Empowering Electrification through Building Envelope Improvements

July 2023

Key Takeaways

- Weatherizing buildings is an excellent first step toward electrifying their heating and cooling systems, especially for buildings in cold climates or those that have high-efficiency fossil-fueled heating systems. State energy offices responsible for distributing electrification funds should strongly encourage households installing heat pumps to pair them with insulation and air-sealing measures.
- Averaged across the United States, modest weatherization measures such as air sealing and increasing the quality and thickness of attic insulation can reliably reduce energy usage by 12–18%. Deeper building retrofits that add insulation to walls, basements, and rim joists, and install higher-efficiency windows could deliver around 33% energy savings.
- Envelope improvements in electrified buildings offer great value to the electric grid, reducing peak electric load by approximately 7–10%.
- The average residential customer who weatherizes an electrified home can expect to save an additional $150–1,200 in operational costs per year, with most households saving $500–800 per year.
- Efficient envelopes' ability to reduce demand during some of the grid's most carbon-intensive hours of the year makes them one of the most effective efficiency measures for reducing GHG emissions.
- Efficient envelopes help make buildings safer, healthier, and more comfortable.
- Scaling envelope improvements nationwide is both a major workforce development opportunity and challenge.

Introduction

The Inflation Reduction Act (IRA) has made billions of dollars in incentives available for home electrification, supporting the replacement of heating equipment fueled by gas, propane, and fuel oil with heat pumps powered by electricity. Fossil fuels burned in buildings are responsible for more than 10% of U.S. greenhouse gas (GHG) emissions, so deploying efficient electric space heating technologies is a key climate mitigation tool (Billimoria and Henchen 2020; EIA 2023; Hight et al. 2020).

As state energy offices prepare their programs to disperse IRA funds, they should strongly encourage households installing heat pumps to pair them with insulation and air-sealing measures. Electrification of buildings, vehicles, and industrial processes will move energy demand away from fossil fuels and onto the electric grid. This could potentially double electricity demand by 2050 (Brattle Group 2018), driving the need for additional electric grid infrastructure investments (Hopkins, Takahashi, and Nadel 2020; Mai et al. 2018). Without these additional improvements, electrification risks substantially increasing customers' utility bills, especially for those living in older buildings or who currently use high-efficiency fossil-fueled heating systems.

To help reduce likely increases in customer costs and strain on the grid, electrification of space heating should be paired with efficiency improvements in the building envelope—that is, the parts of the building that separate it from the outdoors, including walls and windows. Such improvements, known as weatherization, can slow uncontrolled heat transfer between the indoor and outdoor environments by increasing insulation in walls, attics, and basements; sealing air leaks (Harrington et al. 2022); or installing higher-efficiency windows.

Envelope improvements allow a building to maintain a comfortable indoor temperature with a less powerful heat pump. Lower capacity units cost less to purchase, reducing upfront costs and allowing IRA funds to extend further. Such savings are particularly valuable for low-income customers who might otherwise be priced out of electrification upgrades. Weatherization also reduces the risk that a power outage will expose building residents to dangerous outside temperatures. Additionally, envelope upgrades improve occupants' quality of life by improving indoor air quality, reducing outdoor noise, and providing other health and comfort benefits.

Some buildings, including those housing more than 24 million low- and moderate-income residents, can reduce residents' utility bills through space heating electrification alone. This reduction is more likely in buildings that electrify fuel oil, propane, or electric resistance heating systems (Rewiring America 2021). However, the remainder of buildings will require some measure of envelope upgrade to accompany electrification efforts in order to realize utility bill savings and emissions reductions. This includes buildings in cold climate regions, where envelope upgrades should be a first step toward electrification.

The Multiple Types of Envelope Measures

Many buildings, particularly those that were not built in accordance with modern building energy codes, are not sufficiently weatherized.[1] Building envelope improvements can be grouped into three categories: insulation, air sealing, and windows. All three share the same goal—to keep heat inside the building on cold days and outside it on hot days.

