EDF Innovation Lab
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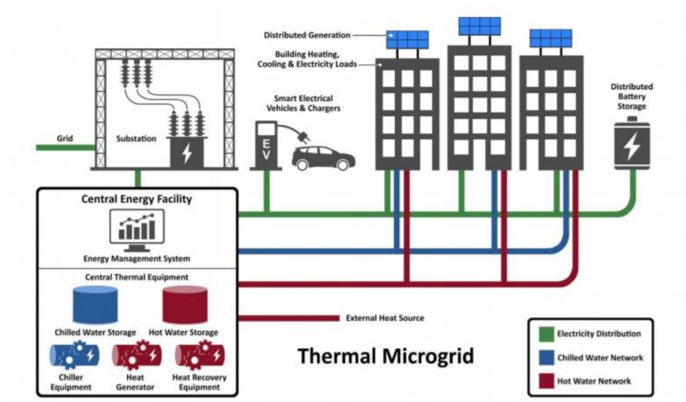
Thermal Microgrids: Palo Alto Feasibility Case Studies



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About this Study

This study was completed as a part of a collaboration between EDF Innovation Lab, Stanford University and the City of Palo Alto Utilities for the project *Leveraging Experience from Stanford and EDF to Develop Information and Tools for Thermal Microgrid Feasibility Assessments*, funded by the American Public Power Association (APPA) Demonstration of Energy & Efficiency Developments (DEED) program. The project objective is to provide information and tools to support municipal utilities in evaluating the feasibility of deploying thermal microgrids. Deliverables of the project include i) a white paper describing the technology, economics, and market of thermal microgrids and comparing them to alternatives; ii) a case study report describing the Stanford Energy System Innovations (SESI) project, in which their campus-wide cogen system was transformed to renewable electricity powered heat recovery with low-temperature hot water distribution; iii) a suite of tools and guidance for assessing technical and economic feasibility; and iv) two municipal case studies (this report includes two case studies within one municipality) applying the tools to carry out feasibility assessments.

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Executive Summary

As introduced in the thermal microgrid white paper, energy efficiency efforts and the combination of electrification and clean energy are the most practical way to achieve a sustainable building energy future.[1] This conclusion draws upon the techno-economic feasibility of decarbonizing electricity, which has been found to be more realistic than using renewable natural gas or transitioning to fuels such as hydrogen. While power and electric cooling are made sustainable as decarbonization is adopted, heating and hot water have traditionally been supplied using fossil fuel such as natural gas, and thus require a switch to new, non-fossil fuel equipment.

The tools assessment report was developed to empower municipalities, specifically cities and resource planners, with the tools necessary to perform the *Pre-Feasibility* and *Feasibility* stages of a thermal microgrid feasibility study.[2] A list of existing software applications was introduced and benchmarked, and detailed guides for the two most applicable tools – RETScreen and CEPOM – were created.

This report expands upon the step-by-step guides presented in the previous tools assessment report (part-3 of the project). Now, two sites within Palo Alto are examined, one encompassing the downtown region and one at a corporate campus. *Pre-Feasibility* and *Feasibility* studies are performed using RETScreen 4 and CEPOM tools. The challenges of gathering the required data, from the perspective of the utility, are discussed. Once the studies are performed, the thermal microgrid solution is compared to the business-as-usual case on a variety of metrics, including capital cost, energy cost savings, emissions, and water use. A cost spreadsheet is introduced which provides a range of cost estimates for a given project.

The results of the study suggest that, for the downtown site, a thermal microgrid could reduce annual heating and cooling costs by over 40%. However, these savings are largely offset by high capital costs. For a corporate campus, annual heating and cooling costs are reduced by over 50%. Importantly, the savings in energy costs more than offset the capital expenditures of the project under two of the four cost scenarios studied. A 40% to 65% reduction in GHG emissions is also estimated for these sites. The energy and emissions savings are achieved by capturing the heat recovery potential and overall efficiency improvements in the thermal microgrid system. These savings could potentially be further increased if the heat recovery potential is greater than estimated and if capital costs of projects are lower than the current estimation for the feasibility studies. Reaching cost parity with existing, fossil-fuel based system types marks a crucial step towards achieving deep decarbonization in the buildings sector.

Finally, we discuss steps that could be taken once a feasibility study has been completed and consider other auxillary benefits such as reduced exposure to fossil-fuel price volatility when planning for a

[1] *Thermal Microgrids: Technology, Economics & Potential*, 2018. http://www.edf-innovation-lab.com/wp-content/uploads/2018/06/20180517_ThermalMicrogrid_WhitePaper_FINAL.pdf

[2] *Thermal Microgrids: A Tool Suite Guide for Feasibility Assessment, 2018* http://www.edf-innovation-lab.com/wp-content/uploads/2019/02/Thermal-Microgrid-Tool-Suite-Guide_FINAL.pdf

thermal microgrid system. We also briefly discuss the potential for restaurant electrification and other variations of electrified heating and cooling systems.

