Exploring Grid-Interactive Efficient Building Strategies for Laboratories Through Energy Modeling

Sarah Turner, Amy Allen, Otto Van Geet, and Rachel Romero

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-7A40-87141
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Suggested Citation
Turner, Sarah, Amy Allen, Otto Van Geet, and Rachel Romero. 2024. *Exploring Grid-Interactive Efficient Building Strategies for Laboratories Through Energy Modeling*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-87141. https://www.nrel.gov/docs/fy24osti/87141.pdf.

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Golden, CO 80401
303-275-3000 • www.nrel.gov

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Federal Energy Management Program Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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List of Acronyms

ACH	air change per hour
CO_2	carbon dioxide
EPA	U.S. Environmental Protection Agency
EUIs	energy use intensities
GEB	grid-interactive efficient building
GHG	greenhouse gas
LBNL	Lawrence Berkeley National Laboratory
LBT	Laboratory Benchmarking Tool
NREL	National Renewable Energy Laboratory
TOU	time of use
VAV	variable air volume

Acknowledgments

The authors wish to thank the Federal Energy Management Program under the U.S. Department of Energy for funding this research. The National Renewable Energy Laboratory (NREL) is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC.

The authors appreciate the subject matter expertise provided by Sheila Hayter from NREL as well as Joshua Kace from the Lawrence Berkeley National Laboratory (LBNL) during the peer review process. The authors also appreciate the research developed under Paul Mathew and Lino Sanchez at LBNL on demand flexibility opportunities in laboratories, which provided a lot of the groundwork for this study. The authors are grateful for Kendall Kam and Jefferey Murrell at the Federal Energy Management Program for supporting this research and overseeing its progress. Lastly, the authors would like to thank Tanna Tennyson, NREL, for her assistance in publishing this report.

All judgements and interpretations of the research methodology as well as the final modeling results are the sole responsibility of the authors and not of the individuals listed above.

Executive Summary

Laboratories are often overlooked in demand flexibility research due to constraints on their operations as mission critical facilities, despite the major role they play in an organization's emissions. Laboratories consume 3–4 times more energy than a typical office building and are commonly the largest energy users on any campus.[1] Consequently, most laboratories in the United States are significant contributors to their organization's carbon footprint if their energy needs are met through the combustion of fossil fuels.

As part of the initiative to decarbonize laboratories, this report documents an analysis on specifically grid-interactive efficient building (GEB) opportunities for reducing energy costs and emissions associated with laboratory operations. The goal of this initiative was to provide a case study and guidance on how to use OpenStudio® and REopt® as modeling tools for GEB technologies and strategies in laboratory environments across different climate zones in the United States. The analysis found that efficiency-based GEB strategies had the most significant impact on laboratory operations, while load-shedding and load-shifting GEB strategies produced smaller results. The culmination of these approaches applied across all five climate zones generated on average:

- 28% energy cost savings and 30% greenhouse gas (GHG) emissions reductions with:
  - 26% reduction in total electricity costs, 12% in demand charges (kW) and 28% in energy charges (kWh), and
  - 36% reduction in natural gas costs.
- 4% enhanced energy cost savings under a time-of-use (TOU) pricing schedule compared to traditional pricing schemes.

Grid-interactive efficiency building measures were found to produce the greatest energy savings in both electricity and natural gas, particularly in regions with high electrical loads, such as warm climates for cooling. Laboratories that had high levels of natural gas consumption, meanwhile, experienced the greatest emission reductions. The report concludes with an analysis on the opportunities for flexible loads in lab spaces and how small-scale measures in addition to opaque pricing structures for peak demand could become barriers to demand flexibility planning. The report also explores how electrifying laboratory buildings with heat pumps could reduce energy costs and GHG emissions.

[1] To learn more about why laboratories consume more energy than a typical office building, visit the Smart Labs Toolkit at smartlabs.i2sl.org.

Table of Contents

List of Figures

List of Tables

1 Background

Interest in grid-interactive efficient building (GEB) technologies and strategies has grown significantly within the last decade as energy planners have turned to flexible loads to manage rising energy costs and greenhouse gas (GHG) emissions in the United States. Periods of utility peak demand result in higher emissions and higher energy costs because utilities deploy less-efficient power plants to meet peak demand. The strain peak demand puts on the grid is likely to increase as organizations electrify their buildings. In this way, incorporating energy efficiency and demand flexibility provides a path to decarbonization and adds resiliency to an organization's operations during power outages and other increased risks during peak demand.

According to the U.S. Department of Energy Federal Energy Management Program, a GEB is:

"An energy-efficient building that uses smart technologies and on-site distributed energy resources to provide demand flexibility while co-optimizing for energy costs, grid services, and occupant needs and preferences, in a continuous and integrated way."[2]

Lawrence Berkeley National Laboratory (LBNL) defines demand flexibility as the capacity to change hourly consumption patterns in response to utility peak pricing.[3] In states that have allowed or encouraged utilities to offer demand or time-of-use (TOU) pricing, customers have achieved this capacity through either the application of demand flexibility strategies or the adoption of demand-responsive technologies. As shown in Figure 1, GEBs can incorporate these strategies through:

- Energy efficiency, where the overall energy consumption of the building is reduced
- Load shedding, where electricity consumption is reduced for a short period of time and typically on short notice
- Load shifting, where the timing of electricity consumption is changed
- Modulating, where the power supply/demand or reactive power draw/supply is autonomously (within seconds to sub-seconds) balanced in response to a utility signal.[4]

One type of building, however, that has historically been overlooked for GEB opportunities is laboratory buildings.

[2] A complete definition in addition to GEB resources can be located at https://www.energy.gov/femp/grid-interactive-efficient-buildings-federal-agencies.
[3] A full definition can be found at https://buildings.lbl.gov/demand-flexibility.
[4] These definitions were borrowed from a National Renewable Energy Laboratory (NREL) study on grid-interactive efficient buildings. To read the full report, visit https://www.nrel.gov/docs/fy22osti/83075.pdf.

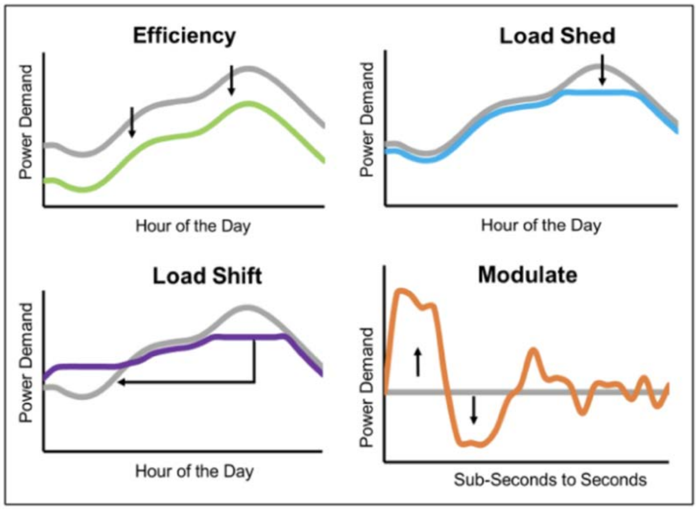

Figure 1. Components of a grid-interactive efficient building

Image Credit: Paul Matthew and Lino Sanchez, LBNL (2022)

1.1 Methodology

Laboratory buildings are functionally complex work environments that possess a number of safety and operational protocols that have made GEB strategies difficult to conceptualize, much less realize. This case study set out to rectify some of this imbalance by simulating GEB strategies using an OpenStudio laboratory building prototype model developed by the U.S. Department of Energy. OpenStudio® is a simulation software that offers users access to a variety of different modeling tools to create and analyze the energy consumption of different buildings.[5] The energy loads produced by the authors' OpenStudio model were then fed into REopt to calculate the approximate electricity costs and emissions associated with the laboratory building's operations. The Renewable Energy Integration and Optimization Tool® (REopt) is a techno-economic decision support platform developed by NREL that optimizes energy systems according to their electricity costs.[6]

The OpenStudio laboratory building prototype model was run under five different climate zones, as defined by the 2013 ASHRAE Standard 169 (Table 1 and Figure 2).[7] Running the model under multiple climate zones enabled a more diverse analysis on the energy cost savings and emission reduction potential produced by: (1) the weather conditions of that region and how they

[5] For more information, visit http://openstudio.net. The laboratory building prototype model used by the authors for this study was developed by LBNL. For more information on the U.S. Department of Energy prototype models, visit https://www.energycodes.gov/prototype-building-models.
[6] REopt can consult regional electricity tariffs and emissions data when developing a building's electricity costs and emissions footprint. Users can also upload custom electric tariffs for cost optimization. It is important to note that REopt uses a marginal calculation to determine a building's emissions profile. See https://reopt.nrel.gov.
[7] More information about the climate zones and how ASHRAE used climatic data to inform building design standards can be found at https://xp20.ashrae.org/standard169/169_2013_a_20201012.pdf.

affect a laboratory building's energy consumption; and (2) the electricity tariffs offered by the local utilities and how the utilities have defined and priced peak demand.[8]

Table 1. City Climate Zones for the Energy Models

City	State	ASHRAE Climate Zone	Zone Characteristics
Phoenix	AZ	1B	Very Hot Dry
Atlanta	GA	3A	Warm Humid
Seattle	WA	4C	Mixed Marine
Denver	CO	5B	Cool Dry
Fergus Falls[9]	MN	6A	Cold Humid

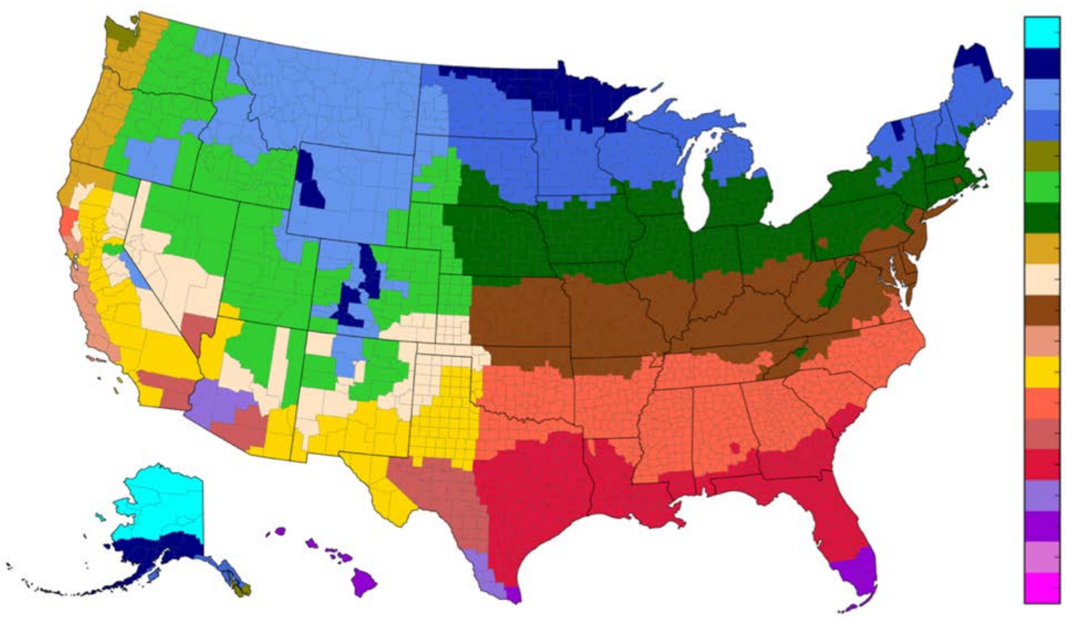

Figure 2. Climate zone codes defined in ASHRAE Standard 169

This case study ran simulations in climate zones listed under Table 1 as the electric utilities in all five cities offer a TOU schedule for large commercial customers and are not subject to wholesale electricity prices. In other words, the authors chose electric utilities where large commercial customers would face bundled charges for electricity in contrast to utilities located in deregulated

[8] Each laboratory building model had to be customized with the building specifications for that region, in addition to weather files. More information about this process can be found in Appendix B.1.

[9] Despite its smaller metropolitan population, the authors chose to run the laboratory data in Fergus Falls, as it was one of the few cities served by an electric utility in a cold climate region that offered a comprehensive TOU schedule. For more information on how utilities were selected for this case study and which electric schedules were used for the laboratory building models, visit Appendix A.1.

markets, where electricity costs regularly fluctuate based on the market's clearing prices. The only small exception was Fergus Falls where the local electric utility has the option to purchase electricity from the Midcontinent Independent System Operator (MISO) but otherwise maintains its own generation assets to meet demand at a known price to the customer.[10]

This approach helped the authors simplify modeling GEB strategies according to the electric rates set by the utility tariff, which in turn demonstrates how customers could plan to reduce their energy costs around the utility peak demand. It is important to note that this fixed modeling approach, even though helpful in the context of this study, may be less applicable to laboratory buildings located in regions with deregulated electricity markets. In these regions, building operators would need to invest in a continuous demand management strategy where flexible loads can be quickly adjusted based on utility price signals. While a continuous demand management strategy is regarded as a key component of a GEB, it was not the central focus of this case study. The consideration of capital costs for implementation of these measures was not in the scope of this study as well.

1.2 Designing GEB Strategies

Although prior research on this topic has been limited, one technical memo published by LBNL identified several GEB opportunities that could be used in laboratory buildings. These opportunities were identified after interviewing laboratory operators and facilities personnel, who ranked the feasibility of each strategy or technology on a scale from high applicability (5) to low or no applicability (1). Although 14 demand flexibility specific strategies and technologies were explored in the technical memo as related to GEBs, most of the interviewees expressed concern about the widespread applicability of these measures in a lab.

Many of these concerns stemmed from the potential of a GEB technology or strategy to interfere with experiments and to receive buy-in from researchers. The interviewees also conveyed skepticism over their ability to make a significant impact on reducing the laboratory's energy consumption, given the large scale of operations at most laboratory buildings. As such, this case study only focused on modeling the demand flexibility components of GEB technologies and strategies that the interviewees thought were the most likely to overcome implementation barriers.[11] Each modeled technology and strategy utilized a different component of GEB planning, including efficiency, load shedding, and load shifting; a modulation method was not considered for this report.

1.2.1 Strategy 1: Smart Ventilation Based on Risk Assessment

Ventilation is a critical component to a laboratory building's operation systems because it exhausts hazards and contaminants produced by research from lab spaces, keeping occupants safe. Ventilation is also the largest consumer of energy in a laboratory, responsible for 45%–85%

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[10] Minnesota officially does not have a deregulated electricity market. For more information, visit https://www.otpco.com/about-us/energy-generation/.

[11] More than half of the demand flexibility opportunities selected for modeling in this study had an average applicability score of 3 out of 5. The full memo can be found at https://smartlabs.i2sl.org/pdfs/demand-flexibility-laboratories.pdf.

of the total energy used in labs.[12] A significant body of research has shown that laboratories operate safer and more efficiently after conducting a laboratory ventilation risk assessment.[13] A laboratory ventilation risk assessment is a systematic process used by ventilation designers and laboratory safety personnel to determine the level of risk associated with a lab that can be mitigated through the use of ventilation. Optimizing a laboratory building's ventilation rate in response to the hazards present in a lab environment has been found to credibly reduce a building's energy consumption while improving its safety.

This approach, combined with a variable air volume (VAV) system equipped with demand-controlled ventilation based on occupancy, was modeled for this case study to determine the energy cost savings and emission reductions associated with optimized ventilation.

To establish a baseline, the laboratory building prototype model was run under its original design specifications.[14] These design specifications were set to the following air change rates, represented in outside air changes per hour (ACHs):

- 15 ACH for laboratory spaces with fume hoods (10% of the total space in the model)
- 6 ACH for open laboratory spaces with no fume hoods (35% of the space in the model)
- 6 ACH for laboratory equipment corridors (5% of the space in the model)
- Less than 1 ACH for office spaces (50% of the total space in the model).

The original model was also designed to operate at a constant air volume. This meant that 50% of the laboratory building models under baseline scenarios were run at a ventilation rate of 6 ACHs or higher all day, even during periods of low occupancy. This is a common system of operation for many laboratory facilities, particularly older ones, because they were not built with VAV capabilities.[15]

Given the challenges identified by the interviewees in LBNL's technical memo to adjust ventilation on a peak-demand basis, the laboratory building model was modified to simulate an energy efficiency GEB strategy, as opposed to a load-shedding approach.[16] This strategy involved:

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[12] To learn more about the role of ventilation and why it is the largest consumer of energy in a laboratory, visit https://smartlabs.i2sl.org/assess.html.

[13] More information about laboratory ventilation risk assessments and laboratory best practices can be read at https://www.i2sl.org/documents/toolkit/bp_opt_vent_508.pdf.

[14] Although the laboratory building prototype model did not come with any documentation, the ventilation design specifications were likely programmed by consulting ASHRAE 62.1. This standard recommends an occupied air change rate of 6 ACH for laboratories with a 10-foot ceiling. For more information on ventilation code requirements, visit https://smartlabs.i2sl.org/resources.html.

[15] More on the history of VAV systems can be found at https://www.trane.com/commercial/north-america/us/en/about-us/newsroom/blogs/variable-air-volume-systems-50-years-of-the-engineers-newsletter.html.

[16] It should be noted that smart ventilation for demand-based ventilation was given a lower applicability score by the interviewees. This was due to the difficulty of receiving buy-in from laboratory staff as well as the tightness that some labs have on their controls. More details can be found in the technical memo at https://smartlabs.i2sl.org/pdfs/demand-flexibility-laboratories.pdf.

- Changing the ventilation rate from 6 ACHs to 4 ACHs in both the open labs and equipment corridors. This is a common ventilation rate employed by organizations after conducting a laboratory ventilation risk assessment.[17] Lab spaces with fume hoods were not changed under the assumption that laboratories with fume hoods are more likely to contain hazardous materials with an increased risk level.
- Simulating a VAV system where ventilation rates were lowered from 4 ACHs to 2 ACHs in the open laboratories and equipment corridors after 5 p.m., because this would be when the spaces were less occupied. The ventilation rates were increased to 4 ACHs again at 8 a.m. to accommodate when laboratory personnel would start to arrive.

1.2.2 Strategy 2: Lighting and Plug Loads

Lighting and plug loads are the next-largest consumers of energy in a laboratory after ventilation, and they are popular targets for GEB opportunities due to their broad applicability. Laboratories have the potential for many load-shedding opportunities through lighting and plug loads, including:

- Reducing laboratory equipment usage during periods of peak demand by scheduling shared loads, such as with autoclaves and dishwashers
- Changing work schedules so that fewer lab spaces are occupied during peak demand; this could include encouraging lab personnel to complete their office-related tasks in office spaces during peak hours
- Switching technologies such as computers to low power mode during peak demand[18]
- Dimming lights or keeping them off unless activated by occupancy sensors, assuming no impact to task lighting
- Increasing the temperature of ultra-low temperature freezers from -80℃ to -70℃ during peak demand, depending on the samples stored.[19]

Rather than modeling each of these opportunities individually, the lighting and plug loads for the model were broadly reduced during the hours of peak demand, as defined by each city's electric utility, to simulate a load-shedding demand flexibility strategy.[20] While many of the laboratory operators and facilities personnel interviewed by LBNL supported lighting controls and scheduled equipment use as GEB strategies, they expressed more doubt about others. Strategies like increasing the temperature of ultra-low temperature freezers or putting equipment into low-power mode were thought to be more likely to encounter resistance from scientists and researchers. Acknowledging these implementation barriers, the model's energy consumption for lighting and plug loads were each reduced by 50% in office spaces and only 25% in lab spaces

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[17] University case studies on this process and details on how to conduct a laboratory ventilation risk assessment can be found at https://smartlabs.i2sl.org/case-studies.html.
[18] Although all computers should be set to go into low power mode when not in use, the authors are treating this strategy as a load shedding approach in contrast to an energy efficiency approach since it is only being applied during the hours of peak demand.
[19] Adjusting the set point temperature of an ultra-low temperature freezer has been found to reduce energy consumption by over 30% without compromising stored samples. Evidence from case studies show that -70℃ is a broadly safe temperature to store most samples. Read more at https://www.mygreenlab.org/-70-is-the-new--80.html.
[20] Additional information on each electric utility used for the case study can be found under Appendix A.1, including how each utility defined its peak demand.

during peak demand. Although these reductions are still aggressive, the authors contend that concentrated efforts can make them technologically feasible based on previous studies.[21] The authors, however, also acknowledge that in practice, lighting and plug load reductions are likely to be much lower than the ones modeled in this case study.

1.2.3 Strategy 3: Service Hot Water Heater

Service hot water heaters equipped with smart controls received positive feedback from the laboratory operators and facilities staff interviewed by LBNL, due to their ability to heat and store hot water during periods of peak demand. This approach would ideally create little disruption to a laboratory's operations, in addition to reducing the building's emissions through electrification. To simulate this strategy, a heat pump water heater with demand-responsive properties was incorporated into the model.[22] This hot water heater could be programmed to increase the temperature of the hot water tank during off-peak demand and then be scheduled to let the hot water temperature "float" during peak demand, minimizing the use of electricity during this time.

1.3 Designing a Heat Pump Model

Given the report's focus on decarbonization, a heat pump building model scenario was also created to understand how electrification can impact a laboratory's energy costs and GHG emissions. The connection between electrification and GEB is a heavily explored topic in decarbonization literature, as they are both recognized for their pivotal role in achieving zero emissions.[23] Electrification has the potential to eliminate GHG emissions associated with a building's heating needs when supplied with clean electricity. This is an initiative that over 22 states have committed to by passing renewable portfolio standards or clean energy standards that require their electrical grids to be 100% carbon-free by a specific year.[24] GEB in this way will be a long-term asset for maintaining grid reliability, because rising building electrification will

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[21] One case study found that flexible control strategies for plug loads in labs could reduce energy by up to 22%, which can be read at https://www.energy.ca.gov/publications/2023/flexible-control-strategies-plug-loads-mitigate-electricity-waste-and-support. An older estimation from the Sustainability Facilities Tool, sponsored by the U.S. General Services Administration, meanwhile, projected that plug loads in federal facility buildings could be reduced up to 50%. This can be read at https://sftool.gov/learn/about/426/plug-loads#private-office/wireless-communication-system. Minnesota Department of Commerce performed a meta-analysis on the savings potential of lighting in commercial buildings and found that task tuning (where building lights are dimmed to levels appropriate to the space and its use) on average produced energy savings up to 36%, occupancy sensors on average produced energy savings up to 24%, and daylight controls (where light levels are adjusted based on available sunlight) on average produced up to 28% energy savings. More details can be found at https://www.cards.commerce.state.mn.us/CARDS/security/search.do?method=showPoup&documentId=%7B7096EDDC-5C59-40F4-ABDD-B285E3246CD8%7D&documentTitle=268195&documentType=6.

[22] The laboratory building prototype model was originally programmed to use a natural gas hot water heater. The authors replaced this hot water heater with the electric demand flexibility one to establish baselines. Additional information on this process can be found in Appendix B.1.

[23] The four pillars of decarbonization and how they apply to laboratories can be found at https://smartlabs.i2sl.org/decarbonization.html.

[24] More information about renewable portfolio standards and clean energy standards at a state level can be read at https://www.cesa.org/projects/100-clean-energy-collaborative/guide/table-of-100-clean-energy-states/#:~:text=There%20are%20currently%2022%20states,including%20Puerto%20Rico%2C%20click%20here.

require more energy to come from the grid, increasing the peak, which can steepen the ramp-up time needed to meet demand.

While there are many ways to electrify a building, this case study focused on modeling heat pumps, because heat pumps use less energy to provide the same heating load as an electric boiler. Heat pumps are also ideal HVAC replacements for boilers, as they can provide cooling and humidity control.[25] It should be noted that heat pump electrification, as it was used in this model, was not considered a GEB strategy. Its analysis in this paper has been strictly limited to considering the function of electrification as another potential decarbonization strategy, which has been made separate from the GEB results.

To determine their energy and emission reduction benefits, water-to-air heat pumps were incorporated into the laboratory building prototype model, as shown in Figure 3. These water-to-air heat pumps drew and rejected heat from a water loop installed on each floor of the building, which was itself conditioned by district heating and cooling objects in the model. In OpenStudio, these district heating and cooling objects functioned to provide an idealized heat source and sink, calculating the units of heating or cooling required to temper the loop. The condenser loop temperature was controlled to a range of 41°F to 70°F, and air-side temperature setpoints in the zones remained the same. The heat pump units considered here had a nominal coefficient of performance (COP) of 6 in cooling and 4 in heating. These heat pumps, intended to emulate distributed zone-level equipment, provided space heating and cooling to the zones, while dedicated outdoor air systems (DOAS) provided tempered ventilation air throughout the building. Heating and cooling capacities, and rated water and air flow rates were auto-sized through EnergyPlus, and performance curves available in EnergyPlus were used to characterize the heat pumps. (The modeling workflow in OpenStudio is discussed in Appendix B3.) Static pressure drop in the heat pump supply fans and in the DOAS supply fans was adjusted to approximate the scale of the total static pressure drop in the baseline conditions, though the use of distributed heat pumps (as opposed to centralized air handling units) still resulted in a net reduction in static pressure drop weighted by airflow throughout the building.

In these scenarios, only a net cooling demand was observed for tempering the heat pump condenser loop, which reflects the ability of individual heat pumps in heating and cooling mode to offset each other's load, since the heat pumps were coupled to a common source water loop. Post-processing was performed to approximate the energy use associated with tempering water to meet the loop temperature cooling setpoint of 70°F, based on an assumed constant COP of 6.[26] Given that a cooling tower could be used to meet this water temperature requirement in many climates, this is a conservative assumption. In the energy model, the DOAS was configured with a DX cooling coil and electric resistance heating coil. To emulate the use of a water-source or ground-source heat pump to treat ventilation air, the heating energy was post-processed with an

[25] To learn more about the different types of heat pumps and their benefits, visit https://www.energy.gov/energysaver/heat-pump-systems#:~:text=They%20can%20reduce%20energy%20use,a%20wide%20variety%20of%20homes.
[26] Additional information about the COPs of water-cooled chillers and cooling towers, visit https://www.sciencedirect.com/science/article/pii/S1876610214033372?ref=pdf_download&fr=RR-2&rr=86f2ca162b994794.

assumed COP of 4 to calculate the equivalent electric energy usage.[27] This emulated another heat pump tied to a ground loop, separate from the existing water loop. The authors took this approach given the limitations of existing OpenStudio measures. Because this case study was created to act as a guide for exploring demand flexibility with laboratory building models, it was important to develop a modeling method that could be relatively easy for interested groups to replicate on their own.[28]

[27] The authors converted the energy use and after converting it to kWh divided it by 4 (water source). The authors a COP of 4 to be conservative. This figure was selected based on water-source-heat pump the same as the rest of the building. We assume that the experimental source from the ground source heat pump from 3.2 COP to 4.7.

[28] To learn more about this process, visit Appendix B.3.