The most common envelope efficiency measure is insulation, which can be placed in attics, walls, rim joists, and basements. Insulation comes in multiple forms including fiberglass, spray foam, and polystyrene. For efficiency purposes, thicker insulation is better, which is one reason why insulating attics (which typically have more available volume than other areas of the building) is one of the first recommended steps for weatherizing buildings.

Another common envelope efficiency measure is air sealing. The average American home is two to four times leakier than a new home built to code (Chan, Joh, and Sherman 2013). By sealing up small gaps and holes in the building's envelope, single-family homes can reduce air leakage by an average of 25–30%, thereby stifling the uncontrolled exchange of air and heat between the indoor and outdoor environments (Blasnik et al. 2015).

Attic insulation and air sealing represent the low-hanging fruit of envelope improvements since they can be installed with only modest disruption to building occupants. "Deep energy retrofits" can deliver even greater benefits, but they often require more substantial interventions that might accompany building renovations. Such retrofits include improving the insulation in wall cavities and rim joists (which usually require removing and replacing walls and ceilings) and replacing existing windows with high-efficiency models that reduce heat flow.

The Multiple Benefits of Envelope Efficiency

In most circumstances, weatherizing buildings alongside electrification is an effective way to reduce energy usage, lower peak demand, reduce emissions, deliver cost savings to customers, and deliver a host of additional benefits, including making buildings more comfortable, improving occupant health and performance, making buildings more resilient during power outages, and reducing risk of building damage. In the following sections, we quantify many of these benefits by summarizing published reports and analyses.

[1] Building energy codes were first implemented in the United States in the late 1970s, but adoption across the country has been uneven.

ENERGY SAVINGS

The amount of energy savings delivered by envelope measures varies between buildings. In general, these measures are most effective when they replace inefficient building envelopes in climates that demand significant heating or cooling. Averaged across the country, modest weatherization measures such as air sealing and increasing the quality and thickness of attic insulation can reliably reduce energy usage by 12–18% (BEI 2020; Edington et al. 2020; ICF 2021; Jones et al. 2023; New York City Mayor's Office of Sustainability, Con Edison, and National Grid 2021; Quinnell and Genty 2022; West Hill Energy and Computing 2019; Wilson et al. 2017). For comparison, these improvements fall short of achieving the energy performance of new buildings that meet 2021 building energy code standards (Edington et al. 2020). For older buildings to rise to the 2021 standards' efficiency level, deeper building retrofits—adding insulation to walls, basements, and rim joists, and installing higher efficiency windows—would be needed. Doing so could deliver 11–47% energy savings (depending on the state), with a national average of approximately 33% savings (ICF 2022).[2,3]

A study of the efficiency potential of the single-family building stock found that of the top 11 efficiency upgrades that had "positive economic potential," 5 of them—wall insulation, attic insulation, duct sealing and insulation, windows, and air sealing—were envelope measures. When the analysis was extended to natural gas, fuel oil, and propane energy savings, 7 of the top 11 measures related to the envelope, with basement wall insulation and insulated wall sheathing joining the list (Wilson et al. 2017).

COLD CLIMATE SAVINGS

Efficient envelopes tend to deliver the most energy savings in regions with high heating or cooling loads. The further temperatures deviate from room temperature (i.e., 65°F), the more energy is typically required, which is why the greatest thermal space conditioning loads (and the greatest benefits from reducing them) tend to occur in cold climates. Moreover, electrification primarily grows heating loads since a majority of U.S. housing already uses electric air conditioning.

As a result, some of the greatest benefits from reducing a building's heating demand will occur in the coldest climates. As part of its statewide decarbonization plan, Massachusetts found that after electrification, improved roof and wall insulation and improved airtightness

---

[2] The vast majority of these savings can be achieved by focusing just on cost-effective retrofits. The highest savings were reported in Rhode Island, New York, Idaho, Massachusetts, and New Jersey.

