Reducing Carbon Emissions from San Francisco Municipal Facilities Through Renewable Heating and Cooling Systems Change: A Preliminary Guide and Lessons Learned for Cities

Background to This Guide

This guide describes a first stage assessment to identify the potential costs, benefits, and feasibility of transitioning San Francisco's municipal building stock to low emission space and water heating systems (collectively "building heating"). The intent of the original analysis was to lay a foundation for subsequent assessments that can build on the information, insights, and lessons learned to continue to grow knowledge around options and strategies in this sector.

The scale of funding available for San Francisco's initial assessment was relatively small ($30,000). Consequently, the project team had to consider whether to analyze a single case study for one large facility, a high level case study of several buildings, or an analysis that attempted to get a preliminary evaluation of feasibility across a broader range of facility types within the city's building inventory. The team concluded that the study of a single large facility would be very specific to that facility and end with a unique path for the design, financing, and retrofit.

The case study of several buildings option was recognized to generate more detailed information on several sites, but it would have only been representative of a few of the dozens of building types in the city's portfolio. The team determined that looking at a broader array of smaller buildings would be more representative of buildings in other cities and the commercial sector. The team also concluded that analyzing the smaller buildings would yield broader information about building and gas-using equipment trends, develop more options and recommendations for the transition strategies, identify key barriers and means to address them, and calculate a variety of cost and energy impacts.

Based on this evaluation, the city contracted with ARUP to conduct an evaluation of renewable heating and cooling opportunities for a portion of the city's municipal building inventory. This is included in **Attachment A** to this report.

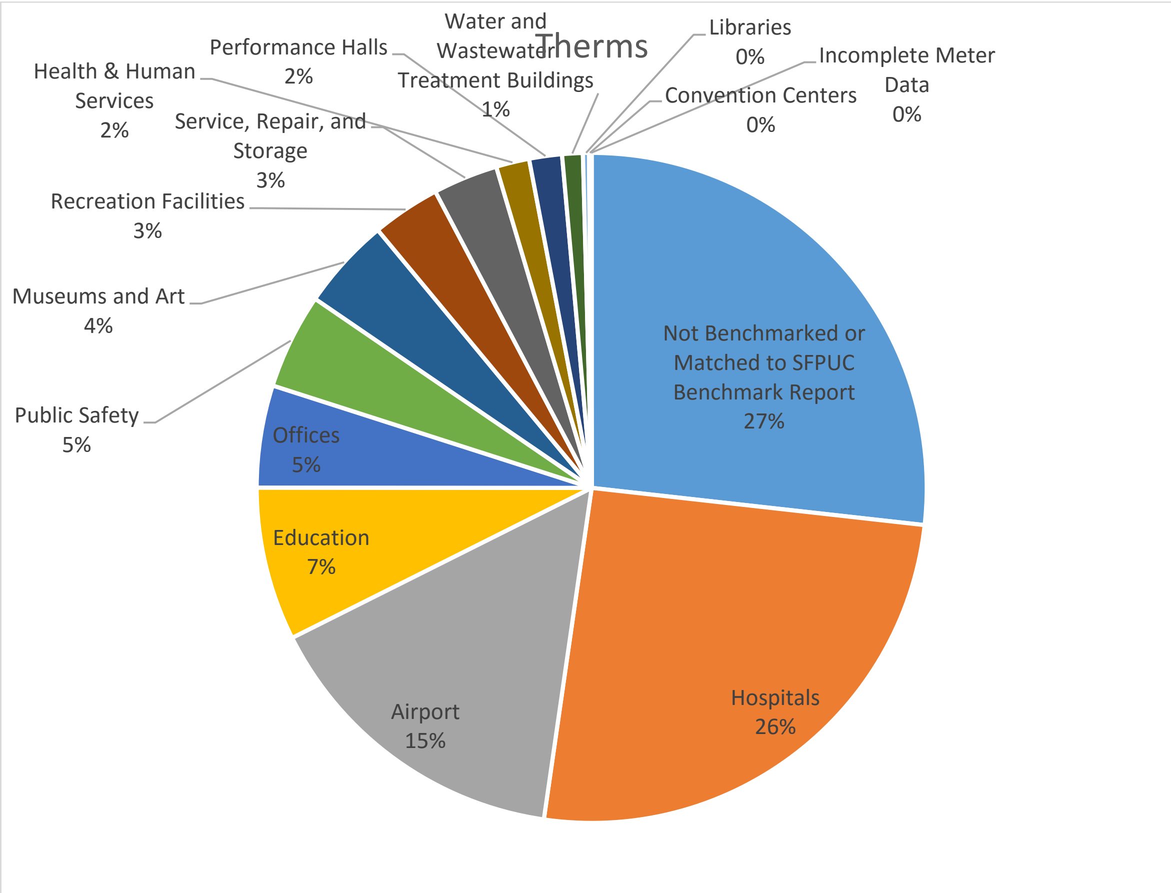
While the recommendations are made for San Francisco, this study review also notes general considerations for other cities and will vary depending on local climate, utility costs, and preferred local design and construction strategies. Although the resources available necessarily limited the depth of analysis to which each building scenario could be considered, we believe the findings of this study will provide a useful foundation on which additional analysis that San Francisco and other cities can build upon.

There are two primary technologies for space and water heating that meet the City's emission reduction objectives: high performance heat pumps and high performance combustion systems, such as boilers. The carbon content of natural gas is essentially fixed. The efficiency of high performance boilers is comparatively fixed (~95%). So the comparative emission profiles between the two systems is driven by two variables: 1) the COP of a heat pump system and 2) the CO_2/kWh emission profile of electricity. Of these variables, the emission profile of electricity has the greatest potential for broad reductions, especially over the long-term.

Underlying building efficiency improvements that reduce heating needs will always be a part of an aggressive municipal decarbonization program. The potential solutions for reducing heating loads are well documented elsewhere and, accordingly, have not been addressed in this assessment due to the limited budget.

The Baseline Study

The study started with an inventory of heating equipment in municipal buildings. The inventory, along with the breakdown of energy use by facility, showed that most of the



heating energy is used by a few large facilities: hospitals, the airport, high schools and office buildings. Large facilities will require unique design, finance, and construction projects to reduce the carbon emissions related to building heating. This report seeks to produce broad recommendations that can be an initial point of inquiry for reducing heating related emissions in the City's smaller facilities.

Focusing on the far more numerous smaller facilities, the consultant developed case studies and estimated replacement costs and savings in energy and carbon emissions. The consultant performed preliminary feasibility studies for several building types on the potential efficiency gains of installing high COP heat pumps. The results were then applied to the broader building inventory, creating summary results for the approximately 12 million square feet in that set of buildings. The results were developed by square foot and weighted by building type. Then results created either a net reduction or net addition per square foot as a multiplier applied to the total square feet:

	Weighted Bldg Avg	Total
Gas Use	-0.3 Therms / SF	-4 GTherms
Electricity Use	2.5 kWh / SF	31 GWh
Total Energy	-26 kBtu / SF	-320 GBtu
Energy Costs	-$0.03 / SF	-$348,000
Capital Replacement Costs	$1.71 / SF	$21,000,000
Carbon Savings	-6.9 lbs / SF	-43,000 tonnes
Negative sign indicates that there are savings.		

High COP heat pumps, as an efficiency strategy, will increase electricity use while reducing natural gas use, with an overall reduction in kBtu. For the Energy Cost, note that San Francisco's municipal electric rates are very low; therefore, savings are likely to be larger in other cities.
Also, if all of the equipment is replaced at end-of-life, much of the $21,000,000 cost would have been spent anyway to install default replacement equipment, generally combustion heaters. The Carbon Savings opportunity in this set of buildings represents a reduction of approximately 25% of San Francisco's overall municipal emissions.

Key Findings

A number of key findings directly impact the strategy options for the implementation of building heating efficiency improvements:

1. Retrofits are seldom a simple swap-out of one piece of equipment for another. Energy dense facilities generally require significant design work.
2. While heat pumps can be more efficient than combustion equipment, adding new large electric loads to a building can require significant investment in infrastructure at the electrical panel, the meter, the service line, and the distribution system. The required analysis of the electrical panel and service line are within the capability of every electrician; however, the utility must determine if the load is going to push the facility into a new tariff or trigger an upgrade in the distribution system. Depending on local regulations, the expense of necessary distribution upgrades may have to be borne, at least in part, by the project.
3. The new system is going to be more efficient than the old system. This will save on operating costs and allow some down-sizing, reducing installation costs.
4. At time of a major building renovation, improvements in the building shell can reduce the load on the active systems by using more passive systems such as solar overhangs and sun shades, tightening the shell, passive cooling and natural ventilation, and passive solar collection and storage.
5. Batteries, combined with photovoltaics and energy management systems can reduce peak loads, reducing demand on service lines and the distributions system, and allowing further reduction of the size of the new equipment.
6. The choice of technologies requires some analysis of the size, timing, and location of the loads in the building. For example, while the pre-existing system in a library may be a single central boiler, the new system might best be a smaller heat pump water heater for the space heating only, and on-demand units in the bathrooms.
7. Heat pump technologies may have different space requirements. Heat pumps need access to the heat-exchange source, be it the outside air, a water source, or the ground, depending on the loads and equipment. This could involve an added or different location for some of the equipment, e.g. space for a ground loop.

Opportunities to Improve Building Heating Efficiency

There are several basic opportunities to improve the efficiency of building heating systems: end-of-life, time of major renovation of the building, new construction, and early retirement.

End-of-life swap outs are possible in very small facilities, such as a park bathroom, or for a facility type, e.g. a neighborhood library, where a typical swap-out can be designed and then replicated in all libraries. This can have complications as noted above; however, the contractor or city workers can be trained, and working with an engineer and the electric utility, they can detect problems and develop solutions unique to each building type. The largest and most energy-dense facilities, e.g. a hospital, are not good candidates for a simple swap-out program. They have large and complex HVAC systems that were uniquely designed for the building. Replacing them will require extensive engineering and adjustments to the building and the electric infrastructure.

Major building renovation and new construction is a better option for many facilities because load reducing measures can be built into the renovation or new construction project. Reducing the load is the most cost-effective strategy, allowing for a much smaller system, and may avoid upgrades to the interconnection and local distribution system.

Early retirement involves the decision to improve building efficiency before the system is due for replacement. This is the most expensive route because it does not leverage the investment that would have already been committed with a default replacement at end-of-life. When shifting from combustion equipment to a heat pump system, the early retirement also may involve modifications to the building that would have been integrated into a broader building renovation at less cost.

Developing a Building Heating Efficiency Program

The following is a description of the technical steps needed for a planned increase in building heating efficiency when attempting to minimize heating related carbon emissions. This does not address two essential parts of a successful municipal effort: community support and financing. The following does not address how to develop a group of community stakeholders and other municipal staff to maintain communications, provide a channel for educating people, provide guidance through the process, and act as champions for the program. It also does not address financing and funding. It does provide suggested steps for developing an implementation plan for efficiency improvements.

1. Locate case studies and/or develop local case studies on existing efforts to reduce carbon emissions from building heating, preferably municipal facilities in a nearby locale. Case studies are useful for educating the many people who will need to be convinced that significant reduction in heating driven carbon emissions is an option.
2. Calculate the benefit of sharply reducing the carbon emissions from building heating systems. For the purpose of reducing emissions, the carbon intensity of the electricity supply is a central variable. For San Francisco, all municipal electricity is already carbon free, coming from hydro, wind, and geothermal. While calculating total potential carbon reductions, include an estimate of the carbon emissions impact of leakage in the natural gas delivery system. (Ask the natural gas utility for the leakage rate.)

Existing Buildings Inventory

1. Develop a database of all facilities, the annual and monthly usage of energy for heating, the size and age of the largest pieces of HVAC equipment, the age and square footage of the building. This information should be obtainable from the accounting office, the utility, and departments in charge of building inspection and building repair. Note that some departments may have their own repair staff and data sets. Also, this step can take considerable effort over a period of many weeks depending on the accessibility of the information. Be prepared that the information you need may be in paper files, multiple spreadsheets from different offices, incompatible or un-exportable formats, etc.
2. Find out any existing plans for new construction and renovations from the finance or budget office and from those responsible for planning large capital expenditures, i.e. the City Manager's Office or the Mayor's Office.
3. Develop an expected year of renovation for each building and compare that to the age of the HVAC equipment and its expected useful life.
4. Divide the building list into groups:
    a. A whole building renovation is expected before the end-of-life of the HVAC system.
    b. Small buildings with simple HVAC systems where the system will reach end-of-life significantly before the expected time of renovation.
    c. Larger, more complex facilities where the HVAC system will reach end-of-life significantly before the expected time of renovation.
5. For Group 'a', wait for the renovation. This is the best option because of the additional measures that can be incorporated into the renovation that capture efficiencies to reduce the size of the systems. For renovations, it is critical to be inserted early in the project development, including in the budgeting and financing as well as in the conceptual design. City staff who work on capital projects know how projects are developed and can provide guidance on successfully intervening. Additionally, see the Whole Building Design Guide: http://www.wbdg.org for help.
6. For Group 'b', develop a program with the building repair department/s and include the building inspection department in the discussions. If the city contracts out equipment replacements, then new contract language is needed as well as education for the contract manager. If city staff will perform the work, the repair staff will need training on the new technologies, as well as how to install and maintain them. For some staff this may mean new certifications. Expect that refresher training will be needed periodically. Also, make sure that the city's purchasing system will incorporate replacement parts for the new equipment.
7. For Group 'c', determine if the systems can be kept operating long enough to reach the renovation dates. If not, determine if efficiency investments are necessary to meet city carbon reduction goals. It may be more cost effective to identify equivalent reductions through other measures in the transportation, buildings, or waste sectors and keep this group in its existing configuration until the renovation. If this group must be improved before the renovation, then it may be most cost-effective to perform all of the projects as a group, achieving economies of scale that will reduce capital and administrative costs for the contractor and for the city.
8. Create a timeline for the list of facilities by year of expected efficiency improvement, including the amount of building heating energy used by the facilities, order of magnitude estimate of the capital expenditure, and estimated carbon reduction from efficiency improvements. This is a tool that will help you explain and advocate for the emissions reduction program.

New Construction

Cities are often building new facilities to meet changing needs and growing populations. In San Francisco, there is strong policy in place to drive the adoption of new technologies. Previously, the City conducted a training program for design staff and departments volunteered projects for a collaborative design process. Later, the ordinance was passed that requires all new construction and major renovations over 5,000 square feet to meet LEED Gold and surpass the California State energy code by a prescribed percentage. These projects receive no additional funding to meet the Green Building code requirements. San Francisco is considering a revision that would require electric technologies or other strategies and prohibit natural gas for heating and water heating.

While San Francisco may be successful with this step, developing policy is complex and typically a unique process in every jurisdiction. One good first step is to locate local buildings that already operate on high-efficiency heat pumps to create case studies. To find case study candidates, ask the City's building department, the nearest chapter of American Institute of Architects, or the Association of Energy Engineers. Case studies should include estimates of the additional costs for construction, operation, and maintenance including specialized training for staff. In San Francisco, the next step was educating City design staff and bringing in private sector stakeholders to advise and help make the case.

Use Case Analysis Methodology

Building portfolio summary

Significant detail on the process used in San Francisco to evaluate building heating efficiency opportunities is provided in the report "San Francisco Municipal Facilities De-Carbonization Study: Findings and Recommendations". The methodology that follows further documents the analytical process that was taken by consultants in assessing building heating efficiency opportunities.
First, consultants produced a summary of primary building types across the whole portfolio. (Table numbers reflect the original report to ease cross-reference.)

"Table 2: SF Municipal Representative Use Cases"

ID	Use Case	Median Size GSF	EUI	Gas EUI	Represented Municipal Facilities	
			kBtu /SF	kBtu /SF	% Gas Consumption	% Building Area
A	Office	52,100	54	20	18%	25%
B	Museum	151,333	179	83	16%	8%
C	Jail / Correctional	250,000	107	95	11%	7%
D	Gas Station / Vehicle Repair	137,263	51	26	7%	13%
E	Performance Hall	264,850	53	25	6 %	6%
F	Pool	12,900	236	195	5 %	1%
G	Fire Station	11,300	74	50	5%	4%
H	Corporation Yard	60,045	64	31	4%	3%
				Total	**73%**	**67%**

For each building type, a representative "Case Study" was selected for analysis from San Francisco's portfolio.

"Table 3: Case Study Representative Buildings"

ID	Use Case	Representative Site	Size GSF	EUI	Electric EUI	Nat. Gas EUI
				kBtu /SF	kBtu /SF	kBtu /SF
A-1	Small Office	160 South Van Ness	14,219	64	49	14
A-2	Medium Office	1440 Harrison St.	52,200	41	27	14
B	Museum	200 Larkin St	185,000	189	114	75
C	Jail / Correctional	375 Woodside Ave	210,000	130	34	96
D	Gas Station / Vehicle Repair	2500 Mariposa St	101,510	65	33	32
E	Performance Hall	201 Van Ness	229,500	56	31	25
F	Pool	5701 03rd St	23,851	216	87	129
G	Fire Station	3305 03rd St	11,420	52	20	33
H	Corporation Yard	1990 Newcomb Ave.	67,500	121	55	65

The evaluation looked at the energy impacts, emission impacts, and likely system costs of moving to high efficiency heating systems optimized to reduce long-term carbon emissions. First, the energy and carbon impact methodology will be discussed.

"Table 7: Case Study Building Resource Impacts"

Index	Use Case	Replacement Impacts				
		Gas	Electric	Total Site EUI		
		Therms / SF-yr	kWh / SF-yr	kBtu / SF-yr	% EUI	Lbs CO2e / SF-yr
A-1	Small Office	-0.1	1.1	-11	17%	-1.1
A-2	Medium Office	-0.1	1.4	-9	22%	-0.9
B	Museum	-0.7	4.9	-52	28%	-5.6
C	Jail / Correctional	-0.8	4.1	-67	51%	-7.5
D	Gas Station / Vehicle Repair	-0.3	2.6	-23	35%	-2.4
E	Performance Hall	-0.2	1.8	-19	34%	-2.0
F	Pool	-1.3	7.9	-102	47%	-49.8
G	Fire Station	-0.3	2.3	-22	42%	-2.3
H	Corporation Yard	-0.7	5.1	-48	40%	-5.1

Negative sign indicates that there are savings.

Analysis at the building level

Consultants developed an Excel-based tool ("the Tool") to analyze the costs and benefits of replacing standard building heating systems with advanced efficiency systems, focused on high-COP heat pumps. The methodology is tailored, to some degree, for the low carbon content of San Francisco's municipal electricity supply. The analysis used a carbon content of 0.00027 tonnes CO_2/kWh, matching the broader rate of the Northern California utility grid. This is low by most standards, but not as low as low as San Francisco's actual municipal supply, which is 100% hydro, wind, or geothermal.

The primary input to the Tool is one year of quarterly electricity and natural gas energy use data for each use case facility. The quarterly data is distributed and interpolated to monthly data using a linear approach. The electricity data is only needed when the analysis includes a potential offsetting of AC loads using recovered cold exhaust from the heat pump systems. Monthly data can be input into the tool, overriding the interpolation process, but San Francisco only had quarterly meter data for its buildings.

Other gas loads

Before the space and water heating loads are assessed, the Tool first estimates the scale of other gas loads that claimed to be in the building.

The first offset comes from swimming pool loads. The Tool includes benchmark monthly load values for a 5,000 ft^2 swimming pool derived from an online tool for estimating pool heating loads.[1] The Tool's analysis is based on Bay Area weather files. The benchmark data is notable for the distinct shift in load between summer (2,500 kBtu/month) and winter (26,800 kBtu/month). The load assigned to each Case

[1] http://noanderson.com/services/swimming-pool-energy-temperature-calculator/

Study Building is scaled for the actual pool size in a linear manner as compared to the 5,000 ft^2 benchmark. The user can also adjust the baseline input of an 80% efficient gas water heater to match the existing condition.

The resulting monthly pool load is subtracted from the monthly gas load, up to the full scale of the metered monthly gas load. The analysis Tool permits the modeling of a heat pump water heater as a replacement unit. The pool heater is sized by the Tool to operate at 50% capacity factor (12 hours per day) in the coldest month. It would operate far fewer hours in other months.

A note on comparable system sizing:
The necessary equipment sizing is scaled to match the heat "as delivered" to a given source. This "as delivered" comparison between equipment types and efficiencies is necessary to accommodate the radically different performance values between combustion technology (~90%) and heat pump technology (~300%). When sized in terms of kBtu of input energy, the heat pump can be much smaller but still deliver the same amount of heat where it is needed. So a heat pump with a 100 kBtu/hr input can meet the same heating needs as a 400 kBtu/hr input combustion boiler.
If a heat pump is installed for the pool, the gas load is reduced accordingly for the succeeding steps of the analysis.

If there is cooking equipment in the building, basic usage information is input by the user, such as Btu capacity, percent of peak power during usual operation, and daily operating hours. The Tool does not evaluate any solutions to reduce natural gas use for cooking. The cooking equipment inputs are used to reduce the gas load on a monthly basis that is subsequently assigned to water heating and space heating loads in the Tool. Cooking loads are assumed to occur 7 days a week.

