Electrification, For the Rest of Us

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ABSTRACT

The electrification movement is gaining support, with proactive and forward-thinking organizations committing to decarbonizing their building portfolios. However, the initial excitement often wanes when decision-makers are confronted with the associated complexities, decision points, and, ultimately, costs. In some instances, owners may even find themselves grappling with higher utility bills after installing heat pumps and other all-electric systems. Building evaluations may also uncover critical building deficiencies and expand the maintenance list, further taxing project funds.

Our team has partnered with various stakeholders, including nonprofits, government entities, and building owners nationwide, to address this pressing challenge. We conducted comprehensive assessments of each building portfolio, scrutinized energy consumption and emissions, meticulously calculated both initial capital outlays and ongoing expenses, and then formulated a strategic framework for prioritizing which properties to electrify first. As compared to the top-down (economics-driven) or bottom-up (engineering-driven) approaches, we meet clients in the middle to answer not only the what but the how to electrify.

We developed practical, actionable pathways to guide owners through this electrification movement. It's clear that lofty ideals and arbitrary timelines will not suffice. Instead, we're distilling the multiple facets of building science, engineering uncertainty, and carbon emission accounting to deliver tangible solutions that enable organizations to make informed decisions and navigate this transition successfully. Electrification was feasible in most buildings but economically viable in fewer. We will present three specific case studies in Colorado, Massachusetts, and Virginia that highlight the building-owner pathway from initial investigation to economic analysis and recommendations on when to electrify.

Introduction

There are many reasons to decarbonize the energy use in buildings. The most obvious is to slow down the effects of climate change, but there are also many public health benefits, potentially improved comfort and cost savings, and energy security improvements. Over the last five years, cities and states have accelerated adoption of policies to encourage and require building decarbonization. New York City's Building Emission Law was passed in 2019, and 2024 is its first year of enforcement. Similar requirements under Boston's Building Emission Regulation and Disclosure Ordinance will go into effect in 2025 for buildings larger than 35,000 square feet. State policies mandating similar changes are likely across the Northeast and the West Coast.

Building owners are experienced with codes and standards that nudge their portfolios toward using less energy or switching to cleaner fuels, but electrification poses an unprecedented challenge. Heat pumps are a maturing technology, but retrofitting large buildings to use them for heating and hot water is still novel in the US. There are many hurdles to overcome – skilled HVAC contractors are in short supply, and these will be complex retrofits requiring experienced teams to execute them. Even when buildings get successfully electrified, owners may face higher utility bills as we found in our Colorado case study – a colder climate state with low natural gas prices.

No matter the location, electrifying buildings will be a costly and difficult process. Low-cost gas makes it challenging to find business cases for electrification. Innovative utility rate structures and new policies will undoubtedly be needed to get most of our buildings retrofitted, and building owners need help plotting out the course to all-electric buildings. Despite the logistical and financial hurdles, there are cases where electrifying a building now makes sense. We found a few examples of those cases while working with our clients that own large building portfolios. We identified certain characteristics that indicate a building could be ripe for retrofitting, and we have documented our guidance to decision-makers for that selection process.

Massachusetts Case Study

In 2023, we helped a non-profit organization in Massachusetts work toward their own and the state's climate goals by reducing their emissions. Over the last two decades, they have made tremendous progress in lowering carbon emissions. We fully documented their current emissions and helped create a plan for meeting their climate goals, which involved a detailed analysis of their building portfolio.

Our team estimated that their greenhouse gas (GHG) emissions (Scope 1 and 2) in 2022 were 727 metric tons carbon dioxide equivalent (MtCO2e), a 57% decrease from its baseline emissions in 2003. The organization's 2022 emissions included 567 tonnes of Scope 1 emissions and 160 tonnes of Scope 2 emissions. With renewable energy credit (REC) purchases, they eliminated the Scope 2 emissions leading to a total decrease of 67% from 2003 levels.

Now the real work needed to begin on reducing Scope 1 emissions from fuel combustion in their buildings. The client wanted a net zero strategy for their 110-building portfolio spanning various vintages, states of disrepair, primary occupancy types, and heating and cooling systems. The client sought more than the standard carbon accounting and they wanted to align with the Commonwealth of Massachusetts' Net Zero by 2050 goal. Critically, the client also sought guidance on the pathways that would help achieve that goal and the costs of differing pathways. There are many ways to achieve this goal, and this section examines the associated methods and costs based on our review of our client's entire building portfolio.