[3] The same ICF study also found that relative energy savings in the commercial sector varied from 1.6% to 8.7%, depending on the building type.

in single-family homes delivered an 18% reduction in energy use, and a 38% reduction after applying deeper measures. A focus on residential building shell upgrades during the electrification transition is projected to lower state residential energy consumption from 131 trillion Btu (TBtu) to 116 TBtu (an 11% reduction) by 2050. Energy reductions were lower in multifamily and office buildings, but still ranged from 2% to 12% (Edington et al. 2020).[4]

Researchers in Minneapolis also took a detailed look at the steps needed to electrify and decarbonize their city's building stock. They found that efficient envelope measures can result in energy reductions of up to 70%, with a citywide average of 30% per building. In fact, the potential energy savings from these measures in single-family homes rivals all other residential energy efficiency measures in Minnesota combined. These reductions are higher than Minnesota's statewide average, largely due to the city's older, and therefore less-well-insulated, building stock (Jones et al. 2023).

PEAK LOAD REDUCTION

Envelope improvements in electrified buildings also offer great value to the electric grid itself. On average, residential envelope improvements can reduce peak electric load by approximately 7–10%, with only slightly smaller reductions seen in the commercial sector (Edington et al. 2020; Hanif et al. 2023; Hledik et al. 2021; ICF 2021; Malo et al. 2021; Jones et al. 2023; New York City Mayor's Office of Sustainability, Con Edison, and National Grid 2021; NYSERDA 2022; Specian et al. 2021). These reductions are important because high peak load drives the need for additional power plants, transmission lines, and distribution system upgrades. Each of these entails significant costs that utilities typically recover from customers through their electric bills; given this, envelope improvements in just a subset of buildings can deliver utility bill savings to all customers.

More-efficient envelopes will always reduce demand during peak hours, though the exact reduction varies by region (ICF 2021). In Washington, DC, the combination of energy efficiency and load flexibility can eliminate approximately 40% of load growth by 2050 (Hledik et al. 2021). Combining envelope upgrades with efficient electrification can reduce winter peak load in Quebec's National Capital Region by up to 25% (Malo et al. 2021). In New York, electrification on its own could double peak demand (NYSERDA 2022), but envelope improvements across the state could decrease peak demand by approximately 18%. In New York City, a combination of energy efficiency measures including envelope measures could reduce peak demand by 4–19%, depending on the city's specific decarbonization pathway (New York City Mayor's Office of Sustainability, Con Edison, and National Grid 2021). In addition, envelope measures are projected to defer upgrades on

[4] Savings are lower in multifamily buildings due to the thermal efficiency inherent in denser units with less envelope exposure per unit.

approximately 225 distribution feeders in National Grid's New York territory, resulting in significant potential savings to utility customers (Brett Webster and Lacey Tan, RMI, pers. comm., March 9, 2023 (based on research in preparation)). An analysis of the Texas grid finds that improving insulation R-values in individual buildings by 22.9–63.9% alongside space heating electrification could actually decrease peak load by 3.4% (Hanif et al. 2023).

Single-family peak demand in Massachusetts is projected to increase 73% with electrification, but envelope improvements can reduce the peak by 23–42%, depending on the depth of the intervention. Similar interventions in multifamily buildings reduce peak demand by 6–18% (Edington et al. 2020). Another study of an electrified Massachusetts in 2040 finds peak load reductions of 400 megawatt (MW) and 800 MW from modest commercial and residential weatherization, respectively (Specian, Cohn, and York 2021). In Minneapolis, a fully weatherized building stock would drop peak load approximately 25%, or up to 37% if exterior insulation and replacement windows are also added in (Quinnell et al. 2022). In these cold climate regions, envelope improvements are a critical component of cost-effective electrification and minimized utility costs.

CUSTOMER SAVINGS

A more-efficient building envelope can significantly reduce the cost of electrification. The average residential customer who weatherizes an electrified home can expect to save an additional $150–1,200 in operational costs per year, with most households saving $500–800 per year.