Glossary

Acronym	Term
AMI	Advanced Metering Infrastructure
APPA	American Public Power Association
BAU	Business as Usual
BTU	British Thermal Unit
CCA	Community Choice Aggregation
CCF	Centum Cubic Feet
CCHP	Combined Cooling, Heat and Power
CEPOM	Central Energy Plant Optimization Model
CHC	Combined Heating and Cooling
CHP	Combined Heat and Power
CEUS	Commercial End-Use Survey
COP	Coefficient of Performance
DEED Program	Demonstration of Energy & Efficiency Development Program
DER	Distributed Energy Resource
DG	Distributed Generation
DHC	District Heating and Cooling
DOE	Department of Energy
DR	Demand Response
EIA	Energy Information Administration
ETS	Energy Transfer Station
GHG	Greenhouse Gas
GIS	Geographic Information System
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt-hour
HP	Heat Pump
HRC	Heat Recovery Chiller

HVAC	Heating, Ventilation, and Air Conditioning
IDEA	International District Energy Association
IEA	International Energy Agency
IOU	Investor-Owned Utility
IRR	Internal Rate of Return
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCOE	Levelized Cost of Electricity
MES	Multi-Energy System
MMBTU	Million British Thermal Units
MW	Megawatt
MWh	Megawatt-hour
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
POU	Publicly Owned Utility
PPA	Power Purchase Agreement
PV	Photovoltaic
PVC	Present Value Cost
RECS	Residential Energy Consumption Survey
SESI	Stanford Energy System Innovations
SHP	Separate Heat and Power
SPV	Special Purpose Vehicle
TES	Thermal Energy Storage
TWh	Terawatt-hour
TMY	Typical Meteorological Year
UNEP	United Nations Environment Programme

Table of Contents

Table of Figures

1 Background & Overview

This report is designed to present how a municipal utility employee can perform a detailed feasibility study for a local district heating and cooling system. Using software tools that they have been introduced to in the previous report, the employee will learn about challenges they can expect to face regarding data acquisition and load estimation, to streamline their processes as much as possible. Finally, we will see how the proposed thermal microgrid compares to the business-as-usual case on a variety of metrics, including cost, energy savings, water use, and carbon dioxide emissions.

The report is broken down into the following sections:

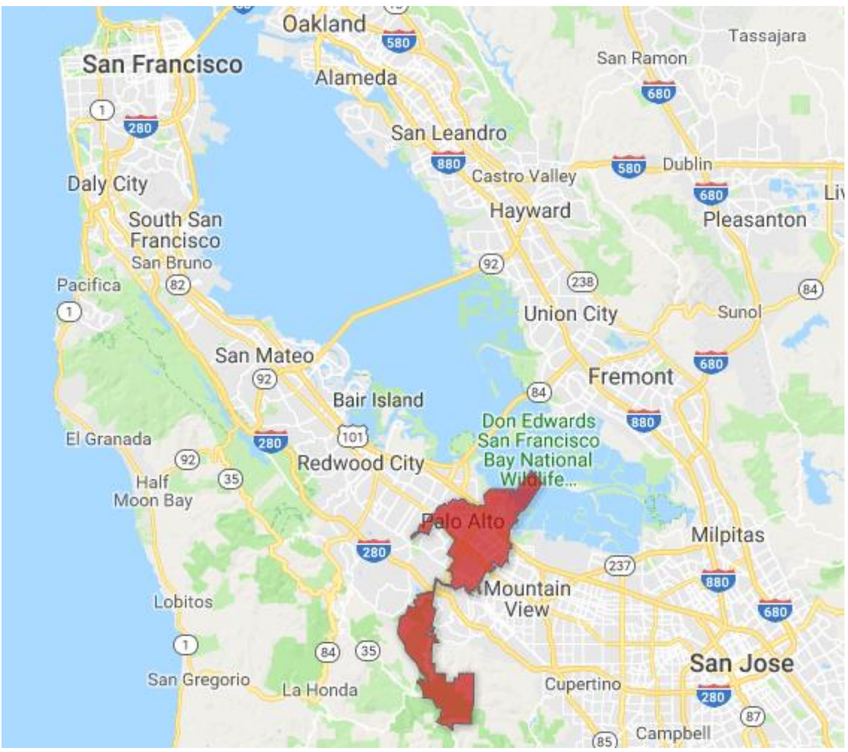
- Section 2: Background on City of Palo Alto and Site Description of Study Areas
- Section 3: Acquisition of utility meter data for energy usage
- Section 4: Feasibility study for the downtown region: Using monthly energy data in RETScreen
- Section 5: Estimating Hourly Loads (input to CEPOM)
- Section 6: Feasibility study for the downtown region: Using hourly loads in CEPOM
- Section 7: Comparison of RETScreen and CEPOM results for downtown Palo Alto
- Section 8: Feasibility study for a corporate campus in Palo Alto
- Section 9: Financial analyses/comparison of results to the business-as-usual case
- Section 10: Conclusions and Future Work