Massachusetts aims to achieve carbon neutrality by 2050 with 80% of its electricity coming from renewables (Massachusetts Department of Energy Resources 2023.). One might conclude that building electrification will result in large emission reductions without much effort at all. Buried in that conclusion is the need for a complicated series of building retrofits that will require significant planning and investment.

Building Analysis and Site Visits

While aiming for 2050 carbon neutrality, several of those 110 buildings are slated to be decommissioned and many more will have their heating systems replaced due to exceeding their useful life. The client organization had already found it hard to get building retrofits done because of a shortage of skilled trade workers and equipment delays, so they knew this work would take years. Existing building retrofits and electrification can be an expensive endeavor for any organization. Costs can be managed by considering which buildings should be upgraded first to plan fundraising and align with normal capital investment cycles.

We helped the client plan upgrades by reviewing their existing building data and auditing their facilities. We conducted three site visits (eleven buildings) in the winter of 2023 to assess opportunities for decarbonization and perform thermographic imaging of the facades and heat distribution systems. Based on those inspections, we created building case studies to summarize the great potential for energy efficiency and identify good candidates for all-electric upgrades. The results of these building case studies show that a few targeted weatherization measures could have big impacts. While not applicable to all buildings (i.e. external facade insulation on historical facades), these insights would not have been possible without the energy audits from the site visits. These measures had the following annual reductions in direct GHG emissions:

- Insulating between basement and first floor: 9%
- Insulating exposed heating pipes: 7%
- Adding external façade insulation: 9%
- Window replacements and air sealing to cut infiltration: 5% and 4%, respectively

The case studies identified the prime candidates for electrification as soon as possible. It would take many years of gradual energy efficiency improvements and electrification upgrades to fully address these direct emissions attributed to burning fuel for heat, hot water, and cooking. The client aimed to retrofit 10 buildings each year, which was double their typical retrofit rate of five per year.

We developed a recommended building decarbonization sequence to achieve this goal. We prioritized buildings into seven groups based on their existing heating system, heating fuel source, overall energy use intensity, and current electrical service capacity. We reviewed several options to decarbonize buildings, including energy efficiency measures, cold-climate ASHPs, ground-source heat pumps, and hot water heat pumps. To enable the decision-making process, we conducted a cost comparison analysis and estimated building retrofit costs across the client's building portfolio.

Financial Costs of Electrification

Cadmus adjusted previous electrification bids given to the client to 2023 prices without incentives and rebates. Costs and incentives will certainly change, so actual costs will depend on the market conditions at the time of construction.

Table 1: Massachusetts Building Retrofit Costs

Building Energy Efficiency and Electrification Upgrades	Cost Factor (2023 USD/SF)	Known Building Count Needing Upgrade
ASHRAE Level 2 energy audit	$0.25	100
Envelope upgrades - air sealing, insulation, and storm windows	$5.25	
Electric panel upgrade	$2.50	40
Heat pump equipment and installation cost	$25.00	
Electric water heating equipment and installation cost	$1.25	
Retire existing oil space heating equipment	$1.75	60
Replace cooking and laundry with all-electric appliances	$1.20	20

Cadmus averaged cost factors from studies and projects across the Northeast, including actual building retrofit estimates prepared for Mass Audubon by independent contractors, Urban Green Council's Going Electric, Massachusetts Clean Energy Center's ASHP cost comparison tool, and the Massachusetts Clean Energy and Climate Plan for 2025 and 2030. Our estimated cost of purchasing and installing heat pumps across Massachusetts for these buildings was $25 per square foot. Actual bids for electrification retrofits were available for a small cohort of buildings that had been prioritized by the organization, and those buildings and cost estimates are show in Table 2 below.

Table 2: Massachusetts site estimated costs

	Use Type	Heating System	Heating System EUL remain (years)*	Existing electrical panel size (amps)	Gross floor area (SF)	Heat Pump Implementation Cost Estimate (2023 USD)	Specific cost factor (USD/SF)
Building A	Workshop	Boiler (fuel oil)	-8	100	800	$12,000	$15
Building B	Barn	Heater (propane)	-6	100	2,100	$60,000	$29
Building C	Public Assembly	Boiler (fuel oil)	-6	200	7,200	$95,000	$13
Building D	Barn	Furnace (propane)	-6	100	2,500	$88,000	$35
Building E	Public Assembly	Furnace (fuel oil)	-6	200	4,300	$35,000	$8
Building F	Public Assembly	Furnace (gas)	-5	60	350	$10,100	$29
Building G	Public Assembly	Heater (propane)	-1	100	800	$13,100	$16
Building H	Workshop	Heater (gas)	-4	60	500	$13,100	$26
Building I	Maintenance	Heater (propane)	-6	100	500	$7,500	$15
Building J	Barn	Boiler (fuel oil)	10		1,000	$26,500	$27
Building K	Barn	Furnace (gas)	10		1,800	$65,000	$36
Building L	Maintenance	Furnace (gas)	7		1,100	$15,130	$14
Building M	Classroom	Heater (gas)	5		400	$15,000	$38