Weatherizing an average electrified Massachusetts home reduces annual space heating and cooling bills by $672 and $85, respectively (Acadia Center 2021). Air sealing and insulation improvements can deliver annual energy cost savings of $150–580 in low-income households, depending on the region (Bradshaw, Bou-Zeid, and Harris 2016). Weatherizing and electrifying an oil-heated, pre-1980 home in upstate New York reduces utility bills by $1,900, or $2,400 with deeper retrofits (NYSERDA 2022). Bringing residential envelopes up to IECC 2021 standards could deliver more than $21 in savings per square foot (ICF 2022).[5]

An analysis of midrise multifamily buildings in Cincinnati finds that installing a heat pump does not guarantee lower utility costs on its own for buildings with average- or high-efficiency gas furnaces. Annual utility cost reductions are realized for these buildings only after they are fully weatherized. In cases like this—or others in which the price of electricity is high relative to natural gas—focusing on weatherization measures *first,* before installing a heat pump, is a more likely pathway for realizing annual bill savings (Browning 2020).

[5] Savings of more than $30/ft.^{2} are reported in South Dakota, Ohio, Illinois, New York, New Jersey, Nebraska, Washington, Kentucky, and Michigan.

A study of the Minneapolis building stock reaches a similar conclusion, reporting that "[w]eatherization is the critical path to cost-effective electrification from an upfront cost and utility bill cost perspective." This study finds not only that customer utility bills will be 25–70% lower by decarbonization through electrification and weatherization than by using renewable natural gas, but that *excluding* weatherization from full electrification programs yields substantial bill increases for nearly all customers (see figure 1) (Jones et al. 2023). In addition to weatherization saving on operational costs, an efficient building envelope helps reduce the upfront cost of electrifying by allowing the building to operate with a less powerful (lower-capacity) heat pump (Veilleux et al. 2022). These lower-capacity models cost less to purchase and operate. If the cost of heat pump ownership is factored in, ACEEE calculates that moderate home envelope improvements can lower lifetime customer costs by $3,000–11,000, while deeper envelope improvements that add window upgrades and more insulation lower the lifetime costs by $8,000–22,000 (Nadel and Fadali 2022). Larger savings are realized in colder climates.

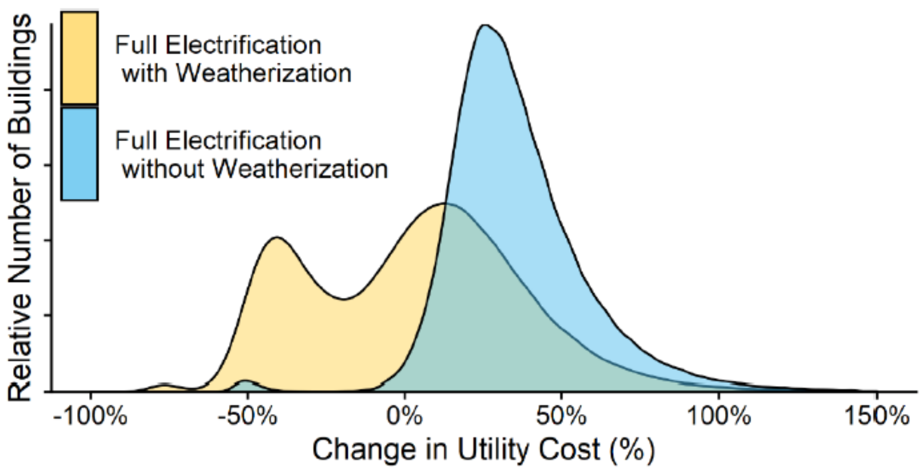

Figure 1. Distribution of buildings by the percent change of utility costs in scenarios with and without weatherization measures. Without weatherization, the average annual bill increase is $980 (34% above current); 75% of households would see annual costs increase by more than $600 (14% above current); and 25% of households would see bills increase by more than $1,310 (46% above current). Source: Jones et al. 2023.

Efficient envelopes also provide substantial value beyond the residential sector, including municipal and commercial buildings, and they could produce significant savings on the bulk power system. RMI finds that Canada's National Capital Region can save CA$700 million in energy costs by combining building envelope upgrades with heating electrification in its municipal buildings (Malo et al. 2021). ICF reports that the installation of code-compliant roof upgrades in commercial buildings can generate close to $68 billion in cumulative lifetime savings (ICF 2022).[6] There is also research underway that seeks to quantify the combined benefits of moderately efficient heating/cooling and envelope improvements on the bulk power system in the United States; this combination is expected to save significant system costs through 2050.