2 Modeling Results

When the prototype models were run with no changes made to their operations for GEB, the baseline energy costs and emissions produced were in line with data collected on laboratory buildings in similar climate zones, as represented in Table 2.[29]

Table 2. Baseline Profiles for Energy Models by City

The following metrics are collected from the baseline laboratory building models, which examine a lab's annual energy consumption before any demand flexibility strategies are applied.[30]

Metrics	Phoenix	Atlanta	Seattle	Denver	Fergus Falls
Total Site EUI (kBtu/sf)	**178**	**199**	**161**	**160**	**194**
Total Natural Gas (Therms)	53,810	72,324	63,872	57,156	86,261
Utility Price Per Therm[31]	$1.0435	$1.3496	$1.1398	$1.1230	$0.6159
Total Electricity (kWh)	3,124,713	3,138,759	2,377,916	2,556,172	2,594,077
Blended Electric Rate ($/kWh)	$0.1047	$0.0797	$0.0927	$0.0855	$0.0804
Annual Cost of Electricity[32]	$327,159	$250,162	$220,515	$218,587	$208,508
Total Energy Costs	$383,309	$347,768	$293,318	$282,773	$261,636
Energy Cost Intensity ($/sf/yr)	**4.26**	**3.86**	**3.26**	**3.14**	**2.91**
Natural Gas Emissions (lbs)	627,673	843,639	745,041	666,705	1,006,205
Electricity Emissions (lbs)	4,276,963	4,653,953	3,950,679	4,420,263	4,964,804
Total CO_2 Emissions (lbs)	4,904,636	5,497,592	4,695,720	5,086,986	5,971,009
Emission Intensity (lbs/sf/yr)*	**54.50**	**61.08**	**52.17**	**56.52**	**66.34**

*The laboratory building prototype model is a 90,000 ft^2 building, which has been used in intensity calculations.

Excluding heat pumps, when all three GEB strategies were applied to the model, they created an average energy cost savings of 28% and a 30% emission reduction from the baseline. This translated into approximately $0.97/$ft^2$ saved and 17 lbs/ft^2 of carbon dioxide-equivalent (CO_2) emissions reduced in the laboratory building, as seen in Figures 4 and 5.[33]

Some laboratory building prototype models experienced higher energy cost savings than others, particularly Atlanta and Phoenix, where the energy savings were predicted to be over $1.10/$ft^2$. This would support the intuitive notion that laboratories with higher electricity consumption

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[29] The laboratory building models used to produce baseline results were cross-checked against the Laboratory Benchmarking Tool at https://lbt.i2sl.org. For more information on this process, visit Appendix B.1.
[30] Complete metrics on each laboratory building prototype model can be found in Appendix B.4.
[31] More information about the natural gas pricing in each city can be found in Appendix A.2.
[32] See Table 3 for a complete summary of the electric rates used for each model, including time-of-use pricing.
[33] Energy cost and emission reductions were calculated first by determining the energy cost and emission intensities of each model. These were quantified by dividing the total respective energy costs and emissions of the building (including electricity and natural gas) by the square footage of the laboratory building model. Once intensity metrics were compiled for each location, the difference between the intensities for the model with all the GEB strategies and the baseline were calculated, and this difference was then averaged. Individual metrics are shown in Appendix B.4.

profiles stand to gain the most from deploying a GEB strategy. Warm climate cities like Phoenix and Atlanta experienced a higher consumption profile for electricity to meet larger cooling loads, while consumption for natural gas was higher in cold climate cities like Fergus Falls, Denver, and Seattle. Atlanta notably had high natural gas consumption profile as well, but this is a common experience for laboratories with cooling needs in humid climates because of the need to overcool the air for dehumidification and then reheat the air.[34] Laboratories often reheat air that has been conditioned to meet the temperature and humidity requirements of one laboratory space, creating simultaneous dual heating and cooling loads.

Figure 3. Total impact of GEB strategies on energy cost savings

Figure 4 graphs the energy cost savings between the baseline model and the laboratory building model with all the GEB strategies included, differentiated by city. Graph includes energy costs for both electricity and natural gas. Heat pumps models are not included.

In terms of emissions, however, the laboratory building models created for Fergus Falls and Atlanta experienced the greatest reduction in their emissions, as shown in Figure 5. This result can be explained by multiple factors, including that Fergus Falls and Atlanta were the largest

[34] The average temperature maintained for each of the lab zones in the model was 71°F. To learn more about reheat systems and how they are used in laboratories, visit https://www1.eere.energy.gov/buildings/publications/pdfs/alliances/minimizing_reheat_guide.pdf.

energy consumers out of the five cities with the highest total site energy use intensities (EUIs). Fergus Falls and Atlanta also had the highest natural gas consumption, in addition to residing in dirtier subregions of the electrical grid. GHG emissions from the electrical grid in Atlanta are on average 5% higher than the national average and even 16% higher than the national average in Fergus Falls.[35]

Figure 4. Total impact of GEB strategies on emission reduction

Figure 5 graphs the emission reductions between the baseline model and the laboratory building model with all the GEB strategies included, differentiated by city. Graph includes reductions for both electricity and natural gas. Heat pumps models are not included.

2.1 Comparing GEB Strategies

Out of the three GEB strategies tested under the laboratory building prototype model, optimized ventilation had the most significant impact on both the laboratory's energy consumption and its emissions profile. In fact, the bulk of the total energy, demand, and emission savings seen from the combined use of GEB strategies are largely attributed to the smart ventilation demand strategy. Because ventilation is the largest energy user in a laboratory, the scale of this approach

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[35] Emissions data comes from the eGrid Power Profiler. More information can be found by visiting https://www.epa.gov/egrid/power-profiler#/.

was considerably massive compared to other strategies. In addition to the scale, the smart energy efficiency ventilation approach meant that a laboratory's energy consumption was being reduced throughout the day, not just when the laboratory was operating during peak demand. Atlanta and Phoenix remained the largest beneficiaries of a ventilation demand strategy in terms of its energy costs, while Atlanta and Fergus Falls encountered the largest emission reductions—as shown in Figures 6 and Figure 7.

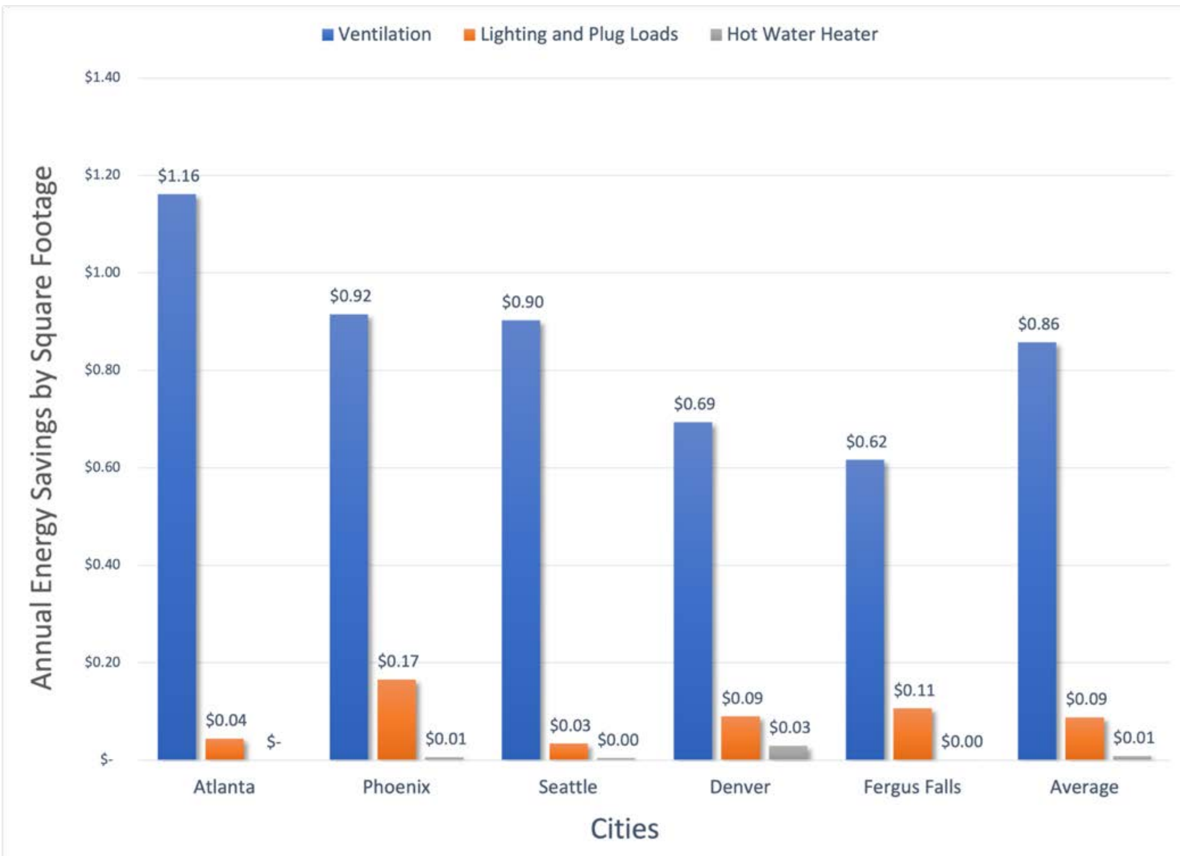

Figure 5. Individual impact of GEB technologies on energy cost savings

Figure 6 graphs the energy cost reductions between the baseline model and the laboratory building models for each GEB strategy. Graph includes energy costs for both electricity and natural gas. Heat pumps models are not included.

Meanwhile, reducing lighting and plug loads during peak demand was a steady GEB strategy as it consistently reduced energy costs and emissions. On average, shedding energy from lighting and plug loads during hours of peak demand reduced annual energy costs and emissions by 2%. While the scale of this strategy was considerably smaller compared to the ventilation approach, it nevertheless demonstrates the potential that lighting and plug loads can have when designing a building for demand flexible operations. For example, even though lighting and plug loads in lab spaces were only reduced by 25% for this study, increasing the temperature of ultra-low temperature freezers has been found to reduce plug load energy consumption anywhere from

30%–40%.[36] If laboratory operators achieve buy-in from researchers and collaborate to develop a schedule for lighting and plug use, load shedding as a GEB approach could generate even greater energy and emission savings. The cities that financially benefited the most from a load shedding GEB strategy included Phoenix, Fergus Falls, and Denver, even if their associated emission reductions were notably smaller.

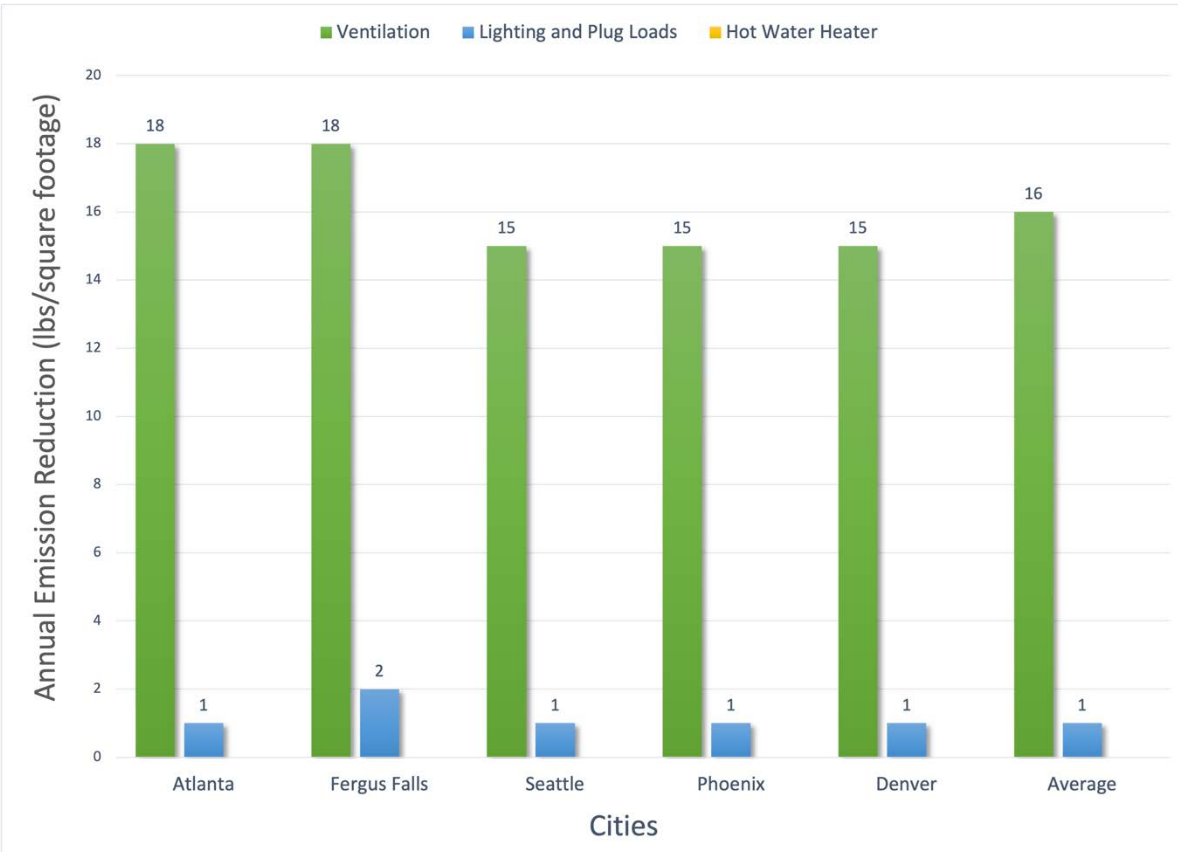

Figure 6. Individual impact of GEB technologies on emission reduction

Figure 7 graphs the emission reductions between the baseline model and the laboratory building models with each GEB strategy. Graph includes reductions for both electricity and natural gas. Heat pumps models are not included.

Some of this variation can be explained by the city's electricity tariff and how local utilities defined their peak demands, as seen in Table 3. Cities that had longer periods of peak demand during business hours like Denver and Fergus Falls experienced higher energy savings while cities with short windows of peak demand outside of business hours experienced much smaller savings. For example, Seattle's peak demand did not start until 5 p.m., when most of the lighting and plug loads in the laboratory were already reduced. Atlanta, meanwhile, had a standard period of peak demand in the late afternoon to evening, but the electric utility only enforced peak demand pricing during the summer months. Because lighting and plug loads were only reduced

[36] More information about ultra-low temperature freezers can be found at https://www.mygreenlab.org/-70-is-the-new--80.html.

on a percentage basis during peak demand in the models, this narrowed the window to achieve energy cost savings through a load shedding strategy considerably for some laboratories.

Table 3. TOU Electric Schedules According to City

The table summarizes the electric rates used in each city and which TOU schedule was consulted to calculate the laboratory's electricity costs using REopt.

TOU Schedule	Phoenix	Atlanta	Seattle	Denver	Fergus Falls
Local Electric Utility	Arizona Public Service	Georgia Power Company	Seattle City Lights	Xcel Energy	Otter Tail Power Company
On-Peak Period	3–8 p.m., weekdays	2–7 p.m., weekdays	5–9 p.m., weekdays	12–8 p.m., weekdays	1–7 p.m., all week
Peak Demand Season*	All Year	Summer	All Year	Summer	All Year
Monthly Fixed Service and Facility Charge	$197.00	$204.00	$54.00	$41.13	$118.35
Demand Charge ($/kW)	Peak: $16.15 Off-Peak: $5.36	N/A	$5.16	$6.17	Peak: $11.804 Off-Peak: $2.06
Energy Charge ($/kWh)[37]	Peak: $0.0598 Off Peak: $0.0476	Peak: $0.1292 Off Peak: $0.0372	Peak: $0.1070 Off-Peak: $0.0809	Peak: $0.0985 Off-Peak: $0.0244	Peak: $0.0739 Off-Peak: $0.0499

*Summer for Atlanta and Denver means June 1 to September 30.

Outside of defining peak demand, laboratory buildings served by local utilities that offered dynamic pricing on both their energy charges and demand charges also experienced increased energy cost savings, such as in Phoenix and Fergus Falls. This is seen in Table 4 where Phoenix and Fergus Falls accrued the highest demand charges out of all the other laboratory models under the baseline scenario, but this also led to significant electricity cost savings for demand charges.[38] Phoenix in particular experienced a 10% reduction to its demand charges after employing the load shedding strategy to its lighting and plug loads in contrast to Atlanta, which did not face any demand charges. As seen in the breakdown of cost savings, the efficiency ventilation based GEB strategy had the most significant impact on total electricity costs, the majority of these cost savings stemming from reductions in energy charges. This result is not surprising given that energy efficiency measures reduce a building's entire energy usage, not just its demand. Even still, every laboratory model regardless of its region underwent notable reductions to its demand charges under the ventilation scenario. Combined with the load shedding strategy, these measures led to a significant decrease in electricity costs, both on a demand and energy charge basis.

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[37] Some of the on-peak and off-peak rates are presented as weighted averages in the table because their prices might fluctuate on a seasonal basis or be combined with a shoulder-peak rate that is not part of the on-peak rate. The table is meant to be representative of the tariff, but more details on the rate structures can be found in Appendix A.1.
[38] For the complete utility charges, see Table B-7 under Appendix B.4.

Table 4. Electricity Cost Savings by GEB Measure According to City

The table summarizes the total annual electricity costs in each city under the TOU baseline scenario and the electricity cost savings according to each GEB strategies.

Utility Annual Charges*	Phoenix	Atlanta	Seattle	Denver	Fergus Falls
Baseline					
Fixed Charges ($/month)	$2,364	$2,448	$657	$494	$1,441
Demand Charges ($/kW)	$115,554	-	$29,875	$56,225	$74,689
Energy Charges ($/kWh)	$209,241	$247,714	$189,983	$161,869	$132,378
Total Electricity Costs	$327,159	$250,162	$220,515	$218,587	$208,508
Hot Water Heater - Electricity Cost Savings from Baseline					
Demand Charges ($/kW)	-	-	-	1%	-
Energy Charges ($/kWh)	-	-	-	1%	-
Total Electricity Costs	-	-	-	1%	-
Lighting and Plug Loads - Electricity Cost Savings from Baseline					
Demand Charges ($/kW)	10%	-	1%	4%	6%
Energy Charges ($/kWh)	2%	2%	2%	4%	5%
Total Electricity Costs	5%	2%	2%	4%	6%
Ventilation - Electricity Cost Savings from Baseline					
Demand Charges ($/kW)	6%	-	12%	7%	9%
Energy Charges ($/kWh)	24%	29%	25%	23%	25%
Total Electricity Costs	17%	29%	23%	19%	19%
Combined GEB - Electricity Cost Savings from Baseline					
Demand Charges	19%	-	13%	12%	18%
Energy Charges	27%	29%	27%	28%	31%
Total Electricity Costs	24%	29%	25%	24%	26%

* Utility annual charges pulled from reports generated by REopt.

Smart service hot water heaters were the only GEB technology that failed to produce any significant results. Across all five cities, the energy cost savings and emission reductions generated from the load-shifting strategy were very low and close to negligible. The laboratory building model that oversaw the greatest energy savings was Denver at $0.03/ft^2 and this was likely due to the city's defined period of peak demand. For Denver, the hot water heater was set to charge the storage tank before 12 p.m., after which the hot water heater was expected to float until 8 p.m. 8 hours was the longest stretch of time out of the five cities that the hot water heater was programmed not to charge the water tank, and while this produced the highest energy savings, there are concerns about this approach in practice.

For one, some laboratories might not be able to operate for 8 hours without needing to charge its hot water tank, depending on its water consumption. Second, obtaining support from scientists to limit their water usage during peak demand may encounter significant resistance if peak demand is defined for long stretches during regular work hours. In other words, while it is technically feasible to make a long load-shifting strategy work for a hot water heater under the laboratory environment, it may not be practical for many organizations. In addition, the energy loads from the service hot water heater only accounted for less than 1% of the total energy used by the laboratory building model, significantly restricting the impact the strategy had on the model's results. Because most of a laboratory's energy consumption is directed to its ventilation, lighting, and plug load needs, load-shifting strategies may generate more energy cost savings and emission reductions if geared toward one of these three major users.

2.2 Energy Cost Savings as a Result of TOU Schedules

Outside of GEB strategies, the case study also explored how opting into a TOU electric schedule changed the energy cost savings associated with each of the laboratory building models. This insight was especially helpful for analyzing the energy efficiency strategy used for ventilation, as energy was broadly reduced for the entire modeled time, as opposed to being restricted during peak demand time.

To calculate the relative energy cost savings produced by a TOU pricing schedule, facility data collected on the model's electricity usage was run through REopt. The first report created by REopt calculated the cost of electricity under a TOU schedule available to commercial customers in each city, while a second report consulted a non-TOU schedule for the same customer category. While there were slight differences between the two schedules, the most important difference was whether the standard commercial rate adjusted charges based on peak demand.

Before any GEB strategies were even applied, energy cost savings from enrolling in a TOU schedule were already produced in most of the baseline scenarios. Electricity costs calculated for the laboratory's baseline using a TOU rate were on average 6% lower than electricity costs calculated using a non-TOU rate. This difference in pricing was translated into the energy cost savings generated by the GEB strategies after they were applied to the laboratory building models. Comparing the energy cost reduction from the two respective baselines, TOU schedules were found on average to produce even greater energy cost savings than what would have been achieved under a non-TOU schedule, as shown in Figure 8.[39] While enhanced energy cost savings were the highest for laboratory building models that employed all the GEB strategies, on average creating a 4% difference, improved energy cost savings were seen for even smaller measures, like reducing lighting and plug loads at 2%. This would suggest that the larger the energy savings are from a GEB strategy, the more a TOU rate would benefit the organization.

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[39] A summary of the electricity costs and the reduction calculations can be found in Appendix B.4.

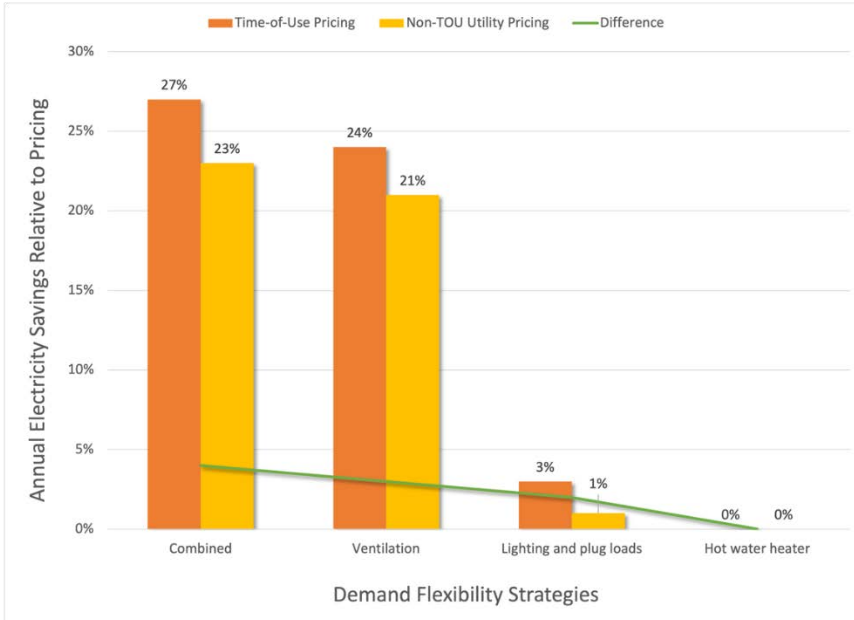

Figure 7. Electricity cost savings relative to non-TOU electric rates by strategy

It is important to note, however, that these changes in savings varied significantly on a regional basis. Taking a closer look at the energy cost savings achieved from a combined application of all the GEB strategies in Figure 9, cities that experienced the biggest benefits of a TOU price structure were the cities that already had the largest energy cost savings. Atlanta most notably oversaw a dramatic energy cost savings difference of 13%. Seattle's energy cost savings, in comparison, had a negligible difference under its non-TOU price structure.

Figure 8. Combined electricity cost savings relative to non-TOU electric rates by city

This gap can be largely attributed to how utilities billed for off-peak consumption, as shown in Table 5. Nearly every electric utility charged a higher rate for electricity consumed during peak demand compared to electric charges under a non-TOU schedule. Yet laboratories that experienced the least enhanced energy cost savings were the ones served by utilities that closely priced their off-peak electric charges under the TOU schedule to their electric charges under the non-TOU schedule. In Seattle, for example, the difference between the off-peak electric charge and the non-TOU electric charge was only $0.0061. Atlanta's utility, meanwhile, priced off-peak energy consumption $0.042 lower than electricity consumed under the cheapest tier of its non-TOU rate. In this way, while high prices for on-peak consumption is an important incentive to encourage GEB, how off-peak consumption is charged can be equally important when calculating energy cost savings.

Table 5. Non-TOU Electric Schedules According to City

The table lists the electric utilities that serve each city and which non-TOU schedule was consulted to calculate the laboratory's alternative electricity costs using REopt.

Non-TOU Schedule	Phoenix	Atlanta	Seattle	Denver	Fergus Falls
Local Electric Utility	Arizona Public Service	Georgia Power Company	Seattle City Lights	Xcel Energy	Otter Tail Power Company
Monthly Fixed Service and Facility Charge	$87.93	$25.50	$54.00	$41.13	$78.90
Demand Charge ($/kW)	First 100 kW: $24.10 Next kW: $16.76	N/A	$5.16	Summer: $15.15 Winter: $9.09	Summer: $11.50 Winter: $9.05
Energy Charge ($/kWh)	Summer: $0.0526 Winter: $0.0354	First 3,000: $0.1327 Next 7,000: $0.1203 Next 190,000: $0.1026 > 200,000: $0.0791[40]	$0.0870	$0.0079	Summer: $0.0578 Winter: $0.0603

*Summer in Phoenix means May 1 to October 30; for all other cities, it means June 1 to September 30.

[40] The table is meant to be representative of the tariff, but more details on the rate structures can be found in Appendix A.1.

2.3 Electrification Through Heat Pumps

Laboratory building models converted from natural gas to relying 100% on electricity to meet their energy needs yielded interesting results on the application of heat pumps. The models that benefited the most from a heat pump conversion were the ones located in warm climates, such as Atlanta and Phoenix. Out of the five models, Atlanta and Phoenix were the only models to experience reductions in their annual electricity consumption, as shown in Figure 9. These energy reductions translated into significant savings for the two cities in terms of energy and emissions, as detailed in Figures 10 and 11.

Figure 9. Changes in electricity usage between heat pump and natural gas model

This result reflects the fact that the heat pump models considered, representative of water-source-heat pumps operating at moderate source temperatures, offered improvements in efficiency in both heating and cooling. Additionally, the implementation of distributed zone-level water-source heat pumps as opposed to centralized air handlers reduced pressure drop and fan energy use in systems serving the office zones. In warm climates, the cooling and fan energy savings offset the comparatively smaller increase in electricity use through heating electrification, due to the low heating loads. Atlanta most notably experienced the highest savings from this transition, reducing the model's energy costs by 46% and creating $1.77/ft^2 of savings. Many factors in Atlanta made the laboratory building model an ideal target for electrification, but the Atlanta model also had the highest prices for natural gas, making electricity a competitive alternative under its TOU schedule.

Other cities experienced increases in their electricity consumption, but this all occurred in cold climate regions, reflecting the increase in electricity consumption to meet higher heating loads offsetting the smaller electricity savings from cooling and fans. These savings in end uses are shown in Figure 10.