*Negative values on remaining expected useful life (EUL) mean the system exceeded the manufacturer's original EUL

Of the buildings identified in Table 2, Cadmus selected eight that our client could begin electrification retrofits on immediately because of the estimated cost savings and available capital in their planning cycle. We assumed all these costs would occur this year (real cost). It would be extremely difficult and costly to upgrade all these buildings in one year, but moving all expenses into the present makes budgeting easier for the client given that construction and HVAC equipment costs will escalate over time.

Properly identifying how to lower a building's energy use starts with an energy audit, but there are many more steps to fully electrify, including decommissioning of old equipment and upgrading electrical capacities. ASHRAE Level 2 audits would be best for this client given the various building typologies, primary use types, and deep energy savings desired by the client. We estimated the cost of an energy audit to be roughly $2,000 per building, while decommissioning and removal costs range from $1,000 to $4,000 per building. Certain costs were not dependent on building size (audits, boiler decommissioning, kitchen appliance upgrades¸ etc.), so we worked with our client to estimate the number of buildings that needed those upgrades. We also considered the soft costs associated with building upgrades. We estimated these to be 20% (about $1.6 million) of the total portfolio upgrade cost (about $8.2 million), and they include the architectural and engineering design costs, permitting costs, and profit allowance for any consultants, as well as administrative overhead.

We sought to maximize financial returns and carbon savings from building heating system replacements through a targeted sequencing approach. There are many ways to sequence the building upgrades and heating system replacements at these sites. Further, we proposed and evaluated the impacts of three scenarios: business-as-usual, moderately aggressive, and aggressive.

Given these 110 buildings, the organization could retrofit 16 buildings annually under an aggressive scenario to finish before 2030. If the client continued at their current retrofit rate, five buildings annually, it would take 20 years to complete all retrofits. Aiming to nearly double that rate would allow their building portfolio to decarbonize by 2035 and meet Massachusetts' net zero goal. In the end, the client chose to target 10 annual retrofits to electrify the entire portfolio by the end of 2035, and their upgrades may be prioritized based on these factors, among others:

- Ease of completion based on existing system and electrical capacity
- Upfront cost
- Age of equipment
- Total energy load (heating use) and fuel costs
- Reduction in overall GHG emissions and other pollutants
- Downside risk (associated damages from equipment failures)

Table 3: Full scenario emissions cuts from 2022 baseline, costs, and timelines

Scenario	Description	GHG Cut in 2030	GHG Cut in 2050	Net Present Cost (2023 USD)	Net Present Incremental Cost
Business as Usual	No additional actions or plan, five annual retrofits		67%		
Moderate	Steady electrification - 2050 finish, 10 annual retrofits	74% (after RECs)	92%	$6.5 million	$4.2 million
Aggressive	Fast electrification - 2030 finish, 16 annual retrofits	92% (after RECs)	92%	$9.8 million	$5.1 million

We selected the building upgrade (efficiency, electrification, etc.) sequence based on three characteristics of the existing heating systems. This sequence aims to reduce older equipment's potential downside risk; remove delivered fuel due to carbon emissions, storage liability, and financial costs; lower heating energy use; and improve the return on investment. Quantitatively, this sequencing approach prioritized estimated useful life first, primary heating fuel type second, and total energy use intensity third.

The organization's staff had also developed a sequence for building upgrades targeting older equipment and strategically decommissioning buildings. One key difference in this study was the prioritization of larger buildings. Their larger buildings tended to be older (with more influence on the portfolio) and, per the building visits and heat load sizing, were prone to having oversized heating equipment. Unfortunately, this is a common problem across the US and oversized equipment results in unnecessary expense and lower efficiency compared to a right-sized system.