GHG REDUCTION

Efficient envelopes' ability to reduce demand during some of the grid's most carbon-intensive hours of the year makes them effective at helping to reduce GHG emissions. Along with electrification and load flexibility (the ability to adjust demand to match supply of electricity), envelope efficiency is an essential component of cost-effective building decarbonization. In Minneapolis, approximately 75% of building decarbonization potential stems from weatherization and space heating electrification (Jones et al. 2023). That same combination can nearly eliminate building sector emissions in Canada's National Capital Region (Malo et al. 2021). Weatherizing a typical electrified Massachusetts home can reduce the tons of CO_2e from space heating from 3.0 to 1.8 in the first year (Acadia Center 2021). The combination of envelope efficiency and air sealing alone can save 0.6–2.6 tons of CO_2e per year per low-income household, depending on the area of the country (Bradshaw, Bou-Zeid, and Harris 2016).

OTHER BENEFITS

Efficient building envelopes provide a number of additional benefits unrelated to energy or GHG emissions. Air sealing and more-efficient windows lead to indoor air quality improvements by reducing uncontrolled air exchange between the indoor and outdoor environments (NYSERDA 2022). These improvements lower the chance of poor outdoor air quality (e.g., due to wildfires, pollen) affecting residents. This provides health benefits by reducing asthma and allergy symptoms, resulting in fewer missed days of work and school (Singh et al. 2010).

Envelope improvements are possible only if the building is free of certain defects, such as water leaks that could degrade insulation's thermal properties (Cowell 2022). In this way, envelope improvements can catalyze other building improvements that leave the building better able to resist structural damage, such as from water (New York City Mayor's Office of Sustainability, Con Edison, and National Grid 2021). These improvements can also reduce mold growth and pest infiltration, conveying additional health benefits.

Tighter envelopes typically necessitate some form of mechanical ventilation (e.g., bathroom fans), which offers an additional level of control that can help make buildings more

[6] The combination of roof upgrades (at time of roof replacement) and pipe insulation generates $68 billion in savings, but most of that amount comes by virtue of roof insulation.

comfortable (Edington et al. 2020). Air sealing and more-efficient windows also improve occupant comfort by reducing drafts, cold surfaces, and noise pollution (Urban Green Council 2021). Improved attic insulation reduces temperature gradients that make a building's upper floors hotter in summer and colder in winter than its lower floors. Studies also show that high-performing buildings can improve sleep quality and cognitive functioning (MacNaughton et al. 2017; Newsham et al. 2012).

Buildings with more-efficient envelopes have increased resilience to power outages, which is crucial during periods of extreme heat or cold when occupants need to shelter in place (Wilson 2005). Buildings with efficient envelopes are also better able to maintain critical life-supporting temperatures. This was demonstrated in December 2013, when an ice-storm-induced power outage deprived the Belfast Ecovillage in Belfast, Maine, of electricity. During that storm, outside temperatures dropped to –4°F, yet interior temperatures were recorded at 58°F four-and-a-half days later. Efficient envelopes can also help save lives by eliminating the need for building occupants to take drastic interventions, such as lighting fires indoors or using a gas stove for heating, which can lead to a deadly build-up of carbon monoxide gas (Specian et al. 2020).

More-efficient envelopes also enhance buildings' grid interactivity. These buildings become more capable of pre-heating or pre-cooling when the price of energy or carbon intensity of electricity are low. Efficient envelopes allow buildings to remain thermally comfortable through peak periods without having to consume as much electricity. Buildings that take advantage of these envelope improvements can earn additional financial incentives from their utility (if a demand response program is in place), as well as reduce additional emissions and help grid reliability.

Providing envelope improvements to all buildings that need them represents a massive workforce development opportunity and challenge (Jones et al. 2023); New York City Mayor's Office of Sustainability, Con Edison, and National Grid 2021). While many quality energy efficiency jobs could be supported by weatherization activities, many areas of the country currently lack enough contractors to implement this solution at scale.