Coarse disaggregation: water heating

The remaining gas load is assumed to be used for either water heating or space heating (inclusive of space heating that relies on a hydronic system). To distribute the remaining load between those two demands, a coarse level of disaggregation and extrapolation is used. First, the lowest remaining monthly natural gas load is identified. This is usually July or August.

The Tool contains hourly load profiles (8760 hours/yr) that approximate a building's actual operation. Those profiles exist for either a business schedule (Office Prototype) or a 24/7 domicile schedule (Midrise Multifamily Prototype).[2] The 24/7 schedule is used for municipal building's like fire stations and jails. The 24/7 profile is not static across every hour of the week, but matches the usual distribution of loads within a residence. The Midrise Multifamily Prototype does include a one week "vacation" in its standard schedule with comparatively low load; that "vacation" was removed for purposes of the municipal analysis.

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[2] The standard research prototype files can be found at:
https://www.energycodes.gov/development/commercial/prototype_models

Monthly profiles are then derived from the hourly data for the prototypes. That monthly data is scaled so that its lowest month matches the lowest month of adjusted meter data for the use case. In this way, the water heating load profile roughly matches what would be found in an actual building, but scaled to match the load of the Case Study Building. For the standard office schedule, this results in a monthly December water heating load that is 14% higher than the summer reference point.

The water heating load is assessed before space heating load because the seasonal variation in water heating is much less variable. The increased water heating load in the winter is driven by cooler ground temperatures that lower the temperature of the incoming water (necessitating more heat per gallon to bring the water to the target temperature.) Changes in ground temperature and the resulting changes in incoming water temperature are fairly predictable. Water heating is also easier to estimate because the load continues through the summer, such that there is a benchmark level of water heating energy in the summer that can be extrapolated to other months.

Caveat: This method can lead to an overestimate of water heating loads if there is substantial heating in the hottest month of the year, or if there is substantial reheat operation in the HVAC system. There is no way to deduce when this is happening in an actual building from the sparse data available for each Case Study Building in this analysis. If some of the assigned water heating load were actually space heating, the resulting model outputs can be thought to reduce both water heating loads and some space heating loads with a combined set of costs and benefits. At the portfolio level, this “blind spot” should not significantly impact results.

Coarse disaggregation: space heating

At this point in the sequential analysis, there is a remaining amount of gas load not assigned to other building loads. That remaining load is aggregated to a single annual sum and assigned to space heating within the model.

As with water heating loads, the Tool has hourly heating load profiles for standard office and domicile prototypes. The aggregate annual heating load is assigned to hourly values across the year to match the modeled loads from the prototypes. Those profiles are based on Bay Area weather files.
Hourly values are needed for the water heating analysis and for the space heating analysis for a few reasons:

- If a heat pump is selected within the tool to serve the load, the peak hourly value is used to size the necessary equipment and therein assign a cost for that equipment.[3]
- As will be discussed below, if there is air conditioning (AC) in the building, the cold air exhaust of a heat pump can be recovered to offset AC loads, further improving overall system efficiency. The analysis of potential AC offsets is dependent on hourly load profiles that match cold air production from the heat pump with a demand for cooling in the building at the same hour.

[3] In sizing the equipment, the Tool user can adjust the “service factor” to size the equipment to address operation and weather uncertainty. The default service factor values are 1.8 for water heating and 1.2 for space heating. The purpose of the sizing calculations is to assess system costs and necessary electric panel capacity.

Solar thermal

For some of the use cases, solar thermal was modeled as a mechanism to reduce the water heating load. It was not modeled as an offset strategy for space heating loads. The offset was distributed on a monthly basis according to prior solar thermal simulations produced by the consultant. In those simulations, summer hot water production is a little over twice the winter hot water production. For that reason, solar thermal technology is better suited to offset the comparatively stable hot water loads rather than the space heating loads that are countercyclical to solar thermal production.

AC offset

For buildings with air conditioning, the Tool can be used to estimate the potential to offset AC loads with discharged cold air from a heat pump. No additional energy is used by the heat pump in this configuration. Some additional ducting, dampers, and controls might be required to implement such a system in an effective manner. The exact configuration will be very site specific.

As with the heating load, a building's AC loads are estimated via a coarse analysis of the differing winter and summer electric loads in the building. At least in San Francisco, where the carbon content of the electricity is comparably low, offsetting AC loads with the recovered cold air produces comparatively small emission reduction benefits as compared to the benefits of reducing natural gas usage.

Electric panel capacity

This analysis foresees the greatest opportunity to reduce the carbon emissions of building heating loads through the use of high efficiency heat pumps. That solution might necessitate additional investment to bring additional electricity capacity to the building to meet the heat pump loads. The analysis assumes that each Case Study Building has existing unused power capacity of 3 W/ft^2. The number can vary significantly, in practice. A fixed cost was assigned to those buildings expected to need additional capacity.

The Case Study analyses did not assess actual spare panel capacity in the Case Study Buildings.

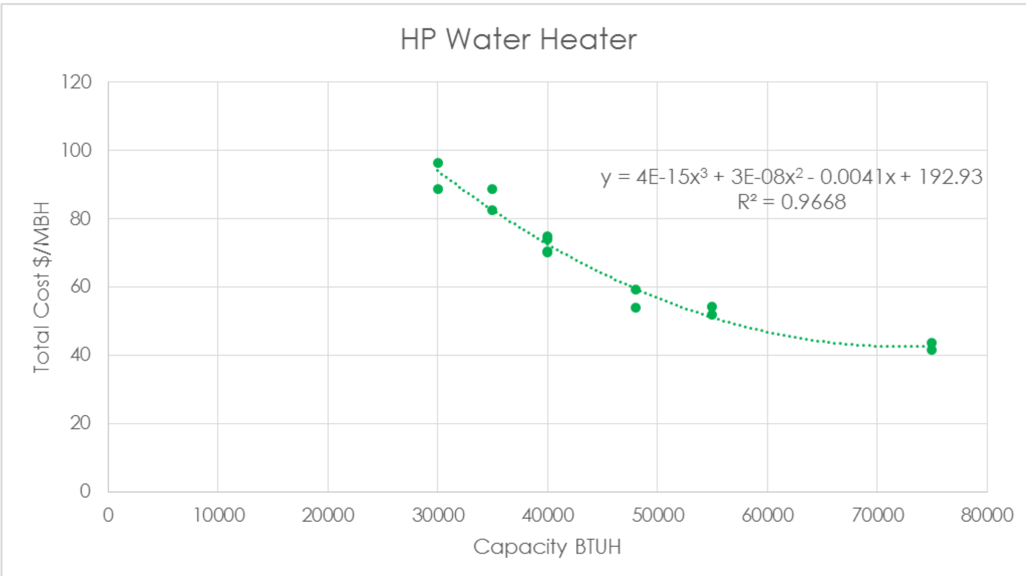
Standard assumptions:

Across the Case Study Buildings, consultants used the following assumptions:

kWh Cost	\$0.09	Existing water heater efficiency	65%
Therm Cost	\$0.74	Existing space heater efficiency	80%
tonnes CO_2 / kWh	0.00027	Existing pool heater efficiency	80%
tonnes CO_2 / Therm	0.006	Service factor: water heating	1.8
Water and space heating load reduction through efficiency	10%	Service factor: space heating	1.2
Cost for efficiency reductions	\$0	Water heating COP	2.0
Spare watts of electric panel capacity	3	Space heating COP	3.0
		Pool heating COP	2.2

Cost inputs

The costing analysis process will not be set out in full here, as it is detailed in Appendix D of the primary report. Costing data came from sources such as RSMeans or the California Solar Initiative (for solar thermal components). Consultants would collect costing information across a range of sizes to permit the creation of a cost curve that could be used by the Tool. For instance, for heat pump water heaters the following data was collected and analyzed:



"Figure 5. Costing correlation diagram for heat pump water heater, (RSMeans Online)."

Based on the regression line for the RSMeans nationwide heat pump water heater data, cost is estimated as follows, where x = capacity in MBH and y = cost per capacity in $ / MBH.

$$y = 4\text{E} - 15x^3 + 3\text{E} - 08x^2 - 0.0041x + 193$$

Results

Using this methodology, the carbon reduction values shown above in Table 7 were derived on a project-by-project basis.

Comparative costs and benefits across system types

This document sets forth the methodologies for analyzing advanced building heating efficiency systems for municipal buildings. It is worth noting a critical variable in the output data from the San Francisco analysis: while it can be quite costly to shift all building heating systems to high COP heat pumps, the benefit / cost analysis varies considerably between water heating loads and space heating loads.

This difference is a result of the comparatively even load profile for water heating from month-to-month, such that an appropriately sized system will be delivering efficiency benefits – or return on investment – on a consistent basis, day after day. In contrast, a space heating system must be sized to meet space heating loads on the coolest days, leaving a vastly oversized system for much of the year. A space heating system in San Francisco might even go unused over the summer months. As such, the benefit / cost ratio for space heating systems will be far smaller, often about a fourth of the benefit / cost ratio for water heating systems.

Attachment A

City of San Francisco Department of Environment

San Francisco Municipal Facilities De-Carbonization Study

Findings and Recommendations

June 15th, 2016

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1 Executive Summary

The City and County of San Francisco has an ambitious goal of achieving 80% reductions in greenhouse gas emissions (GHG) from 1990 baseline levels by 2050, as laid out in its 2004 Climate Action Plan. San Francisco has made steady progress towards this goal thus far, exceeding its 2012 reduction goal to 23% below the 1990 baseline, despite significant local economic and population growth during that period. However, in order to maintain this progress, the City seeks to lead by example through demonstrating significant reductions in its own operational GHG emissions. Since municipal buildings represent 57% of City operational GHG emissions, it will be necessary to dramatically reduce or eliminate natural gas use in city buildings in order for San Francisco to meet its carbon neutral goals in its own operations.

This study recommends steps towards, and estimates impacts due to, transitioning San Francisco's municipal building stock to all-electric operation. This work analysed a select subset of municipal buildings data to determine building and gas-using equipment trends, develop and recommend transition strategies, identify key barriers and means to address them, and calculate cost and energy impacts.

As this work is funded through a grant from the Carbon Neutral Cities Alliance (CNCA), this study also notes general considerations for other cities. While some recommendations made for San Francisco are universal to all cities, some will vary depending on local climate, utility costs, and preferred local design and construction strategies.

1.1 Findings

This study estimated costs and impacts of "one-for-one" replacement of existing gas building equipment with efficient electrical equipment, across a select portion of San Francisco's municipal building portfolio representing 12.3 million gross square feet (GSF). Table 1 summarizes the impacts from a complete replacement of gas-using equipment with efficient electric equipment in the studied municipal buildings.

Table 1: SF Municipal Gas De-carbonization Impacts Summary

	Weighted Building Average	**Total**
Gas	-0.3 Therms / SF	-4 GTherms
Electricity	2.5 kWh / SF	31 GWh
Total Energy	-26 kBtu / SF	-320 GBtu
Total Energy	31%	31%
Energy Costs	-$0.03 / SF	-$348,000
Capital Replacement Costs	$1.71 / SF	$21,000,000
Carbon Savings	-6.9 lbs / SF	-43 MTons

Negative sign convention indicates a savings.

Key findings from this work include:

- Savings: Shifting to efficient electric equipment should incur a net energy and cost savings for most building and equipment types, which will help to offset first costs of early replacement.
- Installation Costs: An order of magnitude absolute first cost estimate of $4/SF for gas equipment replacement, including installation, is in line with commercial estimates.
- Marginal Costs: Marginal costs of efficient electric equipment are in the range of 110% to 150% of traditional gas or electric resistance equipment costs, inclusive of installation. This is not trivial but should not significantly hinder end-of-life replacement efforts, especially given the estimated cost savings.
- Implementation: Equipment replacement from gas to electric may be most limited by the physical size and capacity of existing electrical infrastructure, both in individual facilities and to a lesser degree at a local level.
- Availability: “One-for-one” equipment replacement will be limited for large systems and facilities, i.e. buildings greater than roughly 50000 GSF. This is because certain standalone commercial size electric heating and water heating equipment are still emergent to the market and do not yet have an approved federal test procedure or energy efficiency standard. Such facilities form only 25% of the data set by quantity but 80% by gross area; as a result they may require custom designed or integrated systems.
- Availability: Heat pump technology experiences reduced capacity and efficiency at low outside air temperatures. While not as impactful in a mild climate like San Francisco, it is an implementation barrier in many climates.
- Grid Impacts: Adding electric equipment will increase the winter electrical grid peak load. While not a major concern for a summer cooling-driven electrical grid peak as in San Francisco, it may be a concern in areas that have a heating-driven winter electrical grid peak.

1.2 Recommendations

The following list summarizes recommendations and considerations made in Section 5.1 to begin de-carbonization in municipal buildings in San Francisco, and to create a supportive market and regulatory environment for de-carbonization for municipal and commercial buildings in San Francisco and elsewhere.

1.2.1 San Francisco: Near Term

Recommended near-term steps that the City and County can take include:

1. Conduct a thorough inventory of municipal building gas equipment sufficient to select and specify replacement equipment.
   Select the dozen largest facilities by gas use, conduct targeted engineering audits at these facilities, and develop retrofit design solutions and cost estimates for these solutions for City evaluation.

2. In conjunction with the Department of Public Works, develop City equipment selection and purchasing guidelines for small common equipment, such as domestic water heaters, gas furnaces, and laundry equipment.
3. In conjunction with the Department of Public Works, review current facility operations and maintenance (O&M) and replacement procedures and update these procedures to take advantage of replacement opportunities.
4. Using information collected in Step 1, identify the building gas equipment that is oldest or soonest slated for replacement. Develop a targeted replacement schedule by-building that gets ahead of typical equipment replacements.
5. Work with City facilities staff to assess current training provided, and identify gaps in understanding, of installation and maintenance of efficient electric equipment such as heat pump water heaters. Provide or assist in training for City facilities staff as necessary in installation and maintenance of efficient electric equipment, or arrange training through local resources such as equipment manufacturers or training centers.

1.2.2 San Francisco: Long Term and Local

Recommended longer-term and local steps that the City and County can take to spur the local market and regulatory environment include:

1. Provide funding to assess current electrical infrastructure at key municipal and commercial buildings, and at key distribution sites e.g, substations.
2. Float or implement local code measures or approaches that assess the real compliance rate of energy efficiency measures over time.
3. Support local rebate and incentive programs (e.g. through BayREN) that reward advanced heating systems for both new construction and retrofit, particularly HPWH, packaged ASHP and VRF. Offer early replacement programs and upstream programs.
4. Provide funding or coordination for advanced system training and installation programs for mechanical contractors and technicians.
5. Via local building codes and programs, allow VRF and HP WH / boiler energy modeling for code performance compliance, or provide a “credit” for their use in design or retrofit.
6. Require reporting of heating and gas data specifically through existing benchmarking programs, and explore mandating City benchmarking targets for existing buildings.
7. Support alternative approaches to serve process gas loads in buildings via research and demonstration projects.

2 Introduction

This summary report synthesizes the results of a study funded by the Carbon Neutral Cities Alliance (CNCA) and assesses the steps and impacts of reducing greenhouse gas (GHG) emissions in San Francisco via building decarbonisation. San Francisco aims to achieve 80% carbon-neutral operations for all of its non-industrial functions by the year 2050, and 40% carbon-neutral operations by 2030.

This study includes a detailed analysis based on municipal buildings data provided by City of San Francisco, key findings and recommendations which describes the replacement technologies in order to achieve the GHG emissions reduction goals.

2.1 Objectives

The main objective of this study was to develop a de-carbonization strategy for a subset of San Francisco’s municipal facilities. This included a number of sub-objectives:

1. Estimate total costs of implementation for the selected subset of buildings.
2. Estimate total emissions and energy impacts of implementation for the selected subset of buildings.
3. Identify key barriers to implementation of de-carbonization in municipal and commercial buildings, both in San Francisco and generically, and recommend actions to address them.

This study focuses on San Francisco’s municipal building stock. It also draws conclusions and makes recommendations that are relevant to commercial buildings.

This study does not address transportation or industrial production. This study also does not address the transition to low-carbon central or distributed power generation (e.g. hydropower, solar photovoltaic).

3 Methodology

The analysis focused on "use cases" that typified the San Francisco municipal building stock. The use case analysis took the following steps.

1. Trend analysis for a San Francisco municipal building dataset.
2. Characterization of baseline existing facility use cases, representing typical (average and median) municipal facility characteristics.
3. Selection of specific San Francisco municipal facilities that typify use cases.
4. Characterization of replacement strategies for typical use case facilities.
5. Analysis of costs and energy impacts due to replacement at typical use case facilities.
6. Extension of use case results to whole dataset, and estimation of total dataset costs and energy impacts.

Appendix A: San Francisco Municipal Building Characteristics includes detailed information about the dataset characterization, and Appendix B: Use Case Details includes more information about use cases.

This study is based on original data for the fiscal year 2013 received from City of San Francisco. The combined datasets collected and tabulated by the San Francisco Department of the Environment included data obtained from the San Francisco Public Utilities Commission (SFPUC), Department of Building Inspection (DBI), Department of Public Works (DPW), and Recreation and Parks Department (RPD).

Buildings affiliated with the San Francisco International Airport, Community College District, Housing Authorities, Public Utility Commissions (PUC), Redevelopment Agency, SF Unified School District and Public Health (Laguna and Honda hospitals) were excluded from this study. This is because these facilities represent single-source large contributors to municipal carbon emissions, and / or have unique gas use profiles, and therefore merit individual study instead of the portfolio approach taken here.

293 buildings were ultimately included in this study which belong to 23 Municipal Departments, varying widely in type and function. See Figure 1: these form the "Other Departments" subset.

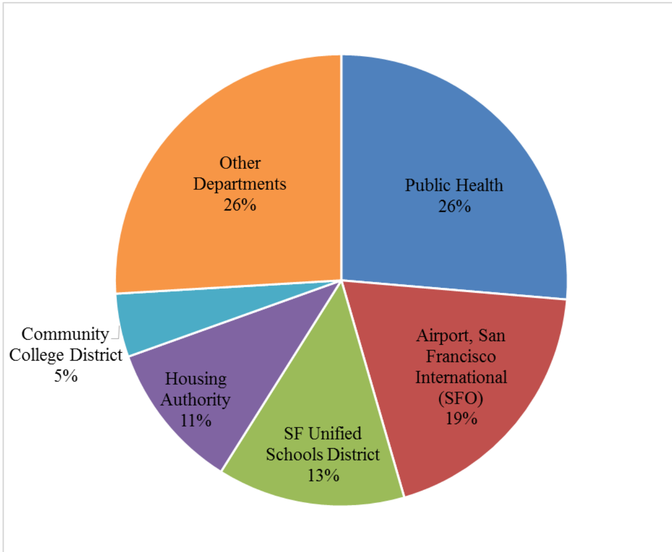


Figure 1: San Francisco Municipal Building Emissions Breakdown

3.1 Data Analysis and Baseline Use Cases

The data analysis phase addressed three key questions:

- Key building types and typical energy, emissions, and building data trends.
- Characteristic existing systems and equipment types for each typology.
- Characteristic existing gas and electric energy consumption by building and system types.

The combined datasets were sorted based on facility place codes, and refined to exclude the specific facilities mentioned above. The final set used for this analysis included 31 building types covering 299 buildings and 386 boilers. From this set, 10 typologies were chosen for the use cases. Use cases, as seen in Table 2, were primarily determined by identifying the building typologies that represented the major gas end-use in the dataset. For each typology, the key use cases are identified as demonstrated in Table 3. Appendix B: Use Case Details describes the use cases in more detail.

Each building type was mapped to a representative use case. To calculate the total set results, each building type total GSF was multiplied by its use case per-square-foot impacts.

Table 2: SF Municipal Representative Use Cases

ID	Use Case	Median Size GSF	EUI	Gas EUI	Represented Municipal Facilities	
			kBtu /SF	kBtu /SF	% Gas Consumption	% Building Area
A	Office	52,100	54	20	18%	25%
B	Museum	151,333	179	83	16%	8%

ID	Use Case	Median Size GSF	EUI	Gas EUI	Represented Municipal Facilities	
			kBtu /SF	kBtu /SF	% Gas Consumption	% Building Area
C	Jail / Correctional	250,000	107	95	11%	7%
D	Gas Station / Vehicle Repair	137,263	51	26	7%	13%
E	Performance Hall	264,850	53	25	6 %	6%
F	Pool	12,900	236	195	5 %	1%
G	Fire Station	11,300	74	50	5%	4%
H	Corporation Yard	60,045	64	31	4%	3%
				Total	**73%**	**67%**

Table 3: Use Case Representative Buildings

ID	Use Case	Representative Site	Size GSF	EUI	Electric EUI	Nat. Gas EUI
				kBtu /SF	kBtu /SF	kBtu /SF
A-1	Small Office	160 South Van Ness	14,219	64	49	14
A-2	Medium Office	1440 Harrison St.	52,200	41	27	14
B	Museum	200 Larkin St	185,000	189	114	75
C	Jail / Correctional	375 Woodside Ave	210,000	130	34	96
D	Gas Station / Vehicle Repair	2500 Mariposa St	101,510	65	33	32
E	Performance Hall	201 Van Ness	229,500	56	31	25
F	Pool	5701 03rd St	23,851	216	87	129
G	Fire Station	3305 03rd St	11,420	52	20	33
H	Corporation Yard	1990 Newcomb Ave.	67,500	121	55	65

3.2 Replacement Use Cases

For each use case facility, we identified baseline and replacement systems. If existing equipment data was available, this was used. If not available, the team made assumptions based on engineering experience with San Francisco building stock. Table 4 summarizes existing and proposed systems.