We also reviewed their list of domestic hot water (DHW) heaters and associated installation dates. Most buildings are used for offices and public education, so they did not require large amounts of hot water, often just hand-washing needs. The simplest solution for these structures was either a 120-volt heat pump water heater or under sink point-of-use heater. Both options would reduce the additional electrical installation expenses and the latter would allow for the disuse of hot water plumbing in most of the structures. When considering the dispersed usage and duration of handwashing in these buildings, there is also an associated water savings. There is still some debate on using heat pump water heaters in colder climates since indoor units will pull heat from indoor spaces. But they also reduce summer cooling and dehumidification loads, and we suggested that these costs will balance over the long-term.

Many of the older DHW systems are served by a space heating system (i.e., an indirect-fired DHW), meaning that those boilers serve double duty to supply heat and hot water. Those DHW systems will need to be replaced as the existing heating equipment is decommissioned. Splitting DHW from space heating in these contexts has the advantage of allowing for data collection of heating system runtimes to help inform the right-sizing of the heating load. Further, once that hot water load is removed from the heating system, the existing system may be downsized at replacement or derated during maintenance. This is especially true for oil-fired boilers using a derated nozzle can increase operational efficiency and decrease short-cycling. Separating energy end uses and reducing equipment size is important to the process we used as it helps prioritize the operational and maintenance needs of the client while they phase-in replacement equipment and seek tangible benefits throughout the process.

Along with the non-profit's net zero targets, heat pumps were also suggested as an incremental add-on to help experimentally right-size heating systems. This option presented itself in larger and older buildings that may have had more than one heating system. Retiring the most problematic, polluting, or lowest efficiency heating unit and replacing it with heat pumps in higher occupancy areas of the building allows for a softer transition for everyone. From a planning perspective, this approach preserves a safety net if the new heat pumps have issues in the first few years after installation, reduces the upfront investment to curtail most of the shoulder and winter season emissions of the heating system, and allows for a data-driven approach for sizing subsequent systems assuming similar weather and usage conditions. This approach was adopted in a different form for the client's first air-source heat pumps, where the aging propane boiler will be removed in 2026 after the heat pumps are in place for several years and their capacity to provide heat to the building is proven.

Operating within a limited budget is difficult for any organization with the variation of building ages, typologies, and maintenance needs. When Cadmus reviewed the replacement sequence, we expected several units to have some estimated useful life remaining. For these units, we advised the client to salvage critical parts (i.e., oil burner, water pumps, boiler controls) for re-use at other sites. This salvaging was intended to act as a stopgap measure to control sudden failures and provide for parts availability for failures at other sites.

Virginia Case Study

We conducted an energy efficiency and decarbonization prioritization study for a government client in Virginia. We worked with the client to assess near- and long-term potential for building decarbonization and energy efficiency upgrades and identify the barriers that may limit near term electrification in certain facilities. We collected facility-level electric advanced metering infrastructure (AMI) and gas utility data on almost 100 buildings. Then we worked with the client to select 12 high-priority facilities that represent their overall building portfolio.

For the 12 high-priority facilities in Table 4, we worked with the client to perform ASHRAE Level I audit to collect detailed existing equipment and envelope data (including make/model, age, and performance), typical operations, and recent energy efficiency project reports. The 12 high-priority facilities included offices, recreation centers, libraries, fire stations, and maintenance shops, to assess existing equipment conditions. Our energy models provided estimated measure energy, GHG, and cost impacts to help the client plan capital investments.

We used this data to create detailed EnergyPlus baseline hourly energy models for the high-priority facilities. Based on the existing building data, we developed a database of 37 unique energy efficiency and decarbonization measures, including efficient HVAC (Heating, Ventilation, and Air Conditioning), lighting, hot water heating, refrigeration, envelope, and motor measures. We then applied various energy efficiency and decarbonization measure scenarios to the energy model outputs to determine energy, emissions, and operating cost impacts. Cadmus conducted detailed data collection of existing equipment and envelope and current operations for the 12 high-priority facilities. We collected make and model numbers, capacity, age, and performance of existing equipment (including HVAC, hot water heating, refrigeration, fans, lighting, and controls) and envelopes (including windows and wall and roof insulation). Using the existing facility data, we created Energy Plus baseline models for each facility, identified and applied up to 11 applicable energy efficiency and decarbonization measure scenarios from the database of 37 per facility (over 120 total measure scenarios), and estimated the energy, demand, and GHG impacts, measure costs, and payback periods. Using historical electric AMI and monthly gas utility data, we estimated the annual carbon footprint for the client's facility stock and estimated the carbon footprint reduction for up to 11 energy efficiency and decarbonization measure scenarios for each high-priority facility. We also estimated the cost per GHG reduction to help the client identify measure scenarios with the lowest cost per ton of carbon reduced.