Conclusion

Weatherizing buildings alongside electrification is an effective way to reduce energy usage, lower peak demand, reduce emissions, improve health and comfort, and deliver cost savings to customers. For that reason, weatherization is an excellent first step toward electrification.

While we encourage energy efficiency programs to conveniently bundle envelope and electrification measures together, we recommend prioritizing interventions in existing buildings that are the most poorly weatherized. These (often older) buildings are frequently occupied by people with low incomes, and prioritizing these buildings offers a pathway to help advance energy equity and alleviate the burden of high energy bills.

References

Acadia Center. 2021. "PowerHouse and Building Electrification: Fact vs. Fiction." *Acadia Center Blog*, February 25. acadiacenter.org/powerhouse-and-building-electrification-fact-vs-fiction/.

BEI (Building Electrification Institute). 2020. *Washington, D.C. Customer Economics Analysis for Building Electrification*. San Diego: BEI. static1.squarespace.com/static/5b6a482db27e39e8fcf65bbf/t/6298044502087000c9537c03/1654129734671/BEI-DC+Customer+Economics+Analysis_Dec+2020_FINAL.pdf.

Billimoria, S., and M. Henchen. 2020. *Regulatory Solutions for Building Decarbonization: Tools for Commissions and Other Government Agencies*. Basalt, CO: RMI. rmi.org/insight/regulatory-solutions-for-building-decarbonization/.

Blasnik, M., G. Dalhoff, D. Carroll, F. Ucar, and D. Bausch. 2015. *Evaluation of the Weatherization Assistance Program During Program Years 2009–2011 (American Recovery and Reinvestment Act Period): Energy Impacts for Single Family Homes*. Prepared by Oak Ridge National Laboratory. Washington, DC: DOE. weatherization.ornl.gov/wp-content/uploads/pdf/WAPRecoveryActEvalFinalReports/ORNL_TM-2014_582.pdf.

Bradshaw, J., E. Bou-Zeid, and R. Harris. 2016. "Greenhouse Gas Mitigation Benefits and Cost-Effectiveness of Weatherization Treatments for Low-Income, American, Urban Housing Stocks." *Energy and Buildings* 128 (September): 911–20. doi.org/10.1016/j.enbuild.2016.07.020.

Brattle Group. 2018. *New Sources of Utility Growth: Electrification Opportunities and Challenges*. Boston: Brattle Group. www.brattle.com/wp-content/uploads/2021/05/13526_new_sources_of_utility_growth_-_electrification_opportunities_and_challenges.pdf.

Browning, V. 2020. *The Relationship between Building Electrification and Weatherization: The Impact of Heat Pumps on Utility Costs and Carbon Emissions for Building Heating and Cooling*. Cincinnati: University of Cincinnati. etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=ucin1668637400345874&disposition=inline.

Chan, W., J. Joh, and M. Sherman. 2013. "Analysis of Air Leakage Measurements of US Houses." *Energy and Buildings* 66 (November): 616–25. doi.org/10.1016/j.enbuild.2013.07.047.

Edington, A., L. Hanson, C. Laurent, M. Walsh, S. Copeland, G. Gunn, R. Hatchadorian, J. Lueker, N. Rekstad, B. Swett, K. Beaton, D. Lane, S. Morse, C. White, D. Hill, R. Jones, and J. Wiliams. 2020. *Buildings Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study*. Prepared by The Cadmus Group, Arup, VEIC, Energy Futures Group, and Evolved Energy Research. Boston: Massachusetts EEA (Executive

Office of Energy and Environmental Affairs). www.mass.gov/doc/building-sector-technical-report/download.

Cowell, S. 2022. "Weatherization without Walkaways: Change Is Coming, but Needs a Push." *E4TheFuture Blog*, April 26. e4thefuture.org/blog/weatherization-without-walkaways-change-is-coming-but-needs-a-push/.

EIA (Energy Information Administration). 2023. "What Are U.S. Energy-related Carbon Dioxide Emissions by Source and Sector?" www.eia.gov/tools/faqs/faq.php?id=75&t=11.

