FINAL REPORT

UC Carbon Neutral Buildings Cost Study

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Point Energy Innovations

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Section 1: Executive Summary

Section 1.1 Key Insights

- All-electric buildings are comparable or slightly less expensive that gas + electric buildings from a 20-year Life Cycle Cost perspective, factoring in both capital and energy costs. The average 20-year Life Cycle Cost for all-electric buildings compared to gas + electric option is \$1.23/sf (about 0.7%) lower for academic buildings, \$5.28/sf (about 3.5%) lower for residential buildings, and \$3.09/sf (about 0.8%) lower for laboratories. This is depicted in the graph below, where blue represents capital costs and yellow represents net present energy costs.

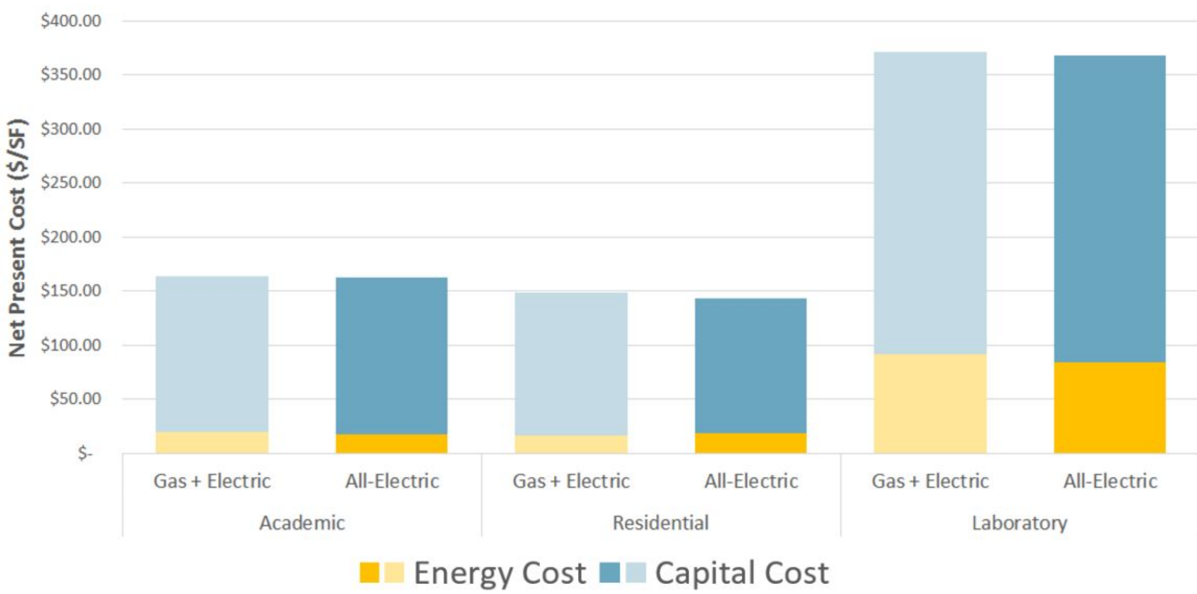


Figure 1. UC Average Total Net Present Costs across All Campuses

- Comparing *only capital costs* (blue bars) all-electric academic buildings are comparable, (1% costlier) than gas + electric, all-electric residential buildings are 6% *less* costly, and all-electric labs are 1.5% costlier upfront. Comparing only the 20-year net present *energy costs* (yellow bars), for all-electric academic buildings energy costs are 14% less, for all-electric residential buildings, energy costs are 16% *more*, and for all-electric labs energy costs are 8% less.
- Discounted payback periods for all-electric buildings relative to gas + electric buildings average 9 years for academic buildings (excluding UCSC) and 12 years for labs; all-electric residential buildings have lower lifecycle costs on day one.
- The study shows an exemplary best practice all-electric system that will deliver these results for each building type and campus condition (with or without available cogen

capacity, thermal loops, etc.) even with arguably conservative assumptions (less favorable to electricity), as noted below:

  - The cost of carbon-free electricity is assumed to start out much higher (based on current UC energy contracts) and to escalate faster than the cost of carbon-free gas.
  - The study assumes that carbon-free electricity is purchased from the grid, rather than campuses employing less-expensive on-site solar, third party solar, etc.
  - The study evaluates the systems over a 20 year period but a 25-year timeframe would favor all-electric systems even more; lifecycle costs for all-electric buildings would be lower than those for gas + electric buildings in all cases except UCSC academic buildings.

- Electric heat pumps significantly improve building energy efficiency, helping buildings meet the UC system's increasingly stringent EUI targets. More generally, the all-electric systems have a margin of efficiency above UC's current EUI target that will give them headroom to more easily continue to meet the targets as the targets ramp up, whereas buildings with gas-based heating systems will need to be made more efficient to comply with the UC target, which could be challenging over time. Title 24 code cycles are also becoming more energy efficient, so buildings with efficient all-electric equipment will have an easier time meeting code over time as well.
- For gas + electric buildings (all three types), gas is a small part of total energy cost. Thus stand-alone gas + electric buildings are relatively insensitive to gas prices. For cogen campuses, higher gas prices would cause dramatic increases in total outlays for cogen-generated *electricity*, but heating expenditures would still be relative low. Therefore, even for gas + electric buildings, it makes sense to focus in particular on efficiency that reduces electricity use, such as daylighting and better building envelope, and installing more efficient electric equipment, such as heat recovery chillers.[1]
- Because upfront capital costs comprise the large majority of lifecycle costs (89% for academic, 88% for residential and 70-83% for labs), it behooves UC to *downsize costly capital equipment* by reducing MEP loads through whole building design efficiency (including airtight and less thermally conductive building envelope, better windows, facade shading, more efficient lighting and equipment, etc.)

Section 1.2 Key Insights by Building Type

- Academic
  - Heat recovery chillers are cost effective and result in marked efficiency gains in academic buildings. This is due to the substantial amount of simultaneous heating and cooling, attributed mostly to reheat.
  - In fact, the models showed that replacing the gas + electric building's boiler and standard chiller with a heat recovery chiller for both heating and cooling, reduced

[1] Of note, campuses *should* focus on reducing electricity use through efficiency, but *eliminating* electricity use for heating by switching to gas-based equipment does *not* reduce overall lifecycle costs, as this study shows.

electricity use in the all-electric building *below* the electricity use of the gas + electric building.

- Residential
    - All-electric equipment has lower capital costs than gas-electric MEP equipment. For buildings without air conditioning, the strategy was to make the building envelope more efficient and supply a small amount of heating with electric baseboards, which are less costly upfront than gas-boiler heated hydronic baseboard systems. For buildings with air conditioning, all-electric variable refrigerant flow (VRF) heat pump heating and cooling has lower capital costs than a four pipe hydronic system with a gas boiler and chiller.
    - Because electric energy is expensive, the best practice strategy is to reduce the amount of heating needed through higher building envelope efficiency and use of heat recovery in the ventilation system.
    - While this study used standard residential occupancy, if residences are particularly densely occupied, UC efficiency targets may not be achievable using gas boilers for DHW with such high hot water loads. Electric heat pumps or solar hot water systems may be necessary to reduce EUI. This condition is described in the Appendix to this report in the UCSF Minnesota Street case study.
- Laboratories
    - Typically labs will be connected to campus district heating and cooling. To be all-electric, labs must disconnect from the campus hot water loop. Replacing the district hot water connection with water source heat pumps connected to the district chilled water return line, and returning cooler water to the central plant, provides a lower 20 year lifecycle cost compared to gas + electric buildings in all cases but UCI and UCSD, which have lower lifecycle costs by year 24.
    - For labs with cooling loops only (UCLA, UCM, and UCSB), the 20 year lifecycle costs for all-electric buildings are relatively more favorable than scenarios that also have heating loops that gas + electric buildings can connect to and avoid purchasing stand-alone boilers.
    - All-electric systems are particularly cost-advantageous at Berkeley and Santa Cruz, which have cogen but not heating or chilled water loops (UCSC has a condenser water loop). Heat recovery chillers at these campuses provide lower lifecycle cost for all-electric buildings within 5 years.

Section 1.3 Cogen Insights

- District heating, district cooling and cogen-produced electricity are all less expensive energy sources than alternatives for stand-alone buildings, assuming costs for adding new cogen plant capacity are not included.
- Costs for adding new cogen capacity are not evaluated in this study, as existing cogen capacity is assumed; however, campus usage exceeds cogen capacity in peak

conditions[2] during which campuses import large amounts of electricity, dampening the benefits of inexpensive cogen-generated electricity.

- If cogen is available, it reduces energy costs for both gas + electric and all-electric buildings of all types (due to the lower cost associated with producing electricity by cogen).
- Cogen cost-reductions are most impactful for lab buildings. Energy comprises 17% of lifecycle cost for labs on cogen, but it comprises 30% of lifecycle cost for labs not on cogen.
- Cogen energy costs are assumed to be constant regardless of actual campus demand for thermal and electric energy (inefficiencies of part load conditions are not factored into this study).

[2] Data taken from the "Deep Energy Efficiency and Cogeneration Study Findings Report" put out by ARC Alternatives for UCOP

Section 2: Background and Methodology

Section 2.1 Motivation for the Study

The University of California's Carbon Neutrality Initiative commits UC to achieving carbon neutrality for campus operations by 2025 for direct emissions and purchased energy (Greenhouse Gas Scopes 1 & 2). The University's strategy for achieving this involves reducing energy use via efficiency in existing building stock, decarbonizing energy supplies, and planning campus growth to minimize net increases in greenhouse gas emissions by meeting increasingly stringent energy efficiency targets while supplying those buildings with carbon-free energy.

UC campuses currently use two kinds of energy on site, electricity and natural gas. While carbon-free electricity can be produced directly by numerous sources (wind, solar, geothermal, tidal, etc.), decarbonizing natural gas is a more convoluted process of purchasing either carbon offsets or directed biogas (methane from remote landfills or agricultural operations that is collected, cleaned and directed into the U.S. natural gas pipeline). Directed biogas is harder to manage and has various issues in the long run, including limited supply, short lifetime for some (namely landfill) biogas production, fugitive emissions from natural gas operations, requirement to purchase outside California, reliance on infrastructure for natural gas which is arguably a "transition fuel" in a completely decarbonized economy[3] and other issues. Directly produced carbon-free electricity avoids these complications, as a long-term path to a carbon-free economy.

Making new buildings all-electric is one strategy that can mitigate growth in UC campus emissions without the complications of decarbonizing natural gas.

This study compares the capital and operating cost of building new buildings with gas-based heating systems, requiring offsetting natural gas with procured biogas and/or carbon offsets, to building all-electric based systems, which can be supplied with onsite renewable generation or purchased 100% renewable electricity (RECs).

Section 2.2 Methodology and Assumptions

2.2.1 Assumed Definition of Decarbonized Gas and Electricity

- Decarbonized Gas: The study assumes a cost for decarbonized gas made up of 50% biogas and 50% voluntary offsets. The cost of biogas is based on current and projected contract values. The cost of offsets is based on current and projected mid-range market values.
- Decarbonized Electricity: The study assumes that cost of grid-purchased electricity includes a premium for 100% renewable energy through the purchase of Renewable

[3] http://thebulletin.org/natural-gas-transition-fuel-bridge-too-far9671

Energy Credits. The cost for cogen-supplied electricity assumes a cost premium for the use of decarbonized gas per the above note.

2.2.2 Energy Costs

The energy costs used in the study were based on extensive discussion, research and deliberation by the consultant and staff from UCOP and individual UC campuses. The resulting costs were established for use in the study.

Table 1. Summary of Energy Costs as Applied to Each Building Type

Discount Rate = 5.75% (applies to all)		Academic & Residential		Laboratory				
	Has Cogen?	Electricity ($/kWh)	Gas ($/MMBtu)	Electricity ($/kWh)	Gas ($/MMBtu)	District Cooling Loop	District Heating Loop (and CW Loop)	Notes
UC Berkeley	Y	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.0868/kWh @1.4%	$12.50/MMBtu @1.4%			Cogen for electricity only; steam is tapped out; no CHW
UC Davis	No; MC Only	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.175/kWh @2.0%		$10.21/MMBtu @2.0%	$15.63/MMBtu @1.4%	No cogen. Yes central steam and chilled water
UC Irvine	Y	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.0868/kWh @1.4%		$8.12/MMBtu @1.1%	$10.15/MMBtu @1.1%	Cogen, high temp hot water and chilled water
UCLA	Y	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.0868/kWh @1.4%	$12.50/MMBtu @1.4%	$8.12/MMBtu @1.1%		Cogen, no steam available, yes chilled water
UC Merced	N	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$10.21/MMBtu @2.0%		No cogen, no steam, yes chilled water
UC Riverside	N	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.175/kWh @2.0%		$10.21/MMBtu @2.0%	$15.63/MMBtu @1.4%	No cogen, steam and chilled water for core campus (labs)
UC San Diego	Y	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.0868/kWh @1.4%		$8.12/MMBtu @1.1%	$10.15/MMBtu @1.1%	Cogen, steam and chilled water
UCSF	N	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.175/kWh @2.0%		$10.21/MMBtu @2.0%	$15.63/MMBtu @1.4%	No cogen, chilled and hot water at mission bay
UC Santa Barbara	N	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$10.21/MMBtu @2.0%		No cogen, no hot water, yes chilled water
UC Santa Cruz	Y	$0.175/kWh @2.0%	$12.50/MMBtu @1.4%	$0.0868/kWh @1.4%	$12.50/MMBtu @1.4%		$10.15/MMBtu @1.1%	Cogen for electricity; condenser water loop

2.2.3 Energy Modeling Inputs and Assumptions

Analysis was performed using industry-standard energy modeling software EnergyPlus to evaluate each building type on each of the 10 UC campuses, factoring in climate using TMY3 weather data and campus energy system context. More specifically, the consultant used the Office, Apartment, and Outpatient ASHRAE 90.1-2013 prototype models as a starting point for Academic, Residential, and Laboratory buildings, respectively. The prototype models were then modified to more closely resemble "typical" UC buildings based on the consultant's experience with UC projects. The models were also calibrated to within 15% of the UCOP 2019-20 Energy Performance Targets[4].

The models compared the energy use of a "gas + electric" building, one with gas-based heating equipment, to an "all-electric" alternative, one that relies exclusively on electric MEP systems, and compares the energy use and cost over a 20-year life cycle. Energy supplies in both cases

[4] http://ucop.edu/sustainability/_files/whole-building-energy-performance-targets-for-uc-buildings.pdf

were assumed to be carbon-free. The analysis reveals the net impact of equipment capital cost, equipment energy efficiency, and fuel costs (over 20 years)[5] in the three different building types. The following assumptions and modifications were made during this process:

- Occupancy:
    - Did NOT increase occupant densities to more closely resemble UC densities.
- Operating hours:
    - Academic:
        - Typical weekday: 6a-10p
        - Weekend: 8a-10p
        - Summer (June 1 - August 15): same schedule, but all values cut by 50%
    - Residential:
        - Typical weekday: Office - 8a-5p; Res - 100% occupied 9p-7a, tapered to 30% occupied mid-day
        - Weekend: Office - unoccupied; Res - same schedule
        - No summer difference
    - Labs:
        - Typical weekday: 6a-10p (6 ACH) (5% occupied @ night w/ 4 ACH)
        - Weekend: 6a-10p (6 ACH) (5% occupied @ night w/ 4 ACH), reduced peak to 50% occupancy
        - No summer difference
- Envelope:
    - Upgraded windows to be Title 24 compliant
    - Increased wall insulation R-value for all-electric residential buildings with no cooling to maintain code compliance for electric resistance heaters
- Laboratory ventilation rates and hood densities:
    - 60% of the GSF is considered “lab” space, and 40% is “non-lab.”
    - For the purpose of this study, the consultant did not delve into the specifics of hood densities, but rather assumed an average (in lab space) of 6 ACH during occupied conditions and 4 ACH setback during unoccupied hours.
- Laboratory plug loads:
    - Based on the Technical Performance Criteria for UCSF lab buildings

The following table summarizes some of the fundamental properties of the final energy models used in the study.

[5] For simplicity, the analysis does not include maintenance or equipment replacement costs, which are assumed to be similar for the two types of systems being compared, gas + electric and all-electric.

Table 2. Fundamental Properties of Modeled Buildings

Property	Academic	Residential	Laboratory
Square Footage	54,000	80,000	115,000
Number of Stories	3	5	5
Window-to-wall Ratio	50%	40%	40%
Window Properties (U | SHGC | VLT)	0.36 | 0.25 | 0.5	0.36 | 0.25 | 0.5	0.36 | 0.25 | 0.5
Average Lighting Power Density (W/sf)	0.82	0.45	0.5 (Non-Lab Space) 1.1 (Lab Space)
Wall | Roof Insulation	R-8 | R-26	R-12 | R-19 (Gas + Electric) R-26 | R-19 (All-Electric)	R-12 | R-26

2.2.4 Capital Cost Estimation Process and Assumptions

Understanding any differences in capital cost outlay is another primary factor in evaluating net present value (NPV) of options to achieve carbon neutrality. A professional cost estimator was employed to develop the capital cost figures. Prices were developed on a “system level” meaning a complete system from piping to large equipment was priced together to better capture synergies or added costs, as opposed simply pricing individual pieces of equipment and applying them where applicable.

It should be well understood that the capital cost figures are order of magnitude estimates only with the greatest sources for possible imprecision arising from that large number of estimates and the assumptions made to develop figures quickly. The sheer scale of the undertaking lead can be a factor in rougher estimates. Fourteen unique systems were priced with some additional customizations to cover all 60 building system by building type combinations. Each unique system itself having around 50 line items of analysis. This quantity of analysis can sometimes lead to a reduction in quality of each individual estimated item. A time efficient process for developing capital cost figures was also required. Prices were developed from the cost estimator’s experience on recent similar projects and professional experience. Inquiries to contractors local to each campus for regional pricing was not performed. Additionally local labor rates were considered at an average cost for California. Local code considerations were not considered. Finally no replacement, maintenance, or salvage costs were assumed.