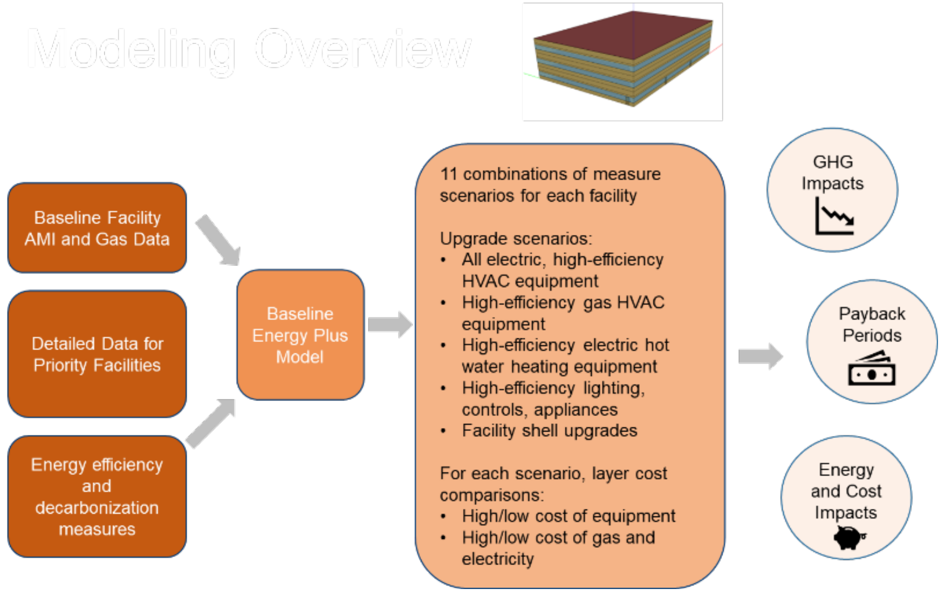
Table 4: Virginia facility primary occupancy type, size, and total energy use

	Primary Occupancy Type	Gross floor area (SF)	Annual Electricity use (kBtu)	Annual Fuel use (kBtu)	Site energy use intensity - EUI (kBtu/SF-year)
Building A	Fire Station	12,000	600,000	689,000	107
Building B	Fire Station	17,000	1,050,000	1,079,000	125
Building C	Office	78,000	2,675,000	2,481,000	66
Building D	Office	18,000	697,000	694,000	77
Building E	Office	53,000	1,658,000	2,763,000	83
Building F	Library	131,000	3,169,000	2,627,000	44
Building G	Community Center	35,000	754,000	1,638,000	68
Building H	Community Center	37,000	1,773,000	2,931,000	127
Building I	Community Center	72,000	3,520,000	3,838,000	102
Building J	Lodging	21,000	994,000	832,000	87
Building K	Warehouse	16,000	318,000	384,000	44
Building L	Courthouse	322,000	15,447,000	5,133,000	64
TOTAL		812,000	32,655,000	25,089,000	

We interviewed local installation contractors to collect equipment and installation cost data and understand potential challenges for the client's facility portfolio, such as electric service and equipment space constraints and aging building envelopes. We interviewed facility staff and local installation contractors and conducted primary research into online literature and the RSMeans detailed cost database to understand equipment and installation costs for various energy efficiency and decarbonization measures. Combined with the measure energy impacts, we estimated measure payback periods to help the client plan capital investments.

We solicited input from the client to create an interactive Power BI decision-making tool, incorporating the baseline energy model outputs and measure scenario energy impacts, estimated measure payback periods, greenhouse gas (GHG) impacts, and utility data load shapes. The interactive prioritization tool allows the client to select various measure scenarios and see the impacts so it can plan capital improvement budgets and serves as a foundational input to the client's energy management information system strategy. In 2023, the client selected four of the modeled priority facilities for retrofits and is moving forward with energy efficiency upgrades.