Key assumptions included:

- Equipment replacements are, to the extent possible, “drop-in” with little to no adjustment or retrofit to the overall building heating or hot water systems. This means that system types that require complete building overhaul – e.g. VRF, thermal storage, change from air-source to water-source system – are not included in this analysis.

- Some minor efficiency measures are assumed (e.g. minor DHW savings from low-flow fixtures), but generally analysis focused on gas-using systems replacement instead of load reduction or passive measures. This is because California and San Francisco already has stringent load reduction measures codified in Title 24 Part 6, Cal Green, and the Green Building Ordinance.

Table 4: Use Case Gas-Using Systems

ID	Use Case	Existing System			Proposed System			
		Heat	**DHW**	**Process**	**Heat**	**DHW**	**Process**	**Solar HW**
A-1	Small Office	Gas Furnace RTU	Gas Storage WH	NA	HP RTU	HP WH	NA	No
A-2	Medium Office	Gas HHW Boilers	Gas Storage WH	NA	HP WH	HP WH	NA	No
B	Museum	Gas HHW Boilers	Gas Storage WH	Cooking	HP WH + HHW Electric Storage	HP WH	NA	20% SSF*
C	Jail / Correctional	Gas HHW Boilers	Gas Storage WH	Cooking Laundry	HP WH + HHW Electric Storage	HP WH	Cooking Laundry	50% SSF
D	Gas Station / Vehicle Repair	Gas HHW Boilers	Gas Storage WH	No	HP WH	HP WH	No	20% SSF
E	Performance Hall	Gas HHW Boilers	Gas Storage WH	NA	HP WH + HHW Electric Storage	HP WH	NA	50% SSF
F	Pool	Gas Storage Pool Heater			Solar Thermal + Electric/HP WH			
G	Fire Station	Gas Furnace RTU	Gas Storage WH	Cooking Laundry	HP RTU	HP WH	Cooking Laundry	20% SSF
H	Corporation Yard	Gas Furnace RTU	Gas Storage WH	NA	HP RTU	HP WH	NA	No

**SSF indicates Site Solar Fraction, the percent of domestic hot water offset by solar hot water capacity.*

3.3 Cost Characterization

For each use case, replacement costs were determined based on replacement system type and estimated capacity. Per-facility replacement costs are shown in Table 5, and costs build-up is provided in more detail in Appendix D: Replacement Costs.

Note that first costs are absolute, not marginal; and are order of magnitude estimates only. Of note:

- Pool type demonstrates unusually high first costs. However the specific use case Pool facility selected is an indoor pool, therefore it incurs costs for three different system types: building heating, building domestic hot water (e.g. showers), and pool heating.
- Costs include installation, however do not account for facility upgrades that may be required to support additional electrical equipment (e.g. physical plant space, electrical infrastructure. These will vary highly by building but are more likely to be incurred for buildings offsetting large gas loads (e.g. Jail, Pool).

Table 5: Use Case Facility Replacement Costs

Index	**Use Case**	**Proposed System Cost**					
		Pool $	**Solar $**	**DHW $**	**Heat $**	**Total $**	**Total $ /SF**
A-1	Small Office	-	-	$2,561	$33,817	$36,378	**$2.6**
A-2	Medium Office	-	-	$2,322	$44,973	$47,295	**$0.9**
B	Museum	-	$334,915	$141,746	$32,606	$509,267	**$2.8**
C	Jail / Correctional	-	$738,243	$97,258	$93,675	$929,176	**$4.4**
D	Gas Station / Vehicle Repair	-	-	$16,159	$529,550	$545,710	**$5.4**
E	Performance Hall	-	$172,464	$54,848	$49,085	$276,397	**$1.2**
F	Pool	$3,444	$125,067	$13,854	$390.295	$532,660	**$22**
G	Fire Station	-	$16,442	$2,643	$95,809	$114,895	**$11**
H	Corporation Yard	-	-	$28,218	$394,401	$422,618	**$6.3**

3.4 Market and Policy Review

3.4.1 Market Landscape

Product Availability

Replacement technology information is summarized in Table 6 and Appendix C: Gas-Replacing Technologies.

Most of the heating and hot water technologies and products evaluated in this study are mature, commonly available in the California and U.S. market from multiple manufacturers, and covered by established test procedures and standards. However, one key exception exists: Commercial Heat Pump Water Heaters (HPWH), defined generally by the US DOE as having a rated input > 12 kW and a rated storage volume > 120 gallons. Key concerns are as follows:

- Residential-duty heat pump water heaters are commonly available in the United States, regulated, and featured in efficiency programs. However, commercial-duty water heaters and boilers are not yet common as standalone or integrated units. As evaluated by the US DOE, nearly all units currently available on the market are "add-on" units designed to be paired with either an electric storage water heater or unfired hot water storage tank in the field.[4]
- No federal test procedure or standards yet exist for standalone or integrated commercial-duty water heaters, although the US DOE is currently establishing a test procedure.
- Most HPWH available, commercial and residential grade, are rated for water heating temperatures (110 deg F to 140 deg F). Heating hot water temperatures used for building heating are generally higher (180F supply). While the authors find at least one high-temperature water heater on the market, it is not yet a proven technology. This limits the ability to "drop-in" heat pump boilers as replacements to existing commercial hot water boilers.

This study did not evaluate electric alternatives to laundry, cooking, or other process end-uses, due to the relatively minor contribution from these processes to total gas use and lack of information about existing systems.

Product Cost

This study did not include a comprehensive cost comparison between baseline gas and replacement electric equipment. As estimated using equipment data from RS Means for common equipment boiler and furnace types and sizes, marginal costs of efficient electric HP alternatives are in the range of 110% to 150% of traditional gas or electric resistance equipment costs. This is inclusive of installation and labor. This is not a trivial difference, but should not significantly hinder end-of-life replacement efforts, particularly given that most replacements will incur energy cost savings.

Replacement equipment cost data and trends used for this analysis is explained in more detail in Table C.2 and Appendix D: Replacement Costs. This includes equipment costs and installation costs, but not related facility upgrades (e.g. electrical infrastructure).

[4] US Department of Energy. Commercial Water Heating Equipment: Energy Conservation Standards Notice of Proposed Rulemaking. Available at http://energy.gov/sites/prod/files/2016/04/f30/Commercial%20Water%20Heating%20Equipment%20ECS%20NOPR.pdf. Pp. 50-54.

3.4.2 Policy and Program Landscape

Codes

The California and San Francisco Bay Area building energy policy landscape is robust and mature. The state energy and green building codes, Title 24 Part 6 and Part 11 respectively, are regularly reviewed and updated. Local jurisdictions are able to adopt "reach" codes which go beyond minimum state requirements, and San Francisco has typically adopted such options, such as a new rooftop solar mandate beginning in 2017.

San Francisco is somewhat impacted by federal action, as the US DOE sets federal energy standards and test procedures for most HVAC equipment including heat pumps, water heaters, boilers, and air handlers. For this reason, states and local jurisdictions cannot take action to regulate these products individually, nor can they easily "ban" a particular product.

San Francisco's existing building benchmarking ordinance has been successful in achieving wide-scale reporting and energy savings, and California will soon implement a similar statewide program.

Programs

The constellation of supportive utility and public incentive programs, energy training centers and resources, and supportive political and economic climate in San Francisco serve to further support the design and construction industry in rapidly vetting and adopting low-carbon technologies in the built environment.

We perceive one significant barrier to the adoption of low-carbon heating and water heating equipment: availability and applicability of training to installers, particularly for VRF systems. Currently, VRF manufacturers typically only allow manufacturer-trained technicians to install and maintain their systems under warranty, which is a barrier to HVAC contractors seeking to install and maintain these systems.

3.5 Technology Review

Table 6 categorizes building gas replacement technologies that were initially investigated for this study, and their applications. As mentioned in Section 3.2, this analysis focused on "drop-in" equipment replacements; therefore not all of the replacement technologies in Table 6 were used in this analysis.

Table C.1 and Table C.2 in Appendix C: Gas-Replacing Technologies contain more information about technology capacity ranges, price ranges, efficiency ranges, and expected useful life, which were used in the impacts analysis.

Table 6. Replacement Technology Applications

New Technology	Application			
	Domestic Hot Water	Pool Heating	Building Heating	Process Heating

High Efficiency Electric Water Heater with Storage Tank	√	√	√	√
Demand-type or Instantaneous Electric Water Heater	√	√		√
Solar thermal Water Heater	√	√	√	√
Air-Source Heat Pump Packaged Unit	√	√	√	
Air-Source Heat Pump Water Heater	√	√	√	
Electric Resistance Pool Heater		√		
Variable refrigerant flow (VRF) HP Systems			√	
Heat Recovery Systems • Economizing • Heat Wheel • Heat Pipes • Plate HX • Run around loop	√	√	√	√

4 Results

Table 7 summarizes energy impacts for each use case.

Table 8 summarizes cost impacts for each use case.

Table 9 summarizes anticipated impacts for the studied municipal building stock should all the recommended changes be implemented in all facilities.

In general, energy impacts are not unusual, however of note:

- High gas end-use types (jail, pool, fire station) demonstrate exceptionally high impacts on total facility energy (40%-50%). While their results are not typical, they're understandable given the high percentage of energy that gas forms at those facilities for their process and domestic loads, and the necessary impacts from replacing that equipment in its entirety.
- The medium office indicates an energy cost increase despite an absolute energy savings due to the breakdown of energy impacts. This outcome is a distinct possibility for some buildings; messaging for decarbonisation efforts should not guarantee that fuel switching will always save energy costs.

Table 7: Use Case Facility Resource Impacts

Index	Use Case	Replacement Impacts				
		Gas	Electric	Total Site EUI		
		Therms / SF-yr	kWh / SF-yr	kBtu / SF-yr	% EUI	Lbs CO_2e / SF-yr
A-1	Small Office	-0.1	1.1	-11	17%	-1.1
A-2	Medium Office	-0.1	1.4	-9	22%	-0.9
B	Museum	-0.7	4.9	-52	28%	-5.6
C	Jail / Correctional	-0.8	4.1	-67	51%	-7.5
D	Gas Station / Vehicle Repair	-0.3	2.6	-23	35%	-2.4
E	Performance Hall	-0.2	1.8	-19	34%	-2.0
F	Pool	-1.3	7.9	-102	47%	-498
G	Fire Station	-0.3	2.3	-22	42%	-2.3
H	Corporation Yard	-0.7	5.1	-48	40%	-5.1

sign convention indicates a savings.

Table 8: Use Case Facility Cost Impacts

Index	**Use Case**	**Replacement Cost Impacts**			
		First Costs		**Cost Savings**	
		Total $	**$ / SF**	**Energy $ / yr**	**Lifetime Avoided $ / lb CO_2e**
A-1	Small Office	$36,378	$2.6	-$0.01	$369
A-2	Medium Office	$47,295	$0.9	$0.02	$250
B	Museum	$509,267	$2.8	-$0.07	$53
C	Jail / Correctional	$929,176	$4.4	-$0.23	$38
D	Gas Station / Vehicle Repair	$545,710	$5.4	-$0.00	$371
E	Performance Hall	$276,397	$1.2	-$0.02	$79
F	Pool	$532,660	$22	-$0.25	$292
G	Fire Station	$114,895	$11	-$0.01	$779
H	Corporation Yard	$422,618	$6.3	-$0.02	$200

Negative sign convention indicates a savings.

Table 9: Municipal Stock Energy Impacts

	Weighted Building Average	**Total**
Gas	-0.3 Therms / SF	-4 GTherms
Electricity	2.5 kWh / SF	31 GWh
Total Energy	-26 kBtu / SF	-320 GBtu
Total Energy	31%	31%
Energy Costs	-$0.03 / SF	-$348,000
Capital Replacement Costs	$1.71 / SF	$21,000,000
Carbon Savings	-6.9 lbs / SF	-43 MTons

Negative sign convention indicates a savings.

4.1 Considerations Beyond the Bay Area

The San Francisco Bay Area has a unique policy and programmatic environment and a very mild climate. As a result certain recommendations that aren't relevant for the Bay Area are relevant to other jurisdictions, and vice versa. We make the following recommendations to other jurisdictions in North America in light of these differences.

1. Support building codes and energy efficiency programs that incentivize or mandate passive building measures, especially those that reduce heating and domestic hot water loads.

   For example:
   a. Air sealing and air tightness: maximum assembly and building air leakage rates
   b. High performance envelopes: low U-value for glazed and opaque surfaces, maximum window-to-wall-ratio (WWR)
   c. Solar heat gain: relaxed minimum solar heat gain coefficient (SHGC) in cold climates to reduce heating demand
   d. Appropriate and seasonally active shading devices: fins, shades, canopies, landscaping features
   e. Water heating use: Low-flow faucets and fixtures
   f. Innovative R&D products that dramatically improve building U-values and air tightness, such as vacuum insulated panels.

   California already mandates rigorous and locally appropriate envelope measures in its code and programs. However, in mild climates, additional envelope measures generate diminishing returns with increased stringency, and as a result such measures are not a current focus area for the Bay Area.

2. Support product development, testing and rating, and incentives for heat pump technology designed for cold climates.
   a. Support national efforts to properly rate and test cold climate heat pumps, such as the Northeast Energy Efficiency Partnerships (NEEP) Cold Climate Air-Source Heat Pump (ccASHP) efforts.
   b. Offer incentives and rebates for cold-climate heat pump technology already provided by innovative manufacturers.

   Typical air-source heat pump technology experiences reduced capacity and reduced efficiency at cold outside air temperatures, and frequently requires electric resistance or gas backup in cold climates. This is not an implementation barrier in San Francisco, but it is in climates that frequently experience temperatures below 40 degrees F. Innovative manufacturers are already marketing products designed to perform better in cold climates.

3. Implement methods to reduce or offset impacts on a winter grid peak.
    a. Implement automated or manual demand response programs to allow large demand users to reduce demand during peak events.
    b. Mandate demand response enabling technology in local building codes, as provided in California's Title 24 2013.
    c. Incentivize, finance, and where appropriate mandate distributed renewable generation measures, "distributed generation ready" measures, and thermal storage measures to offset grid-connected peak loads.
    d. Ban or dis-incentivize the use of electric resistance space heating and water heating in building codes.
    e. Implement time-of-use electricity (TOU) rate rates to charge for peak demand across all tariff structures above a predetermined threshold.

San Francisco, and many cities in California, have a summer electrical grid peak that is cooling-dominated. Therefore a shift from gas to electric heating should not significantly impact required grid capacity. However, jurisdictions with a winter electrical grid peak must carefully consider the impact that adding electrical load will have on that peak, and plan peak demand reductions accordingly to offset this addition and avoid building expensive new generation capacity.

5 Conclusion

5.1 Recommendations

Based on these findings, we note the following recommendations and considerations to San Francisco and all jurisdictions to promote a transformation of gas use in buildings.

5.1.1 San Francisco: Near Term

Recommended near-term steps that the City and County can take for its municipal facilities include:

1. Conduct a thorough inventory of municipal building gas equipment sufficient to select and specify replacement equipment, including at a minimum:
    a. All existing gas-using equipment and their quantity, nameplate data, physical size, age, condition, slated replacement year, and hours of use.
    b. Daily or hourly facility gas use, end-use if available.
    c. Daily or hourly facility electrical use, including historical electrical monthly and annual kW peak.
    d. Existing building electrical capacity including main service type and size, panel and sub-panel size, extra panel slots.
2. The largest and most energy-dense municipal buildings in the dataset – for example, the San Francisco Zoo, the Moscone Center, and the California Academy of Sciences – will almost certainly require custom designed solutions to achieve de-carbonization given their size and unique use profiles. The same applies to all municipal pools.
   Select the dozen largest facilities by gas use, and all pools, and conduct targeted engineering audits at these facilities to develop more detailed retrofit design solutions and cost estimates for City evaluation.
3. In conjunction with the Department of Public Works, develop City equipment selection and purchasing guidelines for small and common/universal equipment, such as domestic water heaters, gas furnaces, and laundry equipment. These selection guidelines should include recommended manufacturers, material specifications, and size classes.
    a. For example, generically:
        i. Gas furnaces (standalone with a blower or as part of packaged rooftop units) below 200,000 btu/h capacity rating should be uniformly replaced with air source heat pump packaged units of equivalent capacity.
        ii. Domestic gas or electric storage water heaters below 75,000 btu/h input or 12kW input should be uniformly replaced with equivalent size heat pump storage water heaters with an Energy Star certification.
4. In conjunction with the Department of Public Works, review current facility operations and maintenance (O&M) and replacement procedures and update these procedures to take advantage of replacement opportunities.
    a. For example, generically:

i. In commercial buildings smaller than 15000 GSF with no gas use besides domestic hot water for sinks and kitchenettes, replace existing domestic gas or electric storage water heaters at end-of-life with instantaneous / tankless or point-of-use electric water heaters.

5. Using information collected in Step 1, identify the building gas equipment that is oldest or soonest slated for replacement. Develop a targeted replacement schedule by-building that gets ahead of equipment replacements to replace with recommended efficient electric products at or before end of useful life.
   a. If economically feasible, work with the Department of Public Works to develop an early replacement schedule that targets gas equipment replacement prior to end of life.
6. Work with City facilities staff to assess current training provided, and identify gaps in understanding, of installation and maintenance of efficient electric equipment such as heat pump water heaters. Provide or coordinate training for City facilities staff as necessary in installation and maintenance of efficient electric equipment, or arrange training through local resources such as equipment manufacturers or training centers.
7. Create an ordinance for City municipal buildings that mandates that all new and replacement heating and water heating equipment below a certain size, be designed with electric systems of a certain minimum efficiency.

5.1.2 San Francisco: Long Term and Local

Recommended longer-term steps that the City and County can take include the following. These steps extend to development of the local commercial market and regulatory environment, which will help to spur de-carbonization locally for both municipal and commercial buildings.

8. Provide funding to assess current electrical infrastructure at key municipal and commercial buildings, and at key distribution sites e.g, substations. Develop or update utility plans to upgrade basic electrical infrastructure as necessary.
9. Via local building codes and building department interpretations, allow VRF and HP WH / boiler energy modeling for code performance compliance. Allow an energy tradeoff, or an exceptional calculation, if project applicant for code compliance is using a software that cannot model HP WH, VRF, or other innovative electric heating technology. Float or implement local code measures that trigger upgrades to the heating or water heating system when one part of the building heating or water heating system is retrofit.
10. Apply a “deemed” approach for local incentives (e.g. BayREN programs, Bay Area Regional Energy Network) and plan check approval for new heating technologies e.g. HPWH and VRF.

11. Float or implement local code measures or approaches that assess the real compliance rate and effectiveness rate of energy efficiency measures over time, for example outcome-based codes, or mandatory periodic energy audits.
12. Support local rebate and incentive programs (e.g. through BayREN) that reward advanced heating systems for both new construction and retrofit, particularly HPWH, packaged ASHP and VRF. Offer early replacement programs for low-efficiency systems, particularly if replacing electric resistance heating – the low relative financial savings from switching to electric heating means that customers will likely require financial incentives to make the switch. Offer upstream rebate programs for vendors of efficient heating and water heating equipment, especially small packaged equipment.
13. Provide funding or coordination to provide advanced system training and installation programs for mechanical contractors and technicians, for novel electric technologies (VRF, HP WH, radiant). If possible, establish partnerships with manufacturers who provide and require product-specific training in order to maintain their products under warranty (e.g. VRF).
14. Require reporting of heating and gas data specifically through existing benchmarking and associated measurement programs for municipal and commercial buildings. Explore mandating City benchmarking targets for existing buildings, e.g. via Energy Star Target Finder, to encourage gas-reducing retrofits.
15. Support alternative approaches to serve process gas loads in buildings. Co-fund research centers and research efforts for efficiency and fuel-switching in process loads including kitchen and laundry technologies, for example the Pacific Gas & Electric Co. Food Service Technology Center. Support test procedures, measurement, and development of local and state energy codes for process loads (kitchens, laundries).
16. Advocate for development of test procedures and minimum efficiency standards for commercial heat pump water heaters and other “uncovered” electric heating and domestic hot water products, at the local (e.g. Title 24) or federal level (e.g. DOE standards).

5.1.3 Beyond the Bay Area

We assume that any jurisdiction seeking to address this issue has already implemented fundamental energy and carbon policies and programs. However we note the following “best practices” as key and universal first steps that have been implemented in San Francisco and other jurisdictions with success.

1. Adoption of a local Climate Action Plan (CAP) including emissions and energy goals and timeframes.
2. Adoption of the most current version of ASHRAE 90.1 or an equally stringent state or local building energy efficiency code for new and retrofit residential and non-residential buildings.