Overall the capital cost numbers are reasonable approximations appropriate for the study and the evaluations performed. The estimates used have a comparable level of confidence as the predicted future costs of energy, as well as the innate inaccuracies to any energy model to predict a real building's energy use. While actual capital costs will vary for real world project, overall capital cost numbers, as well as relative comparisons of those numbers, provide us useful insight into the relative costs of achieving carbon neutrality via all-electric vs gas + electric systems.

2.2.5 Not Included in This Study

The study established assumptions in order to evaluate the primary question of whether designing new buildings to be all-electric is a cost-effective strategy to meeting UC's carbon neutrality goals. The study did not evaluate any of the following variables.

- Costs and effects of expanding campus cogen capacity
- Evaluation of academic or residential buildings on thermal loops or cogen (these were assumed to be stand-alone buildings)
- Title-24 compliance of energy models
    - Energy models are tailored to meet UCOP energy performance targets for 2019-20
    - Energy models are expected to meet T-24 performance compliance, but are based on ASHRAE 90.1-2013 standards
- Evaluation of all possible mechanical systems suitable for scholastic building types
- Optimization of the whole building solution for best energy efficiency, lowest upfront cost or lowest total life cycle cost (while this would be a valuable exercise, it was beyond this study)

Section 3: Life Cycle Results

Each building type across all campuses was evaluated using a Life Cycle Cost Analysis. Key definitions of each part of the analysis are as follows:

- **Capital Cost** includes HVAC capital costs, major plumbing capital costs, and electrical capital costs impacted by changes in HVAC/plumbing equipment. Close percentage differences are within the error range of cost estimating.
- **Energy Use Intensity (EUI)** is the annual whole building energy use in terms of kBTU per square foot per year (kBTU/sf/yr).
- **Net Present Energy Cost** is the Net Present Cost (NPC) of whole building energy costs over 20 years. The prices and escalation rates used are defined in Section 2.2, and the discount rate used was 5.75% in all cases.
- **Life Cycle Cost / Total Net Present Cost** in this study is the sum of the Net Present Energy Cost over 20 years and the Capital Cost.

Section 3.1 UC Average Life Cycle Cost Findings across All Campuses

3.1.1 UC Average Capital Cost Comparison

The capital costs of all-electric buildings evaluated in this study relative to that of gas + electric buildings varies by building and system type. The chart in Figure 2 shows the UC Average across all campuses by building type.

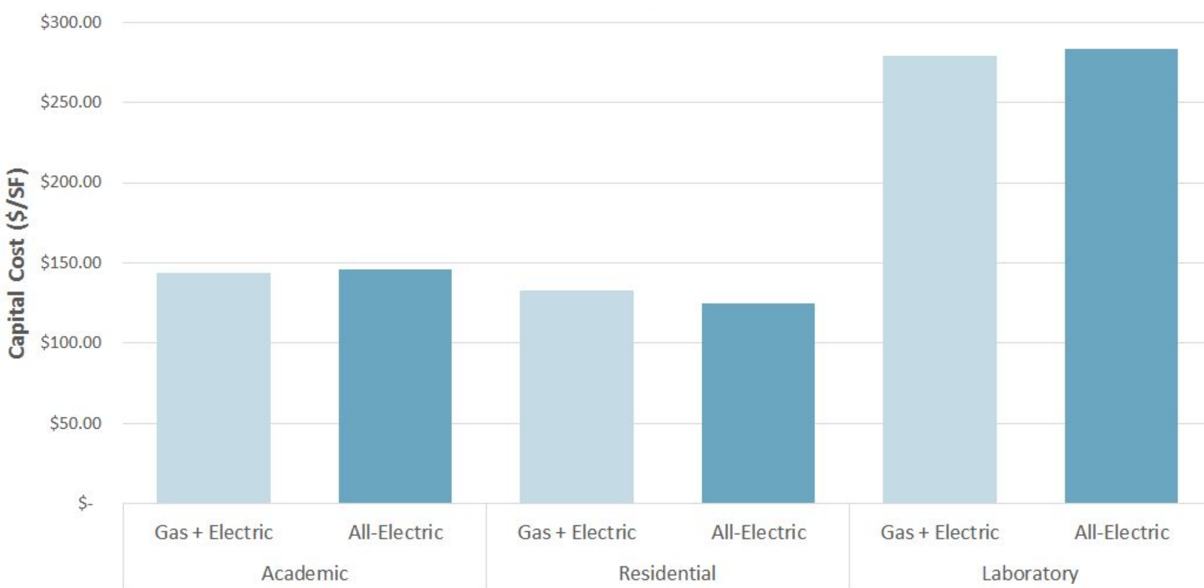


Figure 2. UC Average MEP Equipment Capital Costs across All Campuses

For academic buildings, there is no major difference in cost between the all-electric and the gas + electric options. The average all-electric design is $1.57/sf (just 1.1%) more than the average gas + electric design, attributed mainly to the higher cost of electric heat pumps as compared to gas boilers. However, 1.1% is considered a small difference, particularly considering the error range inherent in cost estimating.

For residential buildings, the all-electric design is on average $7.76/sf (about 5.9%) less expensive than the gas + electric option. This reduction in cost is due to material reductions associated with system selection (for buildings with heating only, electric baseboard heaters cost less than hydronic baseboard systems; for buildings with air conditioning, VRF systems cost less than 4-pipe hydronic with chillers and boilers.) This will be elaborated on in the building type-specific results in Section 3.3.

For laboratory buildings, there is again no major difference in capital equipment costs between the two options. The average all-electric lab is $4.19/sf (about 1.5%) more expensive than a gas + electric lab, attributed to heat pumps being more expensive than stand-alone boilers and much expensive than simply connecting to a district heating loop if capacity exists. It is important to note that this does not include the capital costs that may be associated with expanding any of the central plants that are used to supply heating, cooling, and electricity to many of the lab buildings.

3.1.2 UC Average Energy Use Intensity Comparison

Turning to energy use, all-electric buildings are consistently more energy-efficient than gas + electric buildings. The average across all campuses for Energy Use Intensity (EUI) of all-electric buildings compared to gas + electric buildings is shown in Figure 3 below.

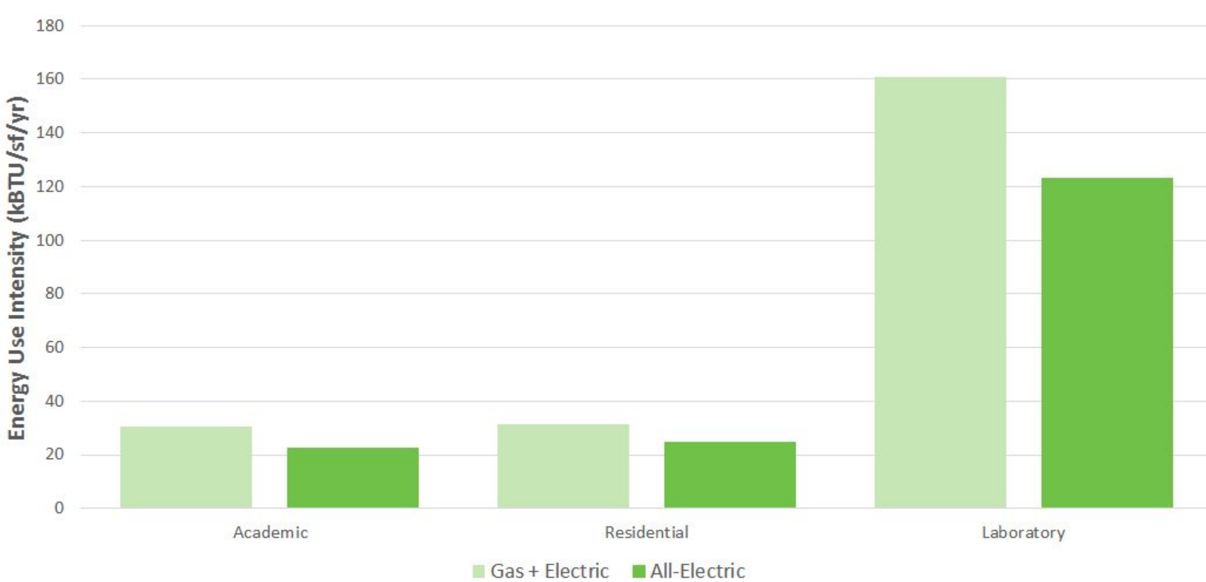


Figure 3. UC Average Energy Use Intensity across All Campuses

EUI is 25% lower in all-electric academic buildings, 21% lower for residential buildings, and 23% lower for laboratory buildings. Electric heating equipment is significantly more efficient than gas-fueled equipment, particularly when it comes to heat pumps. This is due to their ability to produce 3-5 units of heating as compared to a boiler that produces 0.8 - 0.9 units, for the same 1 unit of energy into both types of equipment.

Switching to more-efficient all-electric MEP systems is an effective strategy (in addition to increasing building envelope, lighting, plug load efficiency), for meeting UC's energy efficiency targets.

3.1.3 UC Average Net Present Energy Cost Comparison

Often, the savings in energy use translates into cost savings as well. However, this is not the case for every building type or campus. Figure 4 shows the UC average campus 20 year net present energy costs by building type.

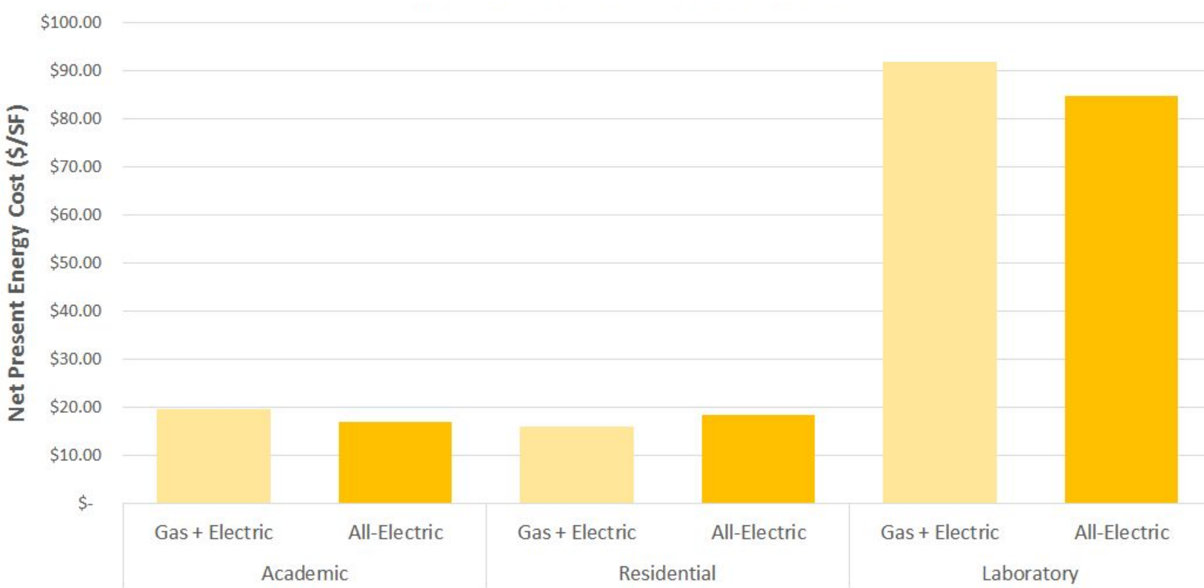


Figure 4. UC Average 20-Year Net Present Energy Costs across All Campuses

Without factoring in building capital costs, the 20-year net present energy cost for all-electric buildings compared to their gas + electric counterparts is 14% lower for academic buildings, 16% higher for residential buildings, and 8% lower for laboratory buildings. The residential building efficiency gains do not translate into energy cost savings largely because of the low cost of gas and large amount of heating and DHW energy relative to other end uses in this building type. A more detailed explanation for these results will be given in the building type-specific results sections.

3.1.4 UC Average Life Cycle Cost Comparison

Capital costs and net present energy costs were combined to evaluate the total Life Cycle Cost from and Net Present Cost perspective. The chart in Figure 5 shows the average LCC for each building type across the entire UC system.

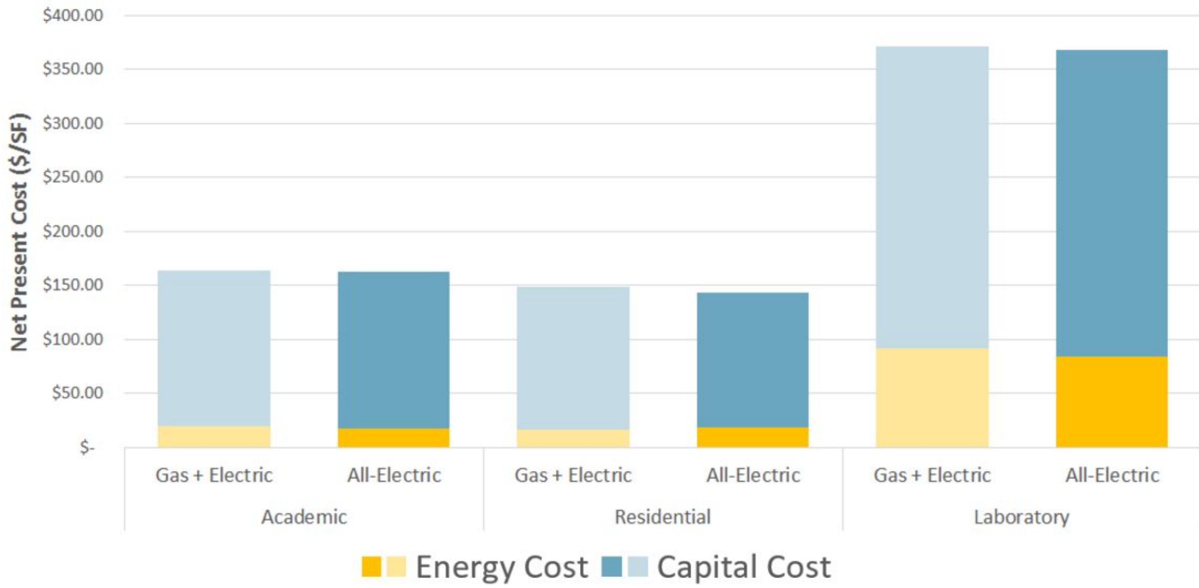


Figure 5. Campus-wide Average Total Net Present Energy Costs

All-electric buildings are comparable to gas + electric buildings from a Life Cycle Cost perspective, factoring in capital as well as energy costs. The average LCC for all-electric buildings compared to gas + electric option is $1.23/sf (about 0.7%) lower for academic buildings, $5.28/sf (about 3.5%) lower for residential buildings, and $3.09/sf (about 0.8%) lower for laboratories. For academic and residential buildings in this study, capital cost is the main predictor of Life Cycle cost performance. This is because energy costs were only 11-12% of the 20-Year Life Cycle cost. For labs, however, energy cost is either 17% or 30% of the total LCC, depending on whether a campus has cogen electricity prices or not. A more detailed explanation of Life Cycle Cost results is given in the building type-specific sections.

Section 3.2 Academic Building Findings by Individual Campus

3.2.1 Modeled Academic Building HVAC Systems

For academic buildings, the systems modeled for the gas + electric and all-electric options are as shown in Table 3.

Table 3. Modeled HVAC Systems for Academic Buildings

Academic Buildings		
System Type	Gas + Electric	All-Electric
All Campuses but UCSC*	- VAVRH System	- VAVRH System
	- Chiller	- Heat Recovery Chiller
	- Boiler	- Air Source Heat Pump
	- Cooling Tower	- Cooling Tower
Notes	*UCSC does not have mechanical cooling. The all-electric option has Air Source Heat Pumps only.	

3.2.2 Academic Capital Cost Comparison

Using the assumptions outlined in Section 2.2.3, the Capital Costs for the gas + electric and all-electric systems outlined in Table 3 were compared per square foot. The chart in Figure 6 shows this comparison for each campus.

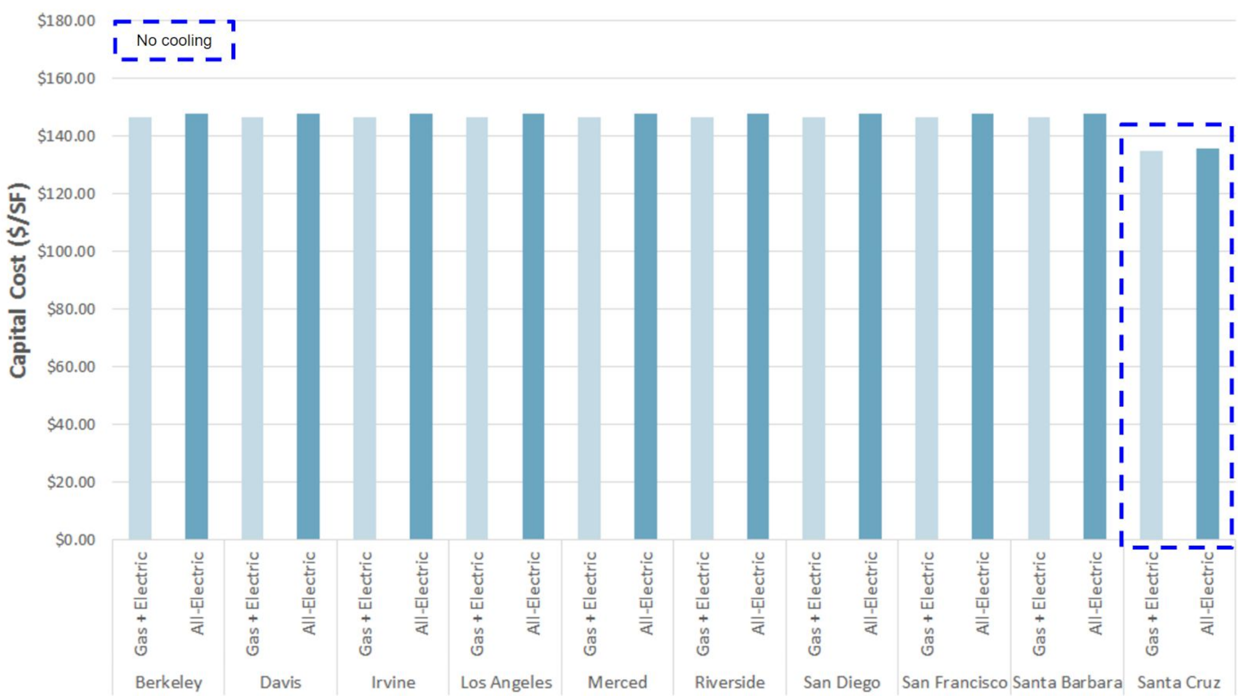


Figure 6. MEP Equipment Capital Costs (per square foot) for Academic Buildings

There is a $1.65/sf (1.1%) increase in cost associated with all-electric MEP systems at every campus with mechanical cooling. There is also a small premium associated with a heat recovery chiller compared to a standard water-cooled chiller used at the mechanically-cooled campuses. There is also a premium for air source heat pump equipment relative to the natural gas boilers that were prices for the gas + electric options, which is the case regardless of cooling condition. The campus without cooling has only a $0.86/sf (0.65%) increase in capital cost.