Figure 1: Virginia analysis process flow



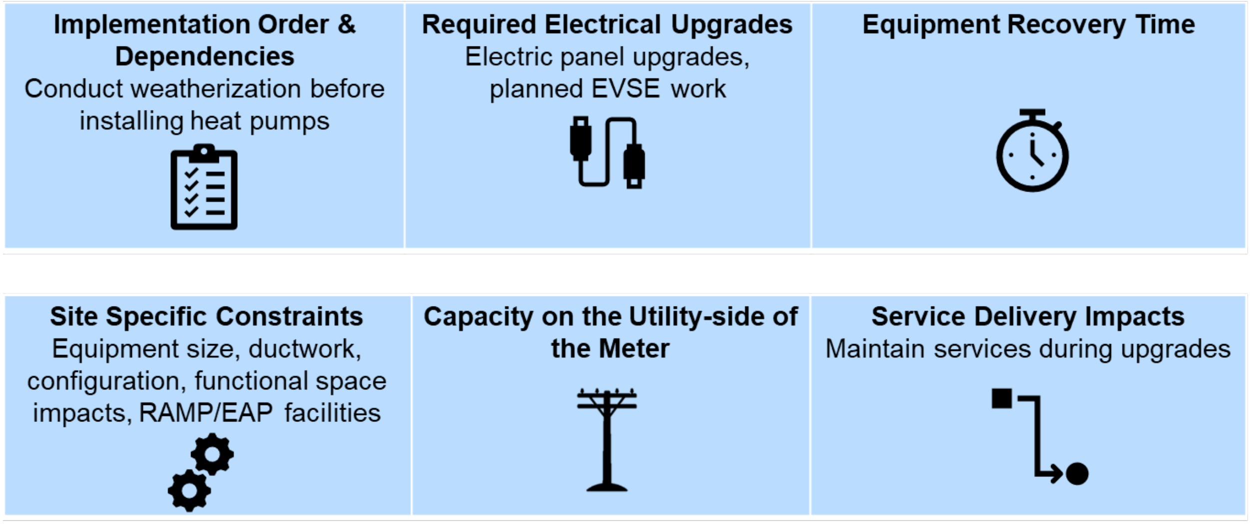
Benefits and uses of the tool:

- Uses a bottom-up, energy modeling approach to analyze and prioritize energy efficiency and decarbonization scenarios for existing facilities to optimize energy, GHG and cost savings across upgrade alternatives
- Model 11 customized measures for each of the selected facilities based on facility characteristics, asset condition data, and planned facility upgrades in budgets
- Enables multiple measures to be bundled within a model and compared to other single or bundled measures scenarios
- Includes high-level screening and ability to integrate other feasibility considerations including implementation order and dependencies, required electrical upgrades on both sides of the meter, equipment recovery times, site specific constraints and service delivery impacts
- Establishes a process for evaluating scenarios for key GHG reductions, cost, and energy metrics
- Provides inputs to the required annual report from the capital improvement plan to transition to all-electric government buildings
- Creates specific facility energy models for a representative subset of existing facilities that span a variety of common building end uses, size, and vintage
- Scopes energy efficiency and decarbonization projects for creating budget inputs

This study was limited because it modeled equipment categories and not specific equipment makes and models. Further engineering work for specific facilities is still needed. Feasibility considerations are high-level inputs and will need to be evaluated for each facility. Our cost inputs are estimates and may be impacted by supply chain impacts as well as direct payments to local governments for specific high-efficiency equipment upgrades

The tool includes higher-level qualitative considerations such as the recommended order of retrofits (such as improving envelope performance to reduce load before sizing and installing new HVAC equipment), whether the facility will need electrical panel or service upgrades, equipment recovery time (especially important with heat pump hot water heaters serving a facility with a lot of simultaneous load), space constraints, and impacts to day-to-day facility operations.

Figure 2: Other electrification feasibility considerations



Implementation Order & Dependencies
Conduct weatherization before installing heat pumps

Required Electrical Upgrades
Electric panel upgrades, planned EVSE work

Equipment Recovery Time

Site Specific Constraints
Equipment size, ductwork, configuration, functional space impacts, RAMP/EAP facilities

Capacity on the Utility-side of the Meter

Service Delivery Impacts
Maintain services during upgrades

Outcomes:

- The tool has been used for capital planning purposes to identify high-impact measures to help meet the client’s decarbonization goals
- Four of the 12 modeled facilities will receive HVAC electrification retrofits in 2024
- Helped identify opportunities for non-modeled buildings

Colorado Case Study

We worked with a government agency in Colorado that adopted a climate action plan (CAP) in 2021 and seeks to reduce greenhouse gas (CO2e) emissions by 74% by 2050 from a 2018 baseline. Our team conducted facility assessments of eight buildings and evaluated electrification measures and costs at four of those facilities that have forced air heating systems.

