consumption between heating and cooling use for each CD, positioned relative to annual space conditioning energy use if each CD's default regional weather data were analyzed.

Across all CDs seeing two recommended downsizing steps informed by microclimate, cooling unmet hours dominated. In contrast, heating energy consumption dominated annual space conditioning energy consumption for those same CDs, with the same pattern persisting for CDs that saw one single recommended downsizing step when analyzing the UWG EPWs.

a)



b)

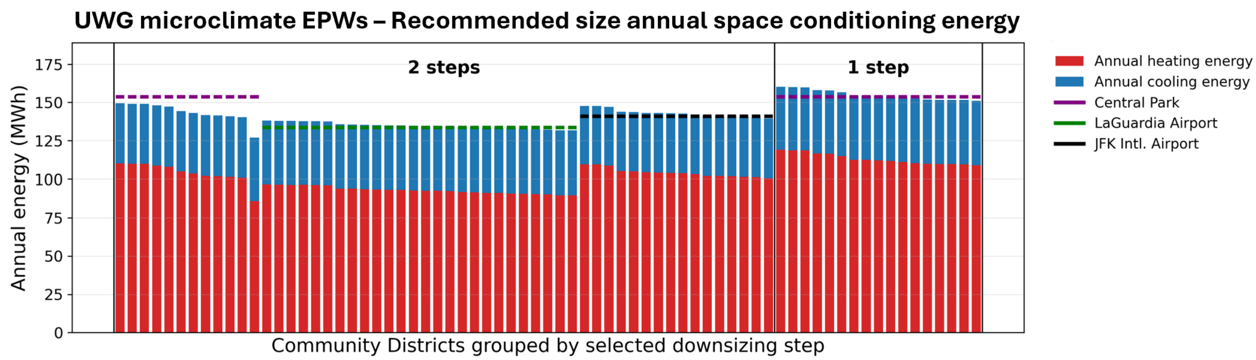


Figure 5. Microclimate-informed equipment downsizing implications across community districts split between heating and cooling season. CD results are positioned relative to annual implications calculated from corresponding default EPW. a) Distribution of seasonal unmet hours. Annual unmet hours are displayed relative to a 300 unmet hours limit. b) Distribution of seasonal annual space conditioning energy.

Heating energy savings from downsizing one single step were overall negligible, with the highest savings seen at 0.7% (0.8% median). This was followed by a gradual ascent in winter heating energy consumption with each further equipment downsize, shown in Figure 6 a). This included CDs that could downsize by two steps, which showed a mean energy increase of 1% (0.9% median), with subsequent downsizing showing even higher increases in energy use. Corresponding summer cooling energy savings for the single-step downsizing regimens were always greater than heating energy savings, revealing a noticeably higher and practically relevant 8.1% mean (8.1% median) within-CD average energy reduction, shown in Figure 6 b). Cooling energy savings from two downsizing steps showed a mean cooling energy savings of 14.2% (14.3% mean), with further cooling energy savings increasing monotonically with further downsizing. Though it must be noted that none of these energy savings were to be realized once the unmet hours threshold was surpassed after the first or second downsizing steps.

Variation in heating energy consumption saw a range of 25.6 MWh across CD microclimates when capacity was left at the 2.3T baseline, entirely overshadowing the overall change in heating energy seen from lowering equipment capacity to 1.8T, suggesting essentially no energy savings. In contrast, summer cooling energy savings were much more substantially driven by downsizing than by the microclimate effect, noting a much smaller range of only 4.5 MWh at the baseline 2.3T capacity.

a) b)