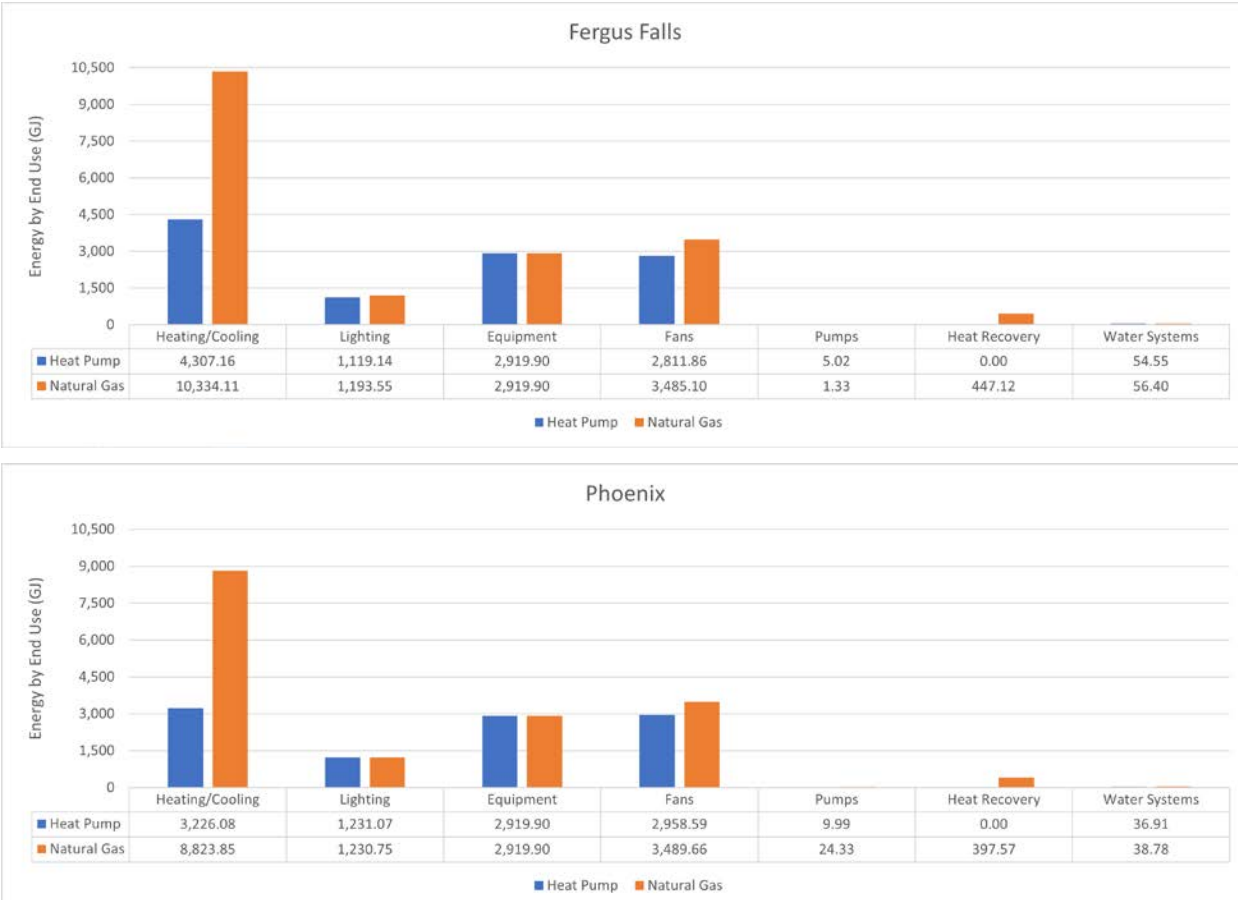

Figure 10. Changes in energy by end use for Fergus Falls (top) and Phoenix (bottom)

The laboratory building models in Denver, Seattle, and Fergus Falls relied heavily on natural gas to meet their heating loads in the baseline condition, so the switch to electricity through heat pumps increased their electricity consumption by an average of 8%. Despite this increase, all three cities experienced considerable energy cost savings, although on a smaller scale than the models ran under Phoenix and Atlanta as seen in Figure 10. The Fergus Falls model had the lowest energy cost savings, which can be attributed to the competitive cost of natural gas—the lowest among the modeled regions—and the area's particularly cold climate.

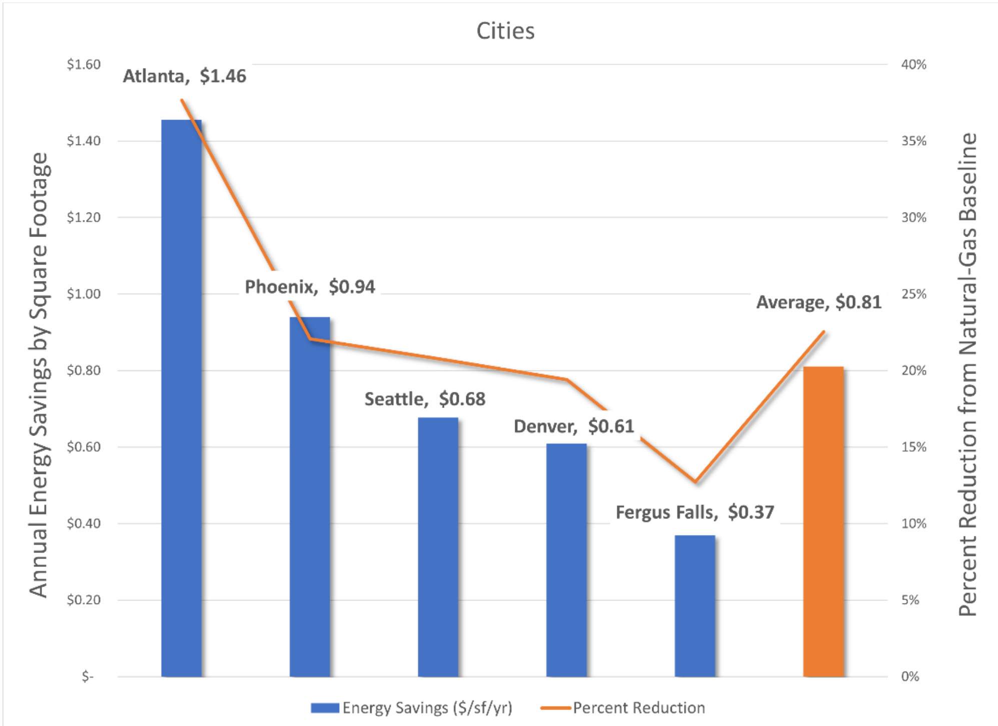

Figure 11. Changes in energy costs between heat pump and natural gas model

Higher electricity consumption can also provide insight into why cold climate regions experienced less emission savings compared to Atlanta and Phoenix after converting to heat pumps. As shown in Figure 11, every laboratory model experienced emission savings from electrification, but Atlanta and Phoenix had the highest emission savings on account of their lower overall energy usage. Fergus Falls notably had improved emission savings compared to other cold climate regions, like Seattle and Denver. This was an interesting observation since Fergus Falls receives its electricity from one of the dirtier parts of the grid.

Figure 12. Changes in emissions between heat pump and natural gas model

The Midwest Reliability Organization territory in the West, which serves communities like Fergus Falls, remains heavily reliant on coal and on average emits 995.8 pounds of CO_2 for every MWh, as illustrated in Figure 12. The grid in Fergus Falls exhibits a higher emission rate compared to other parts of the country, like Atlanta and Phoenix, and especially Seattle, where zero-emission sources make up nearly 60% of the local generation.[41] The only other laboratory building model that had a dirtier grid than Fergus Falls was Denver, which emits an average of 1,158 pounds of CO_2 for every MWh.[42] This can explain why Denver had the lowest emission savings out of the five regions since the electricity the laboratory model used to replace natural gas heating still came from a grid with a high carbon intensity. Despite Fergus Falls' relatively polluting grid, the laboratory model achieved significant emission reductions by eliminating natural gas usage since Fergus Falls had the highest natural gas consumption of all the models. As grids becomes cleaner with investment into zero emission generation sources, improvements in laboratory emissions will be easier to facilitate through heat pump electrification.[43]

[41] To learn more about emissions from the national grid, visit https://www.epa.gov/egrid/power-profiler#/NWPP.
[42] Colorado is considered part of the Rocky Mountain Power Area (RMPA).
[43] Minnesota dramatically updated its renewable portfolio standard in the beginning of 2023, committing to have 100% electricity come from clean-carbon sources by 2040. More information about this legislation can be found at https://mn.gov/commerce/news/?id=17-563384.

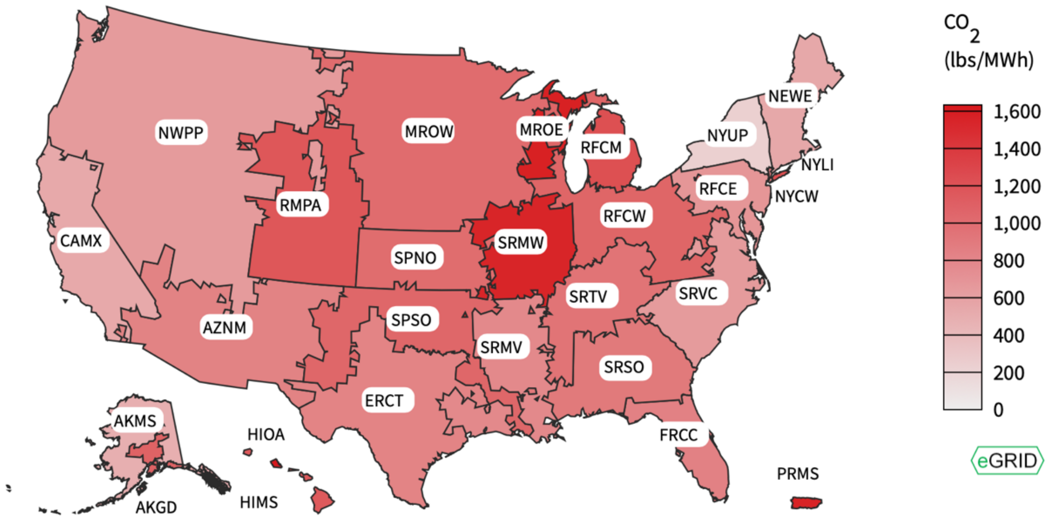

Figure 13. Emission rate map of CO_2 in the United States

Image Credit: eGrid Power Profiler, Environmental Protection Agency (2023)

3 Conclusion

This case study explored the use of three separate GEB technologies and strategies in laboratories and ran simulations to determine how energy costs and GHG emissions could be improved with their deployment. The results from these simulations revealed:

- Significant reductions in energy use from an efficiency-based approach, which translated into substantial emission savings as well as energy cost savings for both demand and energy charges,
- Reliable savings from a load-shedding approach when applied to plug loads and lighting end uses.

Optimizing ventilation by conducting a laboratory ventilation risk assessment is one of the greatest methods to reduce energy for a lab facility, because ventilation is the largest energy user in a lab environment. While load-shedding and load-shifting strategies could be applied to a laboratory's ventilation system, previous research has indicated that it would more likely interfere with the scientists' research and become too difficult to manage. Instead, load-shedding and load-shifting approaches should be applied to lighting and plug loads, where the energy and emission reductions are more likely to have a bigger impact. Smaller operation systems like service hot water heaters, however, while less likely to create disruption to researcher activities, have a limited scale and should be balanced against their costs to implement. Although difficult to capture in an energy model, working with laboratory occupants to coordinate a flexible system of operations will increase the savings potential of any strategy and will even be necessary for long-term success.

Regional data collected by the laboratory building models also revealed interesting energy consumption patterns and trends in local utility electricity pricing:

- Laboratory buildings with high electrical loads financially benefited the most from the implementation of a GEB strategy, while laboratory buildings with high natural gas consumption profiles and EUIs oversaw the greatest emission reductions.
- Load-shedding strategies were impacted by how local utilities defined their peak demand.
- Laboratory building models usually experienced higher energy savings if:
    - Peak demand was defined for longer periods in the day or throughout the year as opposed to one season
    - Peak demand occurred during hours of operation.
- Emission reductions for load-shedding approaches, while consistent, were discernably smaller than energy efficiency approaches.

Energy savings generated from GEB strategies were intuitively enhanced by TOU pricing when compared to traditional rates. Finding cities that offered both TOU and non-TOU rates, however, proved to be a challenge, because there are many utilities that do not offer demand flexibility pricing for large commercial or industrial customers. Even in cities where the electric utility had approved a TOU schedule, the utility had either:

- Not created a pricing difference between its on-peak and off-peak electric charges, or

- Defined the peak demand so broadly that any attempt to create a GEB strategy around it would have been difficult to model in a practical manner.

Utilities serving many major U.S. cities do not offer TOU pricing, posing a significant obstacle particularly for achieving energy and emissions savings in cold-climate regions.[44] Obscure electricity pricing structures like these limit the design of a GEB strategy and the savings that can be accrued from it and can choke an organization's ability to reduce its Scope 2 emissions.[45] As utilities ideally move forward and make progress on creating more-transparent TOU schedules, there may be more opportunities in the future to capture the energy and emissions savings associated with a demand flexible system of operations.

This case study ultimately intended to contribute new information to the relatively unexplored topic of minimizing energy consumption and emissions in laboratory buildings and will hopefully drive more projects in the future to investigate alternative GEB strategies. Additional paths to explore in this research include working with laboratories that have been made fully electric and understanding how significantly GEB strategies impact the energy and emission savings associated with those operations. Furthermore, this case study should be able to serve as guidance to laboratory planners and building operators interested in GEB strategies and how they can be modeled in a laboratory environment. While the report's appendix provides more in-depth information on how to run the simulations, the laboratory building prototype models used in the case study are a promising start to assessing both the strengths and weaknesses of grid-interactive efficient buildings.

[44] More details on this process and utility selection can be found under Appendix A.1.

[45] Scope 2 emissions refer to indirect emissions that occur from off-site combustion to power an organization's activities, such as purchasing electricity. For more information on emissions accounting, visit https://www.epa.gov/climateleadership/scope-1-and-scope-2-inventory-guidance.

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Appendix A. Collecting Utility Data

Before any of the laboratory building models could be run through OpenStudio or REopt, data had to be collected first on utilities to determine how energy was priced, which rates applied to each laboratory building model, and how peak demand was defined for each region. One important website the authors consulted to collect data on utilities was Open Energy Information (OpenEI). OpenEI maintains the Utility Rate Database where current and historic rate schedules can be found for most electric utilities in the United States.[46] This is the same database that REopt uses when calculating electricity costs for different laboratory load profiles.

A.1 Selecting Electricity Rates

When the authors initially started this report, they wanted to select cities that had large metropolitan populations because laboratories are more often found in urban centers. The authors also wanted to select cities of different climate zones, because this would provide more valuable information on how laboratory energy usage changes with its environment.

Atlanta

Georgia Power Company is an investor-owned electric utility that serves 2.7 million customers and 155 of the 159 counties in Georgia, including the city of Atlanta.[47] Georgia Power Co offers TOU schedules for both commercial and residential customers. The authors selected the Time of Use–High Load Factor Schedule or TOU-HLF-11 to calculate the model's electricity costs because it is available for selection in REopt. The rate is also marketed to large businesses that have electricity demands greater than 500 kW. Under the schedule, peak demand is listed from 2 to 7 p.m. Monday through Friday during the months of June, July, August, and September. TOU-HLF-11 is an older schedule from 2022, which Georgia Power Co updated at the beginning of 2023 with TOU-HLF-12.[48]

Under Georgia Power Co's website, the utility states that most large businesses opt into the Power and Light Large Schedule, or PLL-13.[49] This made PLL-13 an ideal alternative to use for a non-TOU rate, as it had no peak demand-pricing components. The only problem was that REopt did not have PLL-13 under its list of pull-down options for Atlanta. As such, the authors created a new custom electricity rate in REopt, importing the data from OpenEI. The authors pulled rate information from PLL-11, because it was updated in 2021 and would allow for more fair comparisons between the TOU and non-TOU rates.[50]

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[46] The Utility Rate Database is a free storehouse of information on electric rate structures in the United States. Additional details can be found at https://openei.org/wiki/Utility_Rate_Database.

[47] More information about Georgia Power Company can be found at https://psc.ga.gov/utilities/electric/#:~:text=Georgia%20Power%20Company%20(GPC)%2C,155%20of%20Georgia%27s%20159%20counties.

[48] TOU-HLF-12 can be read in its entirety at https://www.georgiapower.com/content/dam/georgia-power/pdfs/business-pdfs/tariffs/2023/TOU-HLF-12.pdf.

[49] Georgia Power Company categories all their rate structures by customer type under their website. Visit https://www.georgiapower.com/business/billing-and-rates/business-rates.html.

[50] It is important to note that there was no rate schedule for PLL-12 in OpenEI, so PLL-11 was likely the last rate structure before PLL-13.

Weekday Schedule

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
Jul	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
Aug	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
Sep	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Weekend Schedule

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Jul	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Aug	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Sep	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Tiered Energy Usage Charge Structure

Period	Tier	Max Usage ?	Max Usage Units ?	Rate $/kWh ?	Adjustments $/kWh ?	Sell $/kWh ?
1	1		kWh	0.037172	0.033231532	
2	1		kWh	0.129222	0.055259504	
3	1		kWh	0.037172	0.033778532	

Figure A-1. Georgia Power Company rate structure for TOU-HLF-11

Image Credit: OpenEI (2023)

Fixed monthly charge ($/day) 0.85

Energy Charges

Energy Charges - ***Rate** Periods*

Period	Tier in Period	Max. Energy Purchases (kWh/month)	Energy Charge ($/kWh)
1	1	200.0	0.0
1	2	3000.0	0.132655
1	3	10000.0	0.120303
1	4	200000.0	0.102607
1	5	0.0	0.079109
1	6	400.0	0.013627
1	7	600.0	0.010275
1	8	unlimited	0.00771
2	1	200.0	0.0
2	2	3000.0	0.132655
2	3	10000.0	0.120303
2	4	200000.0	0.102607
2	5	0.0	0.079109
2	6	400.0	0.013627
2	7	600.0	0.010275
2	8	unlimited	0.00771

Time of Use Energy Charges - ***Weekday** Schedule*

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Feb	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Mar	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Apr	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
May	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Nov	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Dec	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Time of Use Energy Charges - ***Weekend** Schedule*

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Feb	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Mar	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Apr	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
May	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Nov	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Dec	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Demand Charges

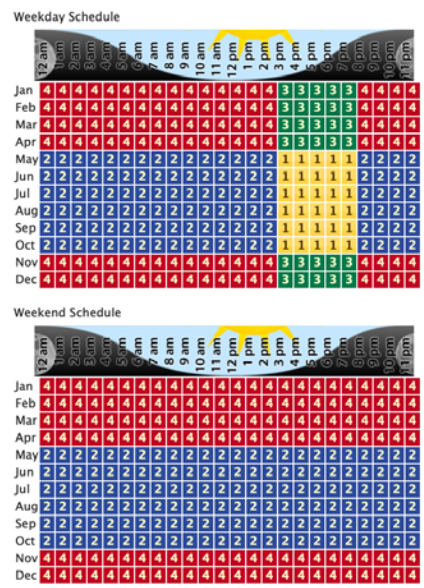
Demand Charges - ***Rate** Periods*

Period	Tier in Period	Max Demand (kW)	Demand Charge ($/kWh)
No demand charges			

Figure A-2. Custom Georgia Power Company rate structure made for PLL-11 in REopt

Phoenix

The city of Phoenix is served by the investor-owned utility Arizona Public Service, which provides electricity to 1.3 million customers in Arizona.[51] The authors selected the Large General Time-of-Use Primary (E-32TOU L) schedule because it applies to industrial customers that have average monthly demands greater than 400 kW and the laboratory building model consumes over 300,000 kWh a month during the summer season.[52] Under the TOU schedule, Arizona Public Service defined peak demand as lasting from 3 to 8 p.m. Monday through Friday. While the utility charged different rates for peak demand during the summer and winter, peak demand in each season was always higher than the off-peak rate, so peak demand in simulations was treated as lasting from 3 to 8 p.m. for the whole year. For the non-TOU rate, the authors selected the Large General Service (E-32 L) Secondary schedule.[53] REopt contained the options to select both these schedules, so no custom tariffs were created.



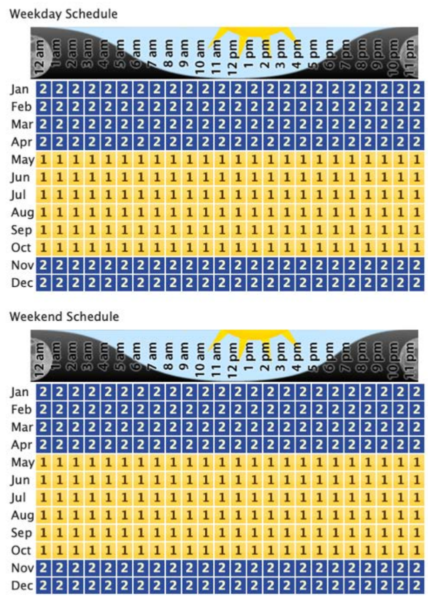
Tiered Energy Usage Charge Structure

Period	Tier	Max Usage	Max Usage Units	Rate $/kWh	Adjustments $/kWh	Sell $/kWh
1	1		kWh	0.07018	0.002182	
2	1		kWh	0.0573	0.002182	
3	1		kWh	0.05552	0.002182	
4	1		kWh	0.04264	0.002182	

Figure A-3. Arizona Public Service rate structure for E-32TOU L

Image Credit: OpenEI (2023)

[51] More information about Arizona Public Service can be found at https://www.aps.com/en/About/Our-Company/About-us.
[52] Additional details about E-32TOU L can be found by visiting https://www.aps.com/-/media/APS/APSCOM-PDFs/Utility/Regulatory-and-Legal/Regulatory-Plan-Details-Tariffs/Business/TOU-Business-NonRes-Plans/e32_TimeOfUseLarge.ashx?la=en.
[53] Additional details about E-32 L can be found at https://www.aps.com/-/media/APS/APSCOM-PDFs/Utility/Regulatory-and-Legal/Regulatory-Plan-Details-Tariffs/Business/Business-NonResidential-Plans/e32_Large.ashx?la=en.



Tiered Energy Usage Charge Structure

Period	Tier	Max Usage	Max Usage Units	Rate $/kWh	Adjustments $/kWh	Sell $/kWh
1	1		kWh	0.05258	0.016082	
2	1		kWh	0.03542	0.016082	

Figure A-4. Arizona Public Service rate structure for E-32 L

Image Credit: OpenEI (2023)

Seattle

Seattle is served by Seattle City Lights, which is a municipal electric utility owned by the city of Seattle. It is the largest municipal utility in the Northwest and provides electricity to Seattle's 734,000 residents in addition to operating four large hydroelectric plants.[54] The utility lists its electric rates under the city's municipal code.[55] The authors selected the Medium General Service: City Time-of-Day schedule for the laboratory building model because the tariff is for customers that have a monthly demand greater than 50 W but less than 1,000 kW. Under its TOU schedule, the utility defines three separate periods of demand: on-peak, mid-peak, and off-peak demand that last Monday through Friday for the whole year. To simplify the demand flexibility strategies used in the model, peak demand was narrowed to match only the on-peak demand from the tariff because it was the highest rate, lasting from 5 to 9 p.m. under the same weekend parameters. The city, however, has only recently started adopting TOU schedules, so all TOU rates will not be available to customers until 2024. As such, the authors had to create two custom electric rates in REopt for Seattle. The first custom rate pulled information from the Medium General Service: City Time-of-Day schedule, while the second electric rate pulled

[54] More information on Seattle City Lights and its history can be read at https://www.skagitwatershed.org/swc-member-organizations/seattle-city-light/#:~:text=Representatives&text=Seattle%20City%20Light%20is%20a,by%20the%20City%20of%20Seattle.

[55] The Seattle Municipal Code can be read at https://library.municode.com/wa/seattle/codes/municipal_code?nodeId=TIT21UT_SUBTITLE_IVLIPO_CH21.49SELIDE_21.49.055MEGESESCMDMDMDMDMDMDMDMDMTMTMTMCMCMC.

information from the Medium General Service: City Default schedule updated for 2024 to allow for a fair comparison.

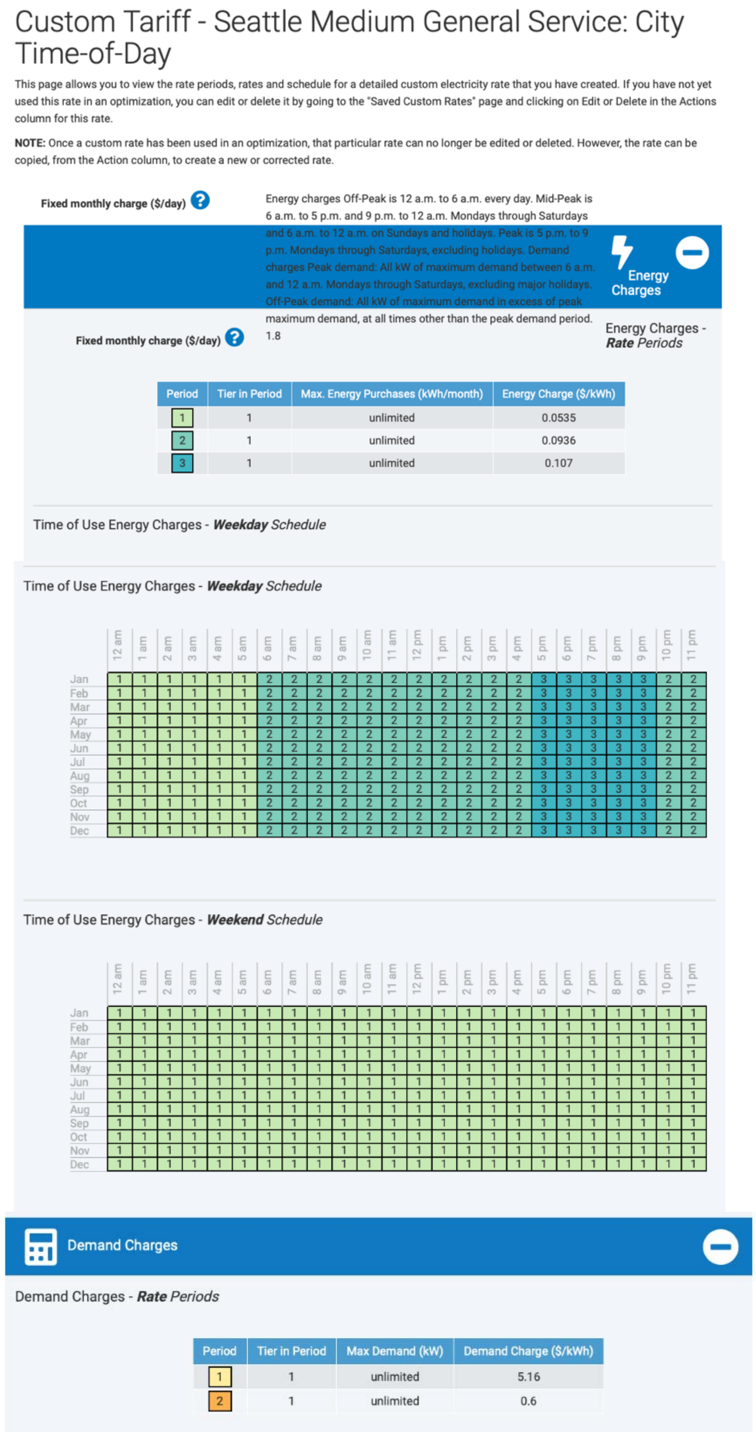


Figure A-5. Custom Seattle City Lights rate structure made for Medium General Service: City Time-of-Day in REopt

Custom Tariff - Seattle - Schedule MDC (Medium Standard General Service: City Default)

This page allows you to view the rate periods, rates and schedule for a detailed custom electricity rate that you have created. If you have not yet used this rate in an optimization, you can edit or delete it by going to the "Saved Custom Rates" page and clicking on Edit or Delete in the Actions column for this rate.