3.2.3 Academic Energy Use Intensity Comparison

The Energy Use Intensity (EUI) comparison, on the other hand, shows that all-electric buildings are consistently more energy efficient than their gas + electric counterparts. Figure 7 shows the EUI results for the gas + electric and all-electric buildings, as well as the UCOP 2019-20 EUI Target for each individual campus.

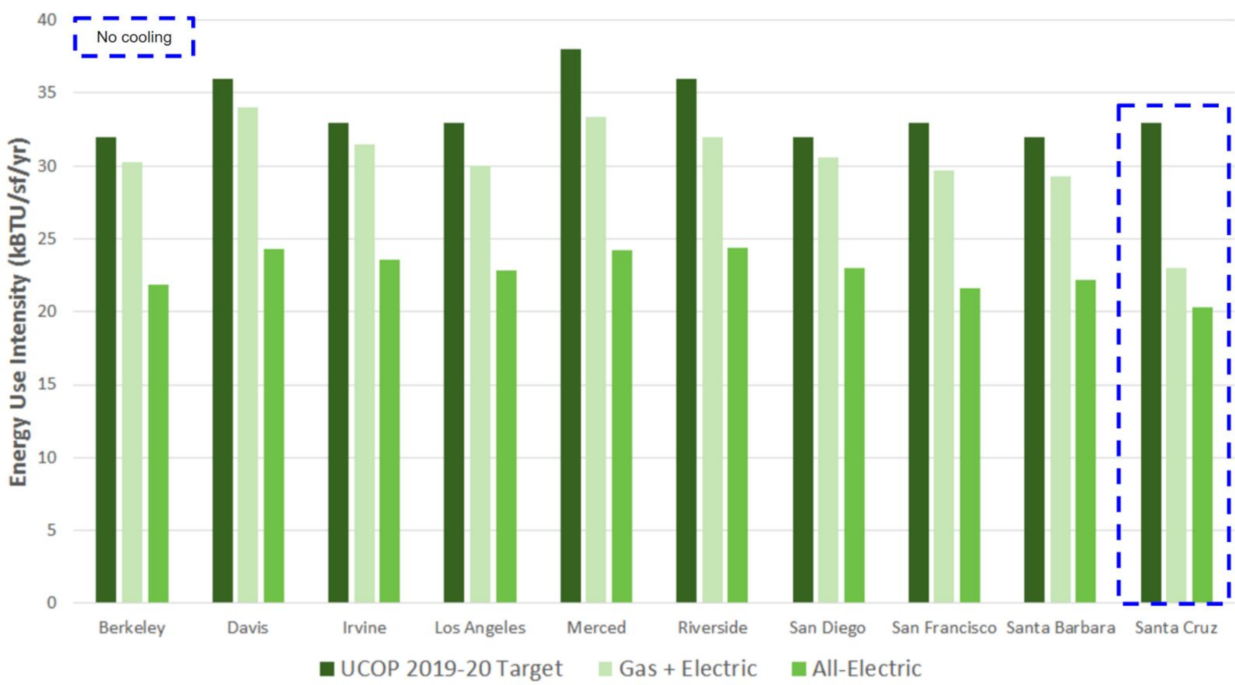


Figure 7. Energy Use Intensity for Academic Buildings

The reduction in energy use associated with the all-electric building options ranges from 24-28% for buildings with mechanical cooling (all campuses except UCSC). This savings is largely due to the use of heat recovery chillers, which leverage the simultaneous heating and cooling loads inherent in VAVRH systems to create both hot and cold water at the same time, reducing energy use. They are also slightly more efficient in cooling, with a COP of 6 compared to a COP of 4 for water-cooled chillers. The energy efficiency savings in academic buildings are also closely related to the ratio of heating energy to total HVAC energy. For buildings with higher proportional heating load (cooler climates), there is more opportunity to save by switching from an 83% efficient boiler to an air source heat pump with a COP of 3.3. By the same logic, campuses in warmer climates see a smaller efficiency gain for switching to all-electric heating equipment.

At UCSC, the EUI savings is only 12% even though it is one of the cooler climates in the UC system. This figure is much smaller than that of the other campuses due to the lack of mechanical cooling. In Santa Cruz, a tremendous amount of efficiency has already been realized by eliminating mechanical cooling altogether. Therefore, there is little room for further energy efficiency improvement without also modifying non-HVAC and plumbing building systems (envelope, lighting, etc.). For additional information and assumptions related to the UCOP targets, see Section 2.2 Methodology.

3.2.4 Academic Net Present Energy Cost Comparison

The energy use savings for academic buildings leads to consistent energy cost savings, as shown in Figure 8.

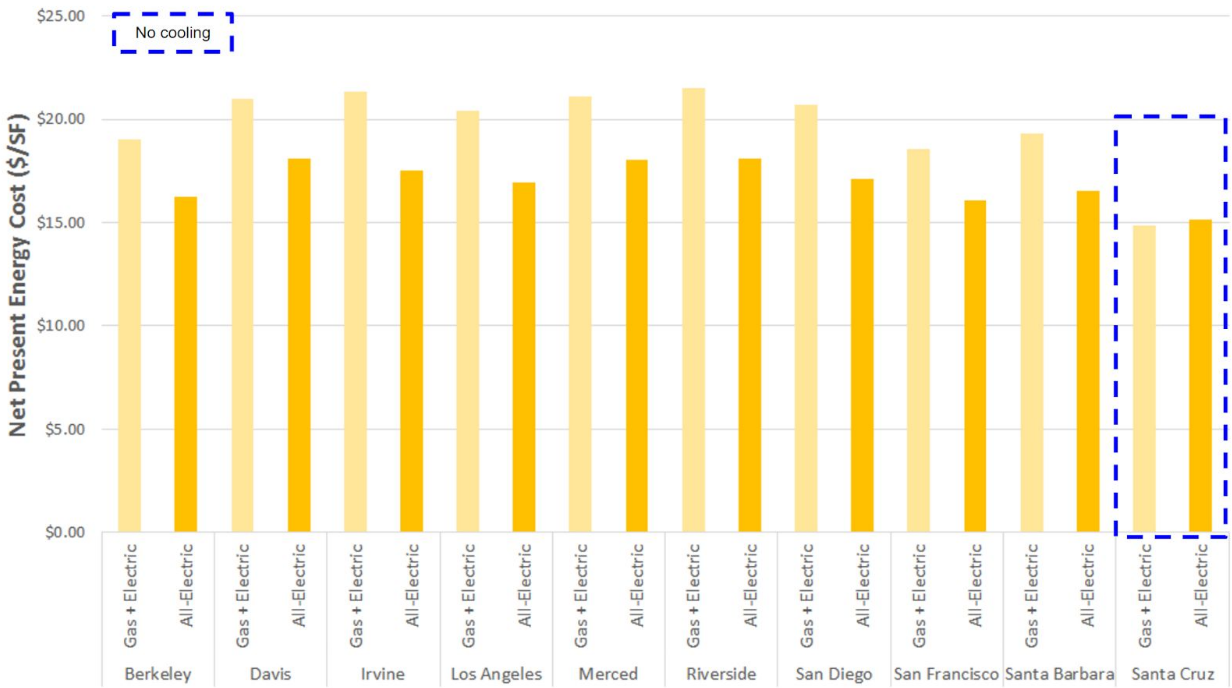


Figure 8. 20-Year Net Present Energy Cost for Academic Buildings

Although renewable grid electricity is considerably more expensive than the 50/50 biogas + offsets fuel source, all-electric buildings still have a lower 20-Year Net Present Energy Cost (NPEC) in every case where mechanical cooling is present. This is because the reduction in HVAC energy use is enough to make up for the 5x premium for electricity over gas.

Since UCSC does not have cooling, the potential for energy cost savings is diminished, and the cost increase for switching from gas to electric heat is reflected in the resultant NPEC.

3.2.5 Academic Life Cycle Cost Comparison

When capital costs and NPEC are evaluated simultaneously, all-electric buildings are comparable to gas + electric buildings in the academic case. The chart in Figure 9 illustrates the Total Life Cycle Cost comparison at each individual campus.

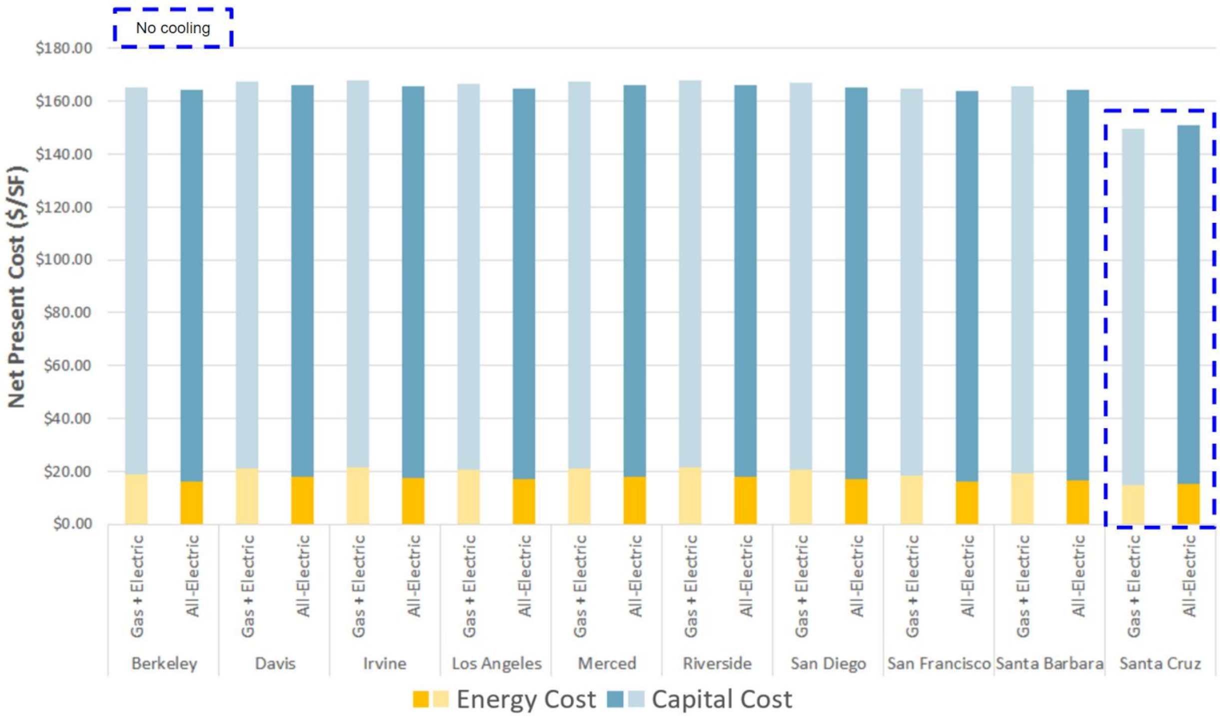


Figure 9. 20-Year Total Net Present Cost for Academic Buildings

All-electric buildings are comparable to gas + electric buildings from a Total Life Cycle Cost perspective. The LCC for all-electric buildings compared to gas + electric option ranges from $1.08/sf - $2.16/sf lower (0.6-1.3% of total LCC) for campuses with mechanical cooling. The energy cost savings outweigh the increase in capital cost associated with all-electric systems. However, for the UCSC campus without mechanical cooling, it is $1.16/sf (0.8% of total LCC) more expensive to switch to an all-electric building design since both capital and energy costs are more expensive.

Section 3.3 Residential Building Findings by Individual Campus

3.3.1 Modeled Residential HVAC Systems

For residential buildings, the systems modeled were as shown in Table 4.

Table 4. Modeled HVAC Systems for Residential Buildings

Residential Buildings		
System Type	Gas + Electric	All-Electric
Campuses with Cooling	- 4-Pipe Fan Coil System	- VRF Fan Coil System
	- Boilers	- VRF; Air Source Heat Pump (DHW only)
	- Air Cooled Chiller	- Air Cooled VRF Compressor
Campuses without Cooling	- Hot Water Baseboard	- Electric Baseboard
	- Boilers	- Air Source Heat Pump (DHW only)

3.3.2 Residential Capital Cost Comparison

Using the assumptions outlined in Section 2.2.3, the Capital Costs for the gas + electric and all-electric systems outlined in Table 4 were compared per square foot. The chart in Figure 10 shows this comparison for each campus.

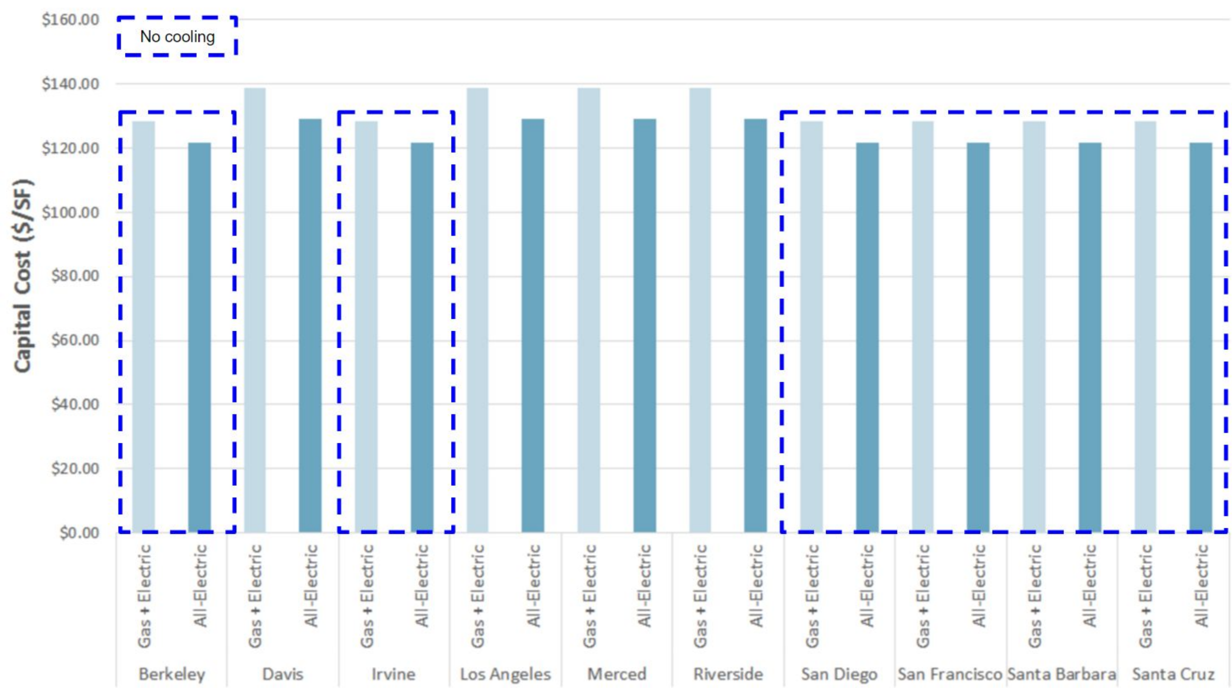


Figure 10. MEP Equipment Capital Costs (per square foot) for Residential Buildings

Unlike in the academic case, residential all-electric buildings yield savings on capital costs at all campuses. In the case of buildings modeled with no mechanical cooling (UCB, UCI, UCSD, UCSF, UCSB, UCSC), this savings of $6.58/sf (5.1%) was realized by the use of inexpensive electric resistance baseboard heaters instead of hydronic radiators. In the remaining campuses, for which there is mechanical cooling, there is a $9.55/sf (7%) savings due the use of Variable

Refrigerant Flow (VRF) instead of hydronic heating and cooling distributed through 4-Pipe Fan Coil Units. The reduction in piping size is one major reason for the cost savings in this case.

3.3.3 Residential Energy Use Intensity Comparison

In addition to reduction in capital costs, the all-electric Residential buildings are much more energy efficient than the gas + electric options. Figure 11 below details this comparison at each campus.