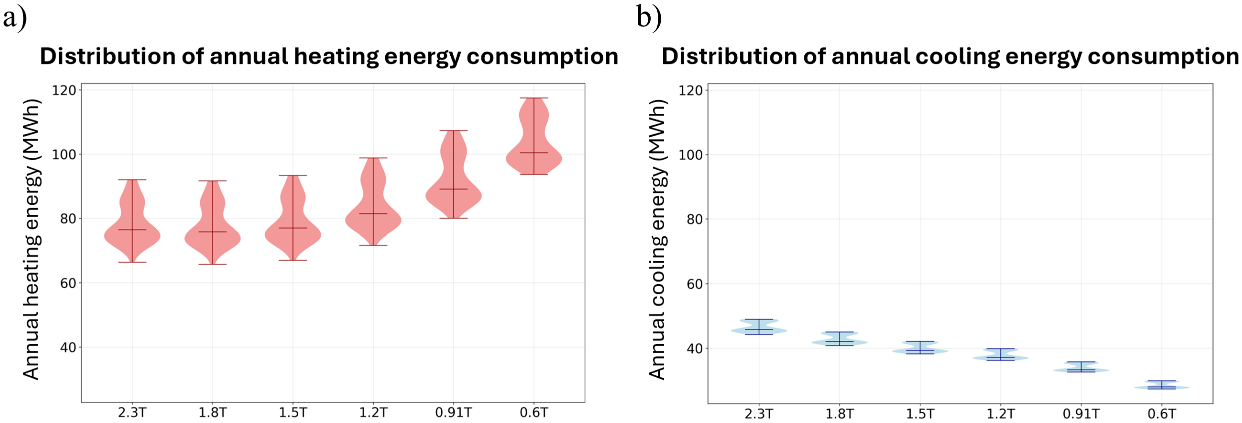


Figure 6. Seasonal energy savings from downsizing steps for both the winter heating and summer cooling seasons across analyzed Community District. a) Winter heating energy expenditure at each equipment size. b) Summer cooling energy expenditure at each equipment size. These values only concern heating and cooling energy use and do not consider unmet hours.

Differences in energy consumption attributed to cycling loss between downsizing recommendations informed by the UWG EPWs and default EPWs are displayed in Figure 7, examined between the summer (7a) and winter (7b) seasons. Short cycling energy losses decrease much more substantially during the heating season than during the cooling season, observing up to 24% loss reduction (18.7% mean), compared to summer short cycling energy loss reduction, which was never higher than 8.5% (6.5%). Variations in these cycling loss differences were substantially more varied for the winter context, seeing a range of 10.0%, compared to the cooling season, which saw a range of 2.5%.

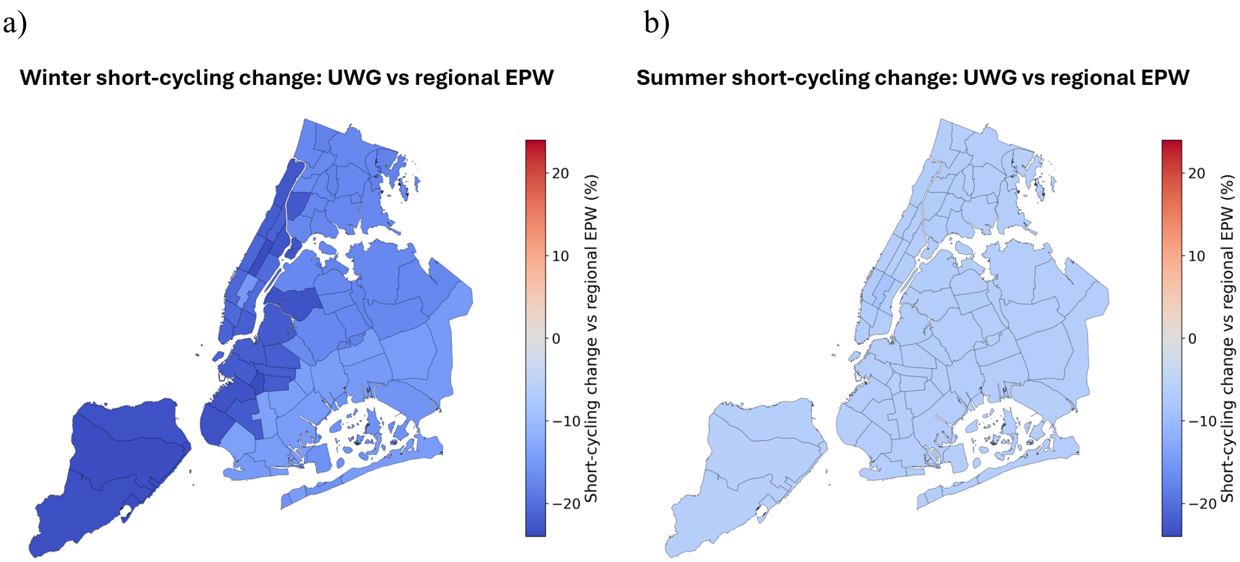


Figure 7. Percent change in seasonal short cycling energy losses from downsizing recommendations across Community Districts when simulations incorporate microclimate weather data instead of default weather data. a) Heating season. b). Cooling season.