NOTE: Once a custom rate has been used in an optimization, that particular rate can no longer be edited or deleted. However, the rate can be copied, from the Action column, to create a new or corrected rate.

Fixed monthly charge ($/day) This will be used as the "regular" pricing schemes labs would fall under if it was not TOU.

Fixed monthly charge ($/day) 1.8

Energy Charges

Energy Charges - ***Rate*** *Periods*

Period	Tier in Period	Max. Energy Purchases (kWh/month)	Energy Charge ($/kWh)
1	1	unlimited	0.087

Time of Use Energy Charges - ***Weekday*** *Schedule*

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Time of Use Energy Charges - ***Weekend*** *Schedule*

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Facility Demand Charges

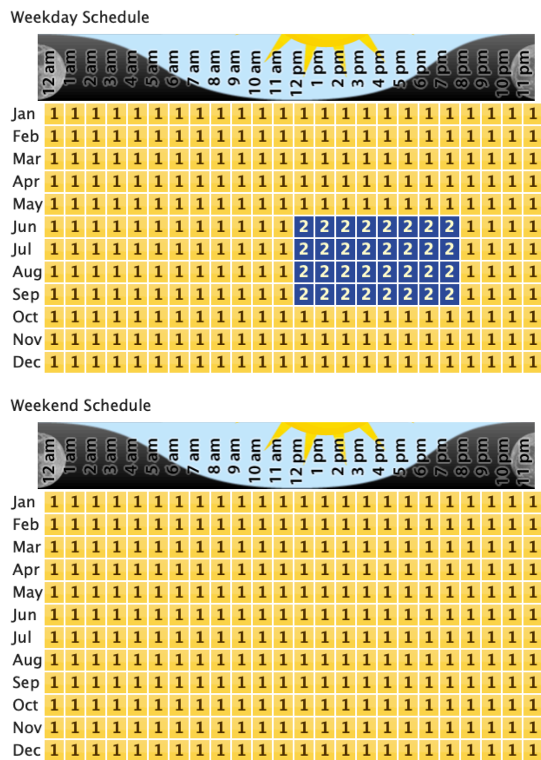
Facility Demand Charges - ***Monthly*** *Schedule*

Month	Monthly Demand Charge ($/kW)	Apply lookback percent?
January	5.16	no
February	5.16	no
March	5.16	no
April	5.16	no
May	5.16	no
June	5.16	no
July	5.16	no
August	5.16	no
September	5.16	no
October	5.16	no
November	5.16	no
December	5.16	no

Figure A-6. Custom Seattle City Lights rate structure made for Medium General Service: City Default in REopt

Denver

Xcel Energy is an investor-owned utility that provides both electricity and natural gas to residents in the city of Denver. The authors selected the Secondary Time-of-Use Service schedule because it was one of the few TOU schedules offered to commercial customers by Xcel that had the most straightforward pricing calculations on peak demand. Xcel defined peak demand as lasting from 12 to 8 p.m. on weekdays during the months of June, July, August, and September. The non-TOU schedule the authors selected to compare to the TOU rate was the Secondary General schedule. Even though Secondary Time-of-Use Service was offered primarily as a pilot program and was set to expire January 2023, the tariff nevertheless provides a valuable point of reference for demand dynamic pricing, especially if the Colorado Public Utilities Commissions decides to extend the program.[56] Both rates were available in REopt, so no custom rates had to be created.[57]



Tiered Energy Usage Charge Structure

Period	Tier	Max Usage ?	Max Usage Units ?	Rate $/kWh ?	Adjustments $/kWh ?	Sell $/kWh ?
1	1		kWh	0.02438	0.02913	
2	1		kWh	0.09854	0.03917	

Figure A-7. Xcel Energy Colorado rate structure for Secondary Time-of-Use Service

Image Credit: OpenEI (2023)

[56] Complete information on the Xcel Energy electric tariff in Colorado can be found at https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20&%20Regulations/Regulatory%20Filings/PSCo_Electric_Entire_Tariff.pdf.

[57] Because Xcel Energy is an electric utility in many states, OpenEI has called Xcel Energy the Public Service Company of Colorado in its database.

Weekday Schedule

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Weekend Schedule

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Tiered Energy Usage Charge Structure

Period	Tier	Max Usage ?	Max Usage Units ?	Rate $/kWh ?	Adjustments $/kWh ?	Sell $/kWh ?
1	1		kWh	0.00791	0.03883219	

Figure A-8. Xcel Energy Colorado Rate Structure for Secondary General

Image Credit: OpenEI (2023)

Fergus Falls

Otter Tail Power Company was one of the few electric utilities the authors found that offered commercial customers TOU rates within reasonably periods of peak demand.[58] Otter Tail Power Company is an investor-owned electric utility that services customers across 70,000 square miles spanning Minnesota, North Dakota, and South Dakota. Out of all the service areas mentioned on the utility's website, the authors selected Fergus Falls because it was one of the most populous cities that Otter Tail Power served, in addition to being the utility's headquarters.[59]

[58] The authors investigated cold climate cities (ASHRAE 6A or 6B climate zones) with large metropolitan populations like Minneapolis and Fargo. Minneapolis is served by Xcel Energy, which defined peak demand for all TOU rates as 9 a.m. to 9 p.m.; visit https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20&%20Regulations/Me_Section_5.pdf. Fargo is served by Cass County Electric Cooperative, which offers a TOU rate in which peak demand is defined from 6 to 9 a.m. and 5 to 8 p.m. More details can be found at https://casscountyelectric.com/timedayrate.

[59] For more information about Otter Tail Power Company, visit https://www.otpco.com/about-us/communities-we-serve/.

The authors selected the Large General Service–Time of Day–Secondary schedule for customers with monthly demand less than 1,000 kW, as customers only need a monthly demand of 80 kW to qualify. The laboratory building model would not have qualified for the Super Large General Service rates, because this rate requires customers to have a minimum electricity consumption of 175,000,000 kWh per year.[60] Otter Tail Power, out of all the utilities selected for this report, had one of the most advanced rate structures for demand flexibility. Not only did Otter Tail Power define three periods of demand (on-peak, shoulder-peak, off-peak), the utility also adjusted the hours for peak demand by the day of the week and by the season. While the dynamic pricing was useful from a transparency standpoint (as it captured when energy costs and emissions would be at their highest), it did complicate designing and modeling a demand flexibility strategy around peak demand.

Time of Use Demand Charge Structure

Period	Tier	Max kW Usage	Rate $/kW	Adjustments $/kW
1	1	1000	0.55	-0.546
2	1	1000	12.35	-0.546
3	1	1000	2.49	-0.546
4	1	1000	10.42	-0.546
5	1	1000	2.5	-0.546

Weekday Schedule

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	5	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	1	1
Feb	1	1	1	1	1	1	5	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	1	1
Mar	1	1	1	1	1	1	5	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	1	1
Apr	1	1	1	1	1	1	5	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	1	1
May	1	1	1	1	1	1	5	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	2	3	3	3	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	2	3	3	3	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	2	3	3	3	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	2	3	3	3	1	1
Oct	1	1	1	1	1	1	5	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	1	1
Nov	1	1	1	1	1	1	5	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	1	1
Dec	1	1	1	1	1	1	5	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	1	1

Weekend Schedule

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	1	1

[60] More information about Otter Tail Power Company's Super Large General Service eligibility requirements can be found at https://www.otpco.com/media/3848/mn_1006.pdf.

Tiered Energy Usage Charge Structure

Period	Tier	Max Usage	Max Usage Units	Rate $/kWh	Adjustments $/kWh	Sell $/kWh
1	1		kWh	0.02949	0.0054843	
2	1		kWh	0.06878	0.0051169	
3	1		kWh	0.05231	0.0052709	
4	1		kWh	0.03525	0.0054304	
5	1		kWh	0.05276	0.0052667	
6	1		kWh	0.05738	0.0052235	

Weekday Schedule

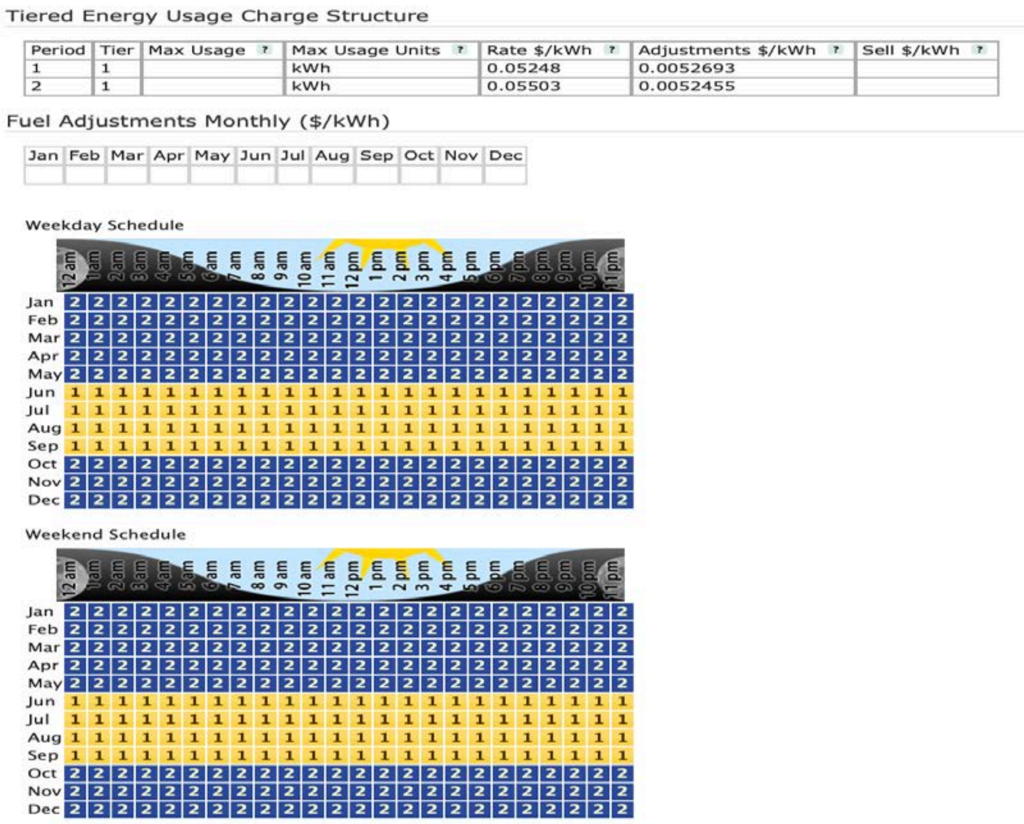
	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10pm	11 pm
Jan	4	4	4	4	4	4	5	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4
Feb	4	4	4	4	4	4	5	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4
Mar	4	4	4	4	4	4	5	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4
Apr	4	4	4	4	4	4	5	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4
May	4	4	4	4	4	4	5	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4
Jun	1	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	2	3	3	3	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	2	3	3	3	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	2	3	3	3	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	2	3	3	3	1	1
Oct	4	4	4	4	4	4	5	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4
Nov	4	4	4	4	4	4	5	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4
Dec	4	4	4	4	4	4	5	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4

Weekend Schedule

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10pm	11 pm
Jan	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	4	4
Feb	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	4	4
Mar	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	4	4
Apr	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	4	4
May	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	4	4
Jun	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	1	1
Oct	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	4	4
Nov	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	4	4
Dec	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	4	4

Figure A-9. Otter Tail Power Company rate structure for Large General Service–Time of Day

Image Credit: OpenEI (2023)



Tiered Energy Usage Charge Structure

Period	Tier	Max Usage	Max Usage Units	Rate $/kWh	Adjustments $/kWh	Sell $/kWh
1	1		kWh	0.05248	0.0052693	
2	1		kWh	0.05503	0.0052455	

Fuel Adjustments Monthly ($/kWh)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Weekday Schedule

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Feb	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Mar	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Apr	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
May	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Nov	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Dec	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Weekend Schedule

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Feb	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Mar	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Apr	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
May	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Nov	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Dec	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Figure A-10. Otter Tail Power Company rate structure for Large General Service

Image Credit: OpenEI (2023)

To simplify the simulation, peak demand was broadly defined as lasting from 1 to 7 p.m., as this was the most expensive charge for on-peak demand in the summer. The authors maintained 1 to 7 p.m. as the peak demand for both the whole week and the whole year, because it would capture some of the shoulder-peak demand pricing, which could translate into enhanced energy savings. Finally, the authors selected the Large General Service schedule as the non-TOU rate to compare for the laboratory building model's energy savings.[61] Both rates were available in REopt, so no custom rates had to be created.

[61] All of the rates, rules, and regulations for Otter Tail Power Company's service in Minnesota can be found at https://www.otpco.com/pricing/minnesota/rates-rules-and-regulations-mn/.

A.2 Selecting Natural Gas Rates

Table A-1 contains information on the utilities that serve natural gas to each of the selected cities.

Table A-1. Natural Gas Prices According to City

Natural Gas Information	Phoenix	Atlanta	Seattle	Denver	Fergus Falls
Utility Name	Southwest Gas Corporation	Liberty Utilities	Puget Sound Energy	Xcel Energy	Great Plains
Customer Schedule	General Gas Service (G-25)–Large-2[62]	General Gas Service–Industrial (820)[63]	Commercial and Industrial General Service (SCH 31)[64]	Large Commercial (CLG)[65]	Firm General Service (Rate 70)[66]
Usage Charge per Dekatherm (if applicable)	-	-	-	$11.230	$6.159
Usage Charge per Centum cubic feet (if applicable)	-	$1.3014	-	-	-
Price Per Therm	$1.04349	$1.34955	$1.13983	$1.1230	$0.6159

[62] Large-2 general gas service customers are defined as those whose average annual requirements are between 50,000 and 180,000 therms. Rates are updated monthly in the natural gas tariff, which can be found at https://www.swgas.com/aztariff.pdf. Rates for this model were pulled during https://www.swgas.com/rate/1409217097328/Revision-No-392-MGC.pdf.

[63] General Gas Service (Schedule 820) is reserved for commercial or industrial natural gas customers that use less than 100,000 Centum cubic feet per year. For more information on schedules, visit https://georgia.libertyutilities.com/uploads/Liberty%20Utilities%20(Peach%20State%20Natural%20Gas)%20Corp%20-%20Tariff%20as%20of%2002-01-2022%20FINAL.pdf. Rates are subjected to change, but rates were pulled from https://georgia.libertyutilities.com/uploads/Rates%20and%20Tariffs/GA%20Rates%20June%202022.pdf.

[64] Prices for natural gas are updated on a monthly basis. For more information, download natural gas prices at https://www.pse.com/-/media/Project/PSE/Portal/Rate-documents/summ_gas_prices_2022_11_01.pdf?sc_lang=en.

[65] The $11.230 per Dekatherm charge was pulled from the total monthly rate, which adds all of riders and gas cost adjustment to the base rate. For a complete calculation, visit https://www.xcelenergy.com/staticfiles/xe-responsive/Archive/Summary%20of%20Gas%20Rates%20as%20of%2011-01-2022.pdf.

[66] Firm General Rate 70 is reserved for customers that do not consume more than 2,000 cubic feet per hour. Adding the distribution charge and the base cost of gas creates a total rate of $6.159 per Dekatherm. More information can be found at https://www.gpng.com/wp-content/uploads/PDFs/Rates-Tariffs/Minnesota/MNGas70.pdf.

Appendix B. Running Energy Simulations

When utility data had been collected on the selected cities, the authors could then begin to run the laboratory building prototype models in OpenStudio and gather information on energy costs and emissions through REopt. This part of the Appendix details the steps that can be modeled in future simulations or be modified to consider alternative laboratory building models or demand flexibility strategies. The Appendix concludes with a series of tables that contain the laboratory metrics from previous runs and how energy and emissions reductions were calculated.

B.1 Establishing a Baseline Model

This section details the steps taken by the authors, as well as their considerations when creating baselines for each of the modeled cities:

1) Downloading OpenStudio and adding the laboratory building prototype model to the Building Component Library are some of the first steps to running any simulation. Details on how to complete this procedure can be found under the HVAC Resource Map.[67] In this study, the authors selected the most up-to-date template, 90.1-2016. Climate zones were then specified for each of the cities' regions. The only climate zone missing from the measure was 1B for Phoenix, so 3B was selected instead as the closest match. Some of the laboratory building prototype models automatically came with appropriate weather files for the cities of interest, but for the ones that did not, appropriate weather files were downloaded from EnergyPlus®.[68]

2) As soon as the laboratory building prototype model was created and customized by region, the authors needed to add a few measures before running the model.

    a. The first measure was to convert the service hot water heater the laboratory building model came with from a natural gas system to an electrical one with demand flexibility properties.[69] Even though none of those demand flexibility properties were utilized while creating the baselines, it was important to establish how much electricity the model would use with no instruction to float or charge the hot water tank. When the measure was added, the authors specified that the existing water heater should be removed, that the set hot water tank volume would be 300 gallons (seen through previous runs), and that the water would be heated using a wrapped condenser heat pump. Because a heat pump was selected, the authors also had to specify where the thermal zone would be for the heat pump evaporator to which the authors specified Lab_bot_corridor_ZN because it is one of the equipment corridors.

[67] Detailed instructions on how to download OpenStudio and set up the laboratory building prototype model by year and climate region can be found at https://hvacresourcemap.net/assets/pdf/openstudio-guide-energy-modeling-laboratory-buildings.pdf.

[68] These weather files can be downloaded by visiting https://energyplus.net/weather.

[69] This measure can be downloaded from the NREL Building Component Library by searching for "Add HPWH for Domestic Hot Water" at https://bcl.nrel.gov.

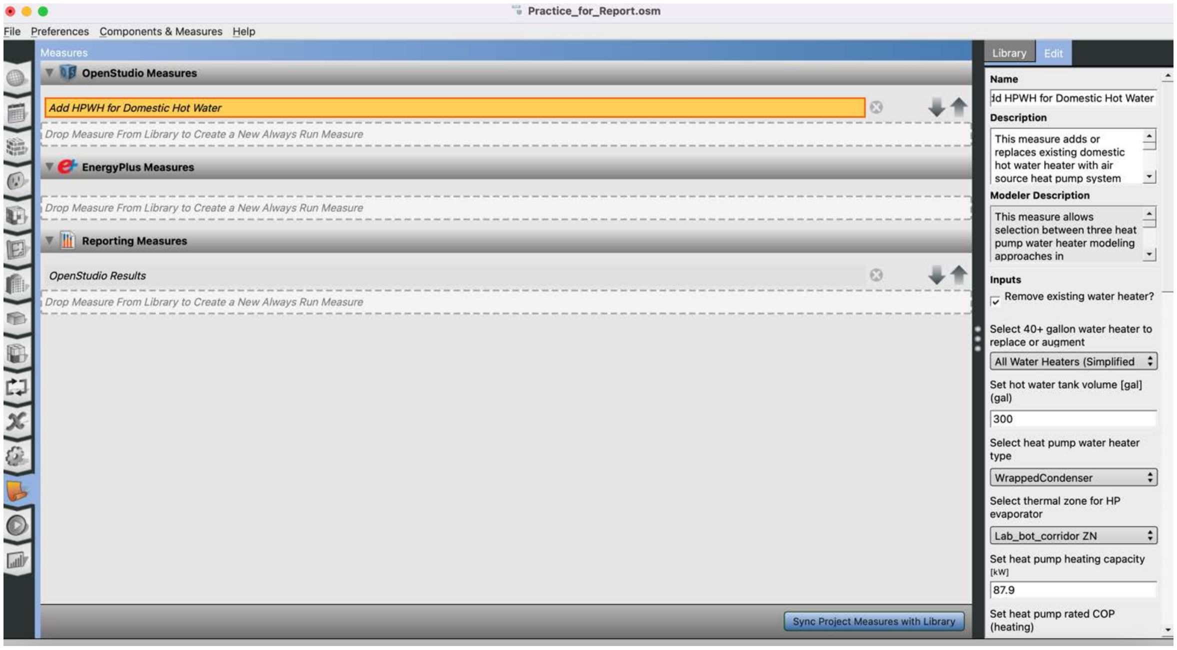


Figure B-1. Adding the Heat Pump Water Heaters for domestic hot water measure in OpenStudio

b. The second measure was a correction made to the laboratory's ZoneHVAC:EquipmentList because the original prototype model came with an error that was causing the laboratory zones to overheat. Because OpenStudio-Standards gem is released every 6 months, however, this issue should be corrected for future downloads.

c. Two last measures were added to the baseline model to record the entire facility's hourly electricity consumption. It should be noted that these steps are taken with every laboratory building model, not just the baselines, to record the model's hourly electrical loads. While most OpenStudio models have Electricity:Facility as an enabled meter by default, adding the Add Meter measure can also help make sure the loads are being reported by OpenStudio. ExportMetertoCSV was the last measure the authors used where they specified to OpenStudio to export the Electricity:Facility meter. This measure will produce a CSV file of the model's hourly electricity consumption in the model's "reports" folder after completing the run, in addition to an OpenStudio report of the laboratory's operations, including energy use profile.

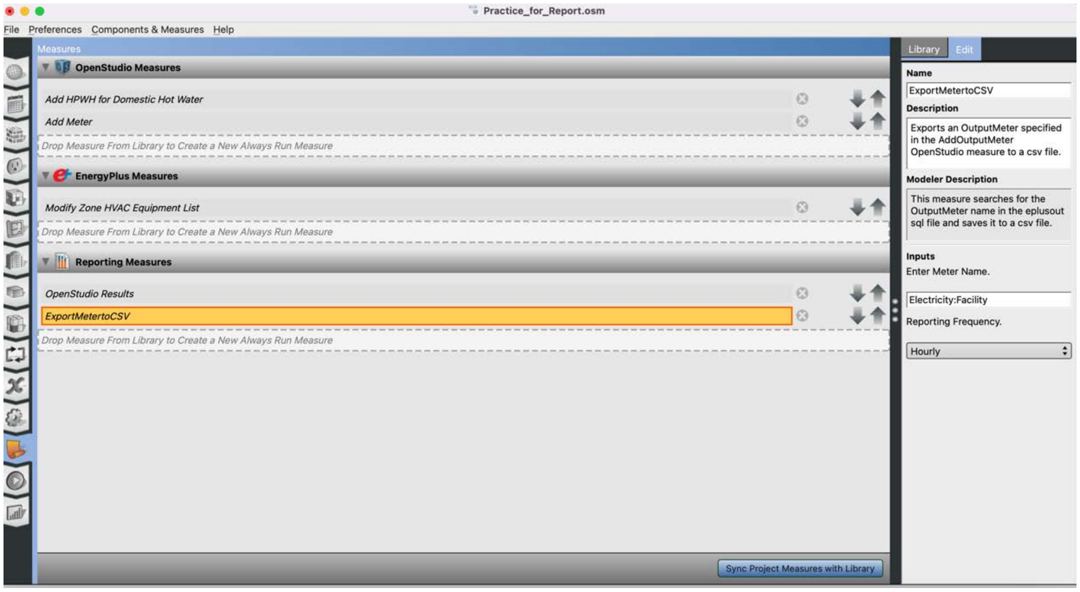


Figure B-2. Adding the ExportMetertoCSV measure in OpenStudio

3) After running the model, the authors recorded the laboratory's natural gas consumption and electricity consumption and verified that laboratory temperature conditions were being met and there were few unmet loads. The authors then went into the "reports" to prepare the metering data collected on electricity consumption for REopt. Because OpenStudio records energy consumption using Joules, the CSV file was edited to show the hourly electricity consumption in kilowatt hours through dividing the reported Joules by 3,600,000, as there are 3,600,000 Joules in 1 kWh. The date time format of the hourly logs also had to be changed to a simple numeric format, as this is how REopt processes electricity data.

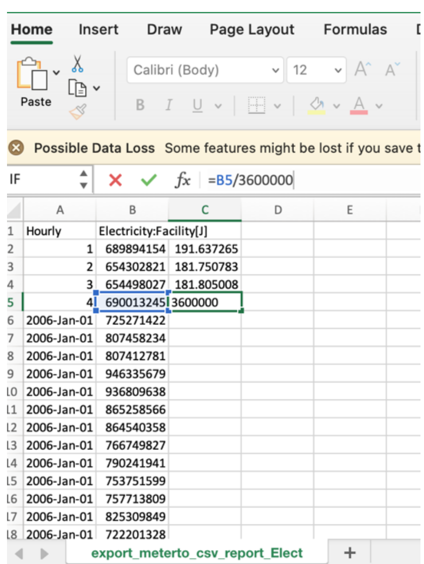


Figure B-3. Converting CSV file from OpenStudio into format for REopt

4) The prepped electricity file was then fed into the REopt Web Tool, which enables users to run evaluations online. While REopt has many distinct features for optimizing renewable energy systems, the primary use of REopt for this study was to calculate the energy costs and emissions associated with the laboratory building model's operations. As such, even though PV and Battery were selected as Technologies, the authors were more interested in the "Business As Usual" column under the Results Comparison tab that would come with the REopt report, because this would document the baseline electricity costs and emissions. The only information the authors needed to provide REopt to get this final report was the location of the model, the selected electric tariff, and an uploaded file of the laboratory's hourly electricity consumption. This step would be repeated twice for one load profile—once to get the electricity costs under the TOU rate and once to get the costs under the non-TOU rate.

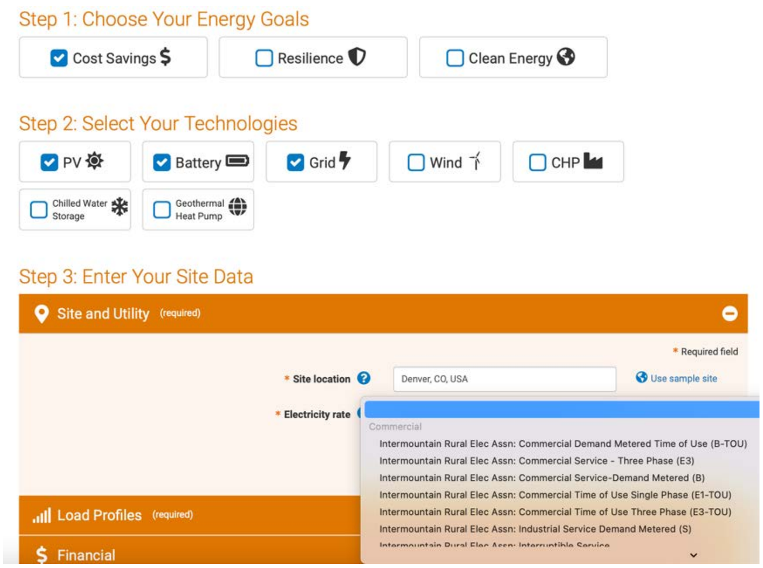


Figure B-4. Entering electricity data into REopt to calculate energy costs and emissions

After completing these five steps, the authors could calculate an estimated baseline for each of the five laboratory building models by city. To verify these results, the authors compared the laboratory building models to the Laboratory Benchmarking Tool (LBT). LBT is a database of metrics on real laboratories that laboratory professionals can consult to benchmark and compare performance.[70] The authors compared the results from the laboratory building models to laboratories in the LBT by sorting the data according to climate zone. The laboratory baseline models, for the most part, were in line with laboratory data collected for similar laboratory buildings in the region. In some cases, the laboratory building models performed slightly lower than the visual average, but this is to be expected because OpenStudio calculates energy consumption under ideal conditions. The authors also double-checked what the ventilation rates were for most laboratories by region. Some regions like in Phoenix and Seattle contained no data on ventilation, but for regions where data did exist, the ACHs and their associated EUIs were similar to the laboratory baseline models.