3. Adoption of local “reach” building codes or model codes, including green building codes that address water, waste, transportation, and energy.
4. Adoption of building benchmarking and building data reporting ordinances. It should be noted that the current San Francisco municipal building benchmarking ordinance is what provided the data that made this study possible; such studies rely on good inventories of facility and equipment data.
5. Implementation of utility or public rebate and incentive programs for energy efficiency and renewable generation.
6. Implementation of training resources and classes for design and construction professionals.
7. Investment in research and development towards energy efficiency and renewable generation, such as grants made available targeting technologies or assistive tools (e.g. modeling and measurement tools).

Additional market and regulatory steps that can spur municipal and local commercial de-carbonization specifically, include the following. Many of these have already been implemented successfully in California and San Francisco, and lessons learned here may be applied elsewhere.

1. Adopt local code sections addressing point-of-use and instantaneous water heaters, as proposed into the 2017 version of California’s building Energy Efficiency Code, Title 24 Part 6 2017. If not already adopted, adopt minimum efficiency standards for commercial heat pump water heaters and other “federally uncovered” electric heating and domestic hot water products.
2. Support code measures to reduce or eliminate reheat in buildings. Implement “dual maximum” reheat control sequence for VAV reheat, as implemented in the 2013 version of California’s Title 24.
3. Through codes and building department interpretations, limit or ban applications in which electric resistance heat can be used, both for space heating and water heating. Limit electric resistance heat to systems or buildings only of a certain size or capacity. Allow electric resistance heat only with a tradeoff of additional energy efficiency measures, or when used in conjunction with a high efficiency system.
4. Ensure local building codes and energy efficiency programs incentivize or mandate passive building measures that reduce heating and domestic hot water loads (e.g. insulation, air-tightness and sealing, and low-flow fixtures).
5. Implement local demand response programs or other methods to reduce or offset a winter electric grid peak.
6. Use codes and internal municipal policies to mandate replacement of gas using systems with efficient electric. Mandate duct testing and sealing for the associated duct system of any replaced equipment.

7. Support use of cost-benefit metrics that incorporate carbon emissions and/or site energy consumption in building measurement for codes and programs, such as California's Time Dependent Valuation (TDV) lifecycle metric.
8. Require that software developed and used for local energy code compliance and program compliance is able to accurately model radiant heat, VRF, and HP WH. Write such requirements into local energy code compliance manuals (local interpretations of ASHRAE 90.1 Appendix G), modeling California Title 24 Alternate Compliance Method (ACM).
9. Support development of local energy codes and programs for gas-using process loads. Invest in local research centers and research efforts for efficiency and fuel-switching in process loads including kitchen and laundry technologies.

6 Appendix A: San Francisco Municipal Building Characteristics

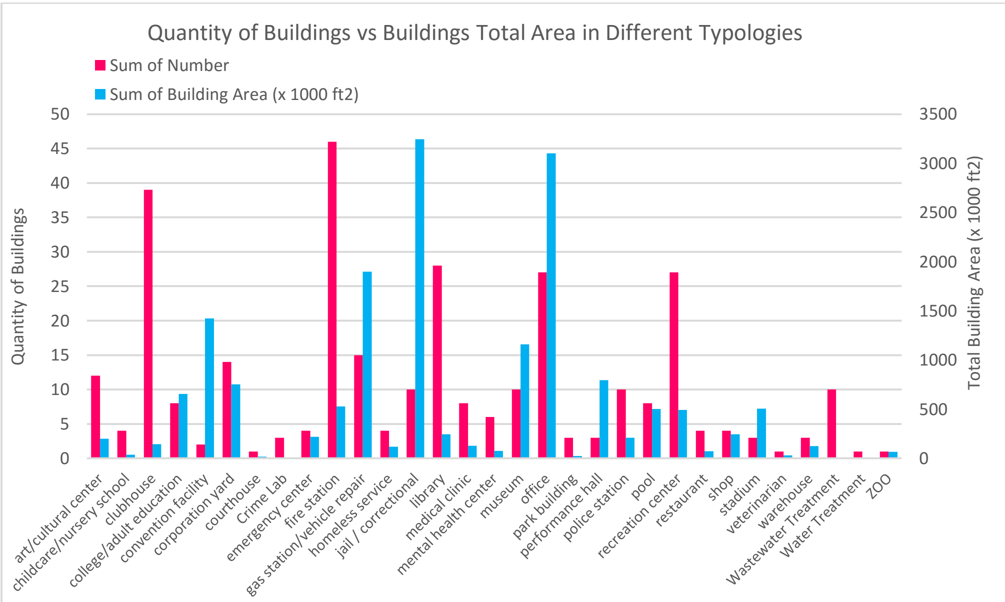


Figure 2. Building Quantity and Total Area by Type.

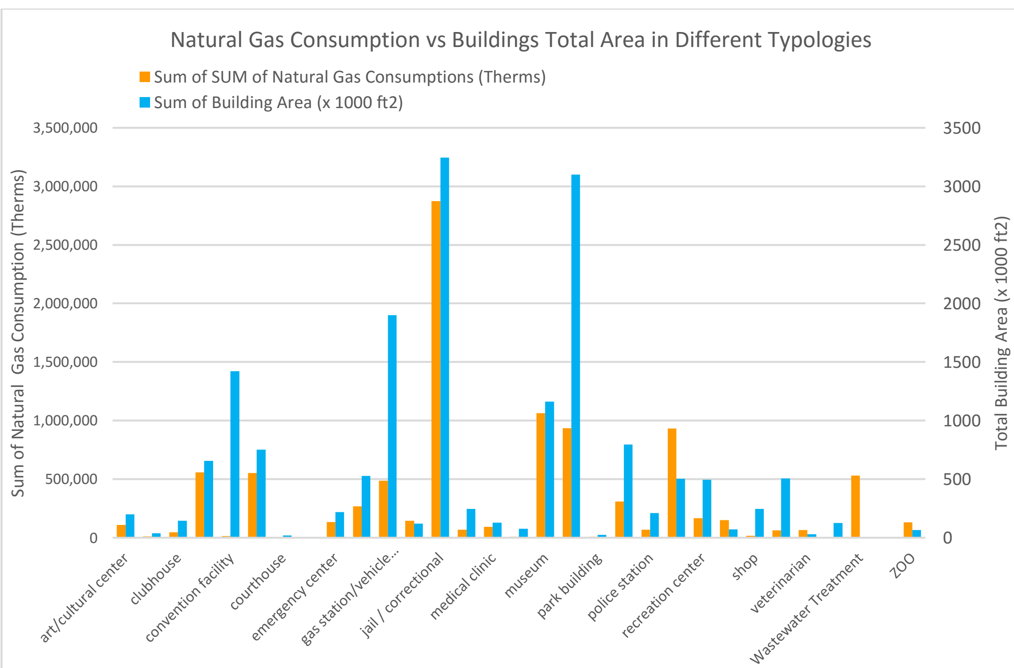


Figure 3. Total Natural Gas Consumption and Total Area by Type.

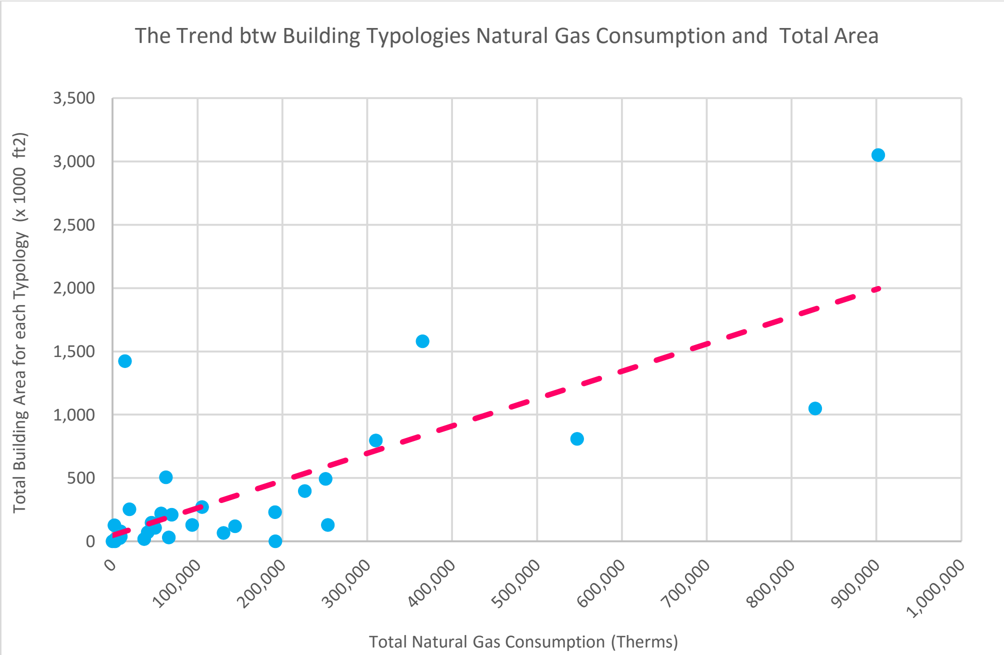


Figure 4. Natural Gas Consumption vs. Total Area.

Table A.1 Different building types and their percentage of total building areas and natural gas consumption.

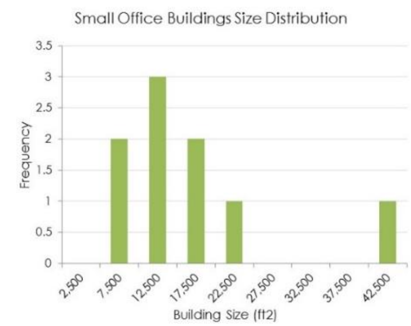
Index	Use Case	Represented Municipal Facilities	
		% Gas Consumption	% Building Area
1	Art/Cultural Center	0.8%	0.6%
2	Childcare/Nursery School	0.2%	0.3%
3	Clubhouse	0.9%	1.2%
4	College/Adult Education	3.8%	1.9%
5	Convention Facility	0.3%	11.5%
6	Corporation Yard	4.5%	3.2%
7	Courthouse	0.1%	0.15%
8	Crime Lab	0.0%	0.0%
9	Emergency Center	1.0%	0.9%
10	Fire Station	5.0%	4.0%
11	Gas Station/Vehicle Repair	7.2%	12.8%
12	Homeless Service	2.9%	1.0%
13	Jail / Correctional	10.9%	6.5%
14	Library	1.1%	1.8%
15	Medical Clinic	1.9%	1.0%
16	Mental Health Center	0.2%	0.6%
17	Museum	16.4%	8.5%
18	Office	17.9%	24.6%
19	Park Building	0.2%	0.2%

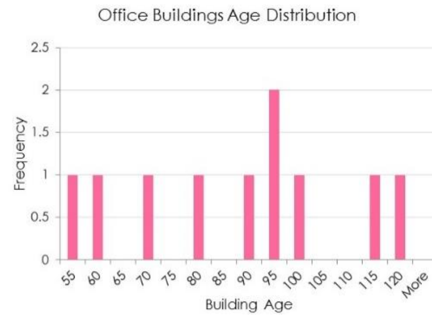
20	Performance Hall	6.15%	6.4%
21	Police Station	1.4%	1.7%
22	Pool	5.0%	1.0%
23	Recreation Center	2.1%	2.2%
24	Restaurant	0.7%	0.15%
25	Shop	0.4%	2.0%
26	Stadium	1.3%	4.1%
27	Veterinarian	1.3%	0.2%
28	Warehouse	0.05%	1.0%
29	Wastewater Treatment	3.8%	0.0%
30	Water Treatment	0.1%	0.0%
31	ZOO	2.6%	0.5%
Total	31	100%	100%

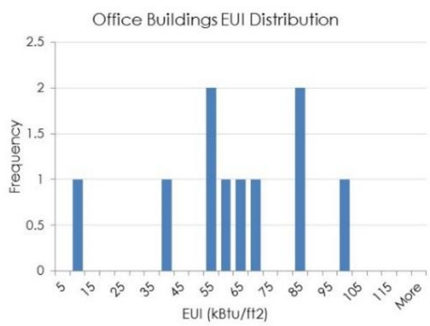
6.1 Use Cases

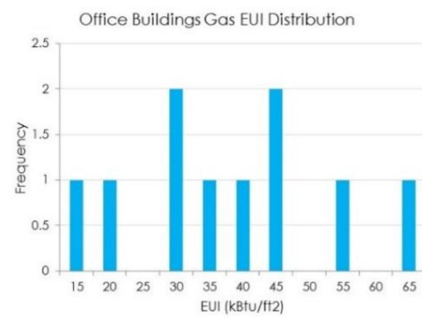
Small Office Dataset Characteristics

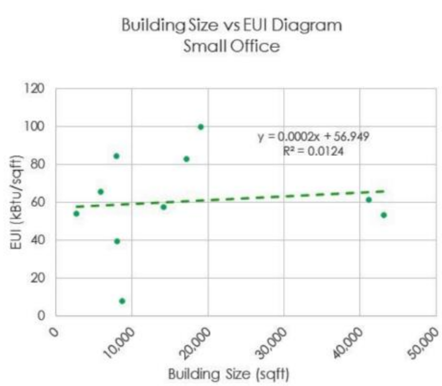
Small office distributions of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.

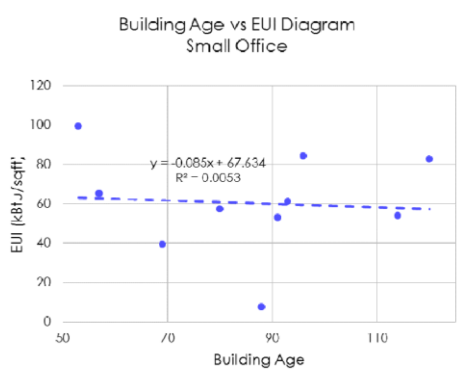






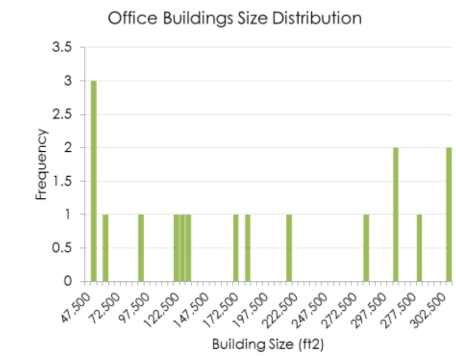


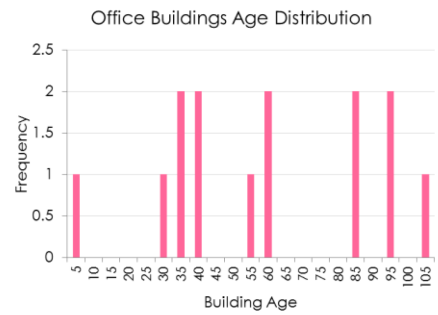


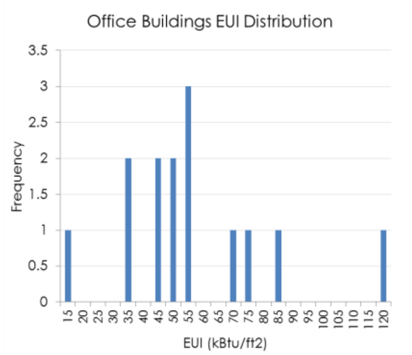


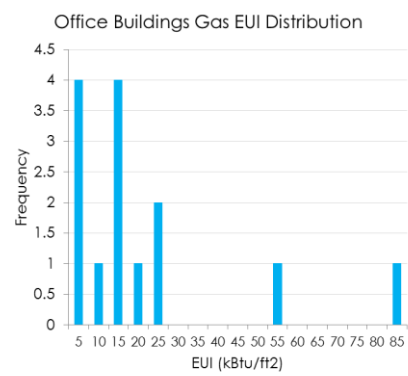
Medium Office Dataset Characteristics

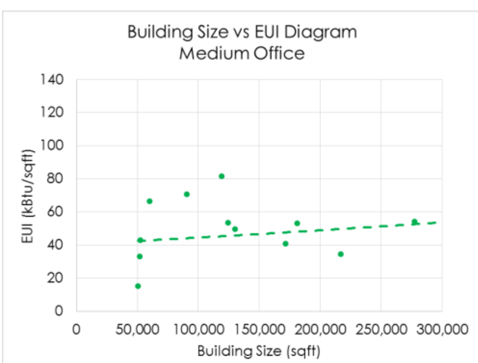
Medium office distributions of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.

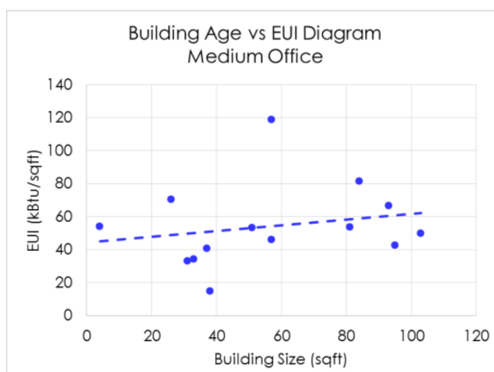






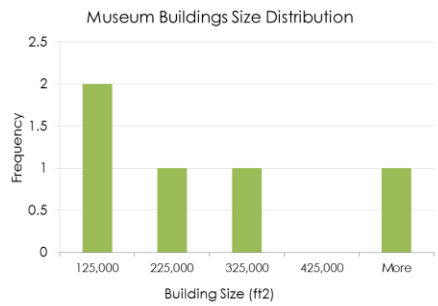


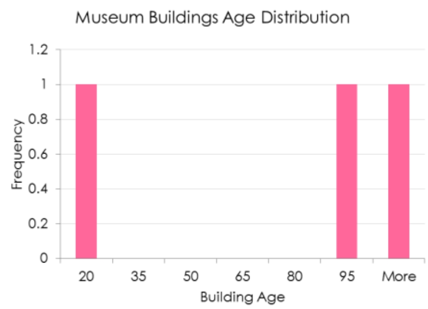


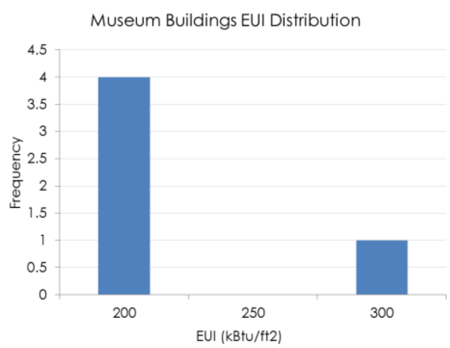


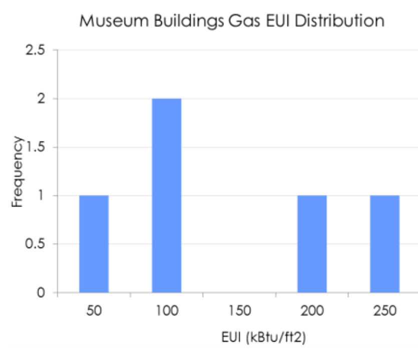
Museum Dataset Characteristics

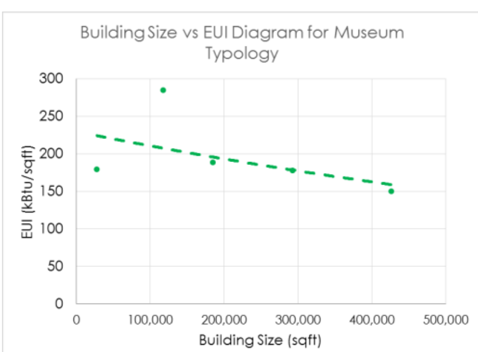
Museum distributions of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.

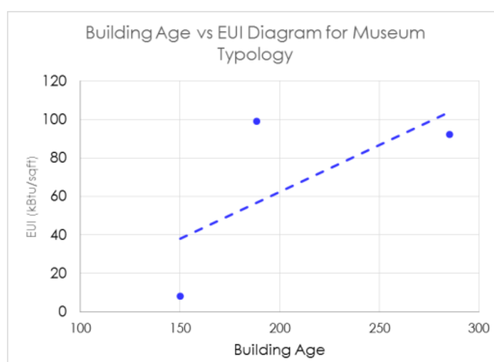






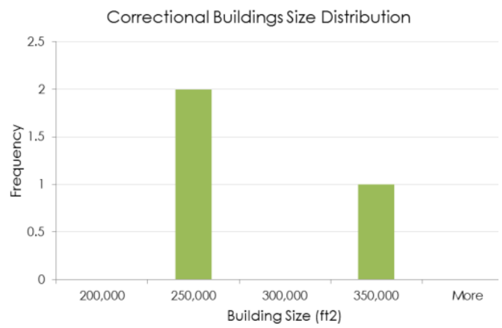


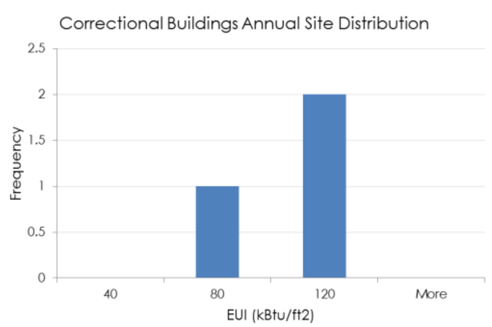


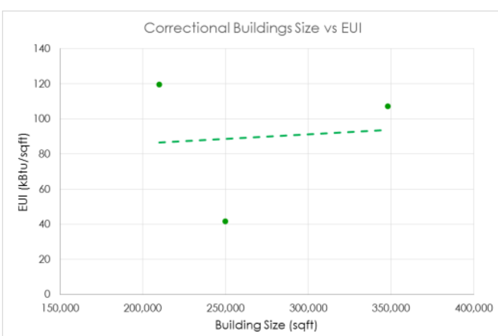


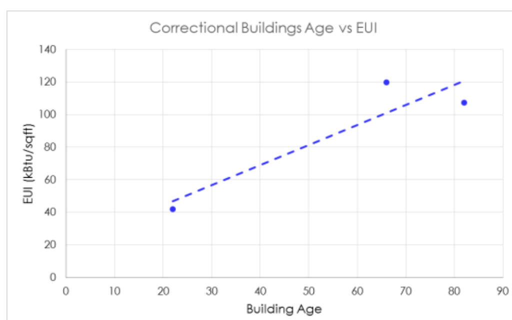
Jail / Correctional Dataset Characteristics

Museum distributions of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.