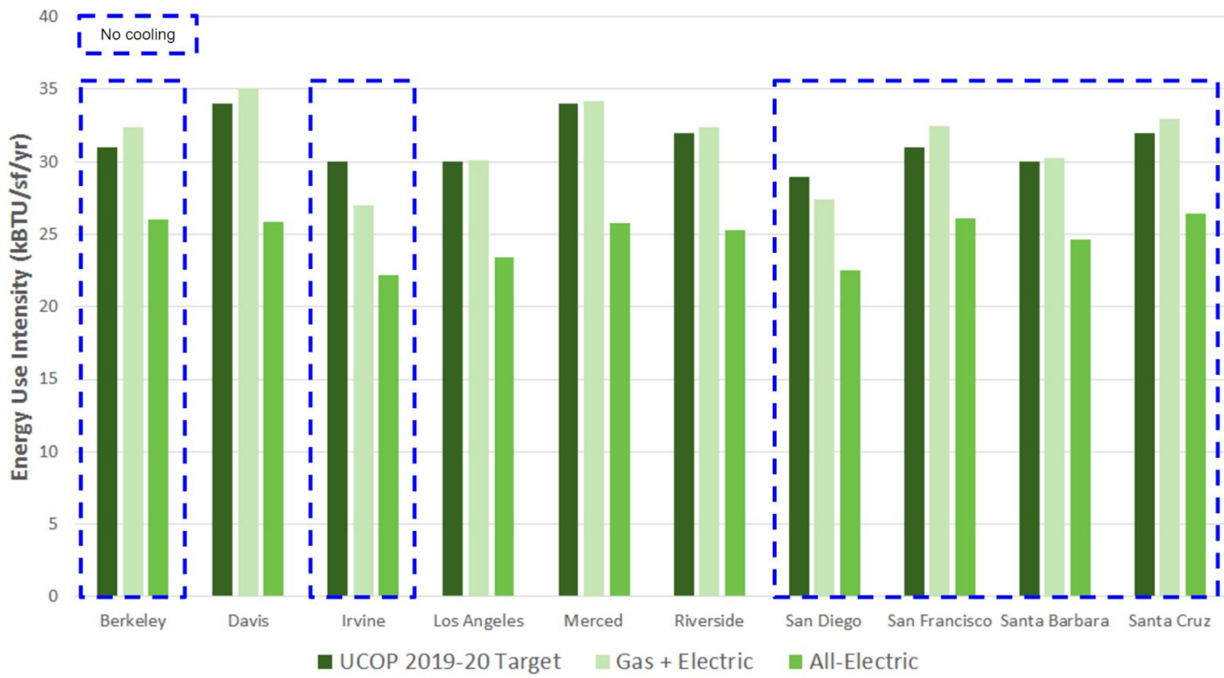


Figure 11. Energy Use Intensity for Residential Buildings

The reduction in energy use associated with the all-electric building options ranges from between 22-26% for buildings with mechanical cooling. This savings is primarily due to the increased efficiency of VRF cooling (COP of 3.5 in heating and cooling) compared to that of standard hydronic systems (heating efficiency of 83%, code minimum COP of 3).

For campuses without mechanical cooling, savings are 18 - 20%. Similar to the academic case, there is more opportunity to reduce energy use at campuses with both mechanical heating and cooling. One key difference, however, is that the campuses with no mechanical cooling yield much more savings for residential buildings due to the higher ratio of heating and DHW energy to total building energy. Since space heating and DHW are a much larger proportion of the energy, savings for those end uses translates to a more significant reduction in overall EUI.

3.3.4 Residential Net Present Energy Cost Comparison

Unlike academic buildings, the significant energy use savings for residential buildings does not lead to consistent energy cost savings, as shown in Figure 12

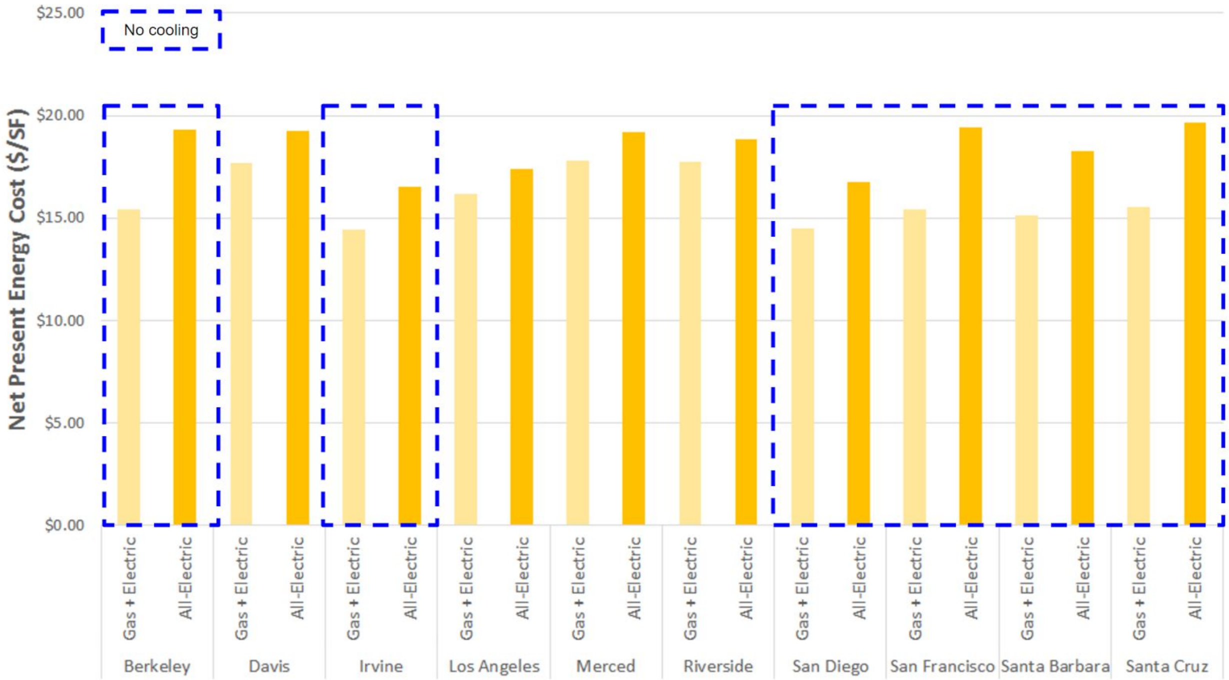


Figure 12. 20-Year Net Present Energy Cost for Residential Buildings

Because renewable grid electricity is considerably more expensive than the 50/50 biogas + offsets fuel source, all-electric buildings have a higher 20-Year Net Present Energy Cost (NPEC) in every case. The reduction in HVAC and DHW energy, although significant, does not overcome the electricity cost penalty. This is because heating and DHW dominate compared to other HVAC energy costs (average 1.5x cooling where relevant).

In cases where there is no mechanical cooling, the increased energy cost is even higher as heating and DHW become even larger portions of the end use energy cost mix.

3.3.5 Residential Life Cycle Cost Comparison

When capital costs and NPEC are evaluated simultaneously, all-electric buildings are less expensive than gas + electric buildings in the residential case. The chart in Figure 13 illustrates the Total Life Cycle Cost comparison at each individual campus.

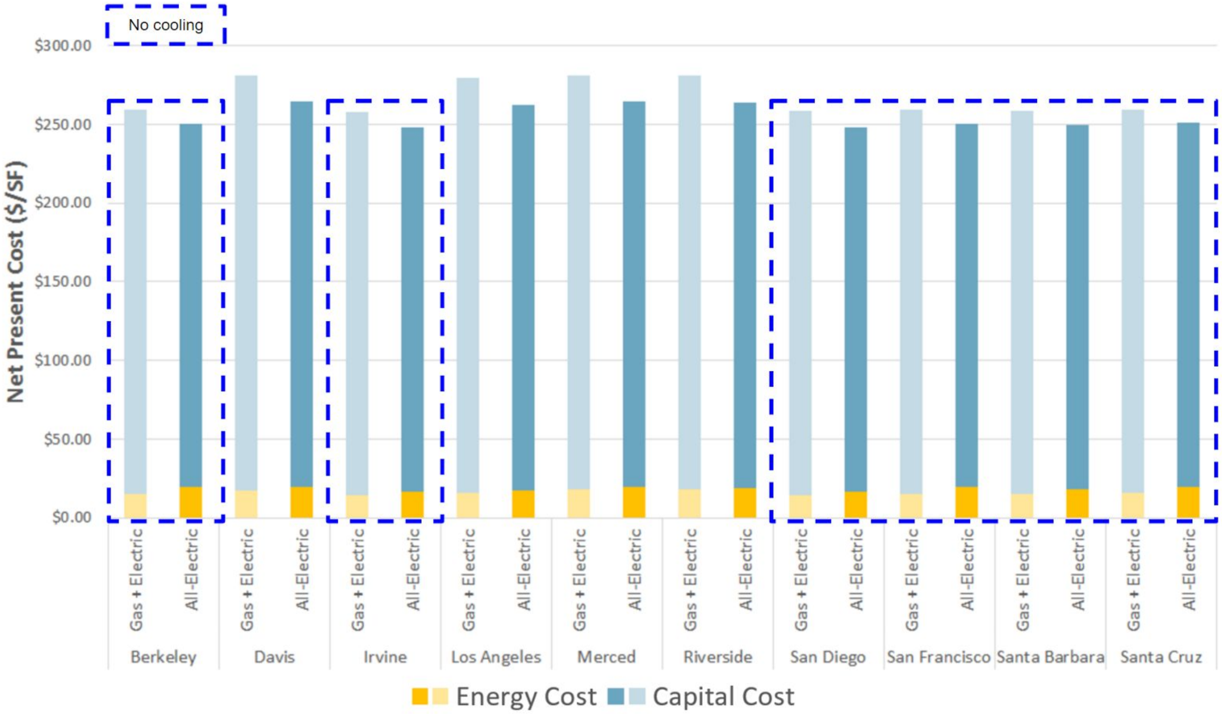


Figure 13. 20-Year Total Net Present Cost for Residential Buildings

All-electric buildings are less expensive than gas + electric buildings from a Total Life Cycle Cost perspective. The LCC for all-electric buildings compared to gas + electric option ranges from $7.99/sf - $8.28/sf lower (5.1-5.4% of total LCC) for campuses with mechanical cooling. However, for the campuses without mechanical cooling, it is $2.47/sf - $4.49/sf (1.7 - 3.1% of total LCC) less expensive to switch to an all-electric building design. The capital cost savings outweigh the increase in energy cost associated with all-electric systems in all cases, though it is more pronounced at campuses with mechanical cooling.

Section 3.4 Laboratory Building Findings by Individual Campus

3.4.1 Modeled Laboratory HVAC Systems

For laboratory buildings, the systems modeled were as shown in Table 5.

Table 5. Modeled HVAC Systems for Laboratory Buildings

Laboratory Buildings		
System Type	Gas + Electric	All-Electric
Campuses with Heating and Cooling Loop	- VAVRH System	- VAVRH System
	- District Heating	- Water Source Heat Pump
	- District Cooling	- District Cooling
Campuses with Cooling Loop Only	- Boilers	- Water Source Heat Pump
	- District Cooling	- District Cooling
Notes	*UCB and UCSC are unique. UCB is modeled without loops. UCSC is modeled with a condenser water loop only.	

3.4.2 Laboratory Capital Cost Comparison

Using the assumptions outlined in Section 2.2.3, the Capital Costs for the gas + electric and all-electric systems outlined in Table 5 were compared per square foot. The chart in Figure 14 shows this comparison for each campus.

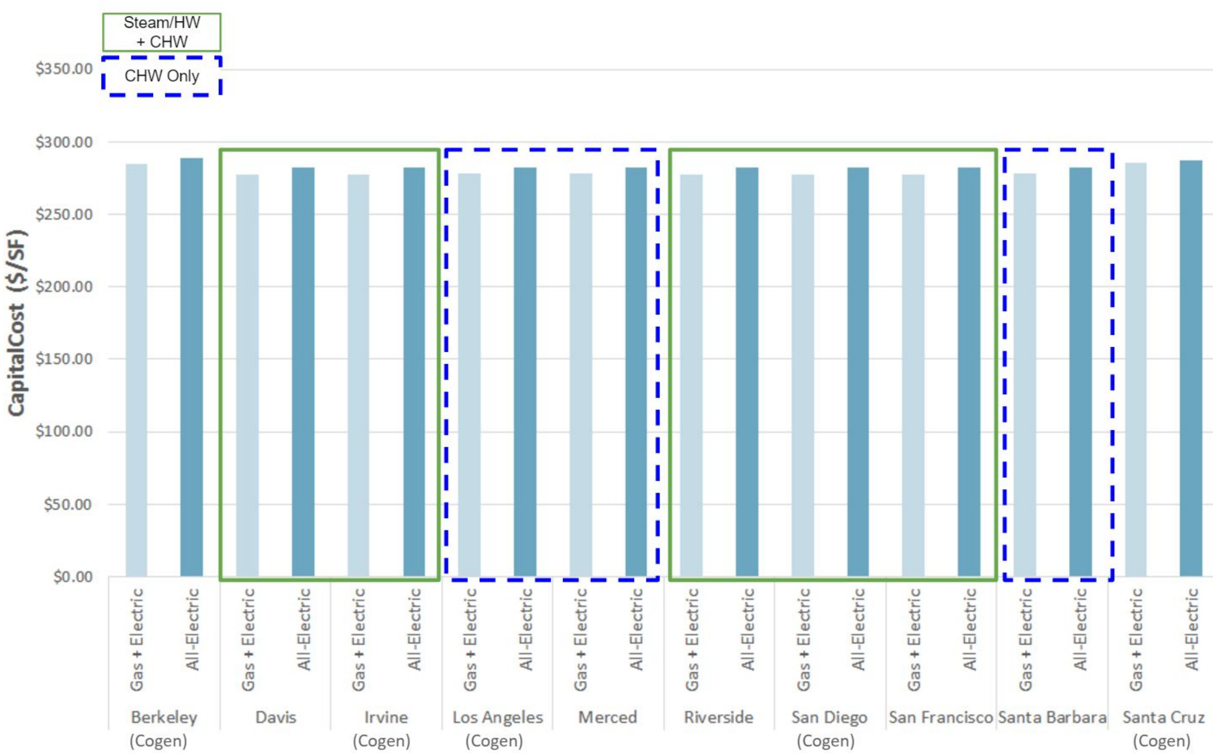


Figure 14. MEP Equipment Capital Costs (per square foot) for Laboratory Buildings

Unlike in the academic case and residential all-electric buildings are more expensive in terms of capital costs at all campuses.

In cases where there are both heating and cooling loops, this increase of $4.68/sf (1.7%) is due to the replacement of a low-cost heating loop connection with more expensive heat pump equipment.

At campuses, for which there is only a cooling loop, there is a $4.45/sf (1.6%) smaller premium for switching to heat pumps from natural gas boilers (which are more expensive than heat exchangers).

In the case of buildings with no heating or cooling loops (UCB and UCSC), this moderate increase is just $3.70/sf (1.3%) and $1.48/sf (0.5%), respectively. In both cases (similar to the academic case) it is due to the premium for all-electric heat pumps relative to gas-fueled standard boilers.

3.4.3 Laboratory Energy Use Intensity Comparison

In addition to reduction in capital costs, the all-electric laboratory buildings are much more energy efficient than the gas + electric options. Figure 15 below details this comparison at each campus.

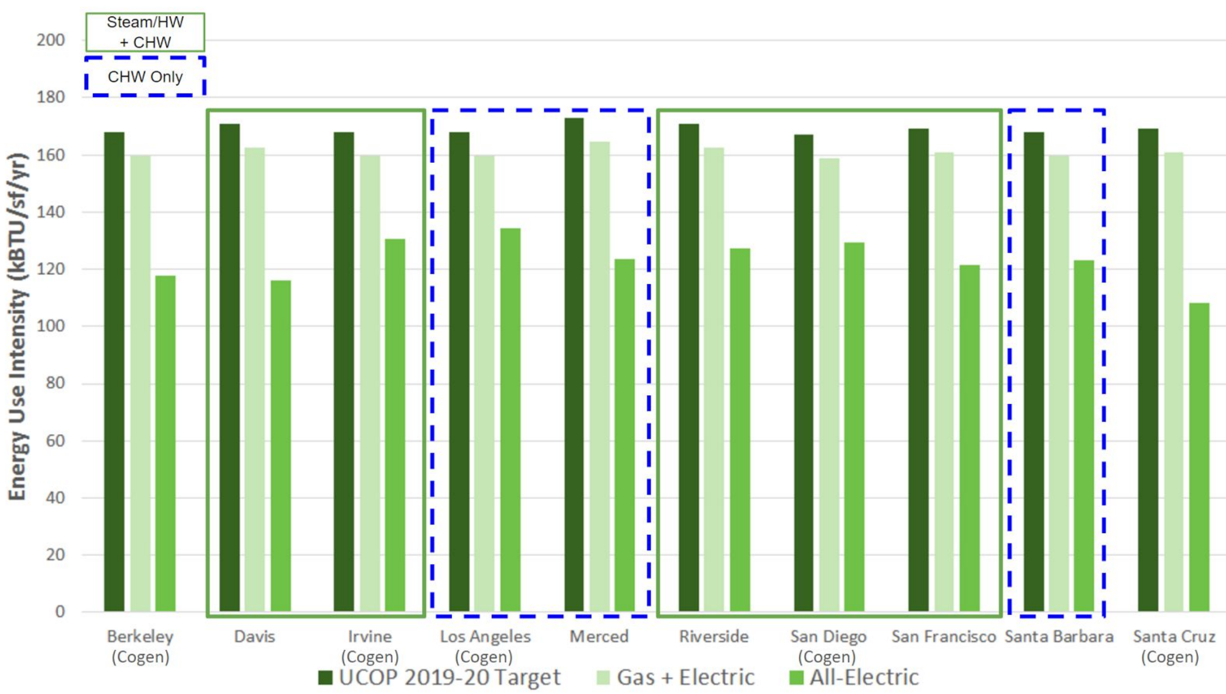


Figure 15. Energy Use Intensity for Laboratory Buildings

The reduction in energy use associated with the all-electric building options ranges from 16 - 33% across all campuses. Hotter climates (such as Davis, Merced, and Riverside) typically saved the most energy due to larger ratios of cooling energy to total energy use (typically 2x heating). Although district cooling is being used in both the gas + electric and all-electric case, the water source heat pumps on CHWR send cooler water back into the CHWR loop, offsetting plant energy use. There is even more savings at UCB and UCSC due to the use of heat recovery chillers, which save expensive electricity when there is simultaneous heating and cooling.

3.4.4 Laboratory Net Present Energy Cost Comparison

Similar to academic buildings, the significant energy use savings for lab buildings translates into consistent energy cost savings, as shown in Figure 16.