[70] To learn more about the LBT, visit https://lbt.i2sl.org.

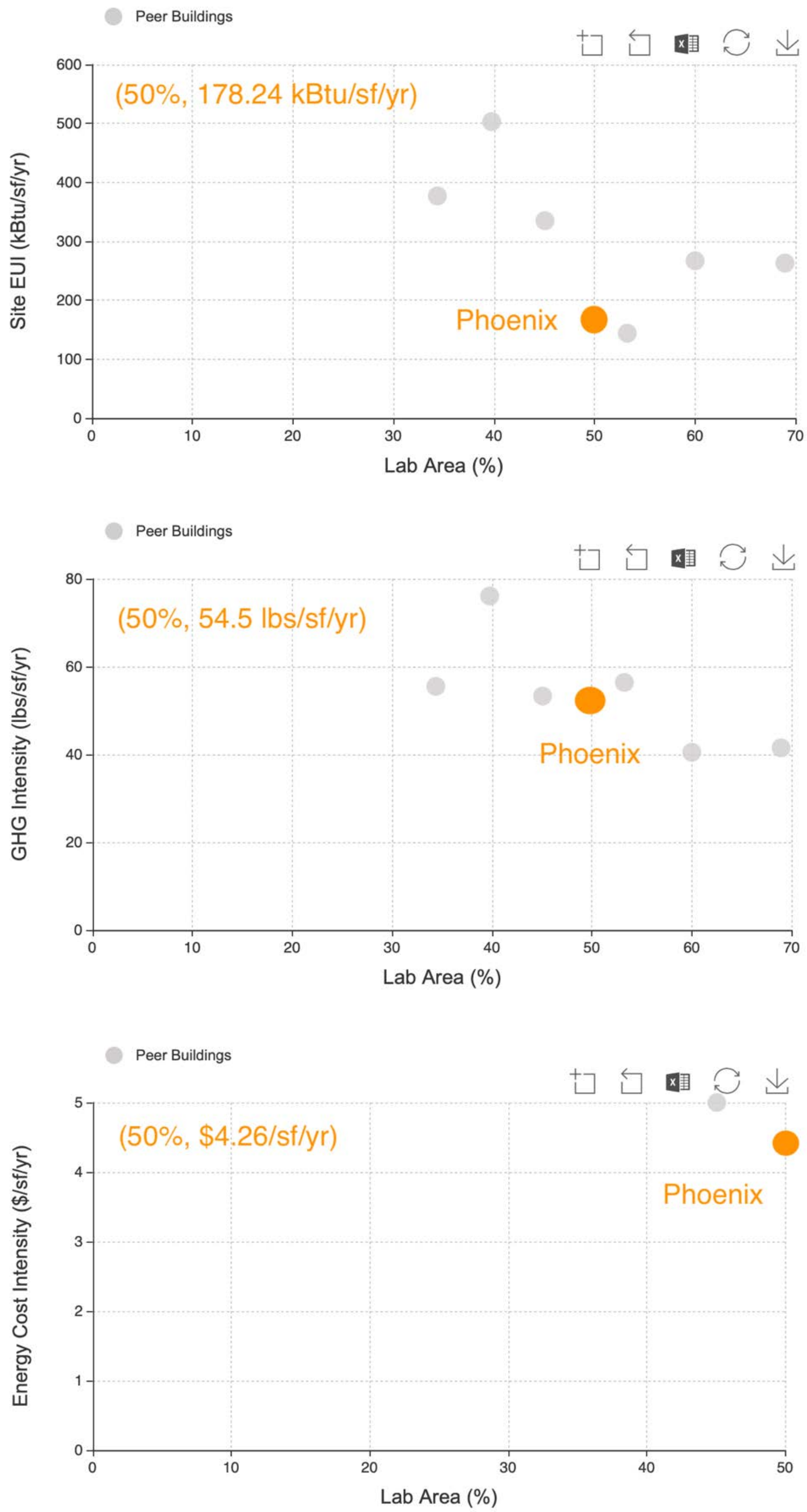


Figure B-5. Comparing Phoenix against data in the LBT (1B)

Figure B-6. Comparing Atlanta against data in the LBT (3A)

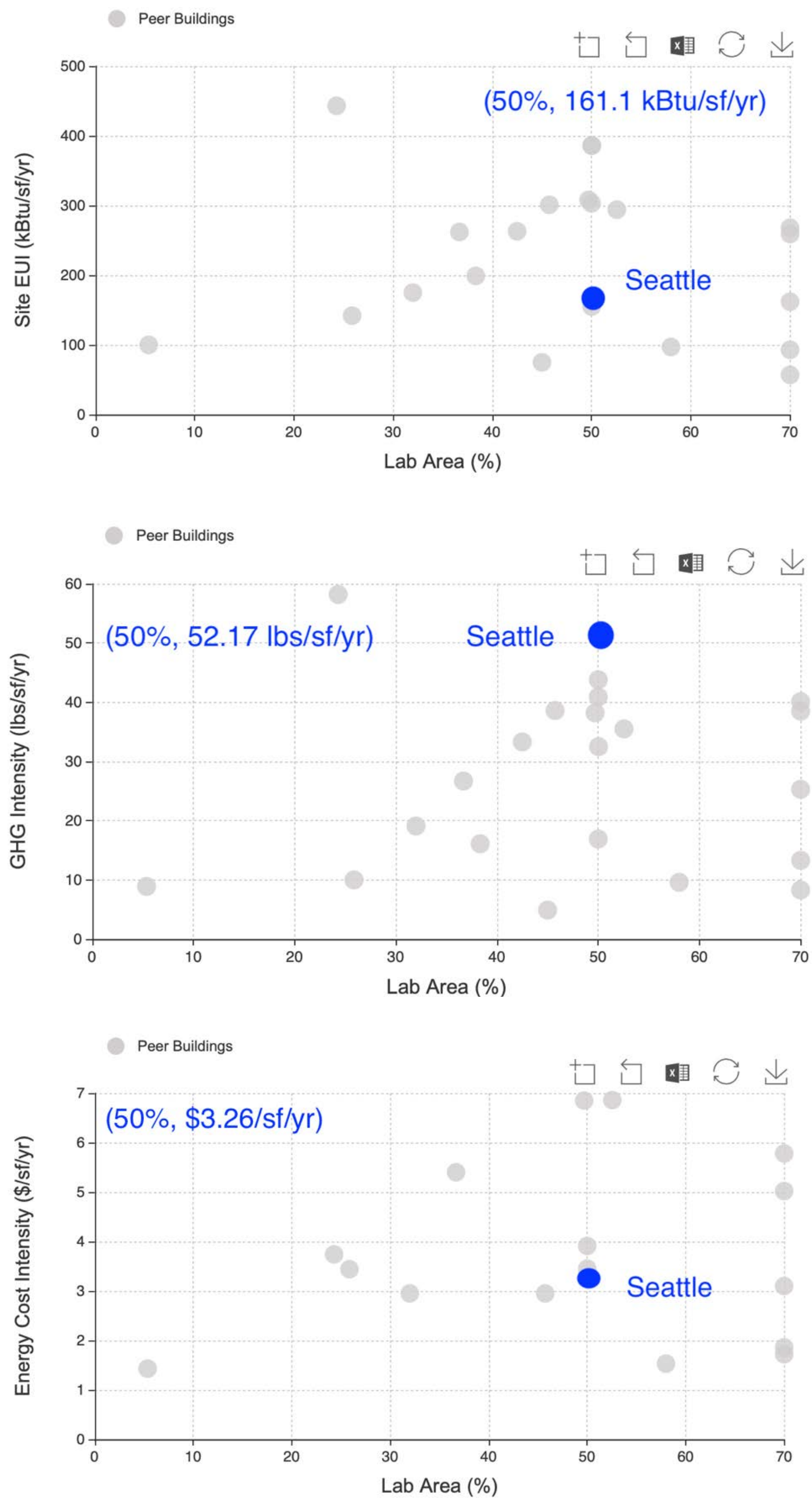


Figure B-7. Comparing Seattle against data in the LBT (4C)

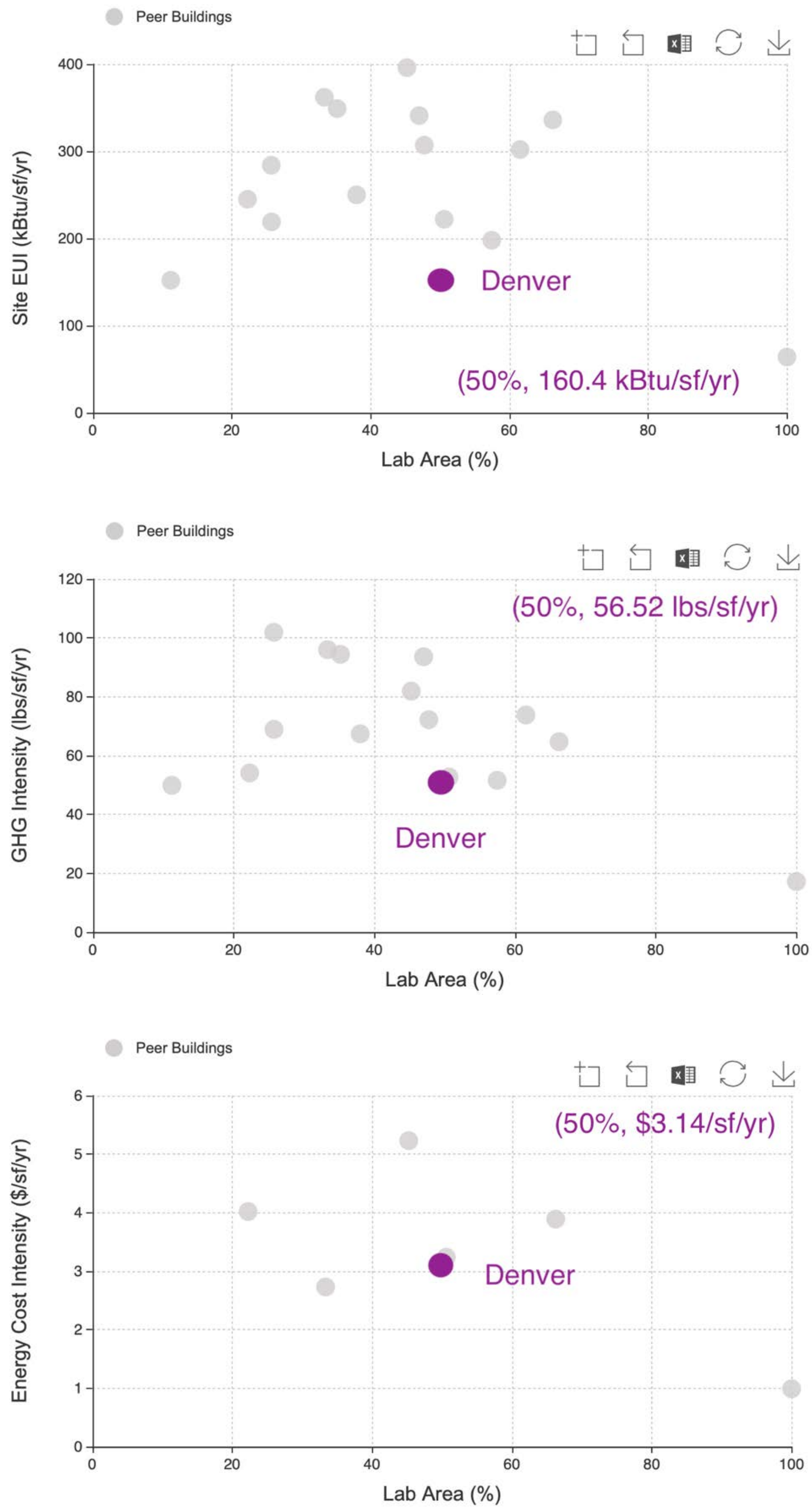


Figure B-8. Comparing Denver against data in the LBT (5B)

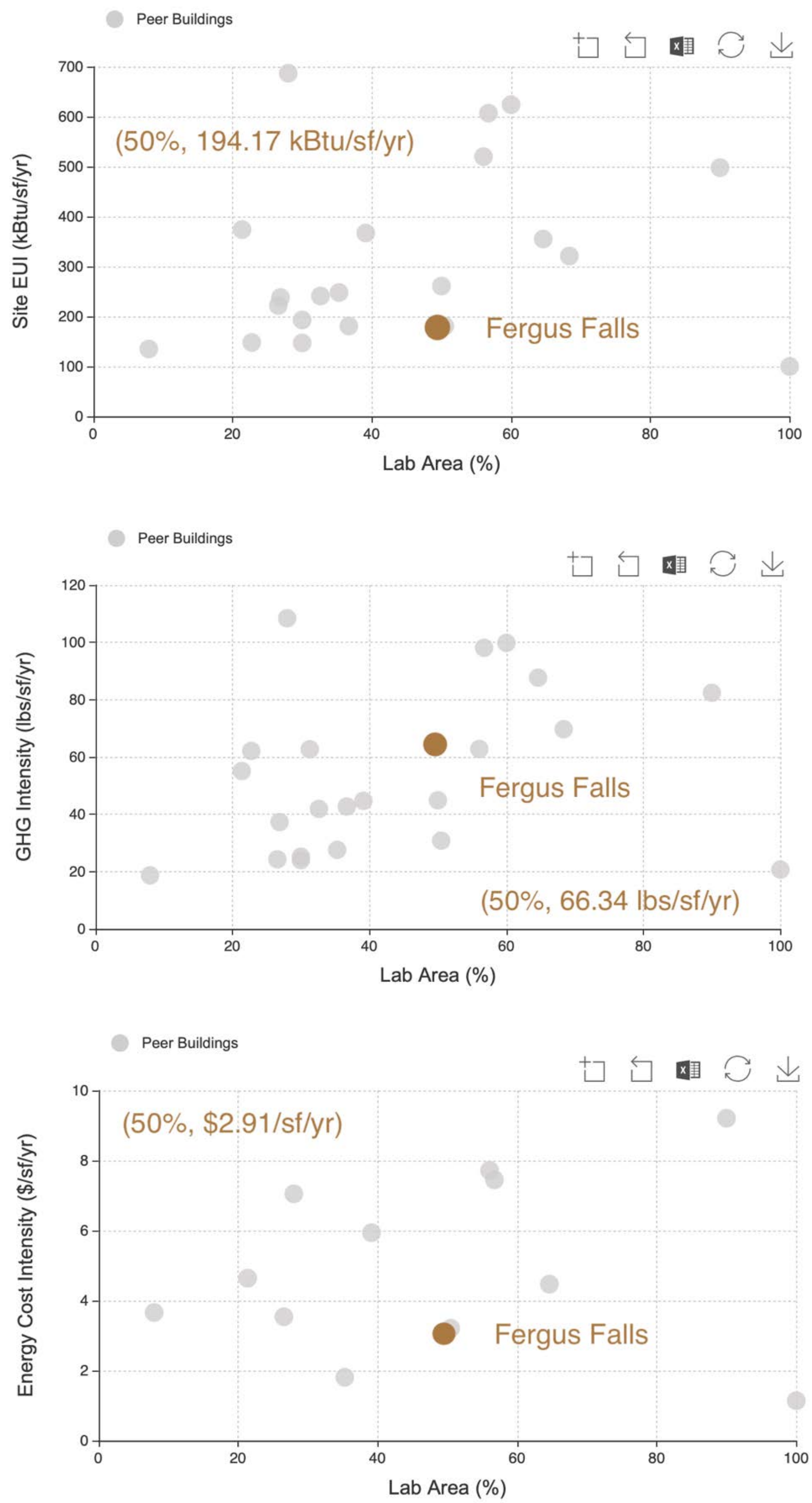


Figure B-9. Comparing Fergus Falls against data in the LBT (6B)

B.2 Employing Demand Flexibility Strategies

After establishing baselines, the authors could then determine the energy and emission savings associated with demand flexibility. To separate the strategies, the laboratory baseline model was duplicated and ran a separate time for each type of demand flexibility strategy. The authors ran a final model for each city that contained all the demand flexibility measures to determine their cumulative effect.

Ventilation

To simulate the efficiency ventilation strategy, the authors walked through the following steps:

1. Under the Schedules tab in OpenStudio, the Lab_HVACOperationSchd was duplicated and renamed to Lab_HVACOperationSchd_Minimum. Because the model has been specified to run each zone at its maximum ACH and the Lab_HVACOperationSchd is a fractional schedule, the ventilation was adjusted to 0.6666 during hours of operation and 0.3333 during hours of low occupancy. This would translate into approximately 4 ACH from 8 a.m. to 5 p.m. and 2 ACH all other hours.

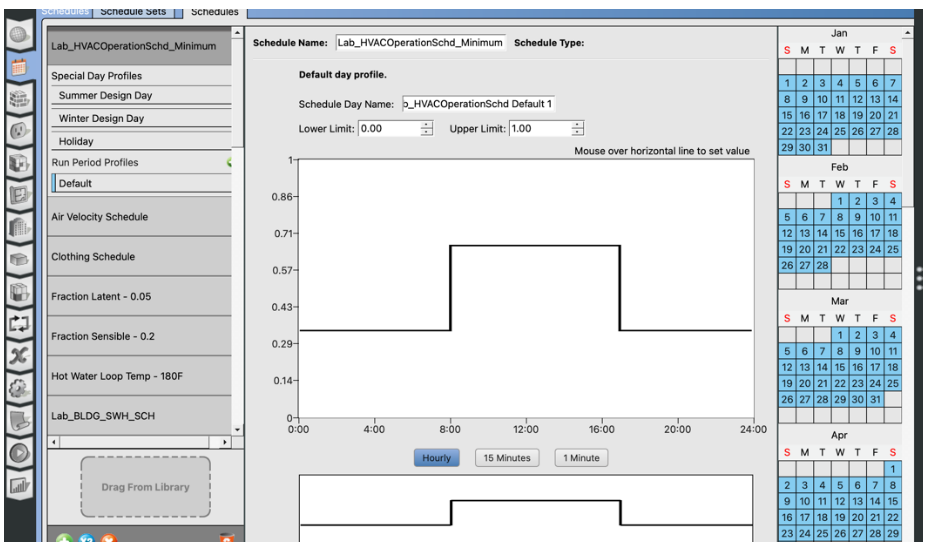


Figure B-10. Creating a new laboratory HVAC schedule in OpenStudio

2. When a new HVAC schedule had been established, the authors went into the HVAC Systems tab to specify on each zone level which schedule to use for its ventilation. All the laboratory spaces were under Lab PVAV All OA, so the authors highlighted every equipment corridor and open lab zone and selected the air terminal. Zone Minimum Air Flow Input Method was adjusted from "Constant" to "Scheduled," and Minimum Air Flow Fraction Schedule Name was changed from being blank to saying "Lab_HVACOperationSchd_Minimum." As discussed in the beginning of the report, the laboratory spaces designated for fume hoods were not modified.

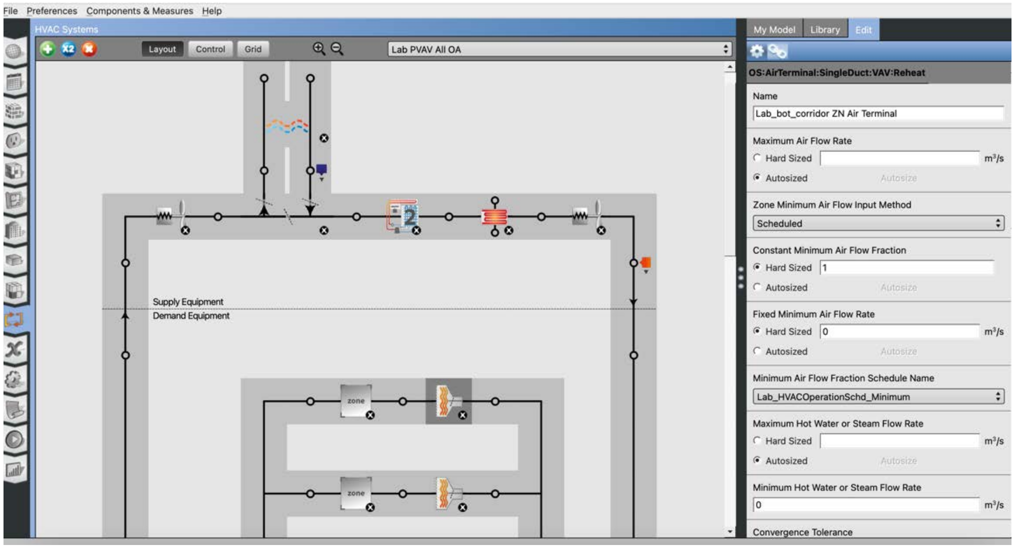


Figure B-11. Adjusting the HVAC schedules for laboratory zones in OpenStudio

3. The last step was adjusting the ventilation rates under the Space Types tab. There, the authors highlighted the relevant laboratory spaces under the Design Specification Outdoor Air column and adjusted the Outdoor Air Flow Air Changes per Hour from 6 to 4 and adjusted the Outdoor Air Flow Rate Fraction Schedule Name to "Lab_HVACOperationSchd_Minimum."

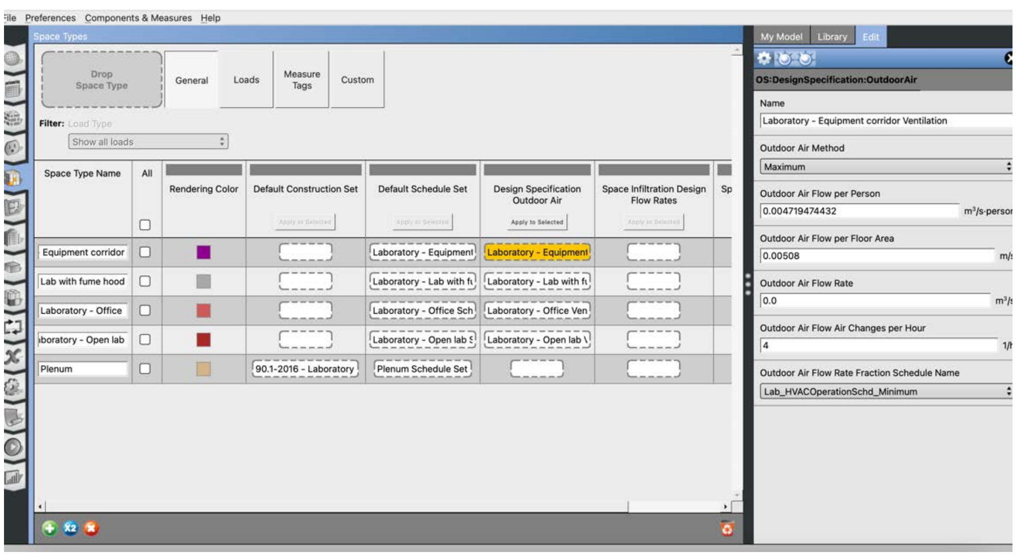


Figure B-12. Adjusting minimum outdoor air flow for space types in OpenStudio

4. After running the model, the authors checked the EnergyPlus report created for the model under the "reports" folder. They ensured that the air change rates had been adjusted for the specified zones by looking at the average and the minimum.

Minimum Outdoor Air During Occupied Hours

	Average Number of Occupants	Nominal Number of Occupants	Zone Volume [m3]	Mechanical Ventilation [ach]	Infil
LAB_BOT_FUMEHOOD ZN	4.40	15.00	849.51	14.718	
LAB_BOT_OPEN ZN	15.41	52.50	2973.27	1.983	
LAB_MID_FUMEHOOD ZN	4.40	15.00	849.51	14.711	
LAB_MID_OPEN ZN	15.41	52.50	2973.27	1.984	
LAB_TOP_FUMEHOOD ZN	4.40	15.00	849.51	14.706	
LAB_TOP_OPEN ZN	15.41	52.50	2973.27	1.983	
OFFICE_BOT_1 ZN	9.76	22.97	1238.86	0.000	
OFFICE_BOT_2 ZN	6.97	16.41	884.90	0.000	
OFFICE_BOT_3 ZN	9.76	22.97	1238.86	0.000	
OFFICE_BOT_4 ZN	6.97	16.41	884.90	0.000	
OFFICE_MID_1 ZN	9.76	22.97	1238.86	0.000	
OFFICE_MID_2 ZN	6.97	16.41	884.90	0.000	
OFFICE_MID_3 ZN	9.76	22.97	1238.86	0.000	

Figure B-13. Example report of ventilation rates for zones under Denver model

Lighting and Plug Loads

1. A measure was created using EnergyPlus that could be uploaded directly into OpenStudio.[71] The measure contained script that created an energy management system for the laboratory building model and lowered the total energy consumption for lighting and plug loads during specified periods of the day. These specifications were adjusted given the established peak demand period for every city's utility.

2. After the measure was created and adjusted for the city's peak demand, it was then uploaded and ran in OpenStudio.

```
    "EnergyManagementSystem:Program,
    Set_DR_var_status,       !- Name
    IF CurrentTime >=12 && CurrentTime  <=19 &&  Month >=6 &&  Month <=9 && DayOfWeek >=2 &&
DayOfWeek <=6,  !- Program Line 1
    SET DR_status = TRUE,    !- Program Line 2
    ELSE,                    !- A4
    SET DR_status = FALSE,   !- A5
    ENDIF;                   !- A6"
```

Figure B-14. Example script to specify peak demand for lighting and plug loads in Denver

Smart Hot Water Heater

1. When the smart hot water heaters were set to become flexible during periods of peak demand, two daily flex periods were activated. The first daily flex period specified when

[71] For more instruction on how to do this, contact Amy Allen at amy.allen@nrel.gov.

the hot water heater would charge the hot water tank. The second daily flex period specified when the hot water heater would not use electricity and let the hot water float in the tank. A 24-hour format was used to specify when the hot water heater would be charging and floating.

2. To charge the hot water tank, the authors selected "Charge – Heat Pump" under "Daily Flex Period 1." The first hour specified would be the end of peak demand and it would last until the last minute before peak demand starts.
3. To have the hot water float during peak demand, the authors selected "Float" under "Daily Flex Period 2." The first hour specified would be the start of peak demand and it would last until the last minute before peak demand ends.