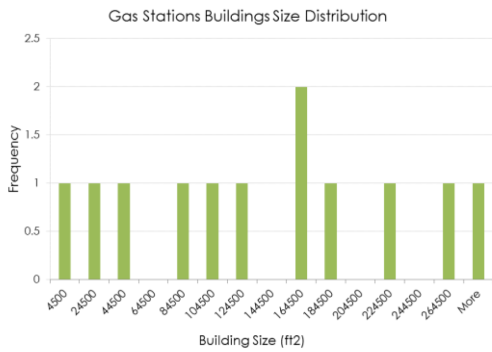


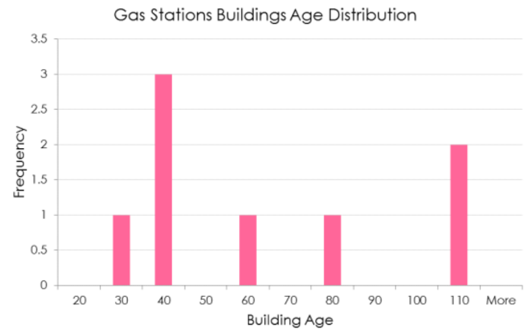


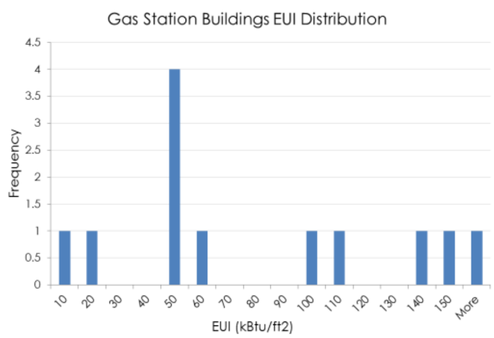


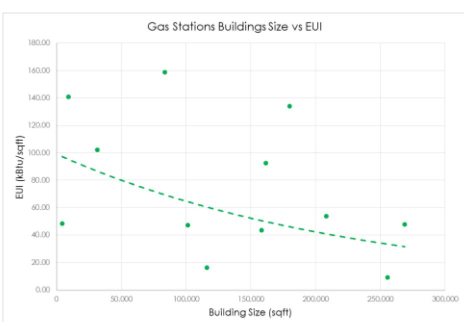
Gas Station / Vehicle Repair Dataset Characteristics

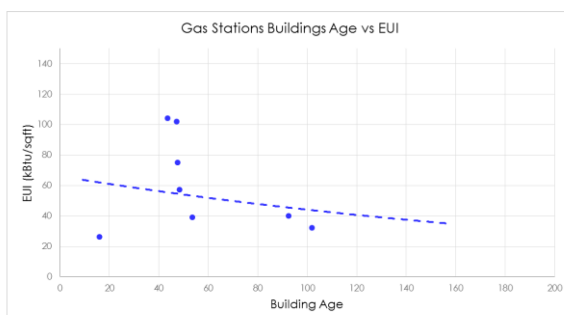
Museum distributions of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.





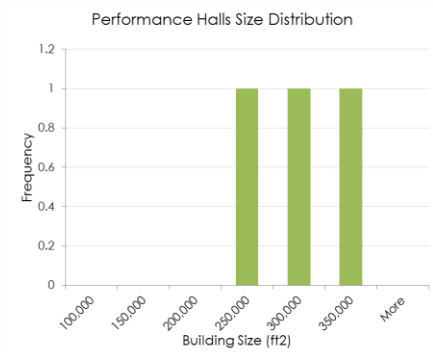


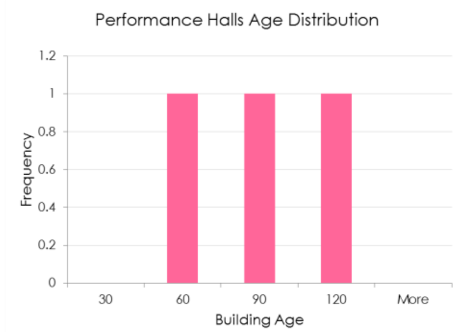


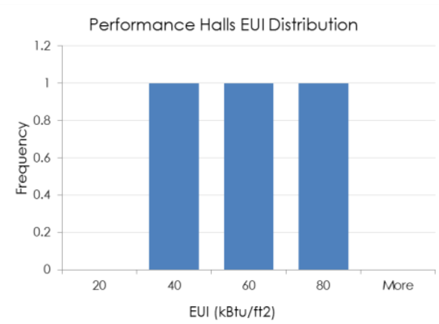


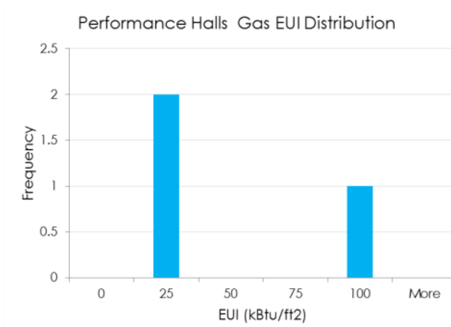
Performance Hall Dataset Characteristics

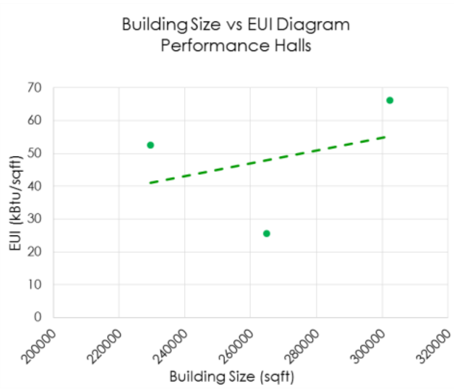
Performance hall distributions of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.

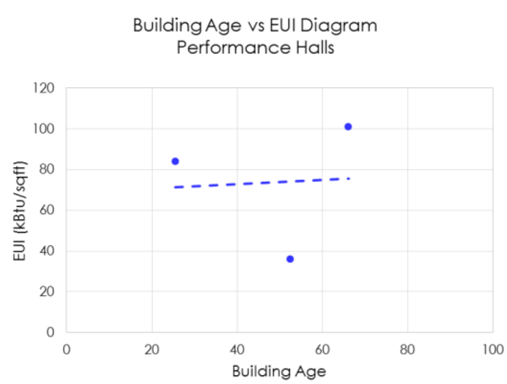






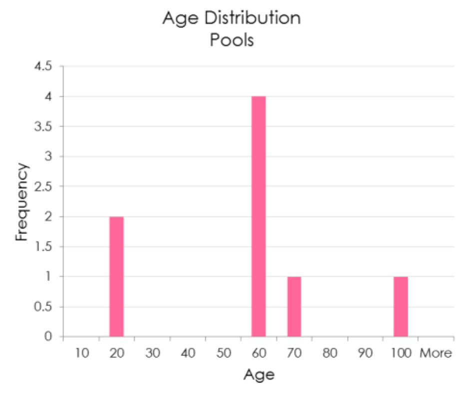


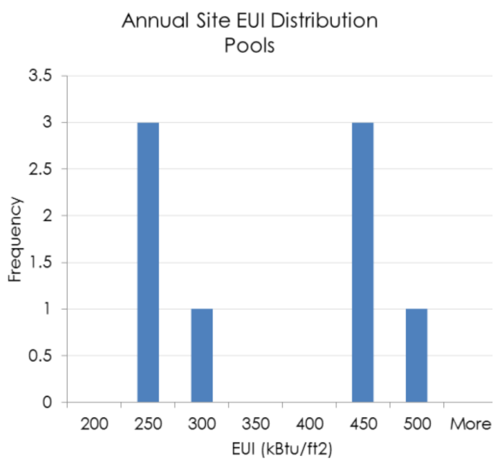


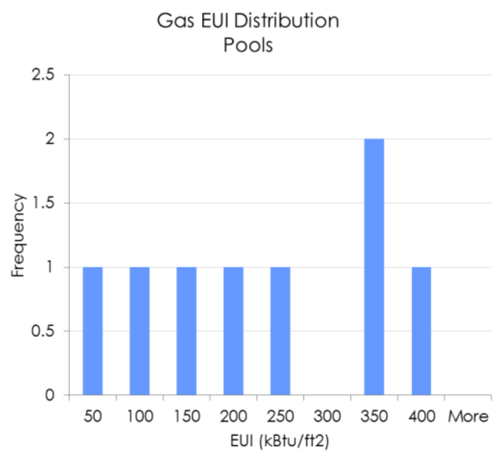


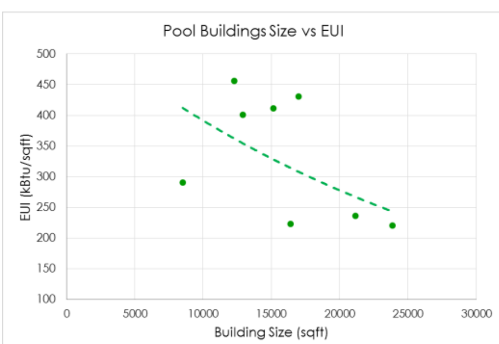
Pools Dataset Characteristics

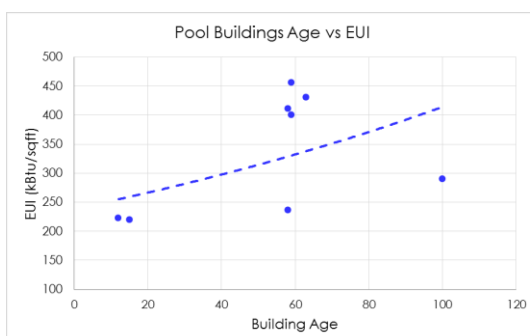
Pools distribution of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.





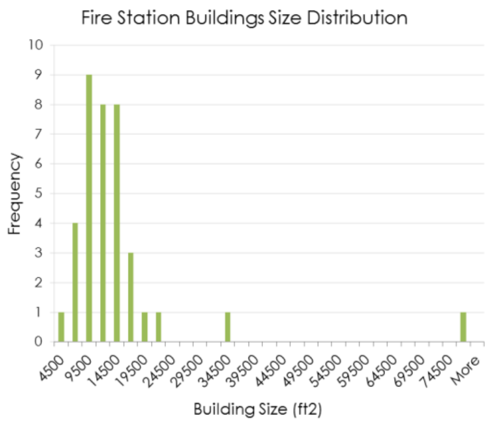


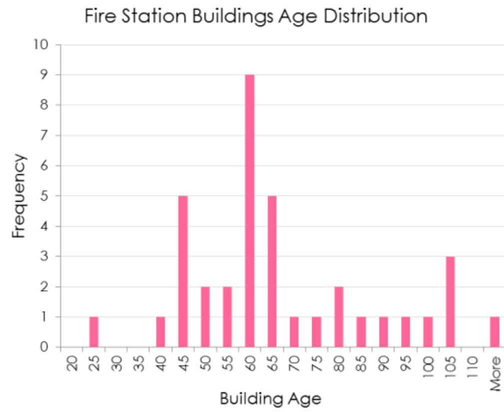


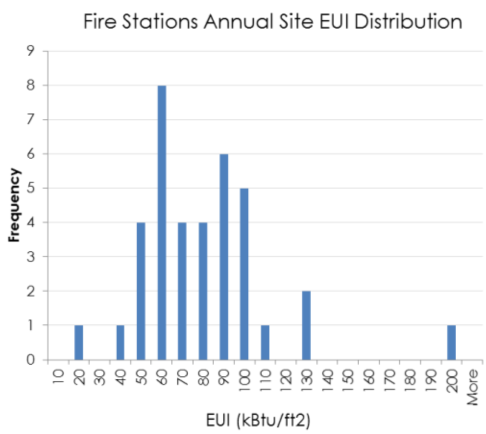


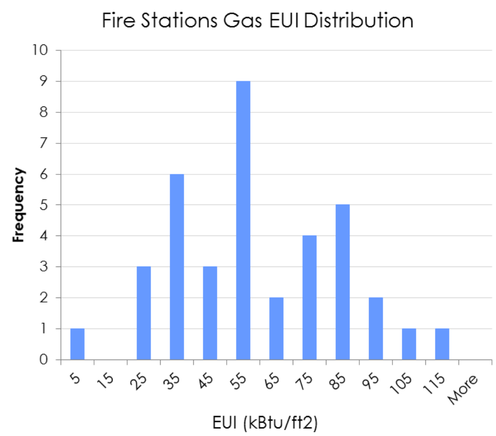
Fire Stations Dataset Characteristics

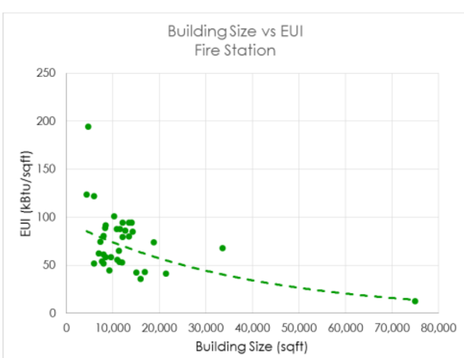
Fire Stations distribution of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.

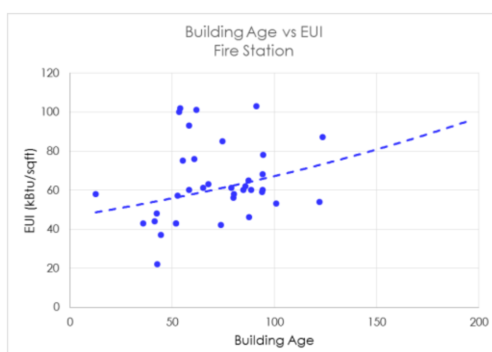






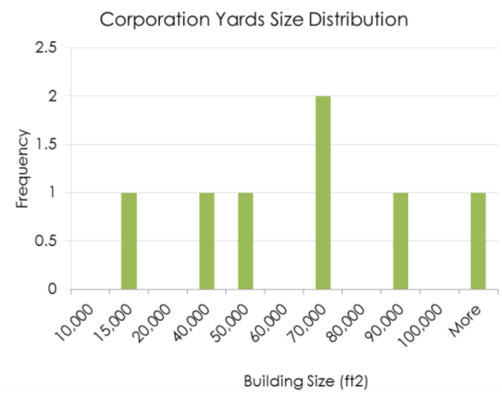


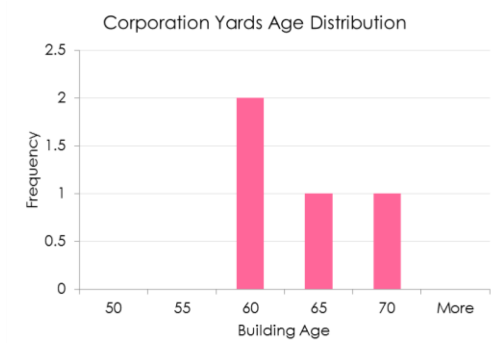


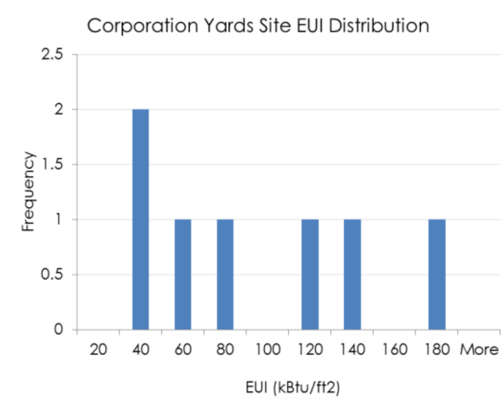


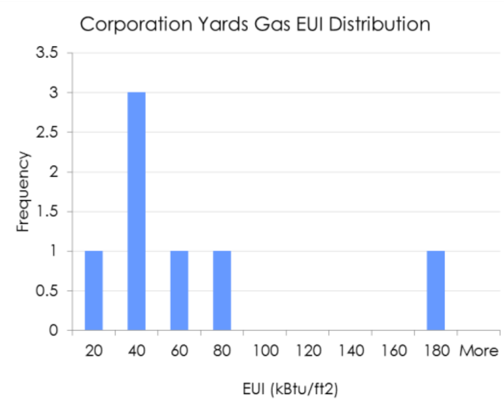
Corporation Yards Dataset Characteristics

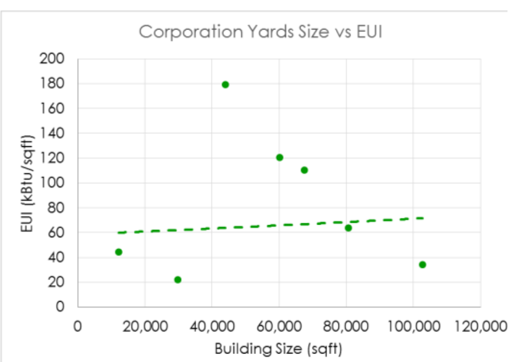
Corporation Yards distribution of size, age, total and gas EUI were used to identify the use case characteristics and select the representative facility.

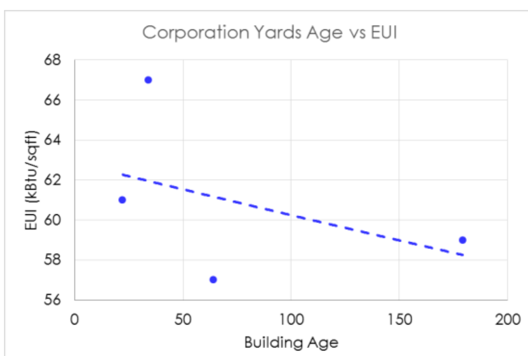








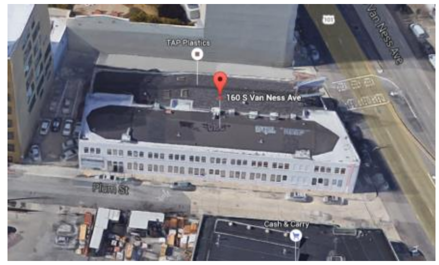




7 Appendix B: Use Case Details

7.1 Small Office (Use Case A-1)

Building Size: 14,219 ft^2 (2 stories)



Existing Condition		Replacement	
Heating System	(1) Gas Furnace / RTU 80% Eff., 80 MBH	Heating System RTU	(1) Heat Pump RTU COP 3.0, 80 MBH
DHW System	(1) Gas Storage Water Heater EF 0.65, 20 MBH	DHW System	(1) Heat Pump Storage Water Heater EF 2.2, 20 MBH
Process Heating	N/A	Process Heating	N/A
		First Cost	$36,378
		Annual Savings	$77/yr

Commentary

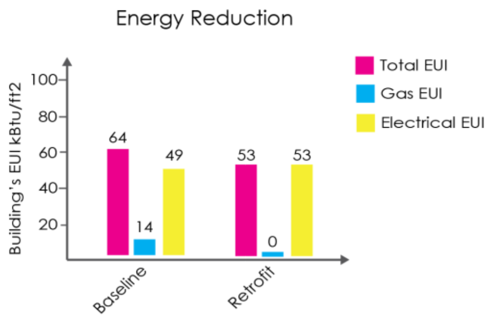
Description: The existing building is assumed to be served by a packaged gas furnace and a standard small gas storage water heater. The simplest replacement pathway is installation of a heat pump packaged unit for building heating/conditioning and a heat pump storage water heater for water heating. No solar thermal or heat recovery technologies are proposed given the small size.

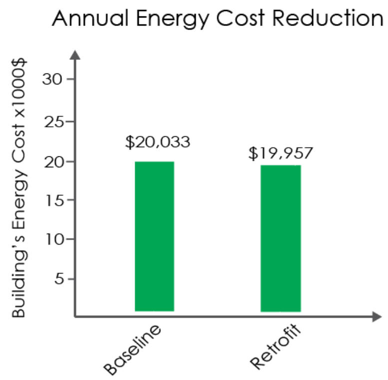
As the building has relatively low domestic hot water use, an alternative water heating option is to replace with small point-of-use or instantaneous electric water heaters to serve restrooms; this could allow abandonment/demolishment of existing domestic hot water piping.