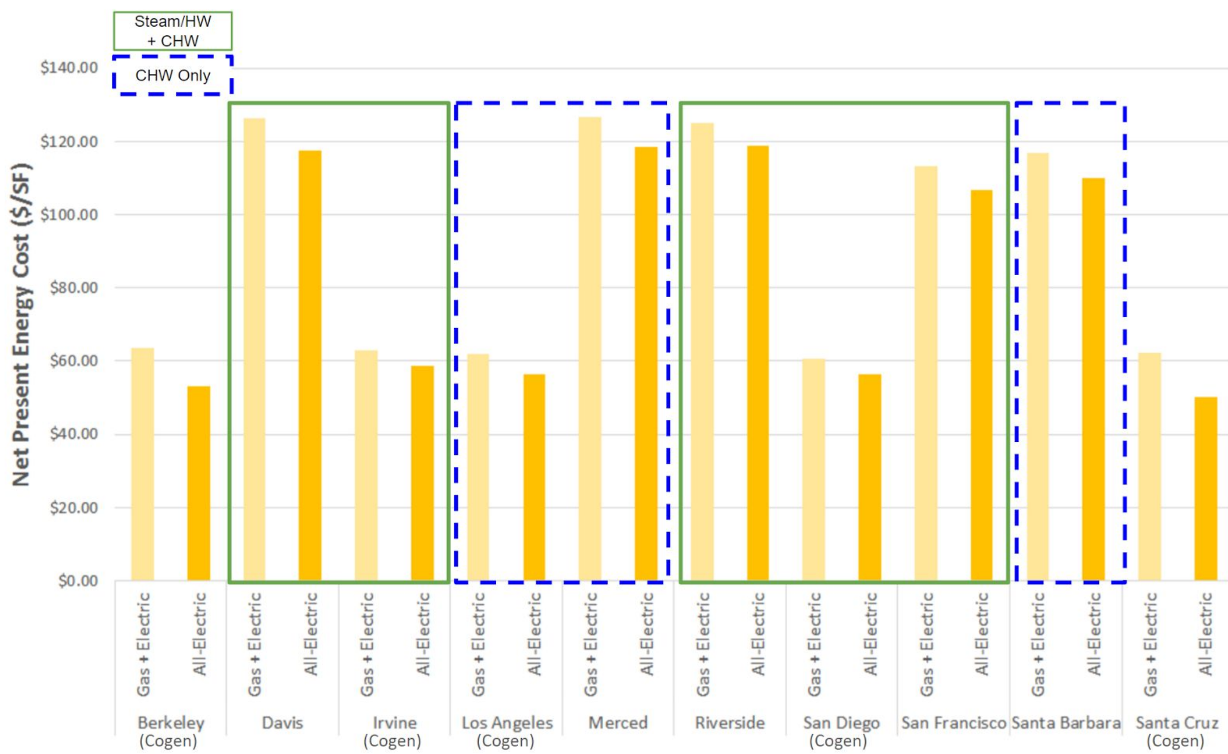


Figure 16. 20-Year Net Present Energy Cost for Laboratory Buildings

Although renewable grid electricity is considerably more expensive than the 50/50 biogas + offsets fuel source, all-electric buildings have a lower 20-Year Net Present Energy Cost (NPEC) in every case. This is because the energy use reduction for switching to heat pumps and heat recovery chillers is enough to make up for the 5x premium for electricity over gas. This savings is consistent across all loop types and whether or not a campus has cogen.

3.4.5 Laboratory Life Cycle Cost Comparison

When capital costs and NPEC are evaluated simultaneously, all-electric buildings are comparable to gas + electric buildings in the laboratory case. The chart in Figure 16 illustrates the Total Life Cycle Cost comparison at each individual campus.

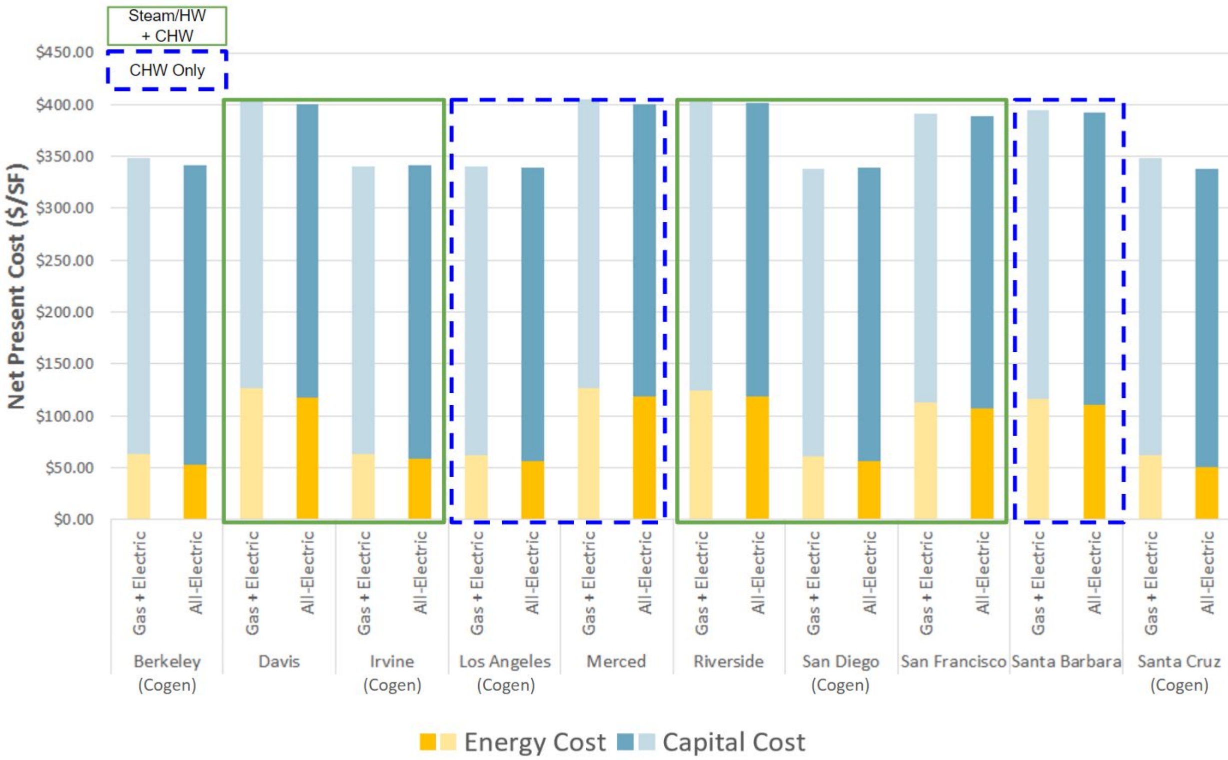


Figure 17. 20-Year Total Net Present Cost for Academic Buildings

All-electric buildings are comparable to gas + electric buildings from a Total Life Cycle Cost perspective, and vary slightly depending on district loop type and the availability of cogen electricity. The LCC for all-electric buildings compared to gas + electric option ranges from $1.20/sf - $4.07/sf lower (0.4 - 1.0% of total LCC) for most campuses with any type of heating or cooling loop. The energy cost savings outweigh the increase in capital cost associated with all-electric systems in all cases, except that of UCI and UCSD. At these campuses, which have both heating and cooling loops as well as cogen electricity prices, the LCC is actually higher, but only by $0.45/sf (0.13% of Total LCC). This is largely because the importance of electricity savings is diminished by the relatively low price of cogen electricity. For campuses with no available heating or cooling loops (UCB and UCSC), the savings are much greater at $6.83/sf and $10.43/sf (2.0% and 3.0%), respectively. For a more detailed analysis of Total LCC for each unique lab building condition, see section 4.2.3.

Section 3.5 Cogen Findings

This study assumed cogen capacity would accommodate lab buildings and did not evaluate the costs and benefits of adding new cogen capacity

- District heating, district cooling and cogen-produced electricity are all less expensive than stand-alone building alternatives assuming capacity exists.

- Cost for adding new cogen capacity is not factored into this study, as existing cogen capacity is assumed; however, campus usage exceeds cogen capacity in peak conditions[6].
- Campuses with cogen facilities import large amounts of electricity during peak demand conditions. This dampens the benefits of inexpensive cogen-generated electricity.
- Currently cogen reduces energy costs for gas + electric or all-electric buildings.
- Cogen cost-reductions are most impactful for lab buildings: energy comprises 10% of lifecycle cost for labs on cogen, but it comprises 20% of lifecycle cost for stand-alone labs.
- Cogen energy costs are assumed to be constant regardless of actual campus demand for thermal and electric energy (inefficiencies of part load conditions are not factored into this study)

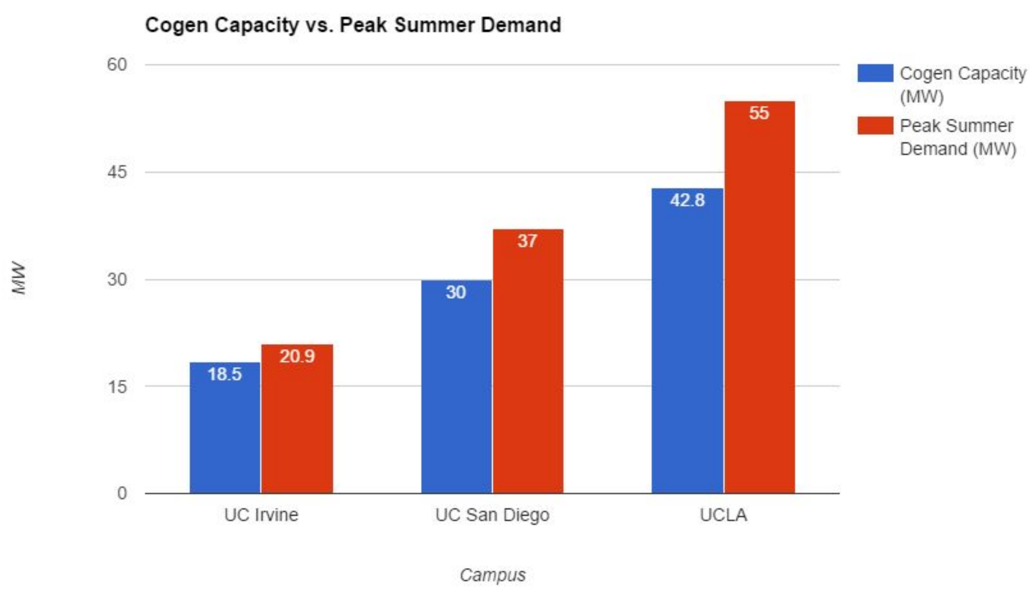


Figure 18. Cogen Capacity vs. Peak Summer Demand

Section 3.6 Sensitivity Analysis Results

The comparative analysis between all-electric buildings and gas + electric buildings was based on assumptions provided by UC staff, that were meant to be generic to UC markets and conditions. For instance, one assumption of the study is that UC carbon-free electricity price escalates at 2% annually, while carbon-free gas price escalates at 1.4%. Also, the timeframe of

[6] Data taken from the "Deep Energy Efficiency and Cogeneration Study Findings Report" put out by ARC Alternatives for UCOP

the study was conservatively set at 20 years. In order to evaluate alternate conditions, the consultant considered:

- The sensitivity of campus buildings to gas and electricity prices,
- The effects of biogas prices escalating at a faster rate
- The effects of renewable electricity prices escalating at a slower rate
- The effects of looking at a timeframe beyond 20 years and when the NPV for all-electric buildings is positive, relative to gas + electric

This analysis found, as shown in the following sections, that even gas-heated buildings are predominantly run by electricity and their costs are much more sensitive to electricity prices than to gas prices; therefore lifecycle energy cost escalation tracks with electricity cost escalation for both gas + electric and all-electric buildings.

Another finding is that, because lifecycle costs are dominated by equipment capital costs, energy cost escalation has a relatively small effect on total lifecycle costs, but whole building design efficiency that is able to downsize costly equipment and save initial capital costs, could have more impact on total lifecycle costs.

3.6.1 Sensitivity of Campus Buildings to Gas and Electricity Prices

The sensitivity of buildings to gas and electricity prices was tested both for direct use of the fuels in stand-alone buildings and for the impact of gas prices at cogen plants.

For gas + electric buildings, annual energy cost is much more sensitive to electricity price than to gas price, due to relatively small gas usage in the buildings, compared to electricity usage.

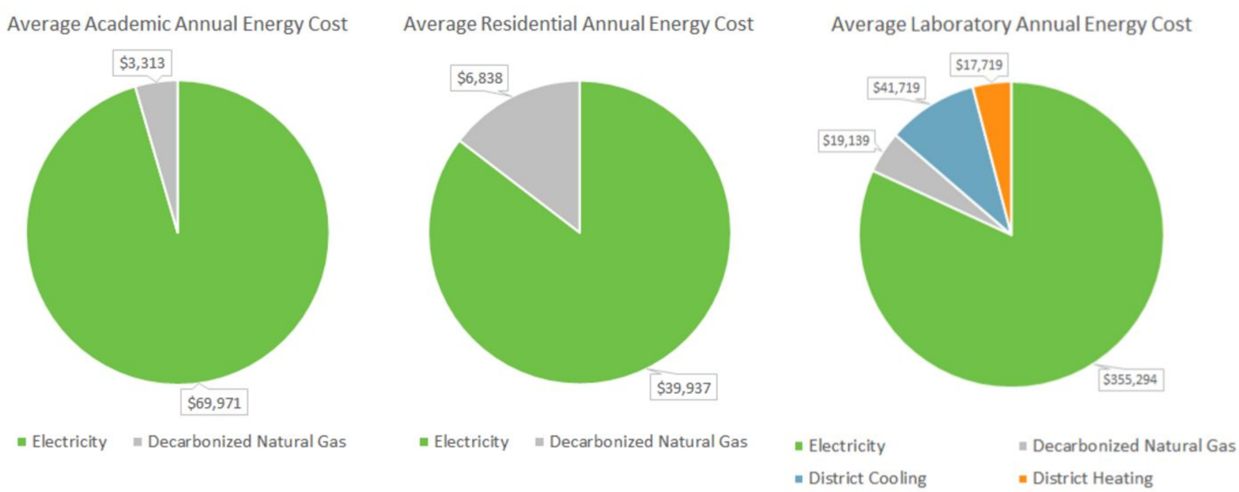


Figure 19. Average Annual Energy Cost by Building and Fuel Type

For cogen campuses, steeply rising gas prices result in a dramatic dollar-value increase in annual electricity costs, but a relatively small dollar-value increase in gas heating costs, due to small use of gas for heating, but large use of electricity produced by gas-fired cogen.

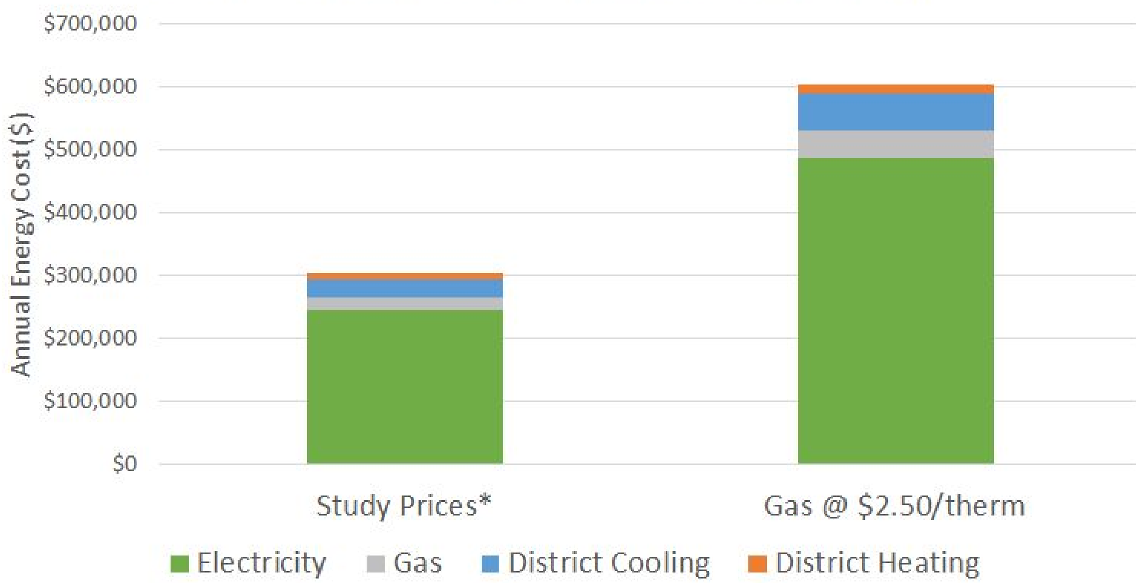


Figure 20. Effect of Doubling Biogas Price at a Cogen Campus

3.6.2 Effects of Variations in Escalation Rates of Carbon-free Gas and Electricity

The main study assumed carbon-free gas to escalate at 1.4% and carbon-free electricity to escalate at 2% annually, but because there is uncertainty in any projection, the consultant studied the effects of biogas prices escalating at a faster rate, a plausible outcome of fluctuating supply, demand, and production cost of biogas.

The consultant also evaluated the effects of renewable electricity prices escalating at a slower rate. This is plausible, for instance, in the case that carbon-free electricity is procured via lower-cost power purchase agreement for on-site solar PV, or the possibility that campus energy storage systems could enable purchase and storage of inexpensive renewable energy during overproduction periods.

The graph below shows that steeply escalating biogas prices could cause decarbonized cogen electricity to approach the cost of decarbonized grid electricity. However, if cogen plants have existing capacity, and gas price escalates at the rate assumed in this study, cogen electricity remains less expensive than grid electricity well after 30 years, even if grid electricity escalates at zero percent.