The aim of this research was to explore ways to save energy in these facilities and examine the potential for switching from fossil fuels to electricity. Based on that analysis, we recommended how and when to electrify those four buildings. The primary uses of fossil fuels in these commercial buildings were space heating and domestic water heating, with space heating consuming most of that energy. The building characteristics are listed below in Table 5.

Table 5: Colorado facility primary occupancy type, size, and total energy use

	Primary Occupancy Type	Annual Electricity use (kBtu)	Annual Fuel use (kBtu)	Gross floor area (SF)	Energy use intensity - EUI (kBtu/SF-year)
Building A	Office	1,338,600	2,501,250	45,500	84
Building B	Mixed	1,022,750	1,741,000	29,500	94

Building C	Office	1,108,900	2,434,400	50,000	71
Building D	Assembly	69,000	389,200	7,500	61
TOTAL		3,539,250	7,065,850	132,500	

We first analyzed energy efficiency measures for these buildings, and we found that lighting retrofits, demand-controlled ventilation, insulation upgrades, and controls were needed. All those efficiency measures had simple payback periods below six years - representing realistic investment opportunities. However, those savings were wiped out when our team analyzed the business case for building electrification. In this area, electricity is over five times the price of natural gas per unit of energy, so heat pumps struggled to overcome that difference even with a coefficient of performance (COP) above three. Once paired with on-site generation from rooftop solar, two of the facilities had electrification packages estimated to yield cost savings. Regardless, the power generation mix would mean heat pump retrofits could reduce emissions at all four facilities.

Financial and Performance Analysis

In this area of Colorado, the cost of using electric heat pumps for heating is 40% higher than using gas-fired equipment. However, that can vary for specific buildings, and we explored a scenario in which gas fired heating equipment was replaced by electric variable refrigerant flow (VRF) air-source heat pumps. The upfront costs and changes in annual energy use and utility costs associated with electrification are shown in Table 6. These results come from our analysis on electrifying the heating systems in facilities conditioned by forced air heat rather than unitary heaters. For each facility, we proposed and investigated a VRF cold climate air source heat pump (ccASHP) system paired with a natural gas fired makeup air unit (for ventilation air) as the new electric heating solution. A small rooftop solar system with on-site generation was analyzed and factored into the electric savings of the heating electrification analysis. Unfortunately, net metering tariff limitations only allow one site, Building D, to install enough on-site generation to completely cover the added demand from the proposed heating systems.

The newest air source VRF systems claim to operate in outside air temperatures as low as -31°F by using advanced technologies to perform at higher speeds without failure. We found that VRF retrofits are a potentially financially viable pathway to electrification even in this cold-climate area for certain facilities. For example, Building D is a single-story event space that could completely offset its electricity use with a rooftop solar system. Our analysis made the following assumptions and Table 6 shows the results:

- VRF incremental cost: $8,000/ton
- System sizing: 400 SF/ton
- Average coefficient of performance of VRF heat pump for this location: 3.08 COP[1]

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[1] The COP for a commercial heat pump operating in climate zone 6B at this location was calculated using the ASHRAE methodology. ASHRAE 90.1 recommends the minimum efficiencies for HVAC equipment, and the 2019 guideline has multiple size categories at two different temperatures. The size category chosen for this analysis was 65-135 MBH (5.5-11.25 tons) cooling capacity. For this size category, the two ASHRAE standard minimum heat pump efficiencies for outdoor air temperatures of 47°F and 17°F are 3.4 COP and 2.25 COP respectively. We created a weighted average COP based on outdoor air temperatures for this location – 3.08.

Table 6: Colorado facility estimated energy, emission, and cost savings from electrification

	Electricity Savings (kBtu/year)	Gas Savings (kBtu/year)	CO2e (tonnes/year)	Estimated Capital Cost of Solution	Estimated Operational Savings
Building A	-707,990	2,209,184	18.1	$ 907,500	$(4,325)
Building B	-185,101	867,347	20.6	$589,000	$375
Building C	-481,092	1,897,959	33.5	$992,500	$(2,600)
Building D	-26,443	433,673	19.5	$150,000	$3,000
TOTAL	-1,400,626	5,408,163	91.7	$2,639,000	$(3,550)

Electricity savings are negative to indicate a net increase in electricity use at those buildings, and negative cost savings show increased operational costs.

The current costs of electricity and natural gas make this retrofit financially unviable. The annual utility costs of operating a heat pump are higher than those from the current gas-fired system. Heat delivered to these buildings would cost about $3 more per MMBtu using the VRF systems compared to their gas-fired equipment. Additionally, the air source VRF systems would not completely remove the need for gas, and a gas-fired dedicated outdoor air system (DOAS) would still be required to temper the ventilation air for the building.