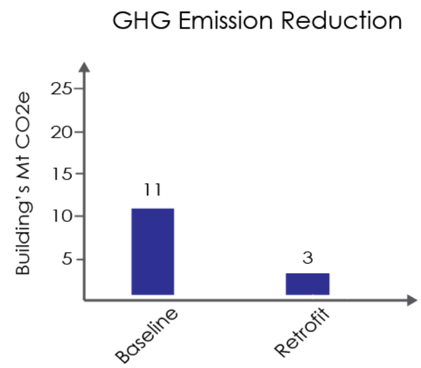
Barriers: There may be limited existing building electrical panel space or service. This can be addressed by conducting an electrical survey prior to verify capacity, and adding a sub-panel if needed. Equipment availability and installation feasibility should not be limiting for the given system and small building size.

Impacts: At the stated first costs and savings the absolute simple payback period is over 100 yrs. First costs should be roughly 110% to 150% to a standard “like with like” replacement (e.g. gas furnace and gas water heater), so incremental simple payback period should be more along the lines of 30 years, however this is longer than the expected lifetime of this equipment. This raises concerns about the feasibility of

Replacement Results

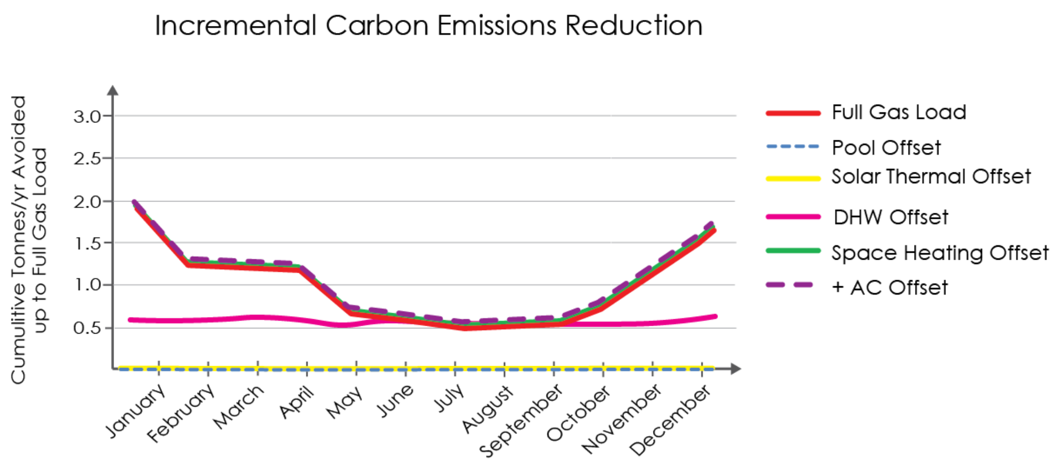






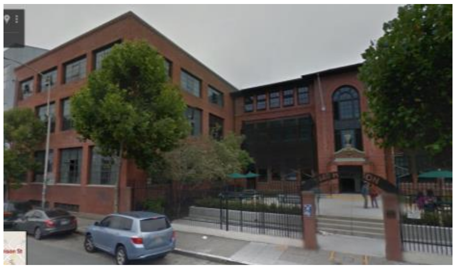
Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile. With no contributions from solar thermal or heat recovery, space heating and domestic hot water sum to the total.



7.2 Medium Office (Use Case A-2)

Building Size: 52,000 ft^2 (3 stories + Basement)



Existing Condition		Replacement	
Heating System	HHW Boilers 80% Eff., 2000 MBH	Heating System RTU	Heat Pump WH +AC Heat Recovery COP 2.2, 2000 MBH
DHW System	Gas Storage Water Heater EF 0.65, 20 MBH	DHW System	Heat Pump WH+10% Reduction EF 2.2, 20 MBH
Process Heating	N/A	Process Heating	N/A
		First Cost	$47,295
		Annual Savings	-$1,214/yr

Commentary

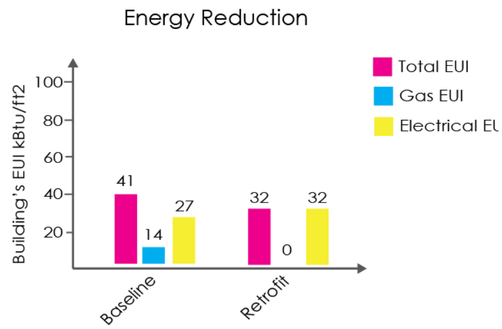
Description: The existing building is known to be served by a heating hot water boiler for building heating/conditioning and a heat pump storage water heater for water heating. No solar thermal or heat recovery technologies are proposed given the small size.

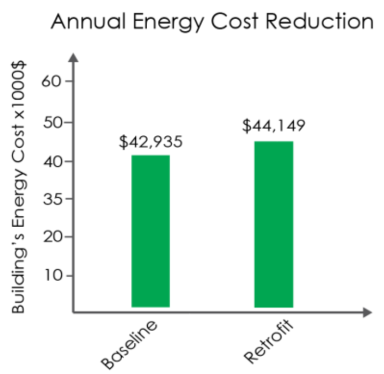
As the building has relatively low domestic hot water use, an alternative water heating option is to replace with small point-of-use or instantaneous electric water heaters to serve restrooms; this could allow abandonment/demolishment of existing domestic hot water piping.

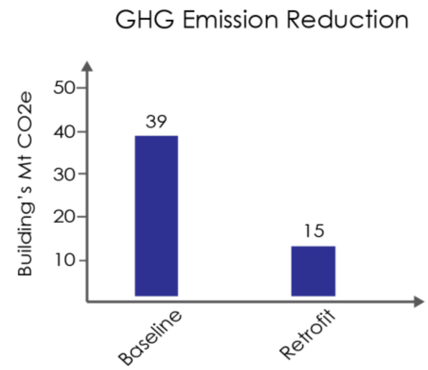
Barriers: There may be limited existing building electrical panel space. This can be addressed by conducting an electrical survey prior to verify capacity, and adding a sub-panel if needed. Equipment availability, size, and installation feasibility should not be limiting for the given system and small building size.

Impacts: This building demonstrates increased energy costs due to the breakdown of electrical vs. gas impacts. While unusual this is certainly possible, and should be a “watch-it” during implementation of widespread decarbonization to avoid unrealistic expectations of the cost impacts of decarbonisation.

Replacement Results

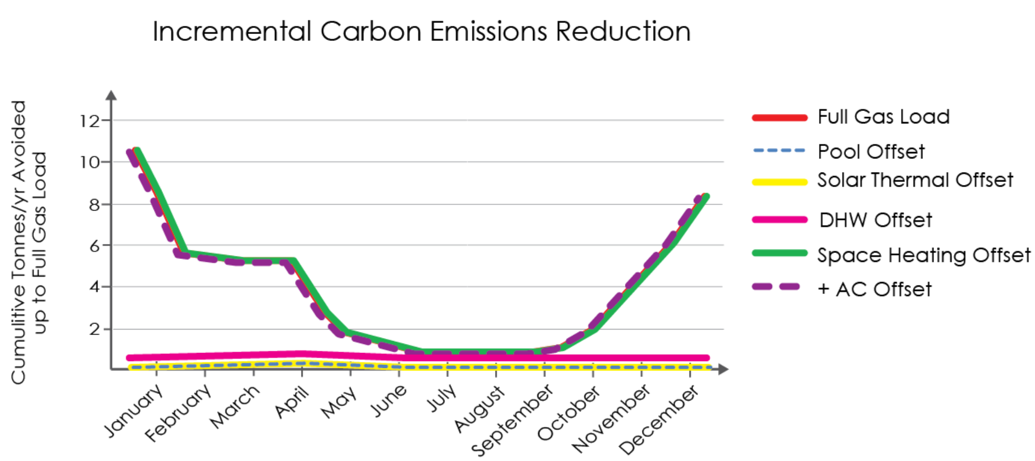






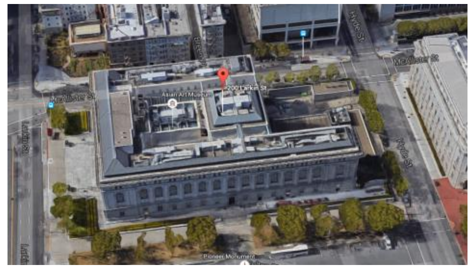
Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile. With no contributions from solar thermal or heat recovery, space heating and domestic hot water sum to the total.



7.3 Museum (Use Case B)

Building Size: 185,000 ft^2 (3 stories + Basement)



Existing Condition		Replacement	
Heating System	HHW Boiler(s) 80% Eff., 2000 MBH	Heating System RTU	Heat Pump Boiler + AC Heat Recovery COP 2.2, 2000 MBH
DHW System	Gas Storage Water Heater(s) EF 0.8, 5000 MBH	DHW System	Heat Pump Water Heater +10% Reduction + 20% Solar Thermal COP 2.2, 5000 MBH
Process Heating	Cooking	Process Heating	Cooking
		First Cost	$509,267
		Annual Savings	$12,932/yr

Commentary

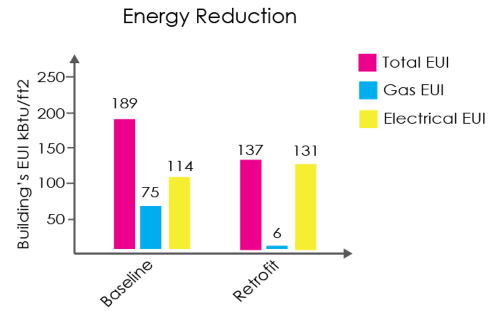
Description: The existing building is known to be served by gas water boiler(s) and standard gas storage water heater(s). The simplest replacement pathway is installation of a heat pump water heater (with electric backup) for building heating/conditioning and a heat pump storage water heater for water heating. Since the building has air-conditioning with a central chilled water plant there is an opportunity for heat recovery. We also propose limited solar thermal to offset domestic hot water use and take advantage of the roof space.

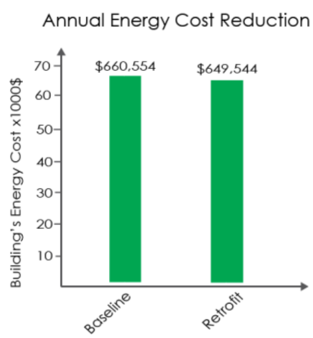
The building has a high gas base load, indicating either high domestic hot water use, high process loads (e.g. cooking at the museum café) or summer heating and reheat.

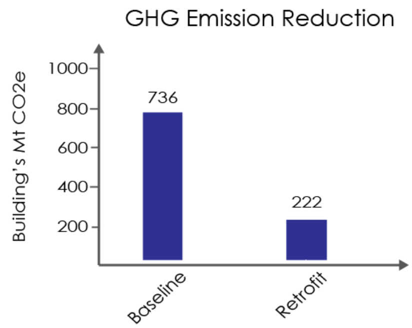
Barriers: Two significant barriers exist. One, it will be difficult to find heat pump boilers at a sufficient size and delivery temperature to serve as an appropriate “drop-in” technology for existing gas heating boilers. This means it might be necessary to instead seek different, more invasive and expensive solutions (e.g. VRF). Two, the high added electrical loads (~1000 kW) may require a service upgrade. This can be addressed by conducting an electrical survey prior to verify capacity.

Impacts: At the stated first costs and savings the absolute simple payback period is about 50 yrs. However incremental first costs should be no more than half of that, so incremental simple payback period should be

Replacement Results

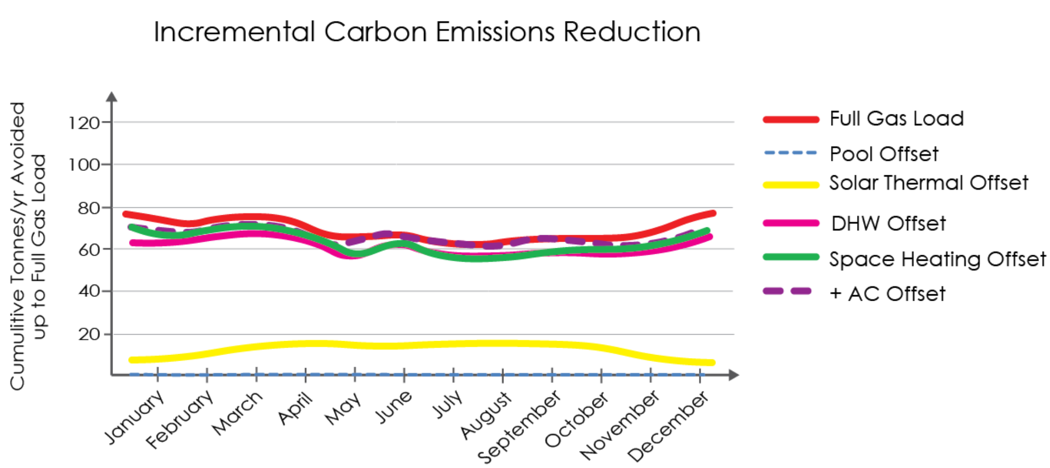






Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile. A strong base load, possibly due to domestic hot water, is offset partially by solar thermal.



7.4 Jail / Correctional (Use Case C)

Building Size: 210,000 ft^2

Existing Condition		Replacement	
Heating System	HHW Boiler(s) 80% Eff., 5000 MBH	Heating System RTU	Heat Pump Boiler + AC Heat Recovery COP 2.2, 5000 MBH
DHW System	Gas Storage Water Heater(s) EF 0.8, 5000 MBH	DHW System	Heat Pump Water Heater +10% Reduction + 20% Solar Thermal COP 2.2, 5000 MBH
Process Heating	Cooking, Laundry	Process Heating	Cooking, Laundry
		First Cost	$929,176
		Annual Savings	$48,644/yr

Commentary

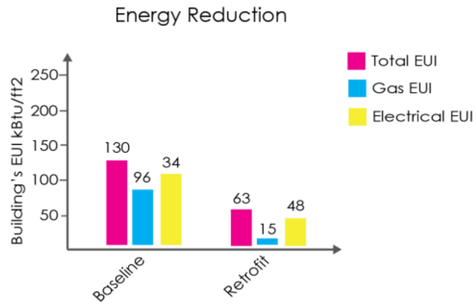
Description: The existing building is assumed to be served by gas water boiler(s) and standard gas storage water heater(s). The simplest replacement pathway is installation of a heat pump water heater (with electric backup) for building heating/conditioning and a heat pump storage water heater for water heating. Since the building has air-conditioning with a central chilled water plant there is an opportunity for heat recovery. We also propose extensive solar thermal to offset high domestic and process (laundry, cooking) hot water use.

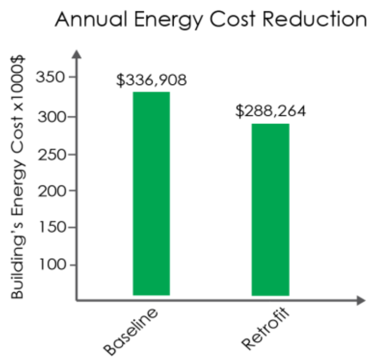
The building has a high gas base load, which makes sense given its high domestic hot water use, high process loads (cooking, laundry), and 24/7 schedule.

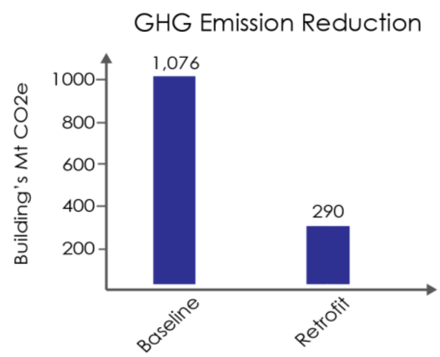
Barriers: Two significant barriers exist. One, it will be difficult to find heat pump boilers at a sufficient size and delivery temperature to serve as an appropriate “drop-in” technology for existing gas heating boilers. This means it might be necessary to instead seek different, more invasive and expensive solutions (e.g. VRF), which may be difficult to implement in an institutional (jail) setting. Two, the high added electrical loads (~1000 kW) may require a service upgrade. This can be addressed by conducting an electrical survey prior to verify capacity.

Impacts: At the stated first costs and savings the absolute simple payback period is about 20 years, and incremental payback will be lower. The high baseline gas use and 24/7 schedule at the building means that

Replacement Results

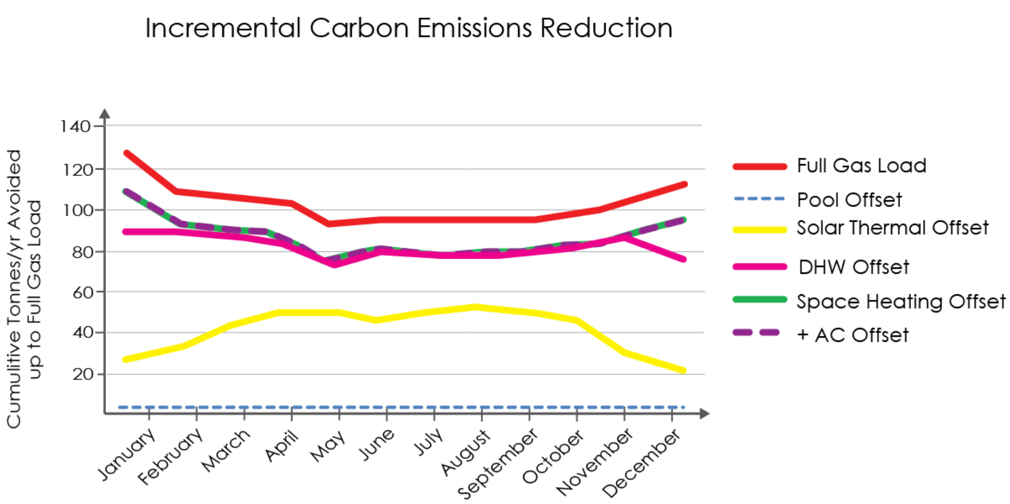






Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile. A strong base load, likely domestic hot water, is offset by solar thermal.



7.5 Gas Station / Vehicle Repair (Use Case D)

Building Size: 101,510 ft^2

Existing Condition		Replacement	
Heating System	Forced Air Furnace 65% Eff., 5000 MBH	Heating System RTU	Heat Pump AC COP 3.0, 5000 MBH
DHW System	Gas Storage Water Heater EF 0.8, 500 MBH	DHW System	Heat Pump Water Heater EF 2.2, 500 MBH
Process Heating	Industrial	Process Heating	Industrial
		First Cost	$545,710
		Annual Savings	$494/yr

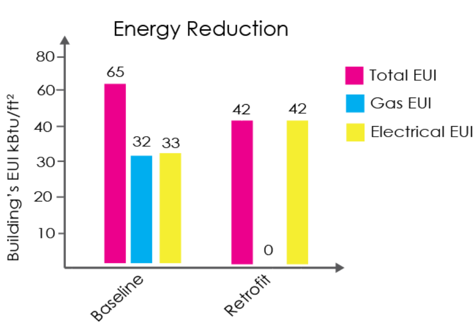
Commentary

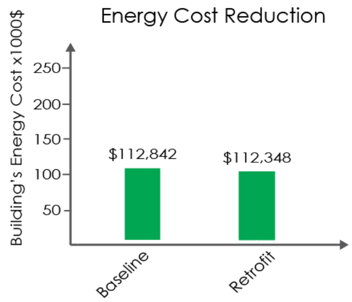
Description: The existing building is assumed to be served by a packaged gas furnace(s) and a standard gas storage water heating. The simplest replacement pathway is installation of a heat pump packaged unit for building heating/conditioning and a heat pump storage water heater(s) for water heating. No solar thermal or heat recovery technologies are proposed given the small size.

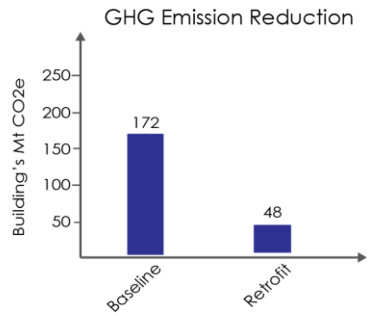
Barriers: Potential barriers specific to this type include possible gas process or industrial use at the facility, which may be difficult to directly replace. Otherwise, equipment availability, size, and installation feasibility should not be limiting for the given heating and domestic system types. Two, the high added electrical loads (~600 kW) may require a service upgrade. This can be addressed by conducting an electrical survey prior to verify capacity.

Impacts: At the stated first costs and savings the simple payback period is well over 100 yrs. First costs should be roughly 110% to 150% to a standard “like with like” replacement, so incremental simple payback period will be much shorter, however will definitely be longer than the expected lifetime of this equipment. This raises concerns about the feasibility of replacement.

Replacement Results

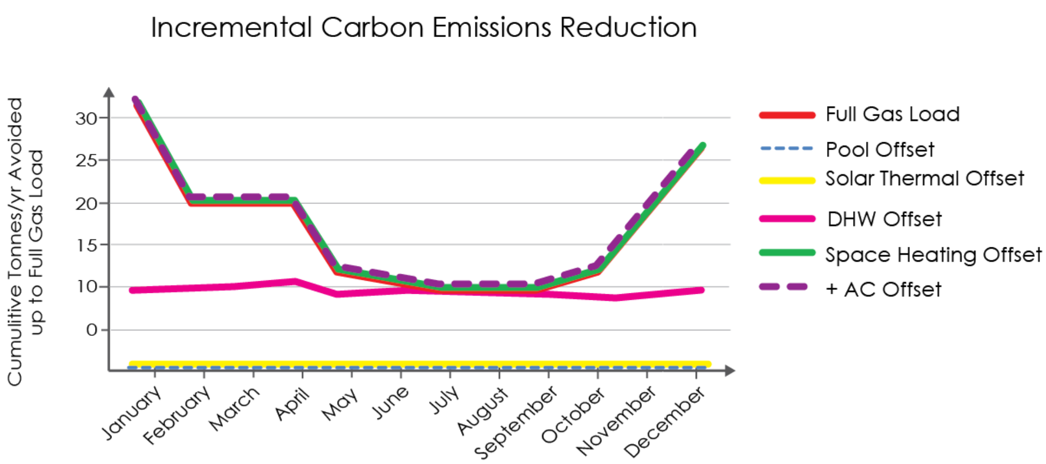






Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile. With no contributions from solar thermal or heat recovery, space heating and domestic hot water sum to the total.