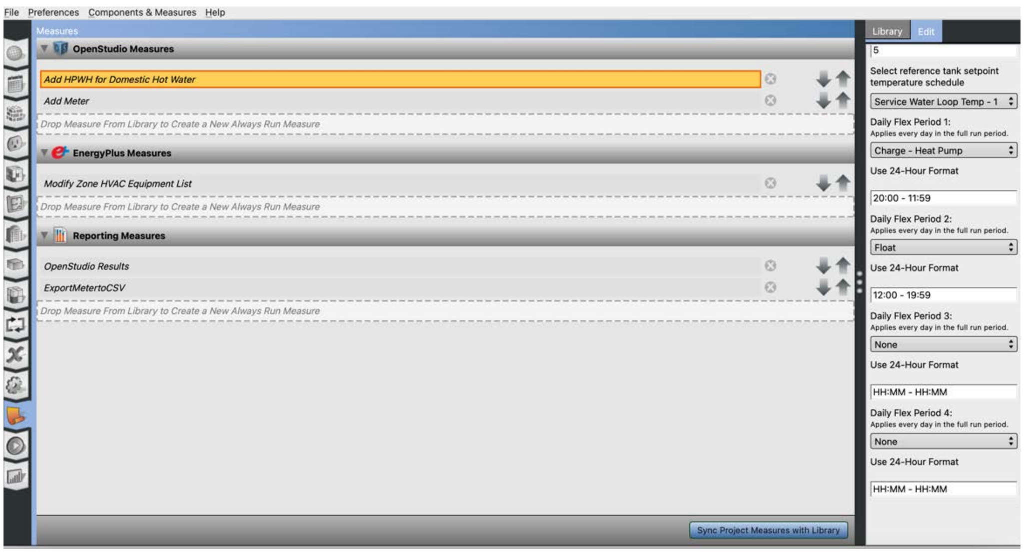


Figure B-15. Adjusting the hot water heater to respond to Denver's peak demand in OpenStudio

B.3 Creating Heat Pump Model

To understand the energy and emission savings associated with electrification, the authors duplicated each of the natural gas baseline models and converted their HVAC operations to rely on heat pumps. The authors encountered difficulty in identifying the best measures to incorporate heat pump modeling, because most heat pump measures have been developed for office buildings. Nevertheless, these measures provided a promising starting point to alter the model and experiment with heat pump application. NREL's Building Component Library contains multiple heat pump measures for office buildings.[72] The authors chose to move forward with a water-source heat pump for the space loads and a ground-source heat pump measure instead of an air-source one, as water-source and ground-source heat pumps are fairly versatile in warm or

[72] This measure can be downloaded from the NREL Building Component Library by searching for "AedgOfficeHvacWshpDoas" at https://bcl.nrel.gov.

cool climates.[73] At the start of this study, current limitations with the heat pump measures prevented the authors from modeling the laboratory building as a centralized heat pump system, so the authors post-processed the data to simulate centralized heat pump conditions.

1. Following a similar procedure for establishing a baseline, the authors uploaded the AedgOfficeHvacWshpDoas measure to the model using the “Apply Now Function” under Components & Measures to enable edits post-upload. After selecting the measure, the authors selected “Plenum” for the space type that should be part of a ceiling return. The authors did not specify a total cost for the HVAC system, but they did uncheck the box that says “Apply recommended availability and ventilation schedules for air handlers?”

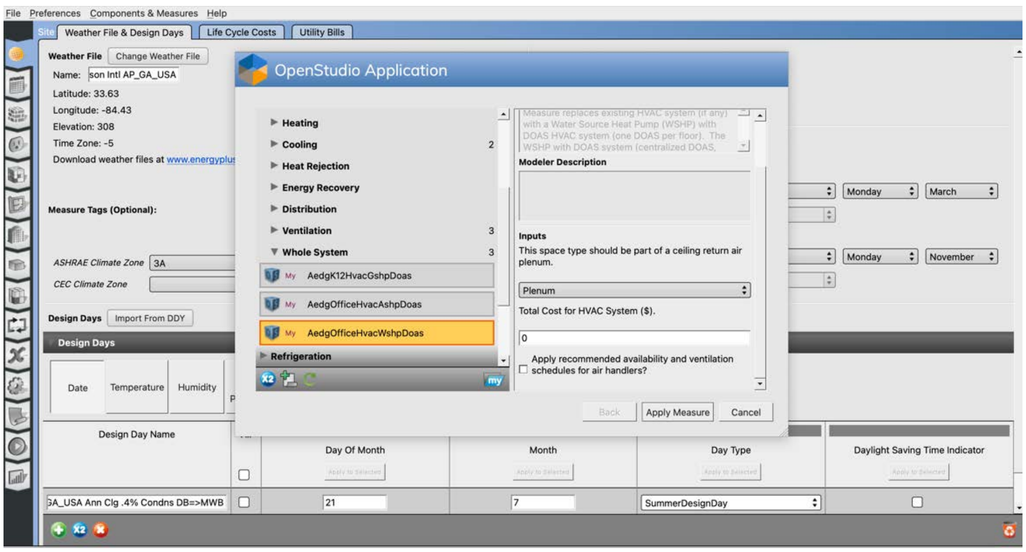


Figure B-16. Applying Heat Pump Measure in OpenStudio

2. After accepting the changes made to the model by the measure, the authors moved into the Schedules tab to adjust the AEDG DOAS Temperature Setpoint Schedule. The original natural gas laboratory building prototype model has a temperature setpoint for both the cooling and heating schedules so that model’s spaces are usually at 22.2°C. As such, the authors adjusted the AEDG DOAS Temperature Setpoint Schedule so that it would be at 22°C, as opposed to 20°C.

[73] The International Institute for Sustainable Laboratories released a best practice guide on decarbonization for laboratories, which explores the use of different heat pumps, including geothermal heat pumps and air-source heat pumps. To learn more about water-source heat pumps, visit https://www.i2sl.org/documents/I2SLBestPractices_Decarbonization_Jan2023.pdf.

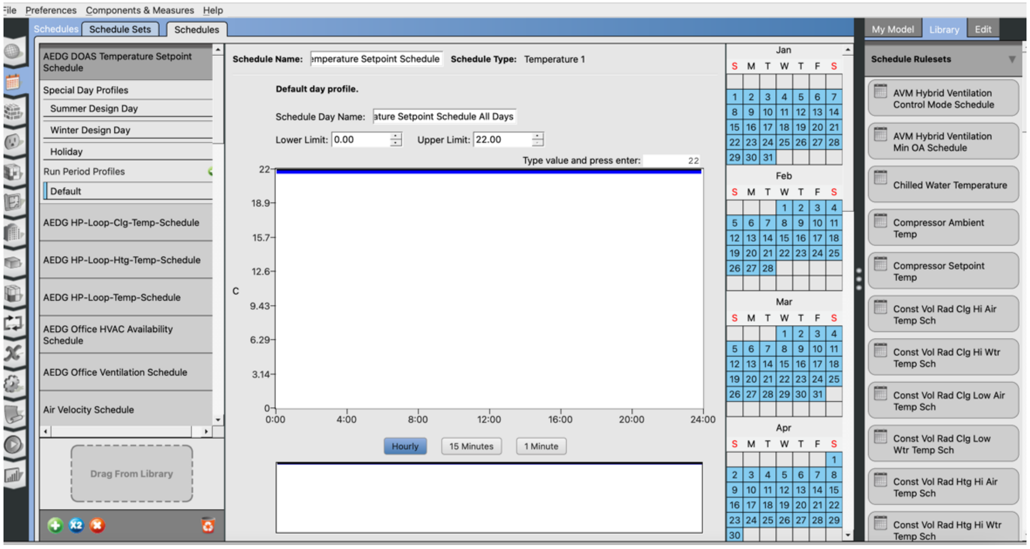


Figure B-17. Adjusting the setpoint temperature in OpenStudio

3. The authors then moved into the Space Types tab to adjust the ventilation schedule, as applying the heat pump measure altered the zones' air change rates. For the laboratory space types (Laboratory–Equipment corridor, Laboratory–Lab with fume hood, and Laboratory–Open lab) under Design Specification Outdoor Air, "Outdoor Air Flow Rate Fraction Schedule Name" was adjusted to select "Lab_HVACOperationSchd." Only Laboratory–Office was not modified by the authors. The ACHs remained at 6 and 15 for the respective laboratory spaces.

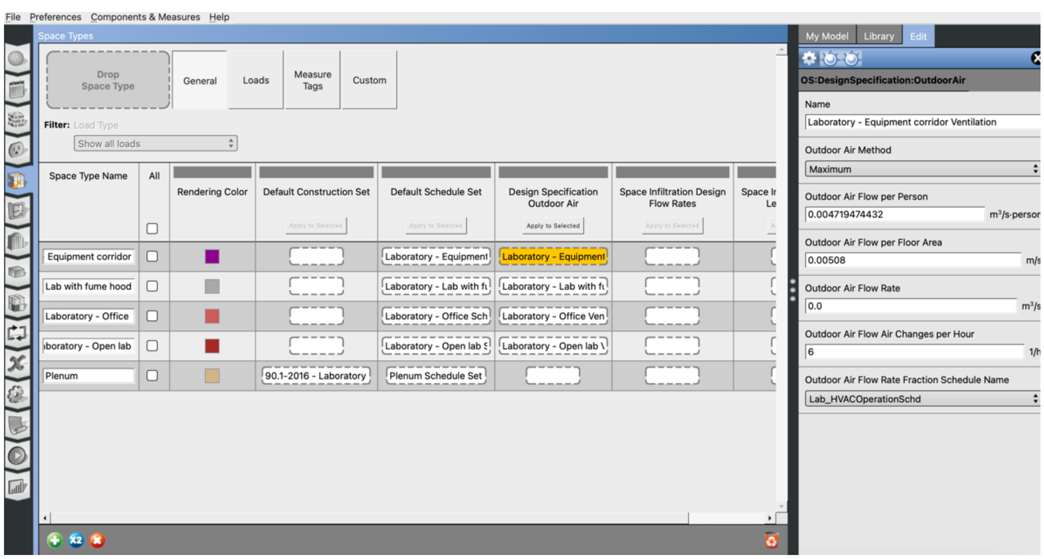


Figure B-18. Adjusting ventilation for heat pump model in OpenStudio

4. Under the HVAC Systems tab, the authors made multiple changes to the model's HVAC operations to account for the changes made by the AedgOfficeHvacWshpDoas measure. For one, the measure changed the layout of the HVAC loops so that each floor had its own AEDG Air Loop, servicing both the laboratory spaces and the office spaces. This is

in contrast to the original natural gas model, in which one HVAC system served the laboratories and one HVAC system served the office spaces.

a. Consulting the drop-down bar at the top of the HVAC Systems tab, the authors first went through each AEDG Air Loop to replace the heating coils from natural gas to electric. The "Elec Htg Coil" was pulled from the Library.

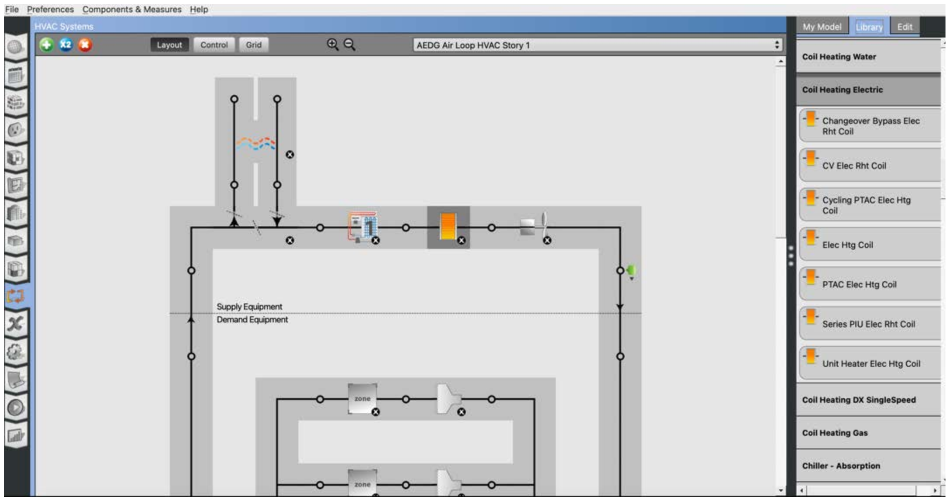


Figure B-19. Replacing natural gas oils with electric heating coils in OpenStudio

b. The AedgOfficeHvacWshpDoas measure replaced all the VAV reheat air terminals from the natural gas model with constant air volume single duct air terminals with no reheat properties. To fix this, the authors replaced all the constant air volume terminals on each floor with "AirTerminal Single Duct VAV NoReheat" pulled from the Library.

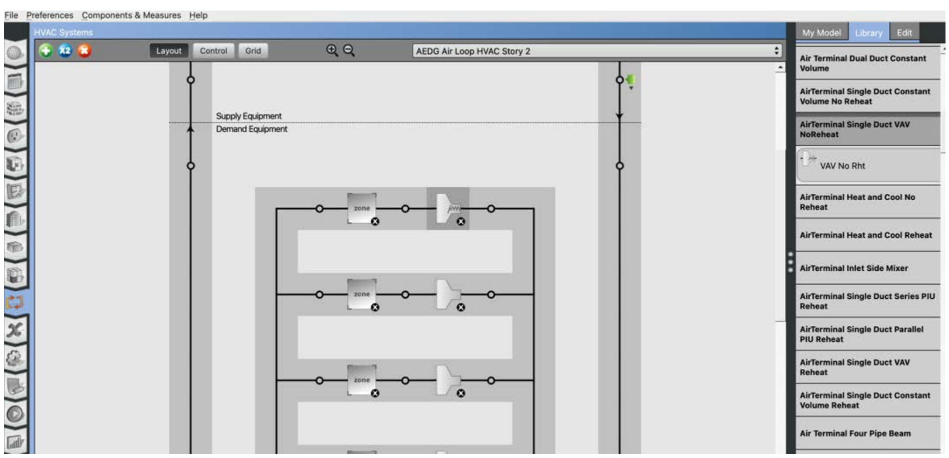


Figure B-20. Replacing constant air volume terminals with VAV terminals in OpenStudio

c. After replacing all the air terminals, the authors could then click on the VAV air terminals for each of the laboratory spaces and specify the ventilation provided to the space. For each of the laboratory spaces, the Zone Minimum Air Flow Input Method was adjusted to select "Scheduled" over "Constant." The Constant

Minimum Air Flow Fraction was also adjusted from "Hard Sized" to "Autosized." Finally, the authors selected "Lab_HVACOperationSchd" under Minimum Air Flow Fraction Schedule Name and toggled "Yes" for Control For Outdoor Air. The authors did not adjust the VAV terminals for the office spaces.

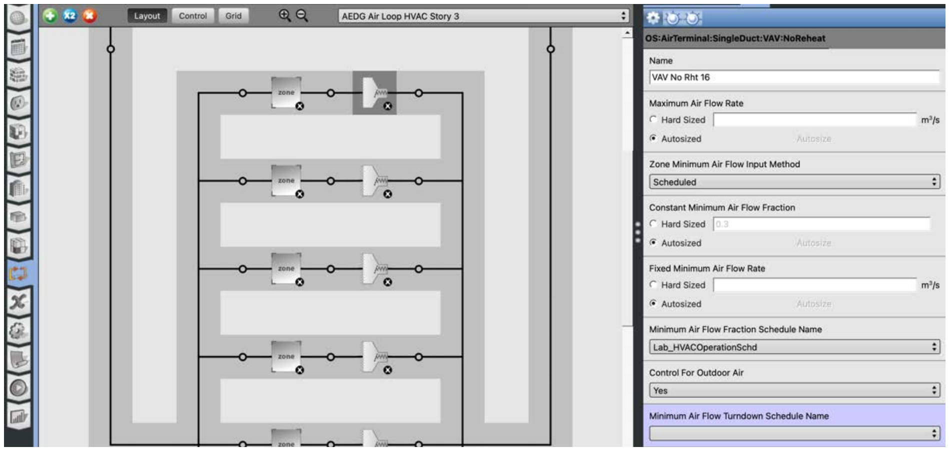


Figure B-21. Adjusting ventilation for air terminals in OpenStudio

d. The last step the authors took before running the model was to adjust the HVAC Operation Schedule under each Advanced Energy Design Guide Air Loop. Selecting the "Control" tab at the top of the window, the authors went into My Model to select the Lab_HVACOperationSchd under Ruleset Schedules. The authors dragged this schedule to replace the AEDG DOAS HVAC schedule under Time of Operation.

Figure B-22. Changing HVAC schedule in OpenStudio

5. To ensure that the heat pump laboratory model has the same ventilation rates as the natural gas model, the authors averaged the ventilation rates for the office spaces as shown in the EnergyPlus report. Then the authors increased the Outdoor Air Flow Air Changes per Hour until it resulted in air changes that matched the natural gas case. This change was made to make sure that the energy usage between the two cases were

comparable in terms of outdoor air delivered to each space. It should be noted that the default Outdoor Air Flow Air Changes per Hour rate for the office schedules was 0.

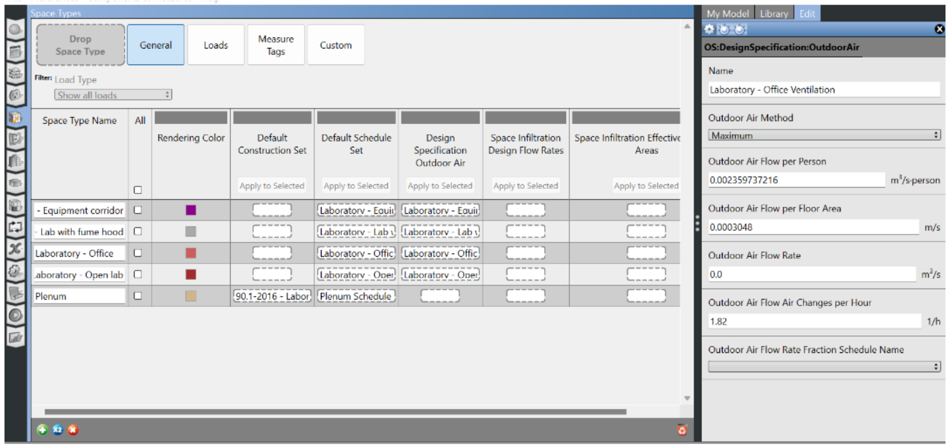


Figure B-23. Adjusting outdoor air flow for office spaces in OpenStudio

6. The authors also noted significant changes in the laboratory building model's fan energy usage after implementing the heat pump measures. The authors attributed these changes to the model assuming a district heating/cooling network where heat pumps are distributed throughout the building. To properly simulate the energy usage associated with a centralized heat pump network, the authors increased the pressure drop in each loop's supply fans to 926.61074 Pascals. The authors arrived at this calculation by dividing the natural gas model's pressure rise in its laboratory supply fan by three to equalize the total pressure drop between both systems.

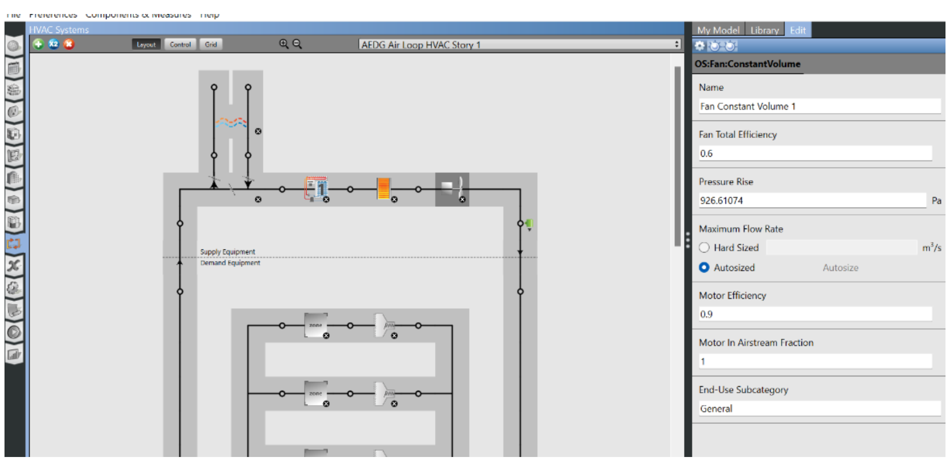


Figure B-24. Increasing pressure rise for supply fans in OpenStudio

7. The authors added exhaust fans to each air loop to compensate for the energy used in the natural gas model since the laboratory loop originally had an exhaust fan for the laboratory spaces' ventilation. The authors copied over the same parameters used to characterize the exhaust fan in the natural gas laboratory air loop, including the Fan Power Minimum Flow Rate Input Method, motor efficiency, and fan power coefficients.

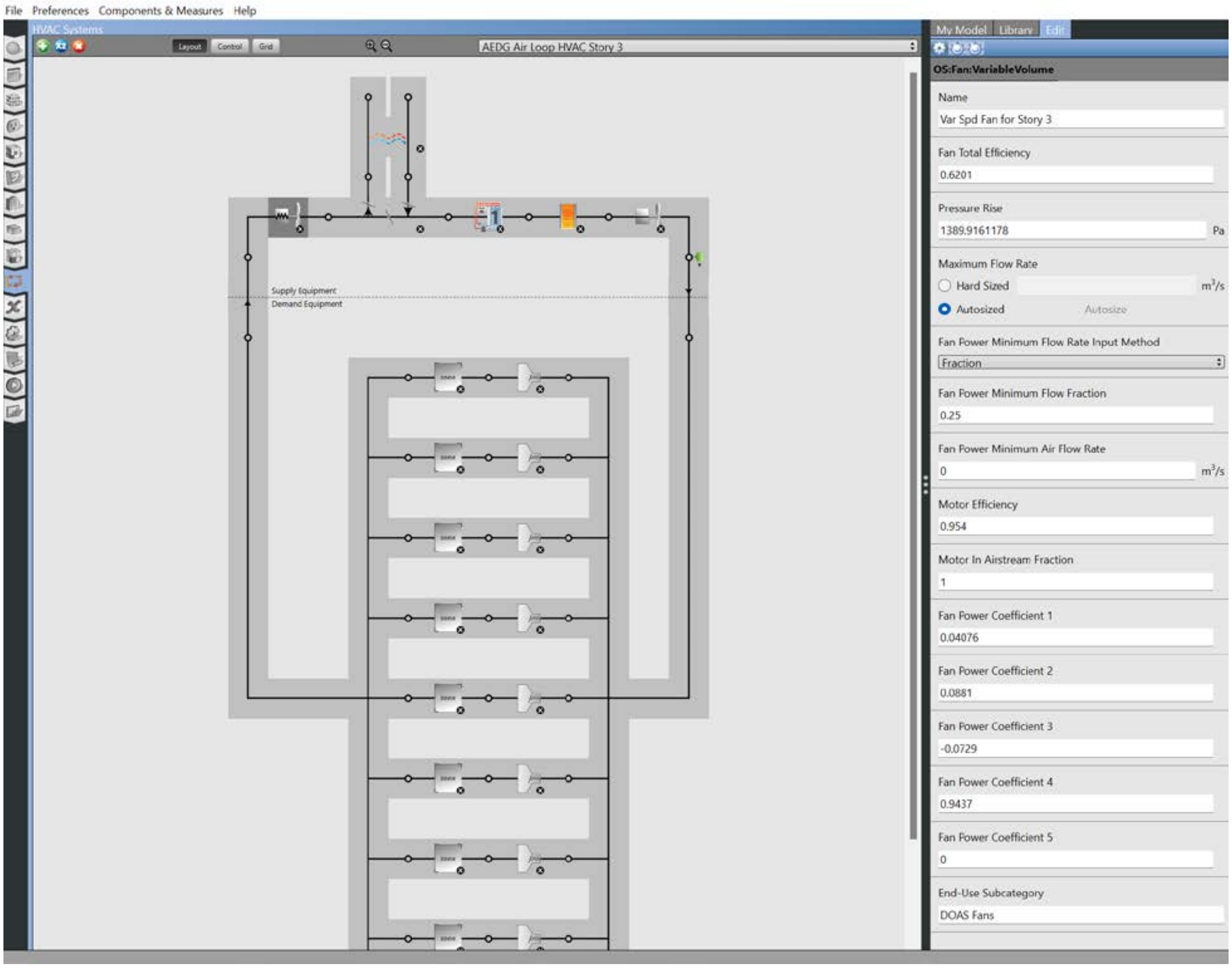


Figure B-25. Creating exhaust fan in OpenStudio

8. The authors also reconfigured the heat pump laboratory building model to match the economizer limits set within the natural gas model for the corresponding region. The authors matched each parameter, including the economizer control type, lockout type, and heat recovery bypass control type.

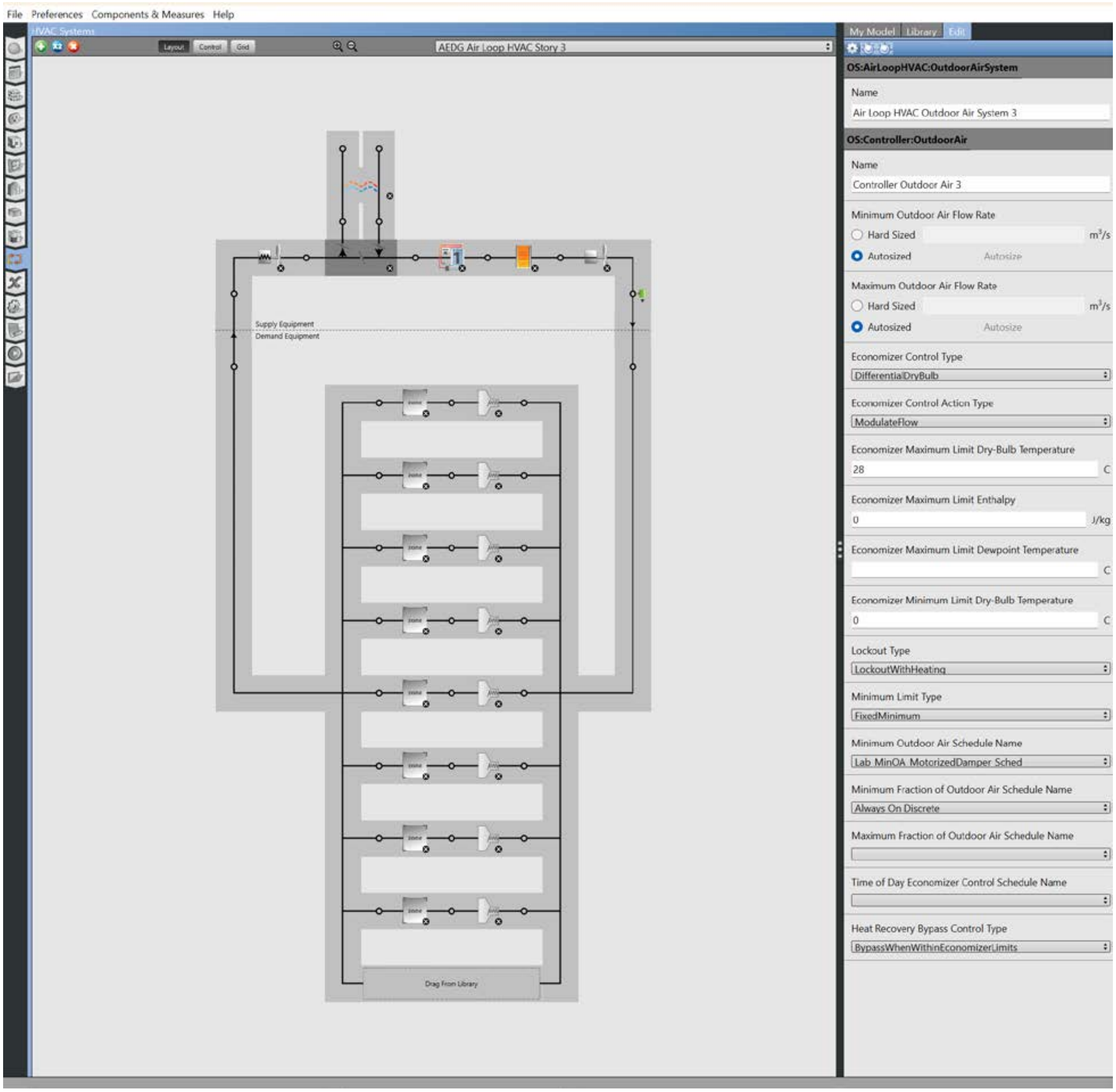


Figure B-26. Configuring economizer limits in OpenStudio

9. The authors added the CreateCSVOutput to the model's measures after enabling the following output variables to track: Cooling Coil Total Cooling Energy, District Cooling Rate, Fan Air Mass Flow Rate, Fan Electricity Rate, and Heating Coil Electricity Energy. These variables were used to post-process the model's energy usage in addition to tracking the ventilation delivered to each of the model's spaces to help ensure consistency between the two models.