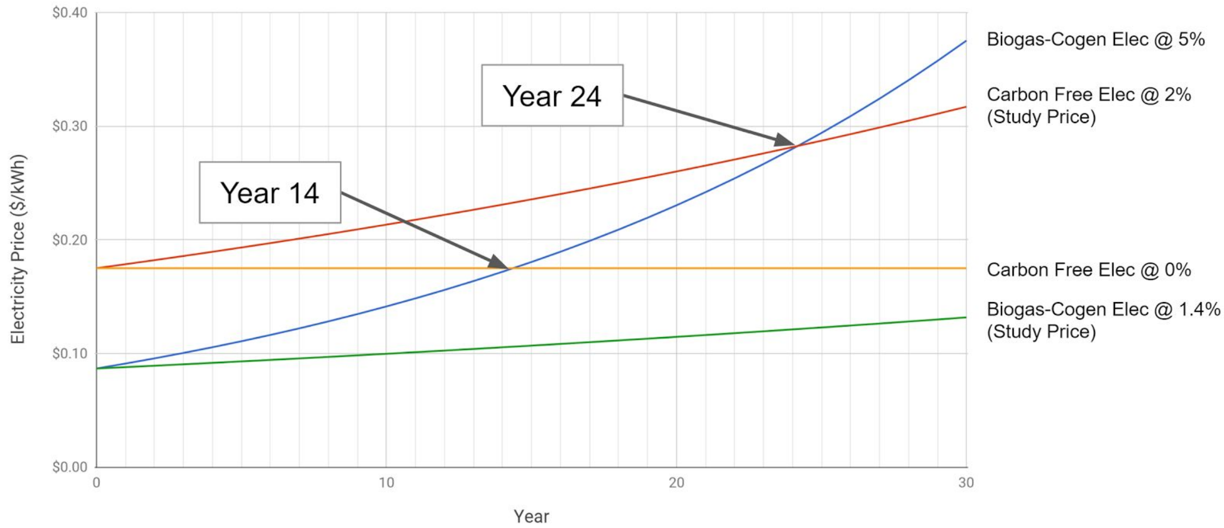


Figure 21. Effects of Variations in Escalation Rates of Carbon-Free Gas and Electricity

3.6.3 Extending the NPV Timeframe

In some cases the discounted payback period for all-electric buildings was determined to be longer than 20 years. The discounted payback period, which is the year when the NPV of all-electric buildings becomes positive relative to gas + electric buildings, is shown in the table below.

Table 6. Discounted Payback Period of All-Electric Buildings in Years

Campus	Academic	Residential[7]	Laboratory
Berkeley	10	GE cheaper in yr 50	5
Davis	9	0	9
Irvine	7	0	24
Los Angeles	8	0	14
Merced	9	0	9
Riverside	8	0	13
San Diego	7	0	24
San Francisco	12	GE cheaper in yr 48	12
Santa Barbara	10	0	11
Santa Cruz	>100 years	GE cheaper in yr 45	2

[7] Gas + electric remains more expensive for >100 years except where noted

The following graphs show the 25-year NPV of all-electric buildings relative to gas + electric buildings, the time period by which all-electric MEP systems are advantageous in every case except academic buildings at UCSC.

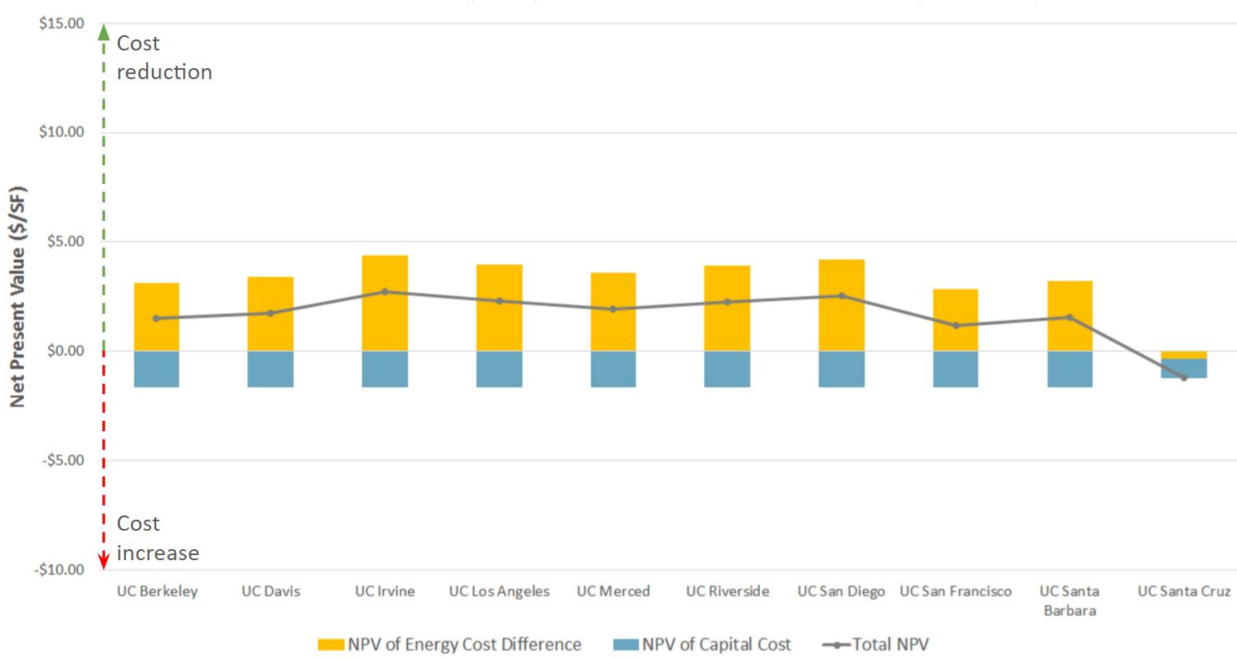


Figure 22. 25-Year Net Present Value (per SF) of All-Electric Relative to Gas + Electric (ACADEMIC)

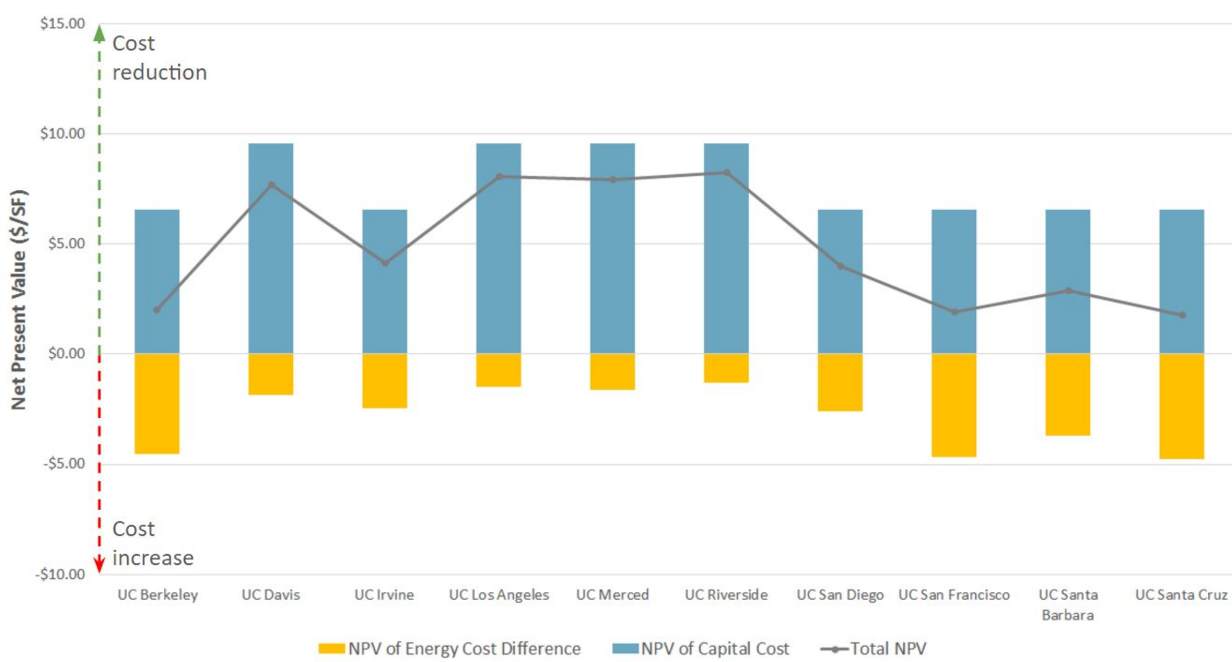


Figure 23. 25-Year Net Present Value (per SF) of All-Electric Relative to Gas + Electric (RESIDENTIAL)

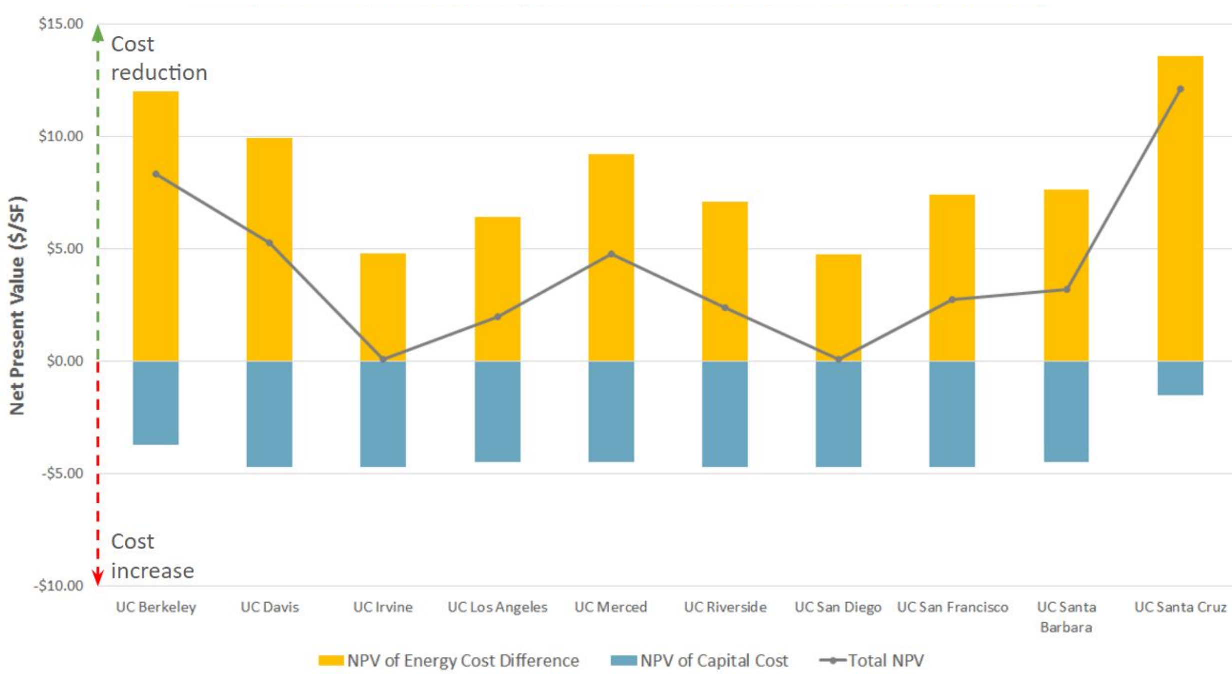


Figure 24. 25-Year Net Present Value (per SF) of All-Electric Relative to Gas + Electric (LABORATORY)

Section 4: Best Practice Guide

Section 4.1 Efficiency factors

A central premise of the study was that the superior energy efficiency of all-electric heat pumps for space and domestic hot water heating compared to natural gas boilers would indemnify any cost premium for the heat pumps themselves. Heat pumps have been growing in popularity, especially in sustainable or energy conscious applications. This is due to their ability to produce 3-5 units of heating as compared to a boiler that produces 0.8 - 0.9 units, for the same 1 unit of energy into both pieces of equipment. The results of this premise were mixed. The higher than expected costs of carbon free electricity compared to carbon free natural gas curtailed the benefits of the heat pump's superior efficiency. Even so, the efficiency benefits of all-electric heat pumps and their ability to be directly net metered against production of renewable electricity such as solar PV makes them an attractive long term solution for building systems.

Buildings with high and frequent domestic hot water peak demands have unique findings. Buildings with small or no heating and cooling systems combined with high occupancy and a dense number of hot water fixtures, especially showers, have a very large percentage of their total building energy use attributed to domestic hot water. In these situations electric heat pump solutions can have a dramatic effect on reducing the overall building energy use (reduction in EUI) compared to natural gas boilers. For this reason it is expected to be very difficult to meet UCOP EUI benchmark targets in building types described above with natural gas boilers. However, the annual cost of energy is expected to be much greater for heat pumps do to the comparable cost of energy. See “Case Study: UCSF Minnesota Street DHW” under Supporting Research.

Section 4.2 Best Practices by Building Type and Campus Conditions

Based on industry experience in practical, cost-effective, energy-efficient MEP systems, the consultant team developed best practice gas + electric MEP systems that would meet or exceed UCOP's 2019-20 efficiency targets and best-practice all-electric options. The systems are compared in more detail below. Alternative all-electric systems are described in the next section.

4.2.1 Academic Building Best Practices

Table 7. Modeled HVAC Systems for Academic Buildings

Academic Buildings		
System Type	Gas + Electric	All-Electric
All Campuses but UCSC*	- VAVRH System	- VAVRH System
	- Boilers	- Heat Recovery Chiller
	- Chiller	- Air Source Heat Pump
	- Cooling Tower	- Cooling Tower
Notes	*UCSC has everything except for cooling equipment. The all-electric option has Air Source Heat Pumps only	

Academic life cycle findings for the best-practice all-electric MEP system modeled in this study:

Table 8. Best Practices for Academic Buildings

Case	Mechanical Cooling	All-Electric System & Life Cycle Findings
1: All but UCSC	✔	Use of heat recovery chiller capitalizes on the simultaneous heating and cooling that takes place in a VAV with Reheat system. The Heat Recovery Chiller is also more efficient on cooling than the water-cooled chiller in the gas + electric case. Every campus "pays back" in 12 years or less.
2: UCSC		Because there is no cooling, the only opportunity to save energy cost is on heating. However, since there is relatively little heat load for this building type, there is just a 12% efficiency savings. This savings is not enough to overcome the electricity cost penalty. Combined with the increased cost of ASHPs over natural gas boilers, it does not prove to be cost-effective. The all-electric option does not become NPV positive relative to gas + electric, within a 100 year timeframe.

4.2.2 Residential Building Best Practices

Table 9. Modeled HVAC Systems for Residential Buildings

Residential Buildings		
System Type	Gas + Electric	All-Electric
Campuses with Cooling	- 4-Pipe Fan Coil System	- VRF Fan Coil System
	- Boilers	- VRF; Air Source Heat Pump (DHW only)
	- Air Cooled Chiller	- Air Cooled VRF Compressor
Campuses without Cooling	- Hot Water Baseboard	- Electric Baseboard
	- Boilers	- Air Source Heat Pump (DHW only)

Residential life cycle findings for the best-practice all-electric MEP system modeled in this study:

Table 10. Best Practices for Residential Buildings

Case	Mechanical Cooling	All-Electric System & Life Cycle Findings
1: UCD, UCLA, UCM, UCR	✔	If cooling is needed, the best-practice all-electric strategy of using VRF heat pump heating and cooling equipment has lower capital costs than a four pipe hydronic system with a gas boiler and chiller. VRF heat pump systems also have much higher efficiency in heating than gas boilers do, significantly reducing the energy use of the all-electric buildings, although expensive electricity still makes their annual energy costs higher. Those higher energy costs never surpass the capital cost savings of all-electric buildings with cooling, even after 100 years.
2: UCB, UCI, UCSD, UCSF, UCSB, UCSC		The best practice strategy is to make the building envelope very efficient and then only need to supply a small amount of heating with baseboard electric resistance heaters, which are much less costly upfront than gas-boiler heated baseboard hydronic systems. Baseboard electric is slightly more efficient too, but expensive electricity will make energy costs higher. However, those higher energy costs will never surpass the upfront capital cost savings of all-electric student housing. The best way to save money is to maximize the envelope efficiency with airtight construction, thermal bridge-free building envelopes, high insulation, good windows and winter solar gain. While energy costs are slightly higher for all-electric buildings, they maintain their total discounted cost advantage, even when forecast over 100 years, in all cases except UCSF, UCB and UCSC for which gas + electric buildings become more cost-effective

		between years 45-50, assuming the gas and electricity prices continue to escalate at the same rates assumed for years 1-20

4.2.3 Laboratory Building Best Practices

Table 11. Modeled HVAC Systems for Laboratory Buildings

Laboratory Buildings		
System Type	Gas + Electric	All-Electric
Campuses with Heating and Cooling Loop	- VAVRH System	- VAVRH System
	- District Heating	- Water Source Heat Pump
	- District Cooling	- District Cooling
Campuses with Cooling Loop Only	- Boilers	- Water Source Heat Pump
	- District Cooling	- District Cooling
Notes	*UCB and UCSC are unique. UCB is modeled without loops. UCSC is modeled with a condenser water loop only.	

Laboratory life cycle findings for the best-practice all-electric MEP system modeled in this study:

Table 12. Best Practices for Laboratory Buildings

Case	Cooling loop	Heating loop	Cogen	All-Electric system & life cycle findings
1: UCI, UCSD	✔	✔	✔	The best practice all-electric HVAC system uses water source heat pumps (WSHPs) on district chilled water return (CHWR) loops and VAV delivery with reheat; the domestic hot water (DHW) system also uses the WSHPs on the district CHWR loops. The gas + electric system is the same except that it uses gas-based district heating. It takes 24 years for the discounted energy cost savings to pay back the high upfront cost of the stand-alone heat pumps in the all-electric building, when compared to connecting to a central plant heating system with negligible upfront equipment costs and low marginal energy costs.
2: UCB			✔	If the campus doesn't have central cooling or heating, the all-electric system consisting of a heat recovery chiller (HRCH) and back-up heat pumps will be more cost-effective than the gas + electric system of a standard chiller and gas boiler. The all-electric system has a discounted payback period of 5 years.