7.6 Performance Hall (Use Case E)

Building Size: 229,500 ft^2

Existing Condition		Replacement	
Heating System	HHW Boilers 80% Eff., 2500 MBH	Heating System RTU	Heat Pump Boiler + AC Heat Recovery COP 2.2, 2500 MBH
DHW System	Gas Storage Water Heater EF 0.8, 3000 MBH	DHW System	Heat Pump Water Heater + Solar Thermal EF 2.2, 3000 MBH
Process Heating	Unknown	Process Heating	Unknown
		First Cost	$276,397
		Annual Savings	$5,508/yr

Commentary

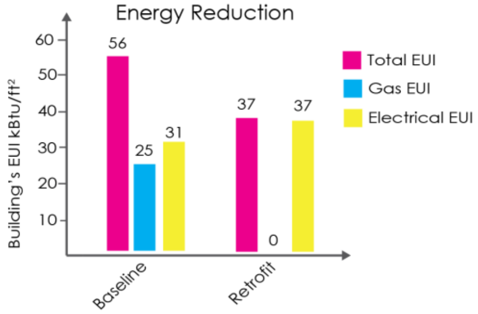
Description: The existing building is known to be served by gas water boiler(s) and standard gas storage water heater(s). The simplest replacement pathway is installation of a heat pump water heater (with electric backup) for building heating/conditioning and a heat pump storage water heater for water heating. Since the building has air-conditioning with a central chilled water plant there is an opportunity for heat recovery. We also propose limited solar thermal to offset domestic hot water use.

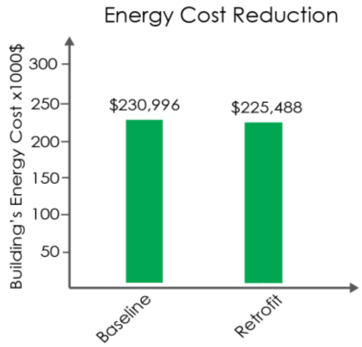
The building has a high gas base load, indicating either high domestic hot water use, high process loads, or summer heating and reheat.

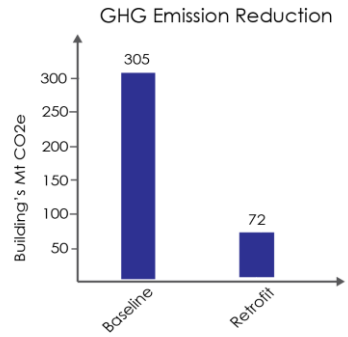
Barriers: It will be difficult to find heat pump boilers at a sufficient size and delivery temperature to serve as an appropriate “drop-in” technology for existing gas heating boilers. This means it might be necessary to instead seek different, more invasive and expensive solutions (e.g. VRF), which may be difficult to implement in a performance or public use type building.

Impacts: At the stated first costs and savings the absolute simple payback period is about 50 yrs. However incremental first costs should be no more than half of that, so incremental simple payback period should be

Replacement Results

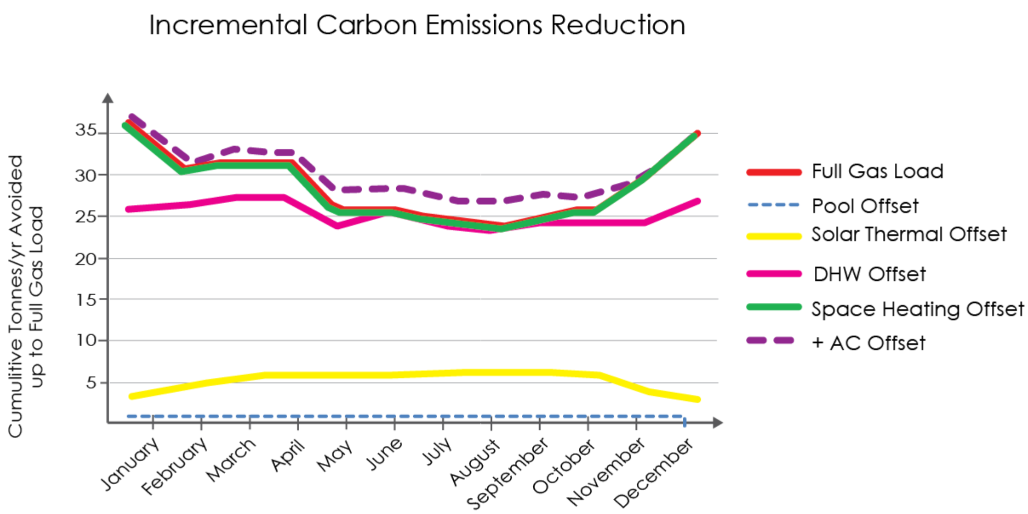






Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile.



7.7 Pool (Use Case F)

Building Size: 23,851 ft^2 Pool Size: 12,000 ft^2

Existing Condition		Replacement	
Heating System	Gas Packaged Furnace 80% Eff.	Heating System	HP Packaged Unit 3.0 COP
DHW System	Gas Storage Water Heater 0.8 EF	DHW System	Solar Thermal + Electric / Heat Pump Water Heater 2.2 COP
Pool	Gas Storage Pool Boiler	Pool	Solar Thermal + Electric / Heat Pump Boiler 2.2 COP
		First Cost	$532,660
		Annual Savings	$5,934/yr

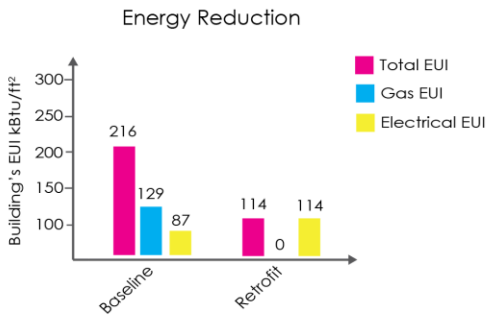
Commentary

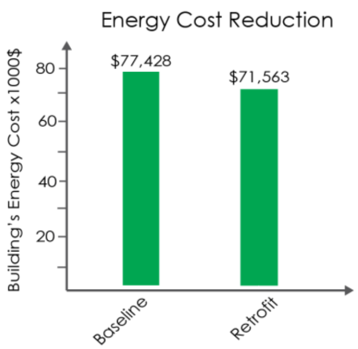
Description: The existing building forms an unusual case as a building that contains an indoor pool. Baseline building is assumed to be served by a packaged gas furnace and a standard small gas storage water heater, and a large gas pool boiler. There is no simple replacement pathway; for this analysis we select a heat pump packaged unit for building heating/conditioning and a heat pump storage water heater for water heating and pool heating. This is an ideal application for solar thermal; significant solar thermal is added for both pool and domestic hot water use.

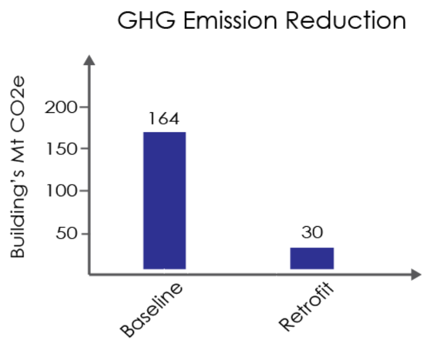
Barriers: This use case has many barriers, and opportunities. It will be difficult to find appropriate heat pump equipment to directly "one-for-one" replace existing water heating and pool equipment. Replacements may not be easily available, and expensive. It may be necessary to include electric resistance systems which are limited by code and are inefficient. Furthermore, the very high added electrical loads (~600 kW) may require a service upgrade. This can be addressed by conducting an electrical survey prior to verify capacity.

Impacts: Despite the high savings, at the stated first costs and savings the absolute simple payback period is 80 yrs. Incremental payback period will be lower than this, however it will likely still be longer than the lifetime of replacing equipment.

Replacement Results

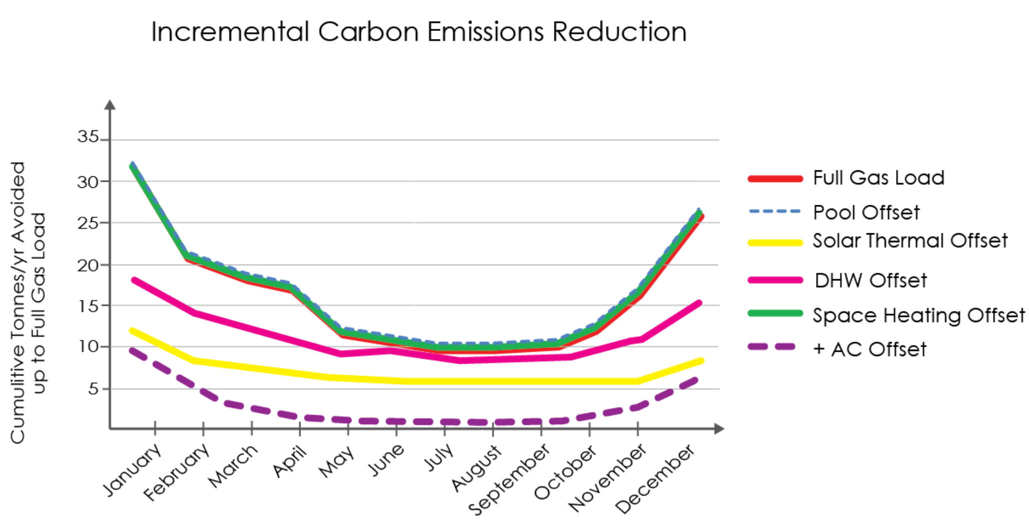






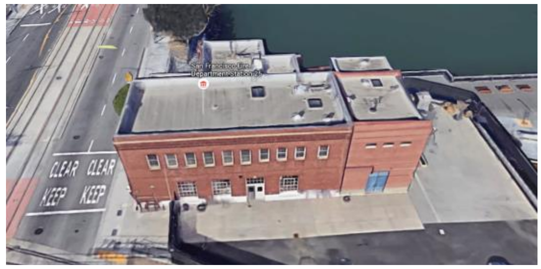
Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile. Combinations of solar thermal, heat recovery, and equipment replacement must all work together to achieve full gas replacement.



7.8 Fire Station (Use Case G)

Building Size: 11,420 ft^2



Existing Condition		Replacement	
Heating System	Gas Furnace RTU 80% Eff., 1000 MBH	Heating System RTU	Heat Pump RTU COP 3.0, 1000 MBH
DHW System	Gas Storage Water Heater EF 0.8, 50 MBH	DHW System	Heat Pump Water Heater EF 2.2, 50 MBH
Process Heating	Cooking, Laundry	Process Heating	Cooking, Laundry
		First Cost	$1134,895
		Annual Savings	$145/yr

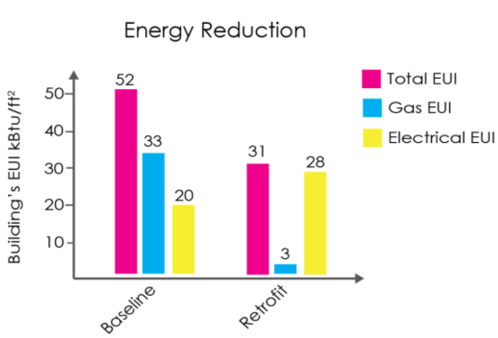
Commentary

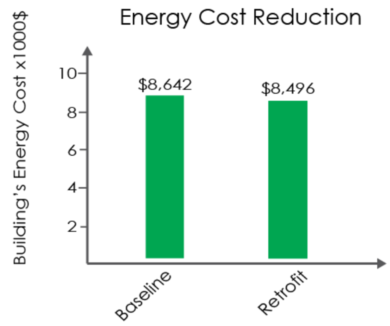
Description: The existing building is assumed to be served by a packaged gas furnace and a standard small residential size gas storage water heater. The simplest replacement pathway is installation of a heat pump packaged unit for building heating/conditioning and a heat pump storage water heater for water heating. Limited solar thermal is proposed to offset domestic and laundry hot water use.

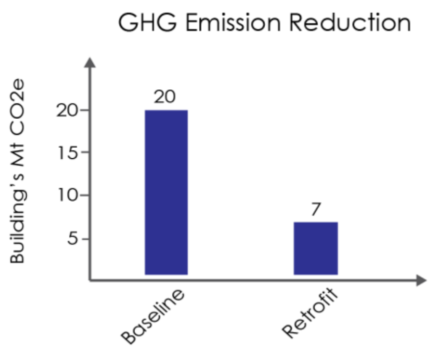
Barriers: Potential barriers specific to this type include the limitations of existing building electrical panel space, common for old buildings in San Francisco. This can be addressed by conducting an electrical survey prior to verify capacity, and adding a sub-panel if needed. Equipment availability, size, and installation feasibility should not be limiting for the given system and small building size.

Impacts: At the stated first costs and savings the absolute simple payback period is about 100 yrs. First costs should be roughly 110% to 150% to a standard “like with like” replacement (e.g. gas furnace and gas water heater), so incremental simple payback period should be more along the lines of 30 years, however this is

Replacement Results

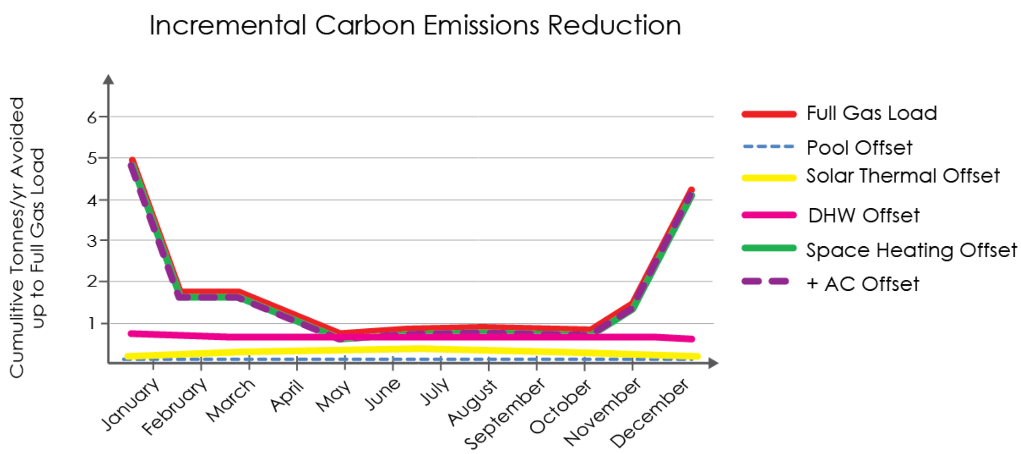






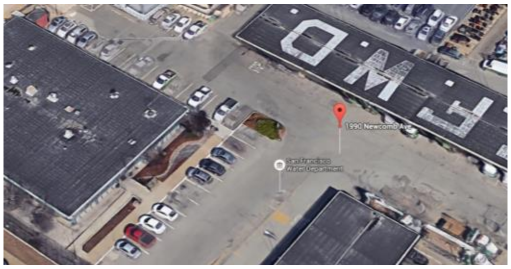
Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile. Contributions from solar thermal, space heating and domestic hot water sum to the total.



7.9 Corporation Yard (Use Case H)

Building Size: 67,500 ft^2



Existing Condition		Replacement	
Heating System	Gas Furnace RTU	Heating System RTU	Heat Pump RTU
	80% Eff., 3000 MBH		COP 3.0, 3000 MBH
DHW System	Gas Storage Water Heater	DHW System	Heat Pump Water Heater
	EF 0.8, 150 MBH		EF 2.2, 150 MBH
Process Heating	Industrial, Unknown	Process Heating	Industrial, Unknown
		First Cost	$422,618
		Annual Savings	$1,664/yr

Commentary

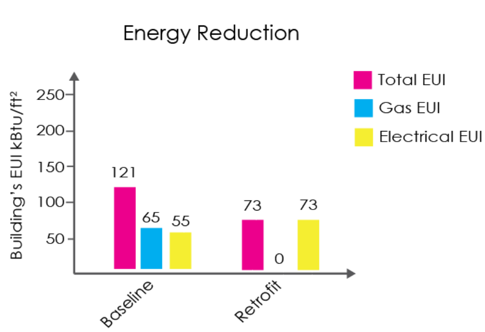
Description: The existing building is assumed to be served by packaged gas furnace(s) and a standard small gas storage water heating. The simplest replacement pathway is installation of a heat pump packaged unit for building heating/conditioning and a heat pump storage water heater for water heating. No solar thermal or heat recovery technologies are proposed.

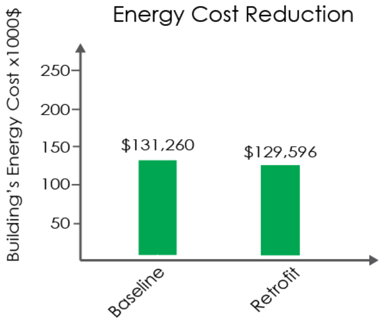
An alternative water heating option is to replace with small point-of-use or instantaneous electric water heaters to serve restrooms; this would allow abandonment/demolishment of existing domestic hot water piping.

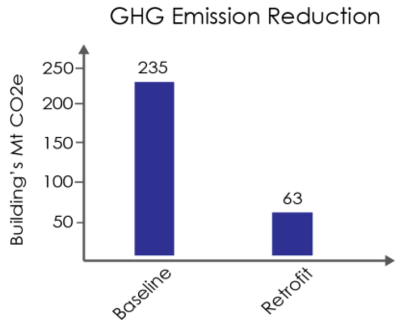
Barriers: Potential barriers specific to this type include possible gas process or industrial use at the facility, which may be difficult to directly replace. Otherwise, equipment availability, size, and installation feasibility should not be limiting for the given heating and domestic system types. Two, the high added electrical loads (~300 kW) may require a service upgrade.

Impacts: At the stated first costs and savings the simple payback period is well over 100 yrs. First costs should be roughly 110% to 150% to a standard "like with like" replacement, so incremental simple payback period

Replacement Results

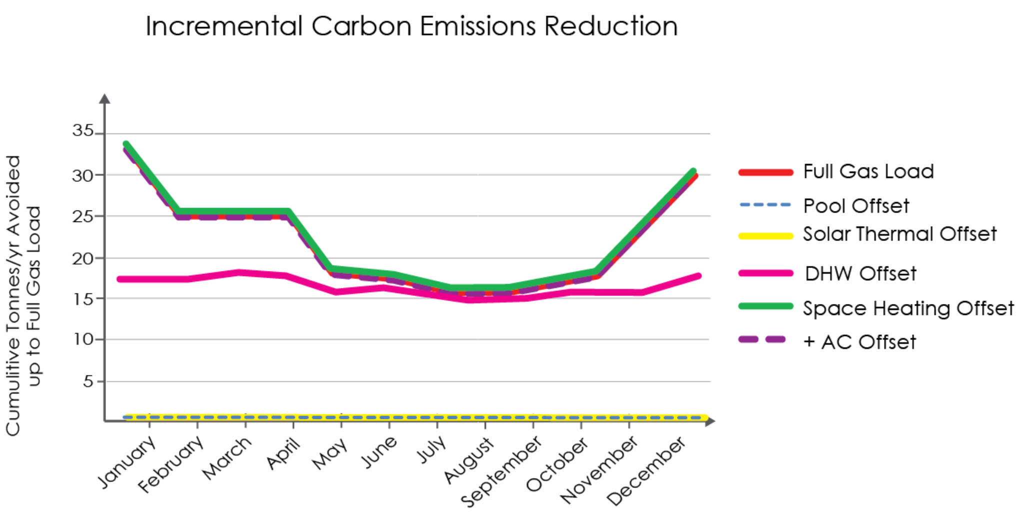






Replacement Results

Incremental emissions reductions profile maps to anticipated annual gas reduction profile. With no contributions from solar thermal or heat recovery, space heating and domestic hot water sum to the total.