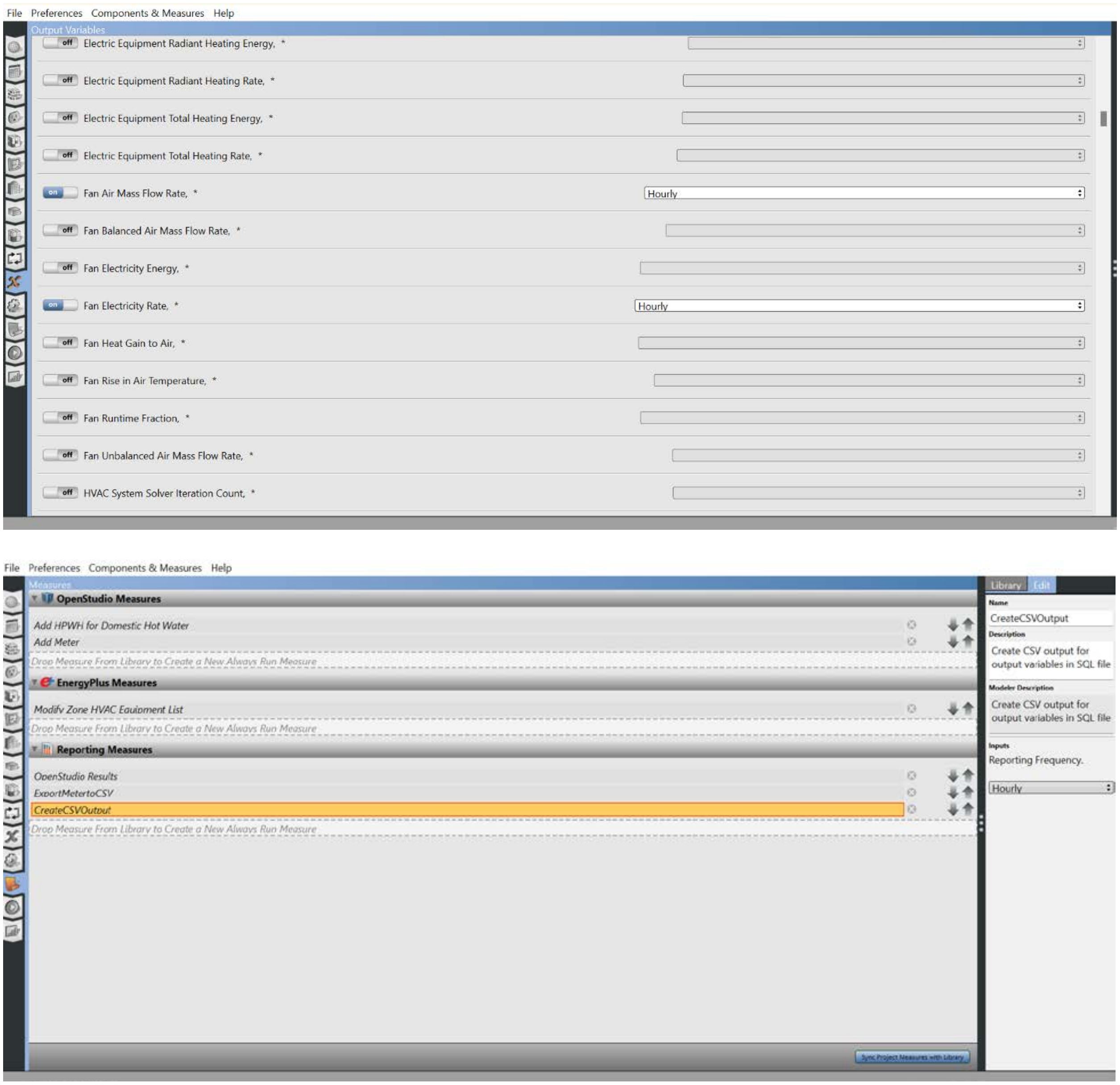


Figure B-27. Tracking output variables through OpenStudio

10. After OpenStudio ran the model, the final step the authors did to account for energy changes between the heat pump and natural gas model was to edit the pressure drop in each of heat pump fans in EnergyPlus. The authors first opened up the in.idf file produced by OpenStudio with the EnergyPlus IDFEditor. Searching for the Fan:OnOff parameter, the authors adjusted each object (with the exception of the heat pump in the hot water heater) to have a pressure rise of 600 Pascals. This process would simulate a centralized heat pump system where the primary equipment to temper the heat pump loop would be located on site, such as the top of the building through a cooling tower to reject heat from the loop.

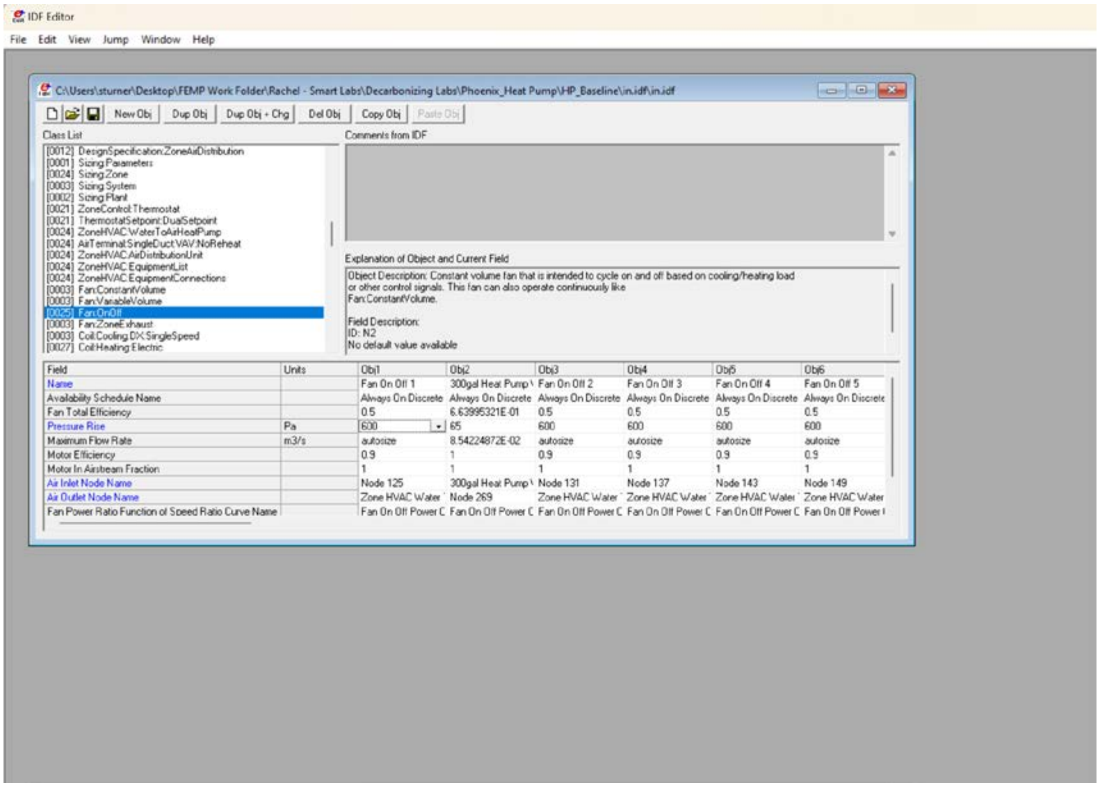


Figure B-28. Increasing pressure rise for individual heat pumps in EnergyPlus

11. Once the heat pumps were configured, the authors re-ran the model using the EnergyPlus EP-Launch, making sure to use the same weather file provided in OpenStudio.

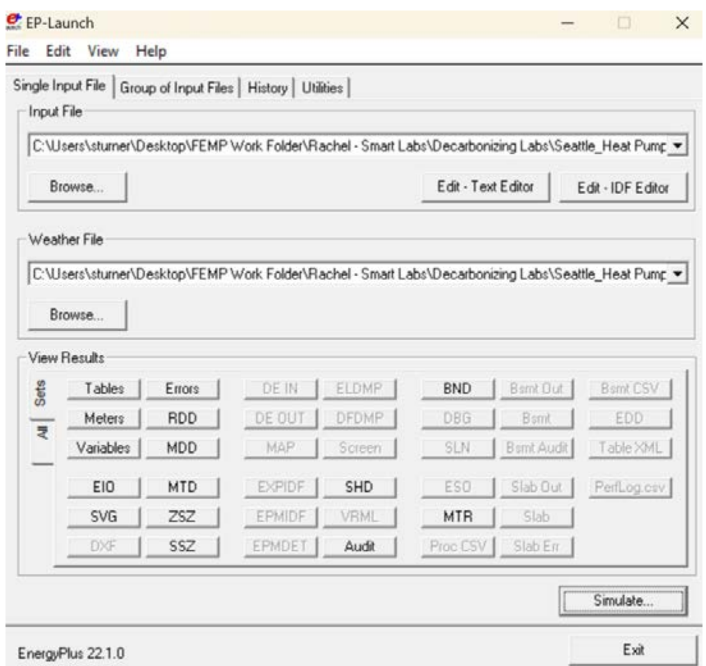
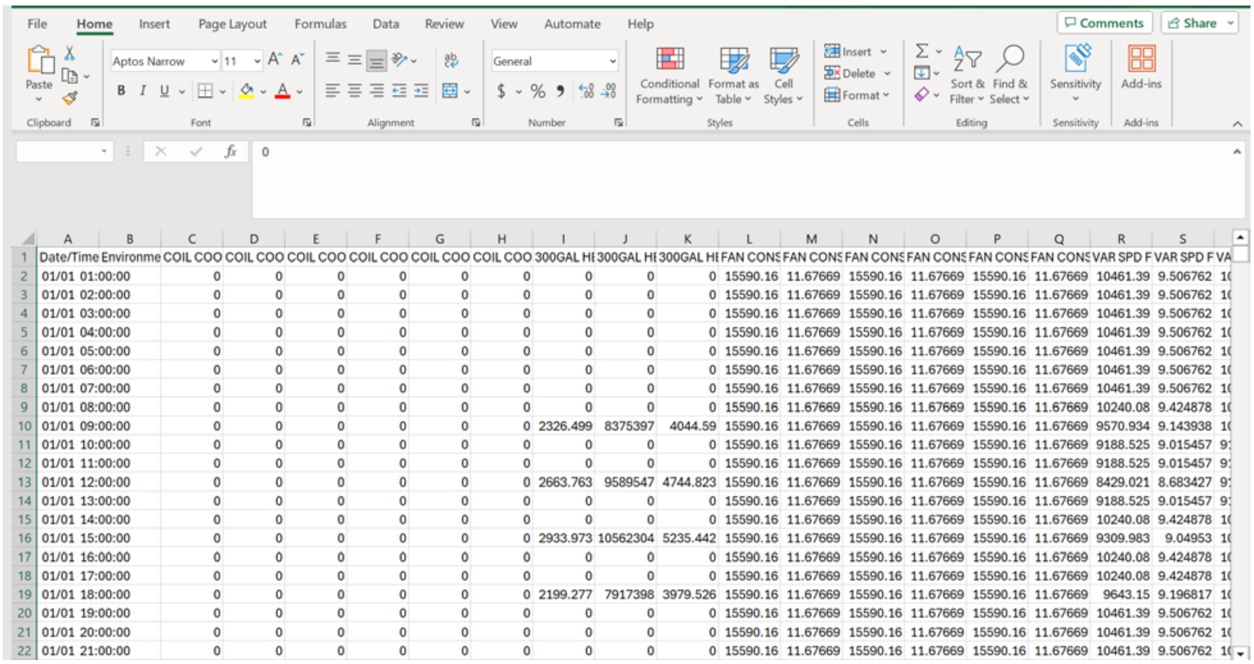


Figure B-29. Re-running model with new heat pump pressure rises in EnergyPlus

12. After copying and pasting the ReadVarsESO.exu application (found in the EnergyPlus PostProcess folder) into the in.idf folder, EnergyPlus created a new eplusout.csv file which tracks each of the output variables identified in Step 9. The authors specifically focused on the variables in columns: DISTRICT COOLING 1:District Cooling Rate [W](Hourly), ELEC HTG COIL:Heating Coil Electricity Energy [J](Hourly), ELEC HTG COIL 1:Heating Coil Electricity Energy [J](Hourly), ELEC HTG COIL 2:Heating Coil Electricity Energy [J](Hourly), and Electricity:Facility [J](Hourly).[74]



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	
1	Date/Time	Environme	COIL COO	COIL COO	COIL COO	COIL COO	COIL COO	COIL COO	300GAL HI	300GAL HI	300GAL HI	FAN CONS	FAN CONS	FAN CONS	FAN CONS	FAN CONS	FAN CONS	VAR SPD F	VAR SPD F	VA
2	01/01 01:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
3	01/01 02:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
4	01/01 03:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
5	01/01 04:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
6	01/01 05:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
7	01/01 06:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
8	01/01 07:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
9	01/01 08:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10240.08	9.424878	1(
10	01/01 09:00:00		0	0	0	0	0	0	2326.499	8375397	4044.59	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	9570.934	9.143938	1(
11	01/01 10:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	9188.525	9.015457	9:
12	01/01 11:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	9188.525	9.015457	9:
13	01/01 12:00:00		0	0	0	0	0	0	2663.763	9589547	4744.823	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	8429.021	8.683427	9:
14	01/01 13:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	9188.525	9.015457	9:
15	01/01 14:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10240.08	9.424878	1(
16	01/01 15:00:00		0	0	0	0	0	0	2933.973	10562304	5235.442	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	9309.983	9.04953	1(
17	01/01 16:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10240.08	9.424878	1(
18	01/01 17:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10240.08	9.424878	1(
19	01/01 18:00:00		0	0	0	0	0	0	2199.277	7917398	3979.526	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	9643.15	9.196817	1(
20	01/01 19:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
21	01/01 20:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(
22	01/01 21:00:00		0	0	0	0	0	0	0	0	0	15590.16	11.67669	15590.16	11.67669	15590.16	11.67669	10461.39	9.506762	1(

Figure B-30. Sample eplusout.csv file generated from ReadVarsESO.exu

a. The first step in post-processing the data to simulate a heat pump's energy usage was to convert the DISTRICT COOLING 1:District Cooling Rate [W](Hourly) into a kWh conversion and then to divide the timestep by 6. A COP of 6 was chosen to account for the energy used in cooling the main district loop for a water-source heat pump.

[74] Note that to have an hourly timestep, users in the IDFEditor would need to search for "Timestep" and change the number of units to one.

	A	B	C	D	E	F
1	Date/Time		DISTRICT (	kWh Conv	COP of 6	
2	01/01 01:00:00		67597.74	67.59774	11.26629	
3	01/01 02:00:00		66559.47	66.55947	11.09324	
4	01/01 03:00:00		65693.86	65.69386	10.94898	
5	01/01 04:00:00		65039.78	65.03978	10.83996	
6	01/01 05:00:00		64507.45	64.50745	10.75124	
7	01/01 06:00:00		83654.5	83.6545	13.94242	
8	01/01 07:00:00		85599.27	85.59927	14.26654	
9	01/01 08:00:00		0	0	0	
10	01/01 09:00:00		0	0	0	
11	01/01 10:00:00		123704.2	123.7042	20.61736	
12	01/01 11:00:00		138244.9	138.2449	23.04082	
13	01/01 12:00:00		111581.1	111.5811	18.59685	
14	01/01 13:00:00		109347.8	109.3478	18.22464	
15	01/01 14:00:00		109083.9	109.0839	18.18065	
16	01/01 15:00:00		105289.7	105.2897	17.54829	
17	01/01 16:00:00		104681.2	104.6812	17.44687	
18	01/01 17:00:00		80386.78	80.38678	13.3978	
19	01/01 18:00:00		74677.13	74.67713	12.44619	
20	01/01 19:00:00		72817.66	72.81766	12.13628	
21	01/01 20:00:00		72493.23	72.49323	12.08221	
22	01/01 21:00:00		71005.13	71.00513	11.83419	

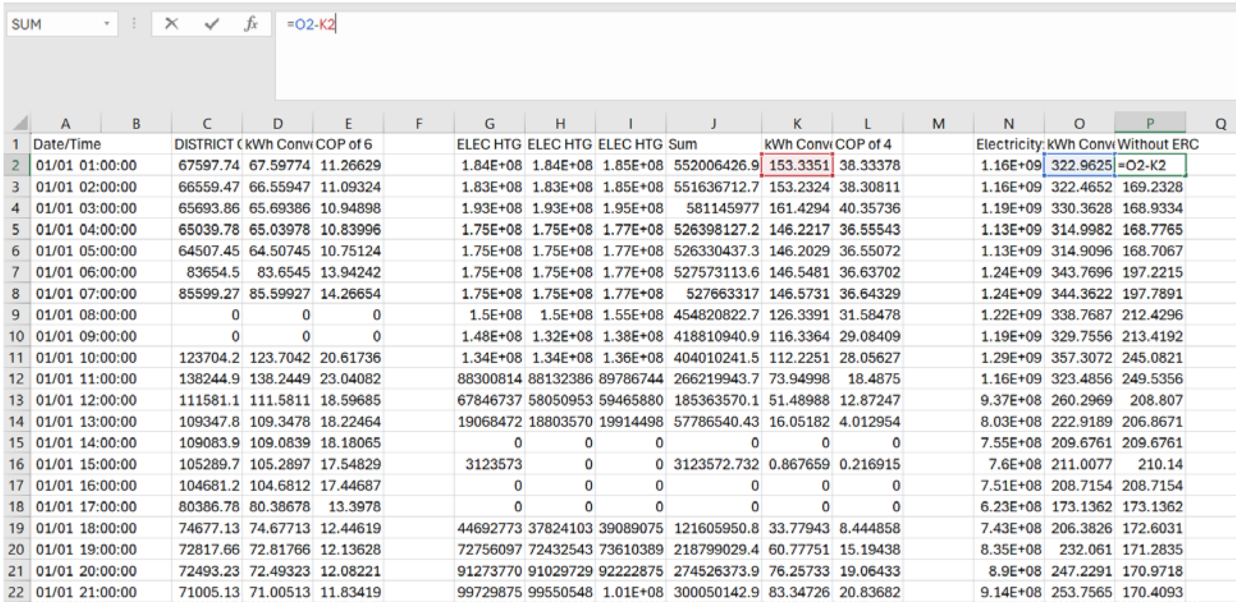
Figure B-31. Converting district cooling energy to COP for a water-source heat pump

b. The second step in post-processing the data was to sum all the energy from the electric resistance-heating coils (ERC) and convert it to a kWh variable. After summarizing and converting the timesteps, the authors then divided the energy by 4 to simulate the COP for a ground-source heat pump.

F	G	H	I	J	K	L	M
	ELEC HTG	ELEC HTG	ELEC HTG	Sum	kWh Conv	COP of 4	
	1.84E+08	1.84E+08	1.85E+08	552006426.9	153.3351	38.33378	
	1.83E+08	1.83E+08	1.85E+08	551636712.7	153.2324	38.30811	
	1.93E+08	1.93E+08	1.95E+08	581145977	161.4294	40.35736	
	1.75E+08	1.75E+08	1.77E+08	526398127.2	146.2217	36.55543	
	1.75E+08	1.75E+08	1.77E+08	526330437.3	146.2029	36.55072	
	1.75E+08	1.75E+08	1.77E+08	527573113.6	146.5481	36.63702	
	1.75E+08	1.75E+08	1.77E+08	527663317	146.5731	36.64329	
	1.5E+08	1.5E+08	1.55E+08	454820822.7	126.3391	31.58478	
	1.48E+08	1.32E+08	1.38E+08	418810940.9	116.3364	29.08409	
	1.34E+08	1.34E+08	1.36E+08	404010241.5	112.2251	28.05627	
	88300814	88132386	89786744	266219943.7	73.94998	18.4875	
	67846737	58050953	59465880	185363570.1	51.48988	12.87247	
	19068472	18803570	19914498	57786540.43	16.05182	4.012954	
	0	0	0	0	0	0	
	3123573	0	0	3123572.732	0.867659	0.216915	
	0	0	0	0	0	0	
	0	0	0	0	0	0	
	44692773	37824103	39089075	121605950.8	33.77943	8.444858	
	72756097	72432543	73610389	218799029.4	60.77751	15.19438	
	91273770	91029729	92222875	274526373.9	76.25733	19.06433	
	99729875	99550548	1.01E+08	300050142.9	83.34726	20.83682	

Figure B-32. Converting ERC energy to COP for a ground-source heat pump

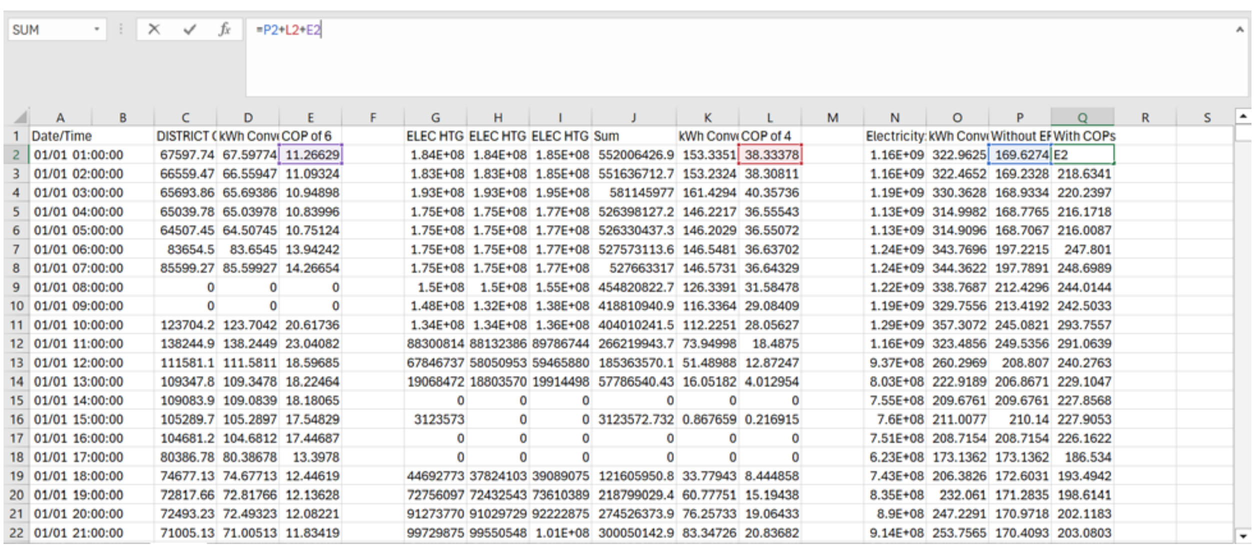
c. The third step in post-processing the data was to convert the total facility's electricity consumption to a kWh energy unit and subtract out the original hourly energy usage for the ERCs. This was done to get the total energy usage of the building outside of its heating and cooling needs.


SUM =O2-K2

	Date/Time	DISTRICT (	kWh Conv	COP of 6	ELEC HTG	ELEC HTG	ELEC HTG	Sum	kWh Conv	COP of 4	Electricity:	kWh Conv	Without ERC
2	01/01 01:00:00	67597.74	67.59774	11.26629	1.84E+08	1.84E+08	1.85E+08	552006426.9	153.3351	38.33378	1.16E+09	322.9625	=O2-K2
3	01/01 02:00:00	66559.47	66.55947	11.09324	1.83E+08	1.83E+08	1.85E+08	551636712.7	153.2324	38.30811	1.16E+09	322.4652	169.2328
4	01/01 03:00:00	65693.86	65.69386	10.94898	1.93E+08	1.93E+08	1.95E+08	581145977	161.4294	40.35736	1.19E+09	330.3628	168.9334
5	01/01 04:00:00	65039.78	65.03978	10.83996	1.75E+08	1.75E+08	1.77E+08	526398127.2	146.2217	36.55543	1.13E+09	314.9982	168.7765
6	01/01 05:00:00	64507.45	64.50745	10.75124	1.75E+08	1.75E+08	1.77E+08	526330437.3	146.2029	36.55072	1.13E+09	314.9096	168.7067
7	01/01 06:00:00	83654.5	83.6545	13.94242	1.75E+08	1.75E+08	1.77E+08	527573113.6	146.5481	36.63702	1.24E+09	343.7696	197.2215
8	01/01 07:00:00	85599.27	85.59927	14.26654	1.75E+08	1.75E+08	1.77E+08	527663317	146.5731	36.64329	1.24E+09	344.3622	197.7891
9	01/01 08:00:00	0	0	0	1.5E+08	1.5E+08	1.55E+08	454820822.7	126.3391	31.58478	1.22E+09	338.7687	212.4296
10	01/01 09:00:00	0	0	0	1.48E+08	1.32E+08	1.38E+08	418810940.9	116.3364	29.08409	1.19E+09	329.7556	213.4192
11	01/01 10:00:00	123704.2	123.7042	20.61736	1.34E+08	1.34E+08	1.36E+08	404010241.5	112.2251	28.05627	1.29E+09	357.3072	245.0821
12	01/01 11:00:00	138244.9	138.2449	23.04082	88300814	88132386	89786744	266219943.7	73.94998	18.4875	1.16E+09	323.4856	249.5356
13	01/01 12:00:00	111581.1	111.5811	18.59685	67846737	58050953	59465880	185363570.1	51.48988	12.87247	9.37E+08	260.2969	208.807
14	01/01 13:00:00	109347.8	109.3478	18.22464	19068472	18803570	19914498	57786540.43	16.05182	4.012954	8.03E+08	222.9189	206.8671
15	01/01 14:00:00	109083.9	109.0839	18.18065	0	0	0	0	0	0	7.55E+08	209.6761	209.6761
16	01/01 15:00:00	105289.7	105.2897	17.54829	3123573	0	0	3123572.732	0.867659	0.216915	7.6E+08	211.0077	210.14
17	01/01 16:00:00	104681.2	104.6812	17.44687	0	0	0	0	0	0	7.51E+08	208.7154	208.7154
18	01/01 17:00:00	80386.78	80.38678	13.3978	0	0	0	0	0	0	6.23E+08	173.1362	173.1362
19	01/01 18:00:00	74677.13	74.67713	12.44619	44692773	37824103	39089075	121605950.8	33.77943	8.444858	7.43E+08	206.3826	172.6031
20	01/01 19:00:00	72817.66	72.81766	12.13628	72756097	72432543	73610389	218799029.4	60.77751	15.19438	8.35E+08	232.061	171.2835
21	01/01 20:00:00	72493.23	72.49323	12.08221	91273770	91029729	92222875	274526373.9	76.25733	19.06433	8.9E+08	247.2291	170.9718
22	01/01 21:00:00	71005.13	71.00513	11.83419	99729875	99550548	1.01E+08	300050142.9	83.34726	20.83682	9.14E+08	253.7565	170.4093

Figure B-33. Calculating building energy usage outside of heating and cooling needs

d. The fourth step in post-processing the data was to add back the heating and cooling needs of the building with the energy usage post-processed to take into account the energy savings of using heat pumps. This included adding in the district cooling loop's energy through a water-source heat pump and the building's heating energy through a ground-source heat pump. The summary of this column was then fed into REopt to generate energy cost projections.