Hanif, S., M. Mukherjee, S. Poudel, M. Yu, R. Jinsiwale, T. Hardy, and H. Reeve. 2023. "Analyzing At-Scale Distribution Grid Response to Extreme Temperatures." *Applied Energy* 337 (May): 120886. www.sciencedirect.com/science/article/abs/pii/S0306261923002507.

Harrington, C., F. Meyers, D. Bohac, M. Anders, and L. Genty. 2022. "Aerosol Sealing of Existing Residences." *Proceedings of the 2022 ACEEE Summer Study on Energy Efficiency in Buildings* 1: 1–16. Washington, DC: ACEEE. aceee2022.conferencespot.org/event-data/pdf/catalyst_activity_32318/catalyst_activity_paper_20220810190427374_40df278a_eddf_4668_85d8_89b87b68e957.

Hight, C., L. Hutchinson, R. Muralidharan, and T. Ide. 2020. *The Role of Gas in the Energy Transition*. Basalt, CO: RMI. rmi.org/insight/the-role-of-gas-in-the-energy-transition/.

Hledik, R., S. Sergici, M. Hagerty, and J. Olszewski. 2021. *An Assessment of Electrification Impacts on the Pepco DC System*. Washington, DC: Public Service Commission of the District of Columbia. www.brattle.com/wp-content/uploads/2021/09/An-Assessment-of-Electrification-Impacts-on-the-Pepco-DC-System.pdf.

Hopkins, A., K. Takahashi, and S. Nadel. 2020. "Keep Warm and Carry On: Electrification and Efficiency Meet the 'Polar Vortex.'" *Proceedings of the 2020 Summer Study on Energy Efficiency in Buildings* 6: 96–108. Washington, DC: ACEEE. www.synapse-energy.com/keep-warm-and-carry-electrification-and-efficiency-meet-polar-vortex.

ICF. 2021. *Economic Evaluation of Building Insulation Measures*. Reston, VA: ICF. insulationinstitute.org/wp-content/uploads/2023/01/Economic-Evalulation-of-Building-Insulation-Measures-.pdf.

_____. 2022. *Insulation Industry Opportunity Study*. Reston, VA: ICF. www.insulate.org/ICFStudy2022.pdf.

Jones, K., R. Olson, A. Otalora-Fadner, and J. Quinnell. 2023. *Minneapolis 1–4 Unit Residential Weatherization and Electrification Roadmap*. Minneapolis: Minnesota CEE (Center for Energy and Environment). www.mncee.org/minneapolis-1-4-unit-residential-weatherization-and-electrification-roadmap-pdf.

MacNaughton, P., U. Satish, J. Laurent, S. Flanigan, J. Vallarino, B. Coull, J. Spengler, and J. Allen. 2017. "The Impact of Working in a Green Certified Building on Cognitive Function and Health." *Building and Environment* 114 (March): 178–86. https://www.sciencedirect.com/science/article/pii/S0360132316304723

Mai, T., P. Jadun, J. Logan, C. McMillan, M. Muratori, D. Steinberg, L. Vimmerstedt, B. Haley, R. Jones, and B. Nelson. 2018. *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States*. Prepared by NREL (National Renewable Energy Laboratory). Washington, DC: DOE. doi.org/10.2172/1459351.

Malo, L., S. Mendonca, M. Huang, and J. Cathcart. 2021. "The Electrification and Deep Retrofit Potential of Canadian Federal Buildings." rmi.org/the-electrification-and-deep-retrofit-potential-of-canadian-federal-buildings/.

Nadel, S., and L. Fadali. 2022. *Analysis of Electric and Gas Decarbonization Options for Homes and Apartments*. Washington, DC: ACEEE. www.aceee.org/research-report/b2205.