8 Appendix C: Gas-Replacing Technologies

Table C.1. Technology Efficiency Ranges and Expected Life

New Technology	Efficiency			Expected Lifetime (Yrs)
	Size Category (Input)	**Min**	**Unit**	
High Efficiency Electric Water Heater with Storage Tank	≤ 55 gallons ≤ 12 kW	0.96-(0.0003*V)	EF	15
	> 55 gallons ≤ 12 kW	2.057 – (0.0013 *V)	EF	
Demand-type or Instantaneous Electric Water Heater	≤ 12 kW < 2 gallons	0.93-(0.00132*V)		20
Solar thermal heater with Electric Back-Up	All Capacities	> 50%	SSF	30
Heat Pump (Air-Source)	All Capacities	2.9 - (0.026 x Cap/1000)	COP	15
Heat Pump (Water Heater)	-	-	COP	15
High efficiency condensing gas Boiler	≥ 300,000 Btu/h	80%	AFUE	
	≤ 2,500,000 Btu/h			
Electric Resistance pool heater	-	77%*	EF	13
Variable refrigerant flow (VRF)	<135,000** Btu/h	4.2	COP	15
	≥135,000** Btu/h	3.9	COP	
Heat Recovery Systems:				
Economizing	NA	75%	Thermal Efficiency	10
Heat Wheel	NA	85%	"	10
Heat Pipes	NA	60%-70%	"	10
Plate HX	NA	70%	"	10
Run around loop	NA	50%	"	10

* *For Climate Zone 3*

Table C.2. Technology Capacity Ranges and Price Ranges

New Technology	Capacity			Price	
	Min Size	Max Size	Unit	$ Min Size	$ Max Size
High Efficiency Electric Water Heater with Storage Tank	7.5	3,600	kW	6,950	120,000
Demand-type or Instantaneous Electric Water Heater	-	-	-	-	-
Solar thermal heater with Electric Back-Up	65	120	gal	6,425	12,100
Heat Pump (Air-Source)	1.5	100	ton	1,925	79,500
Heat Pump (Water Heater)	2.3	11.1	ton	19,625	54,700
	35.5	171	MBH		
High efficiency condensing gas Boiler	42	194	MBH	2,350	4,825
Electric Resistance pool heater	12	57	kW	2,900	5,525
Variable refrigerant flow (VRF)	-	-	-	-	-
Heat Recovery Systems:					
Economizing	-	-	-	-	-
Heat Wheel	1,000	50,000	CFM	8,375	65,500
Heat Pipes	100	620	MBH	5,400	11,000
	1700	4,000	CFM		
Plate HX	-	-	-	-	-
Run around loop 50%	-	-	-	-	-

9 Appendix D: Replacement Costs

9.1 Heat Pump Water Heater

9.1.1 Costing Correlation

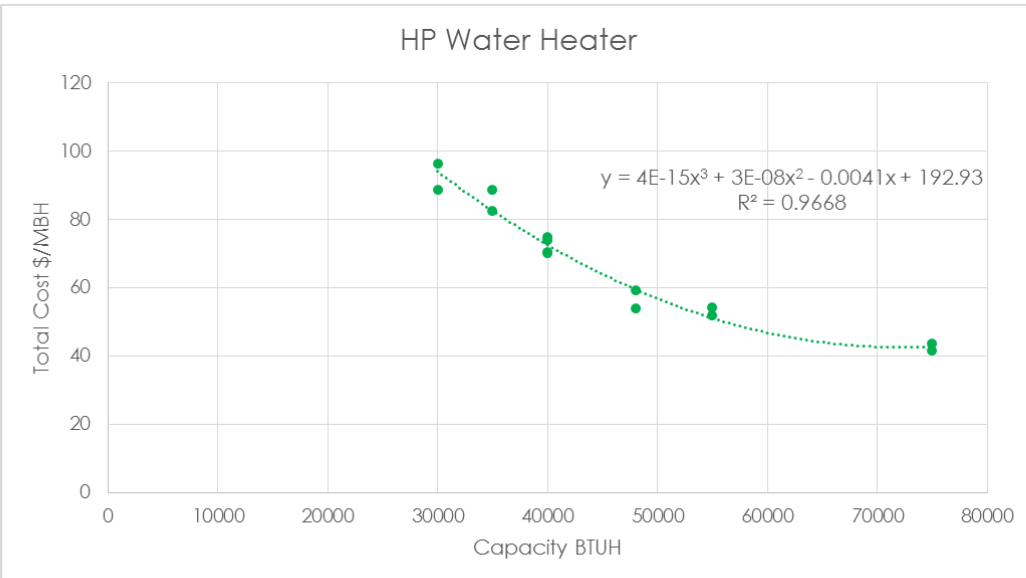


Figure 5. Costing correlation diagram for heat pump water heater, (RSMean Online).

9.1.2 Costing Formula

Based on the regression line for the RSMeans nationwide heat pump water heater data, cost is estimated as follows, where x = capacity in MBH and y = cost per capacity in $ / MBH.

$$y = 4\text{E} - 15x^3 + 3\text{E} - 08x^2 - 0.0041x + 193$$

9.2 Heat Pump (Air Source)

9.2.1 Costing Correlation

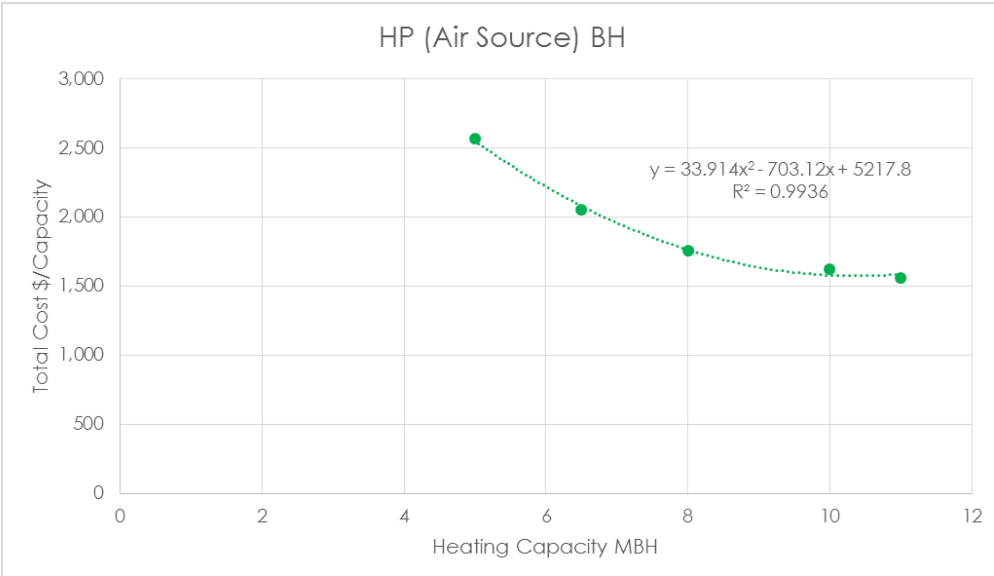


Figure 6. Costing correlation diagram for air source heat pump, (RSMean).

9.2.2 Costing Formula

Based on the regression line for the RSMeans nationwide heat pump data, cost is estimated as follows, , where x = capacity in MBH and y = cost per capacity in $ / MBH.

$$y = 0.106x^2 - 10.25x + 338.5$$

9.3 Condensing Boiler

9.3.1 Costing Correlation

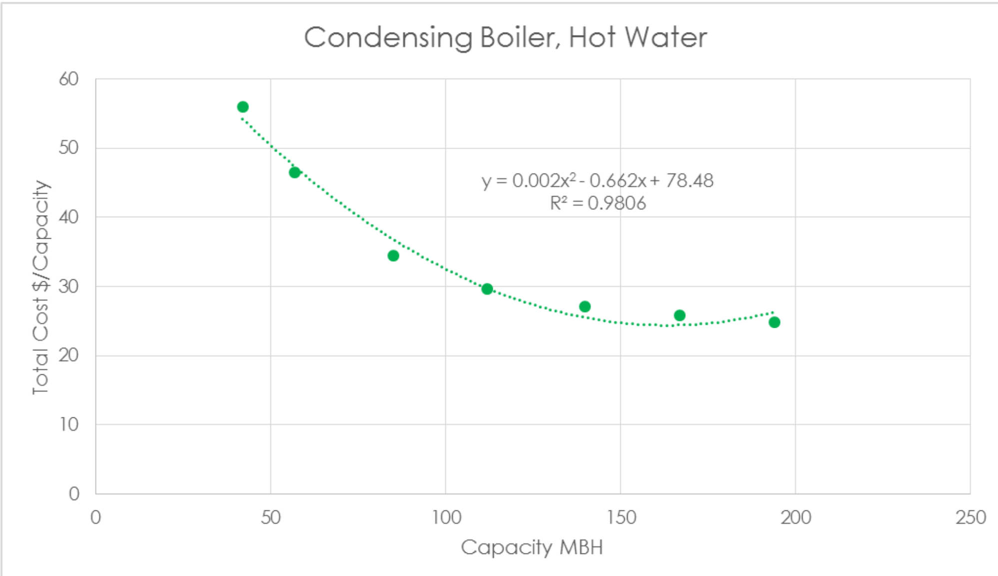


Figure 7. Costing correlation diagram for condensing boiler, (RSMean).

9.3.2 Cost Formula

Based on the regression line for the RSMeans nationwide condensing boiler data, cost is estimated as follows, where x = capacity in MBH and y = cost per capacity in $ / MBH.

$$y = 0.002x^2 - 0.662x + 78.48$$

9.4 Electric Boiler

9.4.1 Costing Correlation

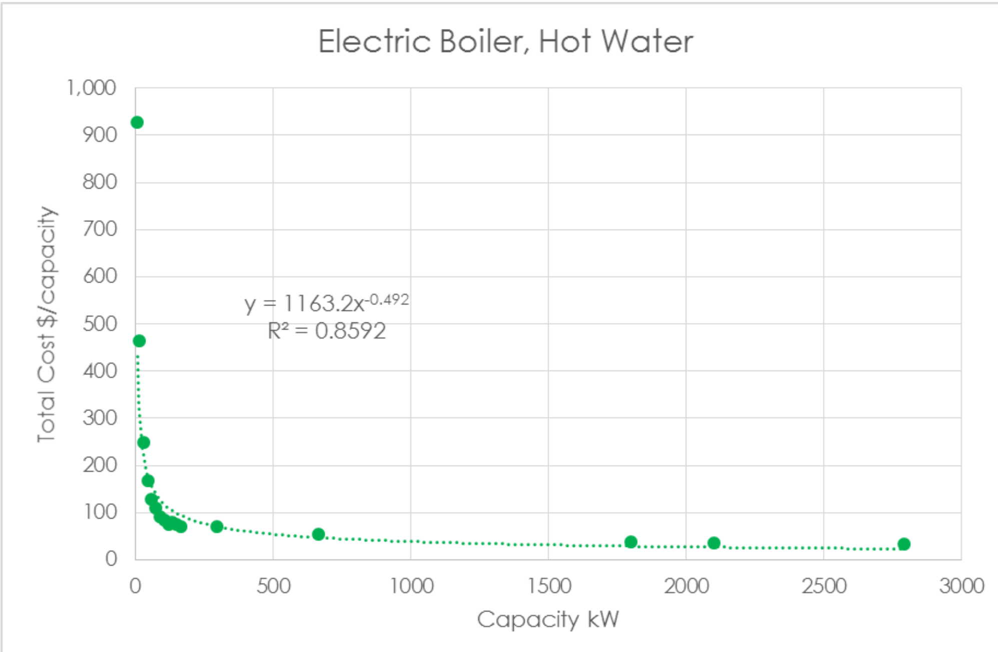


Figure 8. Costing correlation diagram for electric boiler, (RSMean).

9.4.2 Cost Formula

Based on the regression line for the RSMeans nationwide electric boiler data, cost is estimated as follows, where x = capacity in kW and y = cost per capacity in $ / kW.

$$y = 1163.2x^{-0.492}$$

9.5 Solar Thermal (Pool Heating)

9.5.1 Costing Correlation

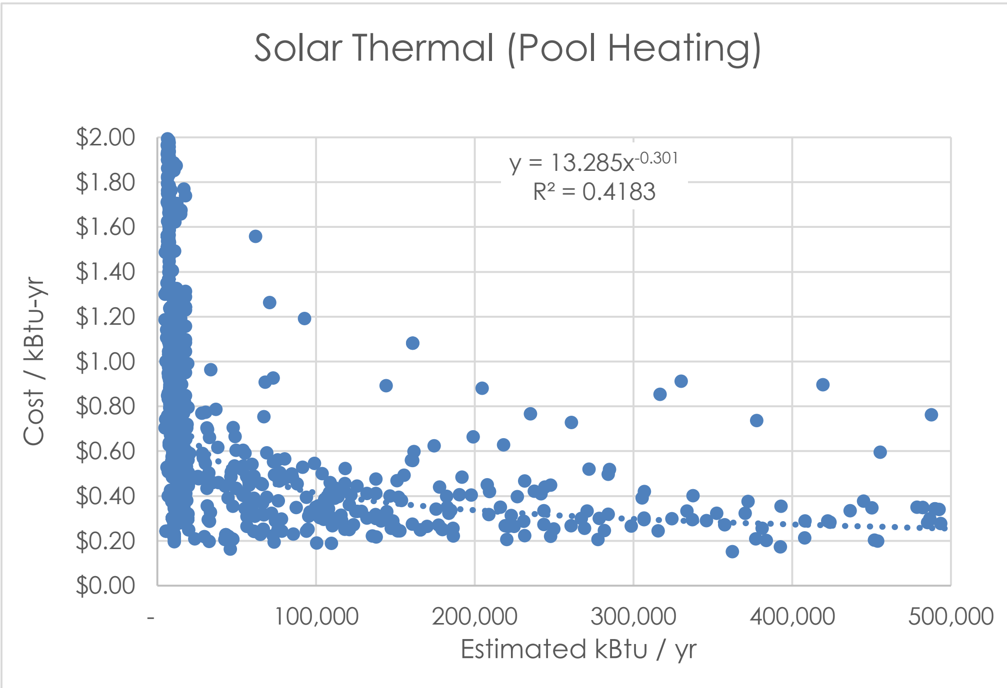


Figure 9. Costing correlation diagram for electric boiler.

9.5.2 Cost Formula

Based on the regression line for solar thermal data, cost is estimated as follows, where x = service in kBtu / yr and y = cost per service in $ / kBtu / yr.

$$y = 13.285x^{-0.301}$$

9.6 Heat Recovery Systems (Thermal Wheel)

9.6.1 Costing Correlation

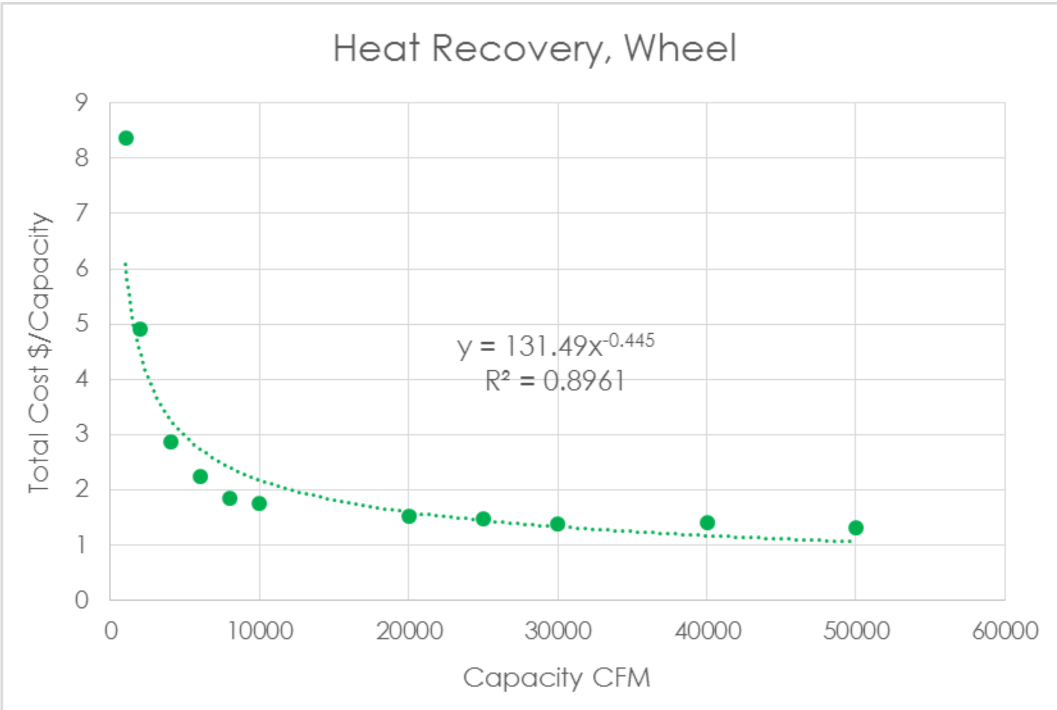


Figure 10. Costing correlation diagram for thermal wheel, (RSMean).

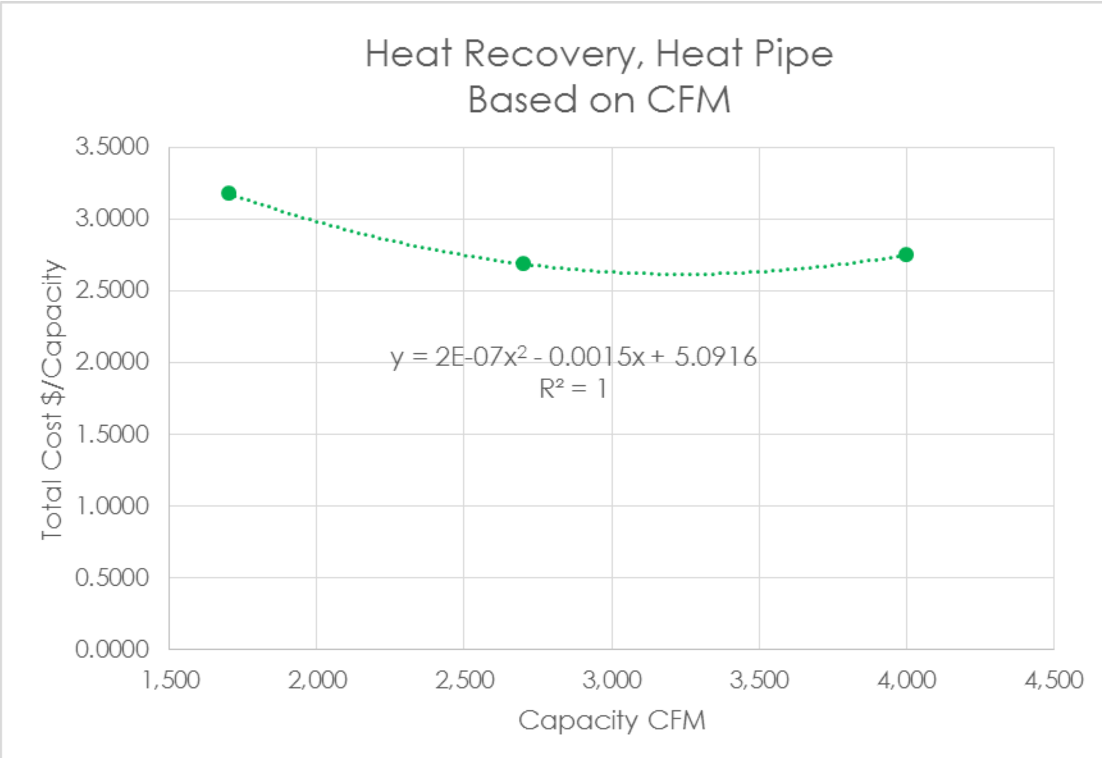
9.6.2 Cost Formula

Based on the regression line for the RSMeans nationwide thermal heat data, cost is estimated as follows, where x = capacity in CFM and y = cost per capacity in $ / CFM.

$$y = 131.49\, x^{-0.445}$$

9.7 Heat Recovery Systems (Heat Pipe)

9.7.1 Costing Correlation



9.7.2 Cost Formula

Based on the regression line for the RSMeans nationwide heat pipe data, cost is estimated as follows, where x = capacity in CFM and y = cost per capacity in $ / CFM.

$$y = 2X10^{-7}x^2 - 0.0015x + 5.0916$$

10 Appendix E: Acronyms Glossary

ACM	Alternate Compliance Method
ASHP	Air Source Heat Pump
BayREN	Bay Area Regional Energy Network
BH	Building Heating
Btu	British Thermal Unit
CAP	Climate Action Plan
CFM	Cubic Feet per Minute
CNCA	Carbon Neutral Cities Alliance
CO_2e	Carbon dioxide equivalent
ccASHP	Cold Climate Air-Source Heat Pump
COP	Coefficient of Performance
DHW	Domestic Hot Water
EFF	Efficiency
EUI	Energy Unit Index
GBtu	Giga British Thermal Unit (10^9 Btu)
GHG	Green House Gas
GSF	Gross Square Feet
GTherms	Giga Therms
GWh	Giga Watt hour (10^9 Wh)
HHW	Heating/ Hot Water
HP	Heat Pump
HX	Heat Exchanger
IWH	Instantaneous Water Heater
KBtu	Kilo British Thermal Unit (10^3 Btu)
KWh	Kilo Watt hour (10^3 Wh)
lbs	Pounds
MBH	1000 BTU/hr
MTons	Mega Tons (10^6 Tons)
NEEP	Northeast Energy Efficiency Partnerships
O&M	Operation & Maintenance
RTU	Roof Top Unit
SHGC	Solar Heat Gain Coefficient
SSF	Solar Savings Factor
TDV	Time Dependent Valuation
Therm	10^5 Btu
TOU	Time of Use
VRF	Variable Refrigerant Flow
Wh	Watt hour
WH	Water Heater