SUM =P2+L2+E2

	Date/Time	DISTRICT (	kWh Conv	COP of 6	ELEC HTG	ELEC HTG	ELEC HTG	Sum	kWh Conv	COP of 4	Electricity:	kWh Conv	Without EF	With COPs
2	01/01 01:00:00	67597.74	67.59774	11.26629	1.84E+08	1.84E+08	1.85E+08	552006426.9	153.3351	38.33378	1.16E+09	322.9625	169.6274	E2
3	01/01 02:00:00	66559.47	66.55947	11.09324	1.83E+08	1.83E+08	1.85E+08	551636712.7	153.2324	38.30811	1.16E+09	322.4652	169.2328	218.6341
4	01/01 03:00:00	65693.86	65.69386	10.94898	1.93E+08	1.93E+08	1.95E+08	581145977	161.4294	40.35736	1.19E+09	330.3628	168.9334	220.2397
5	01/01 04:00:00	65039.78	65.03978	10.83996	1.75E+08	1.75E+08	1.77E+08	526398127.2	146.2217	36.55543	1.13E+09	314.9982	168.7765	216.1718
6	01/01 05:00:00	64507.45	64.50745	10.75124	1.75E+08	1.75E+08	1.77E+08	526330437.3	146.2029	36.55072	1.13E+09	314.9096	168.7067	216.0087
7	01/01 06:00:00	83654.5	83.6545	13.94242	1.75E+08	1.75E+08	1.77E+08	527573113.6	146.5481	36.63702	1.24E+09	343.7696	197.2215	247.801
8	01/01 07:00:00	85599.27	85.59927	14.26654	1.75E+08	1.75E+08	1.77E+08	527663317	146.5731	36.64329	1.24E+09	344.3622	197.7891	248.6989
9	01/01 08:00:00	0	0	0	1.5E+08	1.5E+08	1.55E+08	454820822.7	126.3391	31.58478	1.22E+09	338.7687	212.4296	244.0144
10	01/01 09:00:00	0	0	0	1.48E+08	1.32E+08	1.38E+08	418810940.9	116.3364	29.08409	1.19E+09	329.7556	213.4192	242.5033
11	01/01 10:00:00	123704.2	123.7042	20.61736	1.34E+08	1.34E+08	1.36E+08	404010241.5	112.2251	28.05627	1.29E+09	357.3072	245.0821	293.7557
12	01/01 11:00:00	138244.9	138.2449	23.04082	88300814	88132386	89786744	266219943.7	73.94998	18.4875	1.16E+09	323.4856	249.5356	291.0639
13	01/01 12:00:00	111581.1	111.5811	18.59685	67846737	58050953	59465880	185363570.1	51.48988	12.87247	9.37E+08	260.2969	208.807	240.2763
14	01/01 13:00:00	109347.8	109.3478	18.22464	19068472	18803570	19914498	57786540.43	16.05182	4.012954	8.03E+08	222.9189	206.8671	229.1047
15	01/01 14:00:00	109083.9	109.0839	18.18065	0	0	0	0	0	0	7.55E+08	209.6761	209.6761	227.8568
16	01/01 15:00:00	105289.7	105.2897	17.54829	3123573	0	0	3123572.732	0.867659	0.216915	7.6E+08	211.0077	210.14	227.9053
17	01/01 16:00:00	104681.2	104.6812	17.44687	0	0	0	0	0	0	7.51E+08	208.7154	208.7154	226.1622
18	01/01 17:00:00	80386.78	80.38678	13.3978	0	0	0	0	0	0	6.23E+08	173.1362	173.1362	186.534
19	01/01 18:00:00	74677.13	74.67713	12.44619	44692773	37824103	39089075	121605950.8	33.77943	8.444858	7.43E+08	206.3826	172.6031	193.4942
20	01/01 19:00:00	72817.66	72.81766	12.13628	72756097	72432543	73610389	218799029.4	60.77751	15.19438	8.35E+08	232.061	171.2835	198.6141
21	01/01 20:00:00	72493.23	72.49323	12.08221	91273770	91029729	92222875	274526373.9	76.25733	19.06433	8.9E+08	247.2291	170.9718	202.1183
22	01/01 21:00:00	71005.13	71.00513	11.83419	99729875	99550548	1.01E+08	300050142.9	83.34726	20.83682	9.14E+08	253.7565	170.4093	203.0803

Figure B-34. Adding back in heat pump performance to get total facility electricity usage

B.4 Analyzing Simulation Data

After running the models, the authors collected the data and calculated the energy and emissions savings from each model. Tables B- 1 through B- 7 capture the most relevant data the authors collected from the reports generated by OpenStudio and REopt. An additional resource consulted by the authors was the Greenhouse Gas Equivalencies Calculator, developed by the U.S. Environmental Protection Agency (EPA).[75] This calculator translates energy data into emissions data. The authors fed the data collected on each model's consumption of natural gas into the Greenhouse Gas Equivalencies Calculator, which produced approximations for the CO_2-E emissions produced by burning the natural gas.

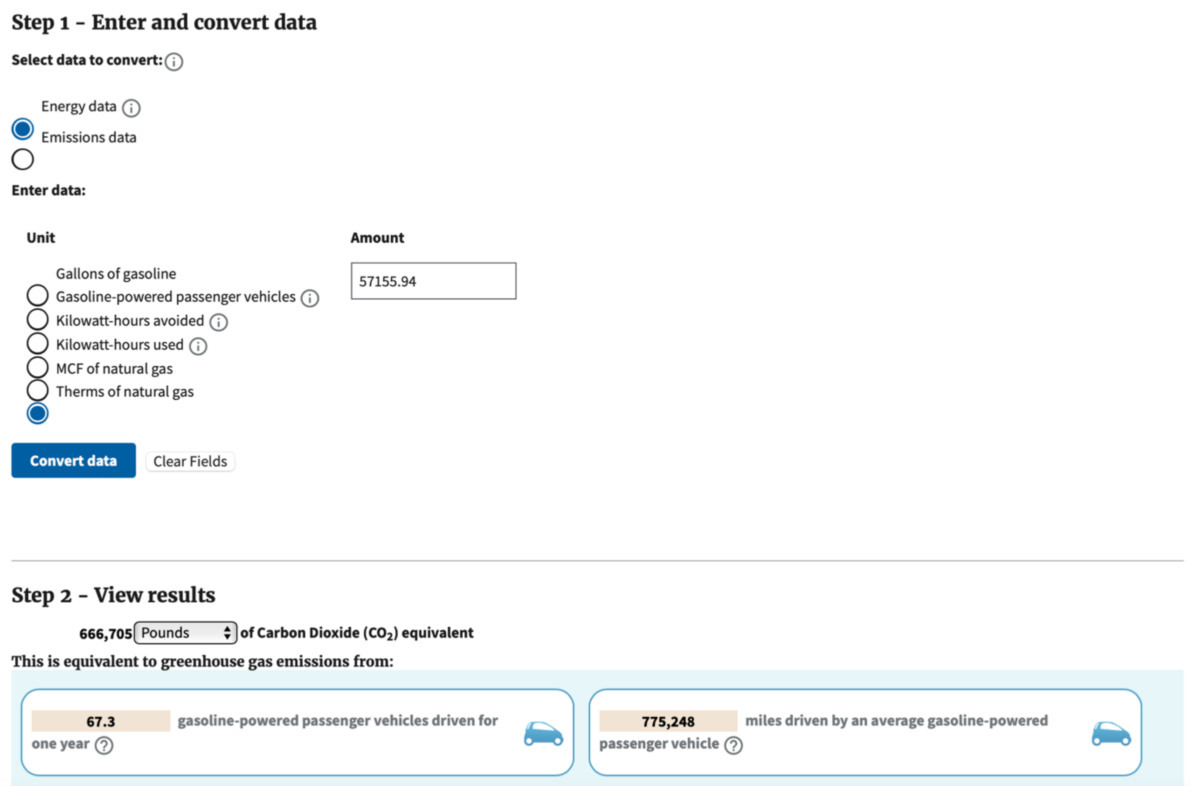


Figure B-35. Greenhouse Gas Equivalencies Calculator

[75] To learn more about the Greenhouse Gas Equivalencies Calculator, visit https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

Table B-1. Data Collected on Phoenix Laboratory Building Prototype Model

Data Collected According to Model Type	Baseline	Lighting and Plug Loads	Smart Hot Water Heater	Smart Ventilation	All Strategies
Total Site EUI (kBtu/ft^2)	178.24	176.91	178.18	122.68	119.37
Energy Costs–Natural Gas					
Total kBtu (pulled from OpenStudio)	5,379,696	5,511,604	5,382,805	2,904,045	2,945,569
Total Therms	53,809.82	55,129.22	53,840.92	29,047.39	29,462.73
Price Per Therm	1.04349	1.04349	1.04349	1.04349	1.04349
Annual Cost–Natural Gas	$56,150.01	$57,526.79	$56,182.46	$30,310.66	$30,744.07
Energy Costs—Electricity					
Total kWh (pulled from OpenStudio)	3,124,713	3,051,042	3,122,176	2,384,784	2,285,237
Annual Cost–Electricity (pulled from REopt)	$327,159	$310,827	$326,521	$270,623	$249,089
Total Annual Energy Costs	**$383,309.01**	**$368,353.79**	**$382,703.46**	**$300,933.66**	**$279,833.07**
Energy Cost Intensity ($/ft^2/yr)	**4.26**	**4.09**	**4.25**	**3.34**	**3.11**
Change in Energy Cost Intensity from Baseline	-	-3.902%	-0.158%	-21.491%	-26.995%
	-	-$0.17	-$0.01	-$0.92	-$1.15
CO_2-Equivalent Emissions–Natural Gas					
Pounds of CO_2-E (pulled from EPA)	627,673	643,064	628,036	338,828	343,673
Metric Tons of CO_2-E	284.71	291.69	284.88	153.69	155.89
CO_2-Equivalent Emissions–Electricity					
Metric Tons of CO_2-E (pulled from REopt)	1,940	1,894	1,939	1,479	1,416
Pounds of CO_2-E	4,276,962.80	4,175,550.28	4,274,758.18	3,260,632.98	3,121,741.92
Total Pounds of CO_2-E	**4,904,635.80**	**4,818,614.28**	**4,902,794.18**	**3,599,460.98**	**3,465,414.92**
Emission Intensity (lbs/ft^2/yr)	**54.50**	**53.54**	**54.48**	**39.99**	**38.50**
Change in Emission Intensity from Baseline	-	-1.754%	-0.038%	-26.611%	-29.344%
	-	-0.96 lbs	-0.02 lbs	-14.50 lbs	-15.99 lbs

Table B-2. Data Collected on Atlanta Laboratory Building Prototype Model

Data Collected According to Model Type	Baseline	Lighting and Plug Loads	Smart Hot Water Heater	Smart Ventilation	All Strategies
Total Site EUI (kBtu/ft^2)	199.34	198.48	199.25	135.55	134.67
Energy Costs–Natural Gas					
Total kBtu (pulled from OpenStudio)	7,230,707	7,256,099	7,230,916	4,456,665	4,487,478
Total Therms	72,324.36	72,578.34	72,326.45	44,577.30	44,885.51
Price Per Therm	1.3495518	1.3495518	1.3495518	1.3495518	1.3495518
Annual Cost–Natural Gas	$97,605.46	$97,948.22	$97,608.29	$60,159.38	$60,575.32
Energy Costs–Electricity					
Total kWh (pulled from OpenStudio)	3,138,759	3,108,590	3,136,449	2,269,331	2,236,834
Annual Cost–Electricity (pulled from REopt)	$250,162	$245,826	$250,021	$183,060	$178,417
Total Annual Energy Costs	**$347,767.46**	**$343,774.22**	**$347,629.29**	**$243,219.38**	**$238,992.32**
Energy Cost Intensity ($/ft^2/yr)	**3.86**	**3.82**	**3.86**	**2.70**	**2.66**
Change in Energy Cost Intensity from Baseline	-	-1.148%	-0.040%	-30.063%	-31.278%
	-	-$0.04	$0.00	-$1.16	-$1.21
CO_2-Equivalent Emissions–Natural Gas					
Pounds of CO_2-E (pulled from EPA)	843,639	846,602	843,663	519,979	523,574
Metric Tons of CO_2-E	382.67	384.02	382.68	235.86	237.49
CO_2-Equivalent Emissions–Electricity					
Metric Tons of CO_2-E (pulled from REopt)	2,111	2,093	2,110	1,525	1,505
Pounds of CO_2-E	4,653,952.82	4,614,269.66	4,651,748.20	3,362,045.50	3,317,953.10
Total Pounds of CO_2-E	**5,497,591.82**	**5,460,871.66**	**5,495,411.20**	**3,882,024.50**	**3,841,527.10**
Emission Intensity (lbs/ft^2/yr)	**61.08**	**60.68**	**61.06**	**43.13**	**42.68**
Change in Emission Intensity from Baseline	-	-0.0668%	-0.040%	-29.387%	-30.123%
	-	-0.41 lbs	-0.02 lbs	-17.95 lbs	-18.40 lbs

Table B-3. Data Collected on Seattle Laboratory Building Prototype Model

Data Collected According to Model Type	Baseline	Lighting and Plug Loads	Smart Hot Water Heater	Smart Ventilation	All Strategies
Total Site EUI (kBtu/ft^2)	161.10	160.56	161.06	107.61	106.47
Energy Costs–Natural Gas					
Total kBtu (pulled from OpenStudio)	6,385,634	6,466,094	6,398,306	3,731,148	3,791,458
Total Therms	63,871.61	64,676.40	63,998.36	37,320.40	37,923.64
Price Per Therm	$1.13983	$1.13983	$1.13983	$1.13983	$1.13983
Annual Cost–Natural Gas	$72,802.77	$73,720.10	$72,947.25	$42,538.91	$43,226.51
Energy Costs–Electricity					
Total kWh (pulled from OpenStudio)	2,377,916	2,340,003	2,373,078	1,744,910	1,697,033
Annual Cost–Electricity (pulled from REopt)	$220,515	$216,523	$219,960	$169,542	$164,637
Total Annual Energy Costs	**$293,317.77**	**$290,243.10**	**$292,907.25**	**$212,080.91**	**$207,863.51**
Energy Cost Intensity ($/ft^2/yr)	**3.26**	**3.22**	**3.25**	**2.36**	**2.31**
Change in Energy Cost Intensity from Baseline	-	-1.048%	-0.140%	-27.696%	-29.134%
	-	-$0.03	$0.00	-$0.90	-$0.95
CO_2-Equivalent Emissions–Natural Gas					
Pounds of CO_2-E (pulled from EPA)	745,041	754,428	746,519	435,330	442,366
Metric Tons of CO_2-E	337.95	342.21	338.62	197.46	200.66
CO_2-Equivalent Emissions–Electricity					
Metric Tons of CO_2-E (pulled from REopt)	1,792	1,764	1,789	1,316	1,280
Pounds of CO_2-E	3,950,679.04	3,888,949.68	3,944,065.18	2,901,279.92	2,821,913.60
Total Pounds of CO_2-E	**4,695,720.04**	**4,643,377.68**	**4,690,584.18**	**3,336,609.92**	**3,264,279.60**
Emission Intensity (lbs/ft^2/yr)	**52.17**	**51.59**	**52.12**	**37.07**	**36.27**
Change in Emission Intensity from Baseline	-	-1.115%	-0.109%	-28.944%	-30.484%
	-	-0.58 lbs	-0.06 lbs	-15.10 lbs	-15.90 lbs

Table B-4. Data Collected on Denver Laboratory Building Prototype Model

Data Collected According to Model Type	Baseline	Lighting and Plug Loads	Smart Hot Water Heater	Smart Ventilation	All Strategies
Total Site EUI (kBtu/ft^2)	160.40	158.64	160.43	115.99	113.85
Energy Costs–Natural Gas					
Total kBtu (pulled from OpenStudio)	5,714,228	5,733,943	5,724,294	3,885,633	3,898,324
Total Therms	57,155.94	57,353.14	57,256.62	38,865.62	38,992.56
Price Per Therm	1.123	1.123	1.123	1.123	1.123
Annual Cost–Natural Gas	$64,186.12	$64,407.57	$64,299.19	$43,646.09	$43,788.64
Energy Costs–Electricity					
Total kWh (pulled from OpenStudio)	2,556,172	2,503,866	2,553,986	1,920,571	1,860,360
Annual Cost–Electricity (pulled from REopt)	$218,587	$210,257	$215,800	$176,709	$167,077
Total Annual Energy Costs	**$282,773.12**	**$274,664.57**	**$280,099.19**	**$220,355.09**	**$210,865.64**
Energy Cost Intensity ($/ft^2/yr)	**3.14**	**3.05**	**3.11**	**2.45**	**2.34**
Change in Energy Cost Intensity from Baseline	-	-2.868%	-0.946%	-22.074%	-25.429%
	-	-$0.09	-$0.03	-$0.69	-$0.80
CO_2-Equivalent Emissions–Natural Gas					
Pounds of CO_2-E (pulled from EPA)	666,705	669,005	667,879	453,354	454,835
Metric Tons of CO_2-E	302.42	303.46	302.95	205.64	206.31
CO_2-Equivalent Emissions–Electricity					
Metric Tons of CO_2-E (pulled from REopt)	2,005	1,966	2,003	1,499	1,455
Pounds of CO_2-E	4,420,263.10	4,334,282.92	4,415,853.86	3,304,725.38	3,207,722.10
Total Pounds of CO_2-E	**5,086.968.10**	**5,003,287.92**	**5,083,732.86**	**3,758,079.38**	**3,662,557.10**
Emission Intensity (lbs/ft^2/yr)	**56.52**	**55.59**	**56.49**	**41.76**	**40.70**
Change in Emission Intensity from Baseline	-	-1.645%	-0.064%	-26.123%	-28.001%
	-	-0.93 lbs	-0.04 lbs	-14.77 lbs	-15.83 lbs

Table B-5. Data Collected on Fergus Falls Laboratory Building Prototype Model

Data Collected According to Model Type	Baseline	Lighting and Plug Loads	Smart Hot Water Heater	Smart Ventilation	All Strategies
Total Site EUI (kBtu/ft^2)	194.17	193.32	194.18	140.83	138.4
Energy Costs–Natural Gas					
Total kBtu (pulled from OpenStudio)	8,624,036	8,939,460	8,612,445	6,188,042	6,411,746
Total Therms	86,260.98	89,415.97	86,145.04	61,895.21	64,132.79
Price Per Therm	$0.6159	$0.6159	$0.6159	$0.6159	$0.6159
Annual Cost–Natural Gas	$53,128.14	$55,071.30	$53,056.73	$38,121.26	$39,499.38
Energy Costs–Electricity					
Total kWh (pulled from OpenStudio)	2,594,077	2,479,289	2,597,819	1,900,949	1,771,356
Annual Cost–Electricity (pulled from REopt)	$208,508	$196,984	$208,669	$168,038	$153,783
Total Annual Energy Costs	**$261,636.14**	**$252,055.30**	**$261,725.73**	**$206,159.26**	**$193,282.38**
Energy Cost Intensity ($/ft^2/yr)	**2.91**	**2.80**	**2.91**	**2.29**	**2.15**
Change in Energy Cost Intensity from Baseline	-	-3.662%	0.034%	-21.204%	-26.126%
	-	-$0.11	$0.00	-$0.62	-$0.76
CO_2-Equivalent Emissions–Natural Gas					
Pounds of CO_2-E (pulled from EPA)	1,006,205	1,043,007	1,004,852	721,986	748,087
Metric Tons of CO_2-E	456.41	473.10	455.80	327.49	339.33
CO_2-Equivalent Emissions–Electricity					
Metric Tons of CO_2-E (pulled from REopt)	2,252	2,153	2,255	1,643	1,532
Pounds of CO_2-E	4,964,804.24	4,746,546.86	4,971418.10	3,622,190.66	3,377,477.84
Total Pounds of CO_2-E	**5,971,009.24**	**5,789,553.86**	**5,976,270.10**	**4,344,176.66**	**4,125,564.84**
Emission Intensity (lbs/ft^2/yr)	**66.34**	**64.33**	**66.40**	**48.27**	**45.84**
Change in Emission Intensity from Baseline	-	-3.039%	0.088%	-27.246%	-30.907%
	-	-2.02 lbs	0.06 lbs	-18.08 lbs	-20.50 lbs

Table B-6. Data Collected for TOU Rates and Non-TOU Rates

Electricity Costs by Utility Schedule	Phoenix	Atlanta	Seattle	Denver	Fergus Falls
Baseline					
Annual Cost–Electricity Under TOU Schedule (pulled from REopt)	$327,159	$250,162	$220,515	$218,587	$208,508
Annual Cost–Electricity Under Non-TOU Schedule (pulled from REopt)	$327,299	$263,715	$235,564	$250,065	$215,438
Enhanced Energy Savings	**0.043%**	**5.418%**	**6.824%**	**14.401%**	**3.324%**
Lighting and Plug Loads					
Annual Cost–Electricity Under TOU Schedule (pulled from REopt)	$310,827	$245,826	$216,523	$210,257	$196,984
Energy Savings (Change from Baseline)	4.992%	1.733%	1.810%	3.811%	5.527%
Annual Cost–Electricity Under Non-TOU Schedule (pulled from REopt)	$322,220	$263,402	$232,018	$241,700	$207,488
Energy Savings (Change from Baseline)	1.552%	0.119%	1.505%	3.345%	3.690%
Enhanced Energy Savings	**3.440%**	**1.615%**	**0.305%**	**0.466%**	**1.837%**
Smart Hot Water Heater					
Annual Cost–Electricity Under TOU Schedule (pulled from REopt)	$326,521	$250,021	$219,960	$215,800	$208,669
Energy Savings (Change from Baseline)	0.195%	0.056%	0.252%	1.275%	-0.077%
Annual Cost–Electricity Under Non-TOU Schedule (pulled from REopt)	$326,642	$263,597	$235,054	$248,889	$215,604
Energy Savings (Change from Baseline)	0.201%	0.045%	0.217%	0.470%	-0.077%
Enhanced Energy Savings	**-0.006%**	**0.012%**	**0.035%**	**0.805%**	**0%**

Smart Ventilation					
Annual Cost–Electricity Under TOU Schedule (pulled from REopt)	$270,623	$183,060	$169,542	$176,709	$168,038
Energy Savings (Change from Baseline)	17.281%	26.823%	23.115%	19.159%	19.409%
Annual Cost–Electricity Under Non-TOU Schedule (pulled from REopt)	$275,719	$222,885	$177,595	$210,974	$169,205
Energy Savings (Change from Baseline)	15.759%	15.483%	24.609%	15.632%	21.460%
Enhanced Energy Savings	**1.522%**	**11.341%**	**-1.493%**	**3.526%**	**-2.051%**
All Strategies					
Annual Cost–Electricity Under TOU Schedule (pulled from REopt)	$249,089	$178,417	$164,637	$167,077	$153,783
Energy Savings (Change from Baseline)	23.863%	28.679%	25.340%	23.565%	26.246%
Annual Cost–Electricity Under Non-TOU Schedule (pulled from REopt)	$268,228	$222,472	$173,253	$201,462	$159,689
Energy Savings (Change from Baseline)	18.048%	15.639%	26.452%	19.436%	25.877%
Enhanced Energy Savings	**5.815%**	**13.040%**	**-1.112%**	**4.129%**	**0.369%**

Table B-7. Utility Electric Charges from TOU Schedule According to City

Utility Annual Charges*	Phoenix	Atlanta	Seattle	Denver	Fergus Falls
Baseline					
Fixed Charges ($/month)	$2,364	$2,448	$657	$494	$1,441
Demand Charges ($/kW)	$115,554	-	$29,875	$56,225	$74,689
Energy Charges ($/kWh)	$209,241	$247,714	$189,983	$161,869	$132,378
Total Electricity Costs	$327,159	$250,162	$220,515	$218,587	$208,508
Hot Water Heater					
Demand Charges ($/kW)	$115,070	-	$29,786	$55,737	$74,677
Energy Charges ($/kWh)	$209,087	$247,573	$189,517	$159,569	$132,551
Total Electricity Costs	$326,521	$250,021	$219,960	$215,800	$208,669
Lighting and Plug Loads					
Demand Charges ($/kW)	$104,268	-	$29,524	$54,002	$69,875
Energy Charges ($/kWh)	$204,195	$243,378	$186,342	$155,761	$125,668
Total Electricity Costs	$310,827	$245,826	$216,523	$210,257	$196,984
Ventilation					
Demand Charges ($/kW)	$108,441	-	$26,351	$52,166	$67,775
Energy Charges ($/kWh)	$159,819	$175,969	$142,535	$124,049	$98,822
Total Electricity Costs	$270,623	$178,417	$169,542	$176,709	$168,038
Combined GEB Strategies					
Demand Charges ($/kW)	$93,707	-	$26,064	$49,636	$61,204
Energy Charges ($/kWh)	$153,018	$175,969	$137,917	$116,946	$91,139
Total Electricity Costs	$249,089	$178,417	$164,637	$167,077	$153,783

Table B-8. Data Collected on Laboratory Heat Pump Models

Data Collected According to City	Phoenix	Atlanta	Seattle	Denver	Fergus Falls
Total Electricity Consumption (kWh)	2,884,038	2,770,292	2,573,456	2,749,622	2,836,365
Change in Electricity Consumption from Natural Gas Baseline (%)	**-8%**	**-12%**	**8%**	**8%**	**9%**
Annual Cost–Electricity (pulled from REopt)	$298,690	$216,740	$232,376	$227,896	$228,377
Energy Cost Intensity ($/ft²/yr)	$3.32	$2.41	$2.58	$2.53	$2.54
Change in Energy Cost Intensity from Natural Gas Baseline (%, $/ ft²/yr)	**-22%, -$0.94**	**-38%, -$1.46**	**-21%, -$0.68**	**-19%, -$0.61**	**-13%, -$0.37**
Metric Tons of CO_2-E (pulled from REopt)	1,788	1,866	1,941	2,162	2,472
Pounds of CO_2-E	3,941,861	4,113,821	4,279,167	4,766,388	5,449,821
Emission Intensity (lbs/ft²/yr)	43.80 lbs	45.71 lbs	47.55 lbs	52.96 lbs	60.55 lbs
Change in Emission Intensity from Natural Gas Baseline (%, lbs/ft²/yr)	**-20%, -10.7 lbs**	**-25%, -15.38 lbs**	**-9%, -4.63 lbs**	**-6%, -3.56 lbs**	**-9%, -5.79 lbs**