3: UCR, UCD, UCSF	✔	✔		The best practice equipment for campuses with both heating and cooling loops but no cogen is exactly the same as in Case 1 (both loops plus cogen). However, unlike campuses with cogen, where all-electric systems take 24 years to become NPV positive, on campuses without cogen, all-electric systems become NPV positive in 9-13 years. This is because if a central cooling plant is buying expensive grid electricity, it is particularly cost-effective for a new building to have a water source heat pump, which will return heating reject "coolth" back into the loop, making the central cooling plant more efficient and saving expensive electricity.
4: UCLA	✔		✔	For a campus with cogen and central cooling but no central heating capacity and therefore stand-alone heating equipment has to be purchased, an all-electric heat pump system will have a discounted payback period of 14 years, relative to a stand-alone boiler. This payback is due to efficiency of producing the hot water and returning its reject coolth into the cooling loop to make the central cooling more efficient as well.
5: UCSC	✔ (CW loop)		✔	For a campus with cogen and a condenser water (CW) loop, an all-electric building with a HRCH on the district CW loop and a backup WSHP on the CW loop, that also serves the DHW needs, will be more cost effective than the gas + electric option of a gas boiler and a water cooled chiller on the CW loop. Relative to the gas + electric option, the all-electric best option is NPV positive in year two.
6: UCSB, UCM	✔			For campuses with a CHW loop but no heating and no co-gen, the all-electric building with a WSHP returning coolth back to the CHW plant will be more cost-effective than the gas + electric system with a gas boiler for heating. The all-electric option saves expensive grid electricity costs and becomes NPV positive by years 9-11.

Section 4.3 Alternate Electric MEP Systems

4.3.1 All-Electric HVAC Heating & Cooling Source Options

Table 13. Evaluation of Different All-Electric HVAC Heating & Cooling Sources

System Type	Acad	Lab	Res	Pros	Cons
Electric Resistance Heating	N/A	N/A	$	Simple, common, inexpensive	Aesthetics, limited applicability
Ground Source Heat Pump	$$$	$$$	$$$	Highly efficient, predictable performance, localized system that is mostly hidden	Requires trenches or bores, testing of soil conductivity, difficult to fix if ever damaged
Air Source Heat Pump	$	$	$$	Great efficiency, flexible installation locations, does not require additional source equipment	Sizes and system configurations not as numerous as boiler or chiller systems
Water Source Heat Pump connected to CW loop	$$	$$	$$	Same as Air Source but more efficient and predictable performance	Same as Air Source but requires condenser water and more hydronic piping and pumps
Air Source Variable Refrigerant Flow System	$$	$$	$$$	Fully variable modern system growing in popularity, highly efficient at part and full load.	Use of refrigerants within the occupied space, lots of refrigerant piping in the space that must be installed with care and detail.
Ground or Water Source (CW) Variable Refrigerant Flow System	$$$	$$$	$$$	Same as Air Source but more efficient and predictable performance.	Same as Air Source but requires condenser water and more hydronic piping and pumps
Heat Recovery Chiller	$$	$$	N/A	High Efficiency. Chilled and hot water from one piece of equipment.	Non traditional piece of equipment may require training, introduces HW temperature restraints
Central or local Water Cooled Chiller (with Cooling Tower)	$$$	$$$	$$$	Chilled water plants are common and can be made to be very efficient.	Chilled water plants can also be operated inefficiently, require substantial infrastructure and site area.
Central or Local Air Cooled Chiller	$$	N/A	$$	Simple piece of equipment, comes in many sizes and configurations	Much less efficient than a water cooled chilled or a heat pump. Less efficient than a heat pump

4.3.2 All-Electric HVAC Ventilation Options

Table 14. Evaluation of Different All-Electric HVAC Ventilation Systems

System Type	Acad	Lab	Res	Pros	Cons
Whole building DOAS AHU	$$	$$	$$	Excellent control of fresh air quantity, temperature, and humidity	Sized for fresh air requirements can limit economizing hours
Whole building DOAS AHU with heat recovery	$$$	$$$	$$$	Same as above plus energy efficiency from heat recovery	Adds an additional component and controls complexity
Energy Recovery or Heat Recovery Ventilators	$	N/A	$	Simple and very efficient specialty system for maximizing energy recovery from fresh air systems	Limited sizes limit applicability (larger demands require DOAS AHUs)
Variable Air Volume	$$	$$	$$	One of the most common HVAC systems today. Allows for maximum economizing hours	Cooling and heating demands are tied to fresh air demands, this can create energy penalties
Natural Ventilation ($$ with automation; $ without)	$	N/A	$	Very cost effective. Can increase occupant comfort through increased user control of their space	Only applicable in limited situations. No true control over amount of fresh air delivered. Can increase building heating and cooling loads without automation or user feedback

4.3.3 All-Electric HVAC Distribution Options

Table 15. Evaluation of Different All-Electric HVAC Distribution Systems

System Type	Acad	Lab	Res	Pros	Cons
Variable Air Volume with Reheat (VAVRH)	$$	$$	$$	One of the most common HVAC systems today. Allows for maximum economizing hours	Reheat innately wastes energy. Cooling and heating demands are tied to fresh air demands, this can create energy penalties
Radiant	$$	$$	$	Highly efficient and high occupant comfort.	Not as common as other systems, requires a good designer, contractor, and commissioning to ensure a well operating system.
Displacement Ventilation	$	$	N/A	Increased occupant comfort through control of their environment. Easy reconfigurability. Fresh air is delivered at the occupant level as opposed to the ceiling.	Fine control of supply air temperatures can be difficult if not well designed. Even airflow distribution can be difficult due to MEPS obstructions or poor design
Variable Refrigerant Flow	$$	$$	$$$	Fully variable modern system growing in popularity, highly efficient at part and full load	Use of refrigerants within the occupied space, lots of refrigerant piping in the space that must be installed with care and detail
Chilled Beams	$$$	$$$	N/A	Highly efficient at delivering heating and cooling as well as fresh air. Can be cost effective for spaces requiring high air change rates.	Condensate must be considered.
HW Baseboard	N/A	N/A	$	Simple, common	Aesthetics, leaks and condensate must be considered. Complex piping can become expensive.

4.3.4 All-Electric Domestic Hot Water Options

Table 16. Evaluation of Different All-Electric Domestic Hot Water Heating Sources

System Type	Acad	Lab	Res	Pros	Cons
Solar Thermal + Electric Backup	$$$	$$$	$$$	Efficient when functions as designed. Limited moving parts.	Solar thermal can have unpredictable performance. May require specialized training.
Ground Source Heat Pump (only reasonable if also used for space heating)	$$$	$$$	$$$	Highly efficient, predictable performance, cost savings possible when tied to GSHP space heating system	Requires trenches or bores, testing of soil conductivity, difficult to fix if ever damaged
Air Source Heat Pump	$$	$$	$$	Great efficiency, flexible installation locations, does not require additional source equipment or a flume	Sizes and system configurations not as numerous as boiler or chiller systems. More expensive than boiler systems
Water Source Heat Pump connected to Bldg CW loop	$$	$$	N/A	Same as Air Source but more efficient and predictable performance	Same as Air Source but requires condenser water and more hydronic piping and pumps
Point of use electric water heater	$	N/A	N/A	Simple and flexible installations. Easily to replace.	Design temps maybe be harder to achieve at higher flow rates. High kW applications require thoughtful electrical design. Possible issues with T24 compliance.

Section 5: Appendix

Section 5.1 Systems Matrix

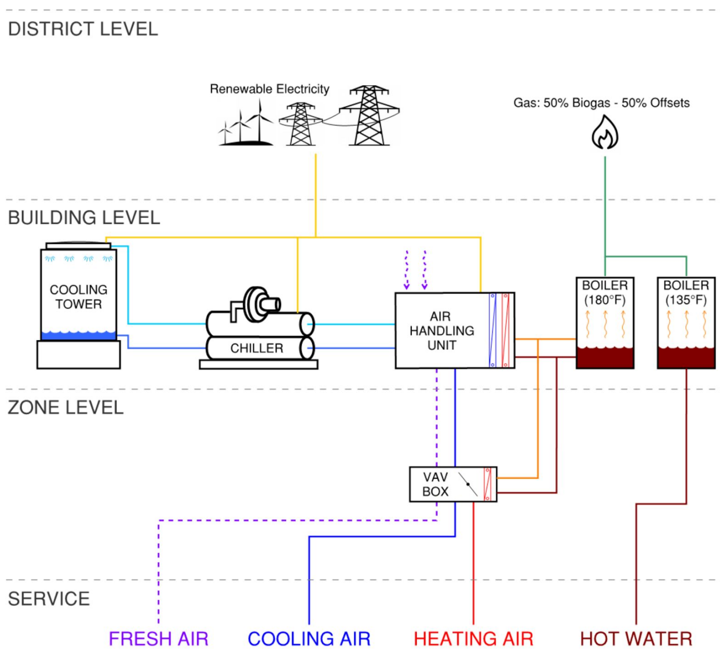
Building Type	Campuses Included	Space Heating		Domestic Hot Water		Cooling	
		GAS + ELECTRIC	ALL-ELECTRIC	GAS + ELECTRIC	ALL-ELECTRIC	GAS + ELECTRIC	ALL-ELECTRIC
Academic With Cooling	All but UCSC	Natural Gas Boiler VAV w/ Reheat	HR Chiller Backup ASHP VAV w/ Reheat	Natural Gas Boiler	ASHP	Water-Cooled Chiller Cooling Tower	HR Chiller Cooling Tower
Academic No Cooling	UCSC Only	Natural Gas Boiler VAV w/ Reheat	HR Chiller Backup ASHP VAV w/ Reheat	Natural Gas Boiler	ASHP	No cooling	No cooling
Residential No Cooling	UCB, UCI, UCSD, UCSF, UCSB, UCSC	Natural Gas Boiler Hotwater Baseboard	Electric Baseboard	Natural Gas Boiler	ASHP	No cooling	No cooling
Residential With Cooling	UCD, UCLA, UCM, UCR	Natural Gas Boiler 4-Pipe Fan Coil	Air-Cooled VRF Fan Coil	Natural Gas Boiler	ASHP	Air-cooled Chiller 4-Pipe Fan Coil	Air-Cooled VRF Fan Coil
Laboratory Standalone	UCB Only	Natural Gas Boiler VAV w/ Reheat	HR Chiller Backup ASHP VAV w/ Reheat	Natural Gas Boiler	ASHP	Water-Cooled Chiller Cooling Tower	HR Chiller Cooling Tower
Laboratory Steam/HW + CHW Loops	UCD, UCI, UCR, UCSD, UCSF	District Steam or HW VAV w/ Reheat	WSHP on District CHWR VAV w/ Reheat	District Steam or HW	WSHP on District CHWR	District CHW VAV	District CHW VAV
Laboratory CHW Loops only	UCLA, UCM, UCSB	Natural Gas Boiler VAV w/ Reheat	WSHP on District CHWR VAV w/ Reheat	Natural Gas Boiler	WSHP on District CHWR	District CHW VAV	District CHW VAV
Laboratory CW Loop only	UCSC Only	Natural Gas Boiler VAV w/ Reheat	HR Chiller on District CW Backup WSHP VAV w/ Reheat	Natural Gas Boiler	WSHP on District CW	Water-Cooled Chiller on District CW	HR Chiller on District CW VAV

Section 5.2 System Diagrams for Modeled Systems

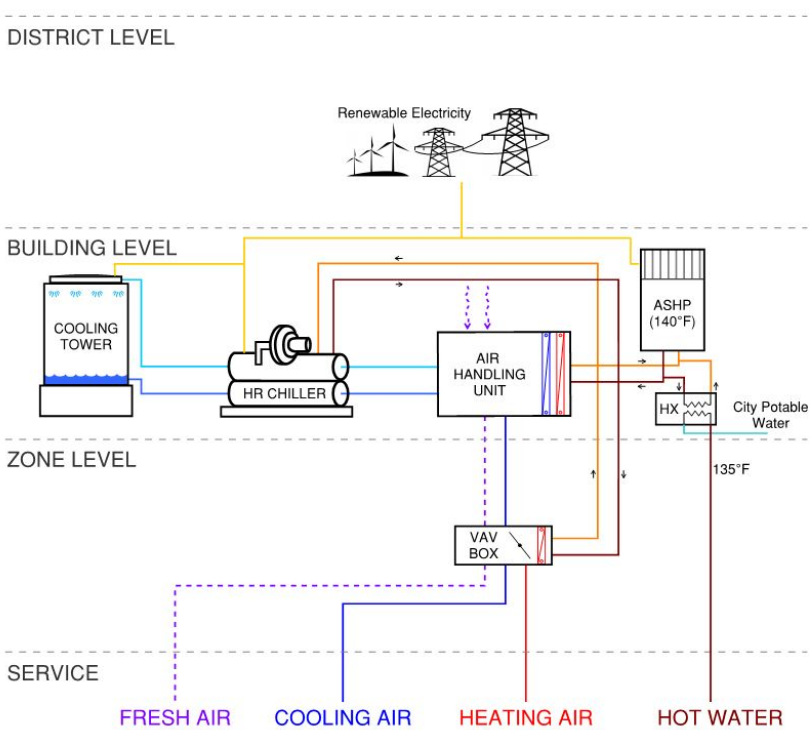
Academic Buildings

Academic Buildings		
System Type	Gas + Electric	All-Electric
All Campuses but UCSC*	- VAVRH System	- VAVRH System
	- Boilers	- Heat Recovery Chiller
	- Chiller	- Air Source Heat Pump
	- Cooling Tower	- Cooling Tower
Notes	*UCSC has everything except for cooling equipment. The all-electric option has Air Source Heat Pumps only	

Gas + Electric Academic



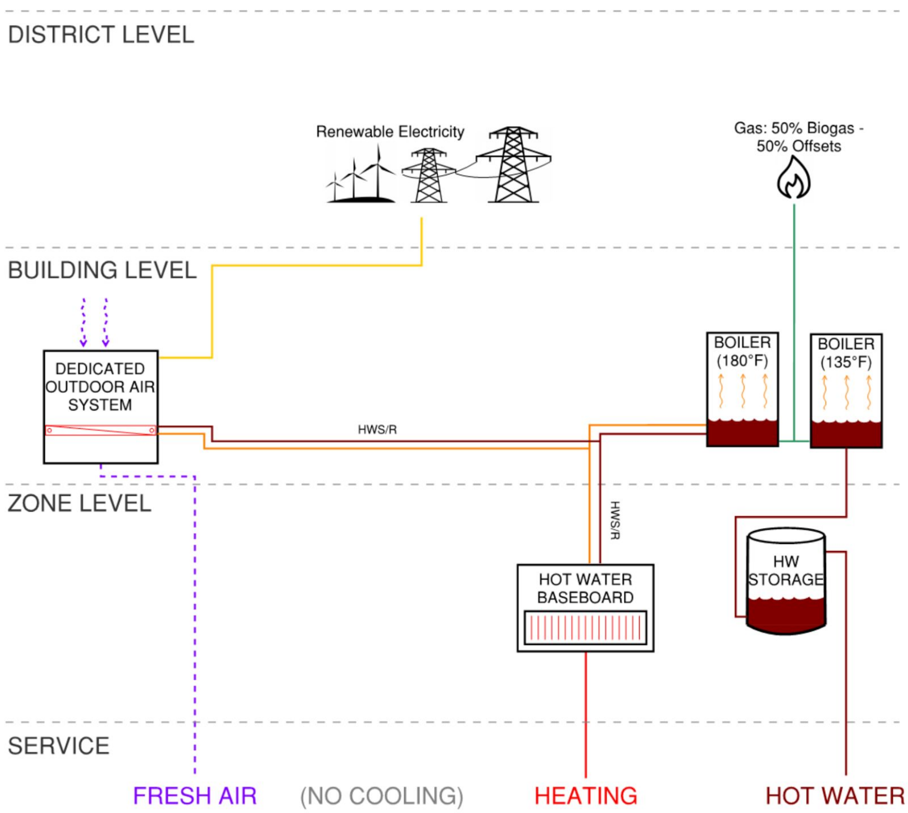
All-Electric Academic



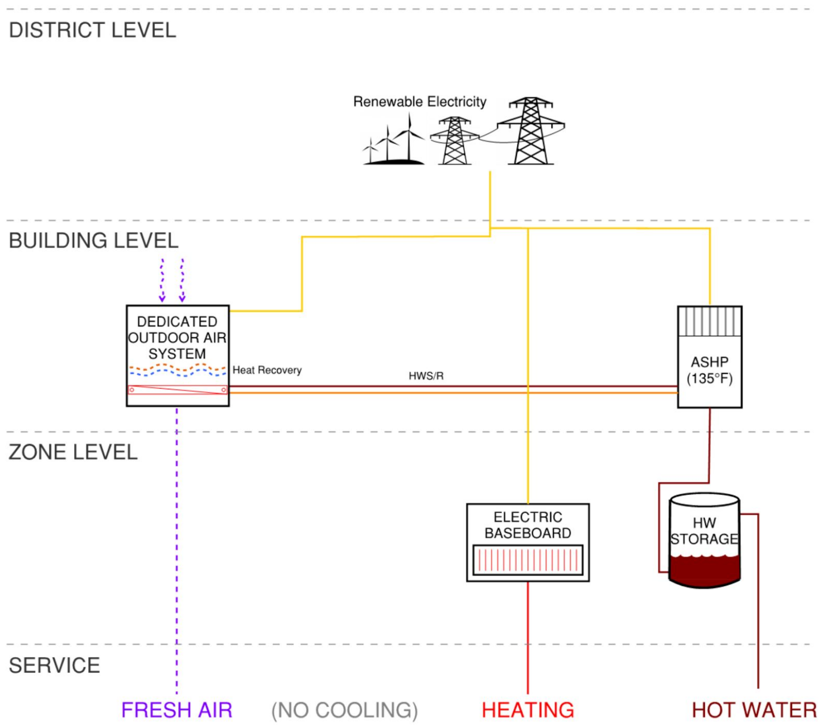
Residential Buildings

Residential Buildings		
System Type	Gas + Electric	All-Electric
Campuses with Cooling	- 4-Pipe Fan Coil System	- VRF Fan Coil System
	- Boilers	- VRF; Air Source Heat Pump (DHW only)
	- Air Cooled Chiller	- Air Cooled VRF Compressor
Campuses without Cooling	- Hot Water Baseboard	- Electric Baseboard
	- Boilers	- Air Source Heat Pump (DHW only)