Annual savings for electrification measures are negative because more electricity will be needed, and most of the additional electricity which will need to be purchased from the utility to operate the systems. If a large enough PV array is installed at the facility utilizing these heat pumps, then that could completely offset grid purchases. Our modeling predicted future heating costs using a heat pump will be less than a natural gas furnace after 2043. The cost model considered expert predictions on price of both electricity (Brown, Gagnon, Corcoran, and Cole 2022.) and natural gas (Leslie 2022) along with a predicted COP growth for heat pumps.[2] Based on changes in energy prices and heat pump performance improvements, our modeling predicted that it should cost less to heat a building using a heat pump than a gas furnace in less than two decades.

Carbon Reduction:

Comparing energy sources can be complex due to different measurement units. To make a fair comparison, we converted all energy sources (electricity, natural gas, and liquid petroleum) to British Thermal Units (BTU). Greenhouse gas (GHG) emissions released per MMBtu of fossil fuel are constant, but electricity's carbon emissions depend on its source. Currently, one MMBtu of electricity produces about three times more GHG emissions than natural gas. Forecasts indicate that by 2032, electricity will produce less GHG emissions than natural gas (Xcel Energy 2022).

However, this raw energy source comparison overlooks the efficiency of end-use equipment. Natural gas furnaces and electric heat pumps are commonly used for space heating, but they have drastically different efficiencies. Our modeled VRF system was almost four times as efficient as a Colorado code-compliant furnace with an efficiency of 80% (a COP of 0.8). We also compared the carbon emissions of different space heating equipment. Heat pumps emit 24%

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[2] Future heat pump COPs were forecasted by creating a regression analysis for past code required COP of heat pumps in the 65-135MBH size segment over time (ASHRAE 1989 – present) and extrapolating out to 2050.

less carbon than the code-compliant furnace per unit of heat delivered to buildings in this location. Colorado's electricity is getting cleaner over time (U.S. EIA 2022), and our analysis showed that heat pumps should be able to deliver a unit of heat with less than half the carbon emissions of gas-fired equipment before 2030.

Conclusions

Building electrification is easy to understand - emissions could be eliminated by converting energy end uses to clean electricity. Assuming renewable power scales to meet that demand, it will still be hard to implement in the real world. Financial constraints and short-term planning habits may make these changes seem impossible. The approach that Cadmus developed in these varying applications focuses first on reducing loads through efficiency, then replacing technologies to serve those loads, and finally on switching their energy sources away from fossil fuels to electricity. Building retrofits start with energy, and that remains the first step in strategic electrification to reduce overall demand and reduce equipment sizes. But it is critical to find motivations to electrify buildings and reduce risk that go beyond the conventional logic on energy and cost savings.

Long-term planning is crucial for electrification, and it requires strategic thinking across building portfolios over a decade or more. Detailed assessments for each facility, considering energy end-uses separately, help identify opportunities for waste elimination and incremental upgrades. As we saw in Colorado, electrification should be prioritized in facilities where operational savings are expected; otherwise, careful consideration of upfront costs against external benefits is necessary. We found these elements most useful and persuasive when prioritizing electrification projects:

1. Upfront cost of retrofit
2. Relative complexity of retrofit and scope of efficiency measures
3. Total energy use and operational cost of new and existing equipment
4. Co-benefits of electrification like improved comfort and reductions in carbon emissions and other pollutants, especially for disadvantaged communities
5. Age and remaining life of existing equipment
6. Downside risk and associated damages from equipment failures

Our team used this approach to consider electrification retrofits in Colorado, Massachusetts, and Virginia for various building types. About 10 percent of the buildings in Massachusetts and Virginia were found to be electrification opportunities that could yield cost savings or were attractive for other reasons. However, only one good potential project was found in Colorado, mainly due to the high cost of the heat pump systems and high heating demand in winter.

While this approach is not innovative in itself, the novelty is in balancing client needs during the process and developing solutions that everyone in an organization believes in - from maintenance technicians to executive leadership. Involving the clients throughout the process allows for both the challenges and unique opportunities posed by the electrification process to be transparent. Each building takes time to understand from building systems, building science, operational, and usage lenses, and the portfolio adds in the unique constraints faced by varying ownership and financial structures.

Building owners need to balance short-term needs with long-term goals. We quantified how building electrification could advance those goals property by property. By giving them accurate information on costs and benefits, our clients can plan electrification strategically.

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