New York City Mayor's Office of Sustainability, Con Edison, and National Grid. 2021. *Pathways to Carbon-Neutral NYC: Modernize, Reimagine, Reach*. Prepared with support from ICF, Energy Futures Initiative, and Drexel University. New York: New York City Mayor's Office of Sustainability, Con Edison, and National Grid. https://www.nyc.gov/assets/sustainability/downloads/pdf/publications/Carbon-Neutral-NYC.pdf

Newsham, G., B. Birt, C. Arsenault, L. Thompson, J. Veitch, S. Mancini, A. Galasiu, B. Gover, I. Macdonald, and G. Burns. 2012. *Do Green Buildings Outperform Conventional Buildings? Indoor Environment and Energy Performance in North American Offices*. Ottawa: National Research Council of Canada. doi.org/10.4224/20857897.

NYSERDA (New York State Energy Research & Development Authority). 2022. *The Future of Buildings: New York's Carbon Neutral Buildings Roadmap*. Albany: NYSERDA. www.nyserda.ny.gov/All-Programs/Carbon-Neutral-Buildings.

Quinnell, J., and L. Genty. 2022. "Energy Savings and Project Cost Estimates of Weatherization and Exterior Insulation Measures across a Very Cold Climate Building Stock." *ASHRAE Buildings XV Conference Proceedings.* .

Quinnell, J., D. Bohac, L. Phillips, N. Cindrich, and E. Werling. 2022. "It's All about the Envelope: Prioritizing Envelope Upgrades for Electrification of Cold Climate Homes." *Proceedings of the 2022 ACEEE Summer Study on Energy Efficiency in Buildings* 9: 168–82. Washington, DC: ACEEE. aceee2022.conferencespot.org/event-data/pdf/catalyst_activity_32589/catalyst_activity_paper_20220810191631016_06175f89_3494_46fb_a308_2d5f2ae83b36.

Rewiring America, 2021. "46 Million Homes Are in the Money. Is Yours?" *Newsletter*. https://www.rewiringamerica.org/newsletter/49-million-homes-are-in-the-money-is-yours

Singh, A., M. Syal, S. Grady, and S. Korkmaz. 2010. "Effects of Green Buildings on Employee Health and Productivity." *American Journal of Public Health* 100 (9): 1665–8. www.ncbi.nlm.nih.gov/pmc/articles/PMC2920980/.

Specian, M., C. Cohn, and D. York. 2021. *Demand-Side Solutions to Winter Peaks and Constraints*. Washington, DC: ACEEE. www.aceee.org/research-report/u2101.

Specian, M., D. Godo-Solo, N. James, M. Reiner, and K. Sawyer. 2020. "A Framework for Resilience and Energy Efficiency in Buildings." *Proceedings of the 2020 ACEEE Summer Study on Energy Efficiency in Buildings* 11: 255–70. Washington, DC: ACEEE. www.aceee.org/files/proceedings/2020/event-data/pdf/catalyst_activity_10936/catalyst_activity_paper_20200812133204310_7166b82a_054e_4a2e_aa98_e217f4ab388e.

Urban Green Council. 2021. *Grid Ready: Powering NYC's All-Electric Buildings*. New York: Urban Green Council. www.urbangreencouncil.org/grid-ready-powering-nycs-all-electric-buildings/.

Veilleux, N., C. Amero, J. Walczyk, J. Koo, M. Janett, N. Hinkle, and A. Greening. 2022. *Residential ccASHP Building Electrification Study*. Waltham, MA: Cadmus. cadmusgroup.com/articles/residential-heating-electrification-in-the-northeast/.

West Hill Energy and Computing. 2019. *Efficiency Maine Trust Home Energy Savings Program Impact Evaluation: Program Years 2014–2016*. Augusta: Efficiency Maine Trust. www.efficiencymaine.com/docs/HESP-Evaluation-2019.pdf.

Wilson, A. 2005. "Passive Survivability." *BuildingGreen* 14 (12). www.buildinggreen.com/op-ed/passive-survivability.

Wilson, E., C. Christensen, S. Horowitz, J. Robertson, and J. Maguire. 2017. *Energy Efficiency Potential in the U.S. Single-Family Housing Stock*. Prepared by NREL. Washington, DC: DOE. www.nrel.gov/docs/fy18osti/68670.pdf.