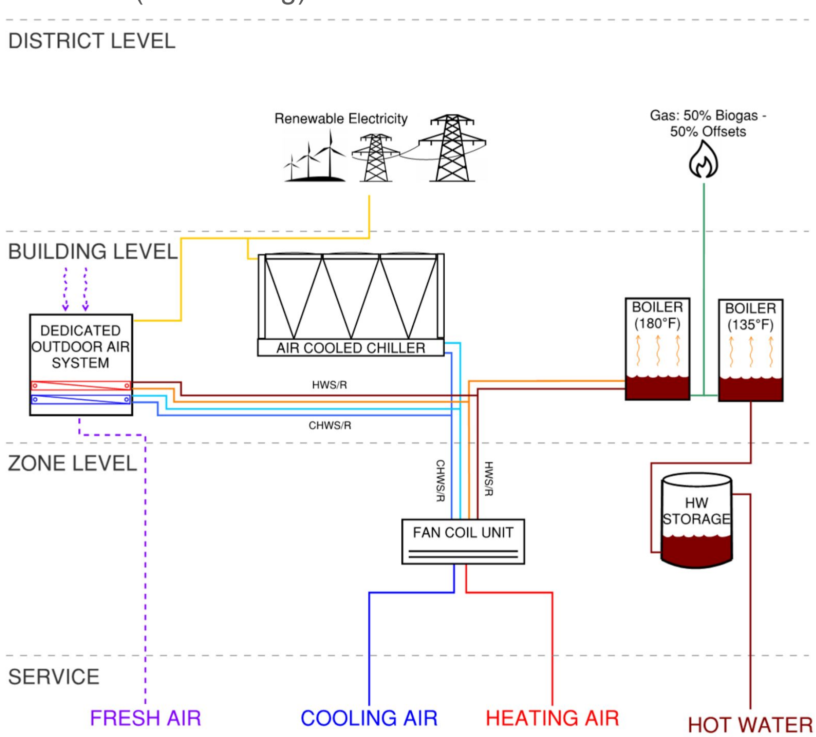
Gas + Electric Residential (no cooling)



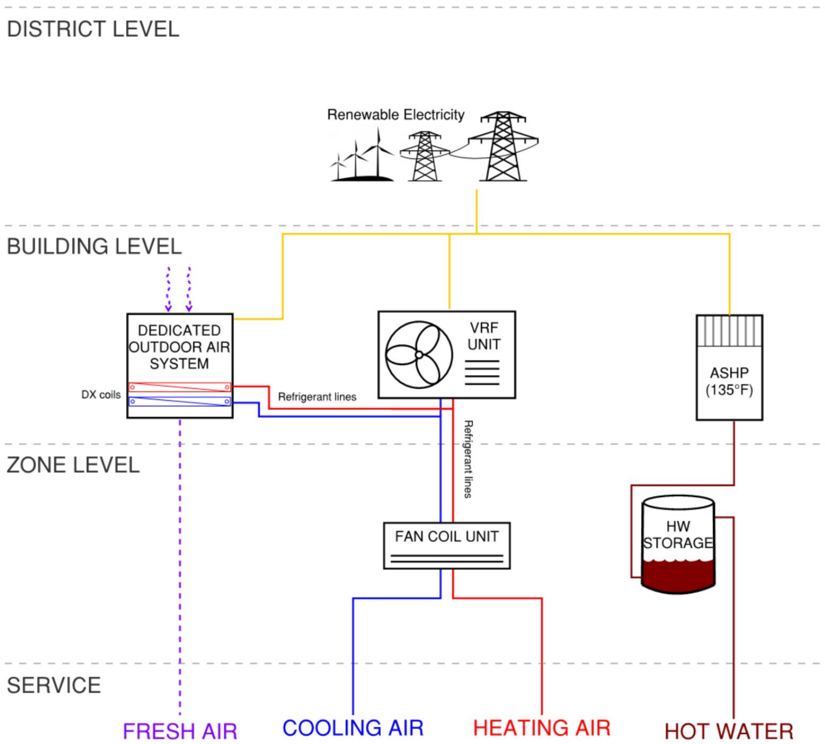
All-Electric Residential (no cooling)
(Enhanced building envelope)



Gas + Electric Residential (with cooling)



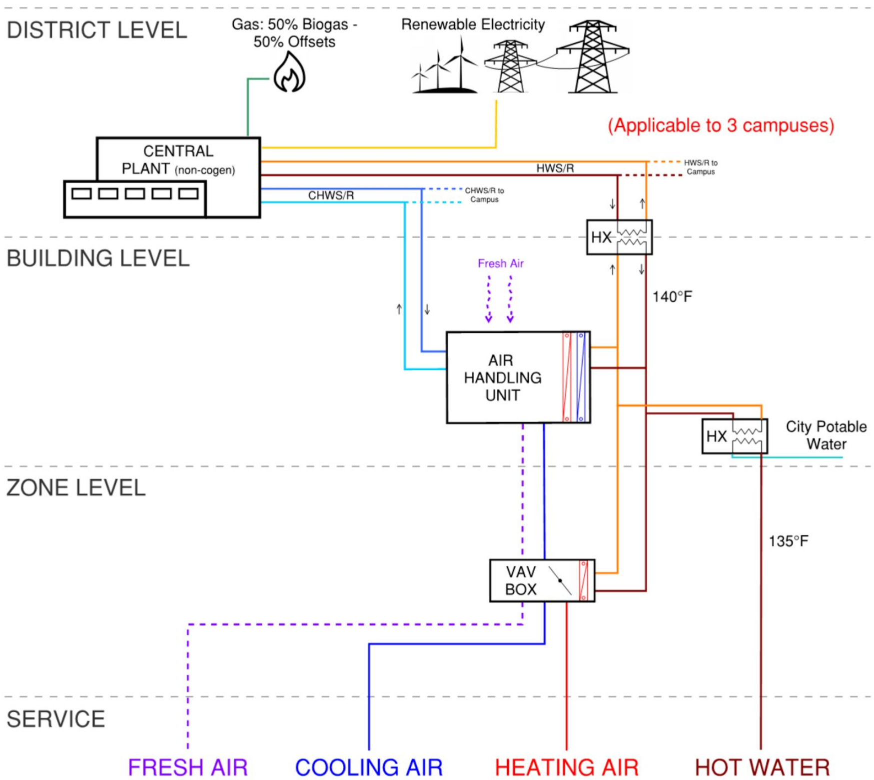
All-Electric Residential (with cooling)



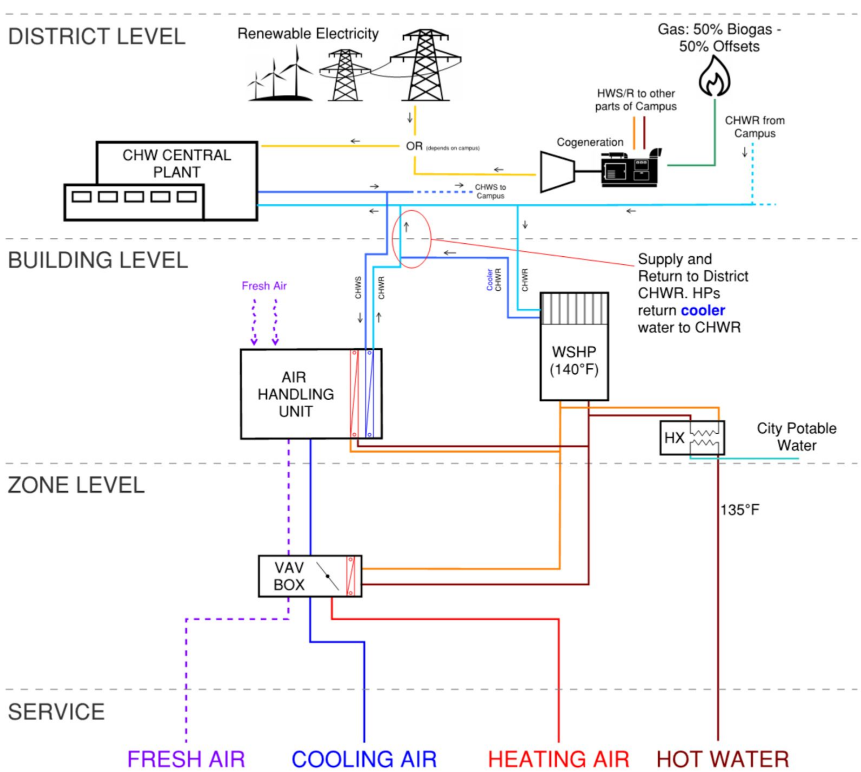
Laboratory Buildings

Laboratory Buildings		
System Type	Gas + Electric	All-Electric
Campuses with Heating and Cooling Loop	- VAVRH System	- VAVRH System
	- District Heating	- Water Source Heat Pump
	- District Cooling	- District Cooling
Campuses with Cooling Loop Only	- Boilers	- Water Source Heat Pump
	- District Cooling	- District Cooling
Notes	*UCB and UCSC are unique. UCB is modeled without loops. UCSC is modeled with a condenser water loop only.	

Gas + Electric Labs



All-Electric Labs



Section 5.3 Supporting Research

UC All-Electric and Zero Net Energy Achievements

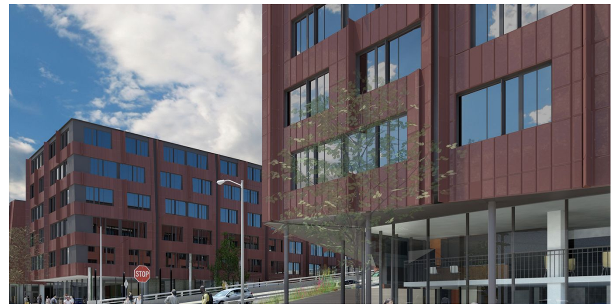
- UC Santa Barbara:
  - 900 seat auditorium - air source heat pump and electric water heaters
  - Physics building - heat recovery chiller
- UC Irvine:
  - Housing - net-zero energy goal
- UC Merced:
  - Downtown office building - all-electric
- UCSF:
  - Housing - electric baseboard and DHW air source heat pumps
- UC Davis:
  - Net-zero energy buildings planning with air source heat pumps, radiant, and DOAS
  - Small office building, air source heat pump
- UC Berkeley:
  - LBNL Integrative Genomics Laboratory - all electric heating with airside and waterside recovery
    - Modeled EUI reduced to 28% of the EUI of the existing facility, from 328 kBtu/sf-yr baseline to 92 kBtu/sf-yr as modeled, which is 30% of the 1999 UC building energy benchmark
    - Radiant, dedicated outside air, and chilled beam space conditioning
    - Roof space designed for solar photovoltaic generation to offset 14% of energy use

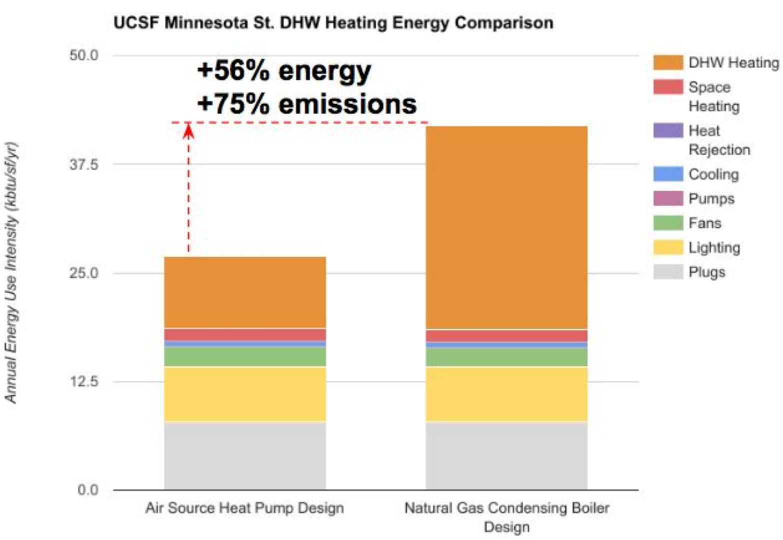
Case Study: UCSF Minnesota Street DHW

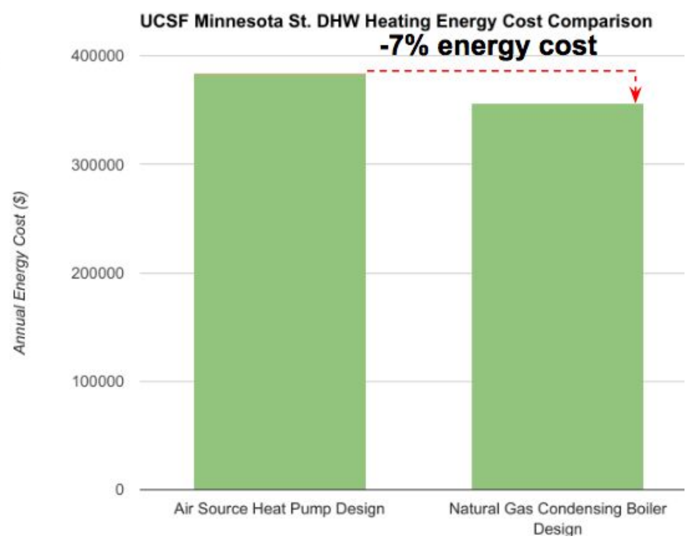
Project Type: Mid-Rise Residential
Total Floor Area: 336,000 gsf
Apartment Units: 594

Cost increase for DHW heat pumps: $480,000 (0.3% increase in total project cost)

Relevant finding: for high DHW demands of densely populated student housing, UC’s energy efficiency (EUI) target was not achievable with a gas boiler.







Case Study: Lawrence Berkeley National Laboratory Integrative Genomic Building[8]

Type Genomics Laboratory **Size** 80,880 gsf, 4 stories 2 wet laboratory floors 2 office and meeting floors **Construction** II-A Occupancy Mixed B (Lab & Office) and A-3 (Assembly)	**Phase of Implementation** UC Regents design approval June 2015 Construction began November 2016 Expected completion January 2019 **Project Delivery Method** CM/GC **Cost** Building Cost: $828/sf Project Cost: $1,131/sf

Highlights of Energy Efficiency and Low-Carbon Design Strategies

- Energy performance driven by whole-building energy targets with a goal to encourage integrated design and find cost-effective strategies that enable high-performance
- Modeled energy use is 28% of the energy used by the future tenants in their current facility (corresponding to 30% of the 1999 UC Building Energy Benchmark)
- Design features:
  - Careful orientation and passive design strategies
  - Radiant/dedicated outside air and chilled beam space conditioning
  - All-electric heating systems with both airside and waterside heat recovery
  - Elevated-temperature equipment corridor using cascaded air from laboratories
  - Separate modular and medium temperature chilled water plant designed to expand for future buildings
  - Maximized open roof space designed for solar photovoltaic generation, financed

[8] May 1, 2017, UCOP Workshop,``````` Presentation

and installed separately, to offset 14% of the building energy use
    - All-LED Lighting
    - Segregation of electrical circuits by end use to enable cost-effective metering
    - Plug-load control and monitoring
    - LEED gold certification
- Mechanical design right-sized by detailed plug-load survey of existing facility
- Plans and specifications fully define metrics for monitoring-based commissioning

<table>
<tr><td>Whole-Building Energy Performance Targets</td><td>Business-As-Usual Baseline:

Design Target:

Stretch Design Target:</td><td>328 kBtu/sf-yr
Measured performance of future tenants in their current facility, corrected to Berkeley climate

164 kBTU/sf-yr
50% of Business-As-Usual Baseline

70% of ASHRAE 90.1 2010

115 kBTU/sf-yr
35% of Business-As-Usual Baseline</td></tr>
<tr><td>Projected Energy Performance</td><td>Annual Energy Use (modeled):

Annual Electricity Use:

Annual Natural Gas Use:</td><td>92 kBTU/sf-year
28% of Business-As-Usual Baseline
30% of 1999 UC Building Energy benchmark

27.0 kWh/sf-yr

None</td></tr>
<tr><td>System-Level Performance Targets</td><td colspan="2">
<table>
<tr><th></th><th>Current Design</th></tr>
<tr><td>Cooling Plant Efficiency[3]</td><td>0.45 kW/ton at design conditions,
0.25 kW/ton average over year</td></tr>
<tr><td>Laboratory Ventilation Efficiency</td><td>0.70 W/cfm supply</td></tr>
<tr><td>Office Ventilation Efficiency</td><td>0.65 W/cfm supply
0.65 W/cfm exhaust</td></tr>
<tr><td>Building Load Efficiency</td><td>450 sf/ton</td></tr>
<tr><td>Laboratory Lighting Efficiency</td><td>0.75 W/sf peak</td></tr>
<tr><td>Office Lighting Efficiency</td><td>0.75 W/sf peak;
0.45 W/sf average with daylighting</td></tr>
<tr><td>Laboratory Plug Load Efficiency</td><td>Plug EUI: 53 kBtu/sf-yr (includes process loads)</td></tr>
<tr><td>Office Plug Load Efficiency</td><td>Peak: 1.5 W/sf
Plug EUI: 8.5 kBtu/sf-yr</td></tr>
<tr><td>Peak Electricity</td><td>5.24 W/sf</td></tr>
<tr><td>Peak Chilled Water Use</td><td>1.80 tons/1000 sf</td></tr>
</table>
[3] This target applies to a modular utility plant

Table prepared by Integral Group
</td></tr>
</table>

Section 5.4 Glossary of Terms

- **ASHP -** air source heat pump
- **CHW -** chilled water (such as a district chilled water loop)
- **CT -** cooling tower
- **CW** - condenser water (such as a district condenser water loop)
- **CHWR -** chilled water return
- DOAS - dedicated outdoor air system
- **DHW** - domestic hot water
- **HR chiller -** heat recovery chiller
- **HW baseboard -** hot water baseboard
- **HVAC -** heating ventilation and air conditioning
- **VAV -** variable air volume (conditioned air delivery method)
- **VAVRH** - variable air volume with reheat
- **VRF -** variable refrigerant flow
- **WSHP -** water source heat pump