Discussion and Conclusions

We identified how much heat pumps can feasibly be downsized across New York City to save energy, while meeting comfort requirements, which we found to be by one single capacity step, and two at the most if conditions allowed. Using microclimate data to inform equipment sizing revealed modest, but noticeable (>5%) annual space conditioning energy savings for 7 out of 71 CDs, driven primarily by summer cooling savings.

Downsizing efforts will likely appeal to new construction contexts where the HVAC design phase is still in conversation, and in planned retrofits when the system needs to be replaced and improvements to building envelope can be used to compensate for heating and cooling efficiency shortcomings. We saw a single downsizing step result in a maximum 28.7 MWh building-wide winter heating energy savings, roughly $7,800 in annual cost savings based on a 27.2 cents/kWh wintertime price rate in NYC (U.S. Bureau of Labor Statistics 2025). The same downsizing regimen resulted in a maximum 2.71 MWh summer cooling energy savings, roughly $780 in annual cost savings based on a 28.8 cents/kWh summertime price rate in NYC.

We sought to discover how downsizing by microclimate could influence space conditioning energy consumption compared to a "typical" oversized installation. Because equipment downsizing potential could still be revealed when simulations relied on default EPW files, our investigation further entailed investigating the degree of equipment downsizing potential that was only realized with a switch to using microclimate weather data. Comparing these energy savings from microclimate-informed downsizing across CDs helped us to confirm how much of these savings could have instead been attributed to variation in microclimate over the isolated effect of systems running at lower installed capacities. Our findings show that reported winter heating energy savings were most heavily dominated by variation in microclimate compared to any energy savings from equipment downsizing, while in contrast, summer cooling energy savings were most heavily dominated by equipment downsizing over variation in microclimate, but to a lesser degree. The comparatively lower summer cooling energy savings, in contrast, were more accurately attributed to equipment downsizing potential "only discovered" when leveraging microclimate data.

A major finding from this analysis was that systems could be downsized by at least one sizing step with no significant energy or comfort consequence. Since equipment damage caused by short cycling could not be adequately captured through EnergyPlus, it stands that downsizing could lead to potentially further energy and comfort benefits by avoiding compressor "wear and tear", also reducing repair and maintenance costs. This suggests that achievable summer energy savings, along with potentially reduced summer grid strain, could be informed by an updated equipment sizing protocol that leverages microclimate data to reveal the energy implications of a pronounced UHI effect. Though the summertime UHI effect may be more familiar, our study showed how for cold climates, downsizing could better be guided by the winter heat island effect, when sizing heat pumps to meet heating loads remains the primary concern. Further work may seek to measure these findings against newer variable-speed systems, where higher COPs and more precise load management may compensate for any additional installed capacity.

We showed that GIS methods involving remote sensing data can provide substantial opportunity to uncover the energy implications of urban microclimates, but the clear limitations in using vector polygons to delineate these urban microclimates must be acknowledged. While the boundaries of certain CDs may more directly resemble distinct urban environments, such as Central Park, these shapes are still political and therefore have no bearing on the flow of heat throughout any city. These boundaries, therefore, are meant to provide critical decision-making context for sustainability officials to capture the continuous nature of urban microclimate in a manner that is both intuitive and practical for program planning purposes.

This study can provide a rough assessment of downsizing capabilities, though we acknowledge that simulated results often emerge with a level of theoretical abstraction that is removed from the everyday practice of contractors and engineers involved in new construction projects. We propose that further field study is necessary to comment on when it is indeed warranted to rework system design protocols to allow for lower equipment sizing, considering the multifaceted nature of real buildings dynamics that we could not fully emulate.

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