2 City of Palo Alto Background

Palo Alto is located in the heart of Silicon Valley in California. With a population of 67,000, Palo Alto is smaller than many cities in the region. Palo Alto, with its proximity to Stanford University, is at the forefront of many cutting-edge trends. As of June 2018, it led the state of California in terms of electric vehicle adoption rates[3] and its utility has achieved a 100% carbon-neutral portfolio since 2017.[4]

Furthermore, as the only California municipal utility that covers all assets (electricity, gas, water, wastewater, fiber optics), Palo Alto is uniquely positioned to spearhead efforts such as building electrification and decarbonization. Palo Alto has adopted a Sustainability and Climate Action Plan that calls for 80% GHG reduction by 2030.[5]

Figure 1: Palo Alto's location in the San Francisco Bay Area



2.1 Sites Description

Two sites within the city of Palo Alto were considered for the thermal microgrid feasibility study. The first region includes the downtown area, which contains many blocks of densely packed restaurant, retail,

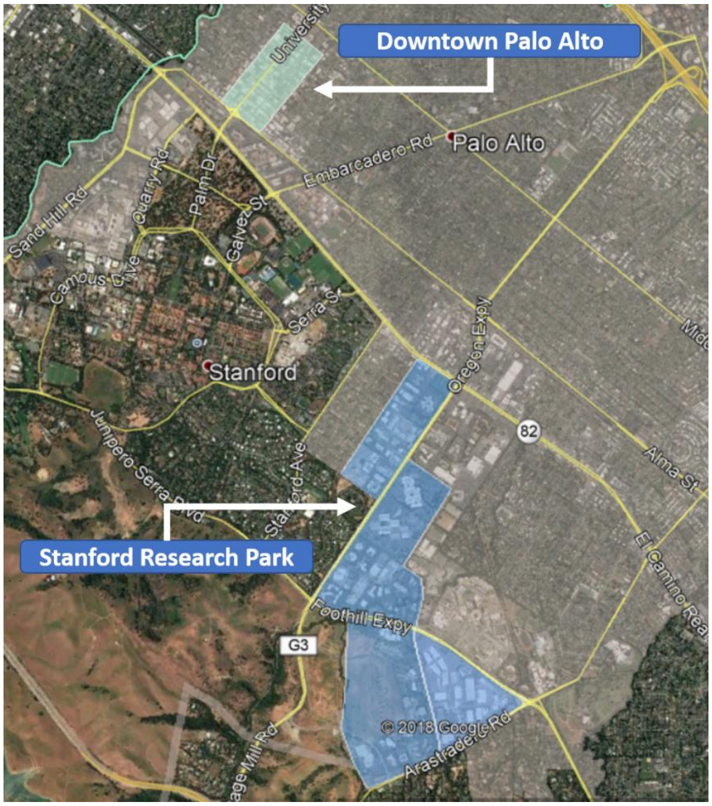
3 https://www.cityofpaloalto.org/gov/depts/utl/residents/sustainablehome/electric_vehicles/

4 https://www.cityofpaloalto.org/gov/depts/utl/residents/sustainablehome/carbon_neutral/default.asp

5 https://www.cityofpaloalto.org/services/sustainability/sustainability_and_climate_action_plan/default.asp

residential, and office space. The second region encompasses a corporate campus in the Stanford Research Park. The Stanford Research Park is a large region of Palo Alto that is on land owned by Stanford University, but electricity and gas utility services are provided by the City of Palo Alto. Maps of both regions are shown in Figure 2.

Figure 2: Location and Size of Downtown Palo Alto and Stanford Research Park



Downtown Palo Alto

The selected region in downtown Palo Alto is approximately a 3 block by 10 block region which parallels University Avenue. This region is 0.14 square miles (or 90 acres) in area, with a perimeter of 1.59 miles (2.56 km). The downtown region is bordered by Alma St, Lytton Avenue, Webster St, and Forest Avenue. It contains dozens of restaurants as well as many mixed-use developments, offices, and city hall. The downtown district was considered because of both its high load density as well as its variety of uses, which tends to improve heat recovery ratios. This site is also representative of the building mix in downtowns of other cities throughout the country.

Corporate Campus

For the Thermal Microgrid feasibility assessment, we have studied a corporate campus situated in Stanford Research Park, encompassing approximately 0.18 square miles (or 115 acres) of the area. Many of the buildings in the Research Park, including this campus, are mainly large commercial office buildings. These buildings are also enabled with interval meters that can record electricity consumption with 15-minute resolution. This makes for more accurate system sizing, as hourly cooling loads can be inferred more directly. A cohesive campus can also adopt a district or campus level energy system more efficiently, as demonstrated by the successful implementation of Stanford's SESI system[6].

[6] *Stanford's "4th Generation" District Energy System: Comb. Heat & Cooling Opens Path to Sustainability*, 2018. http://www.edf-innovation-lab.com/wp-content/uploads/2018/06/2018_SESICaseStudy_FINAL.pdf

3 Acquisition of Utility Meter Data for Energy Usage

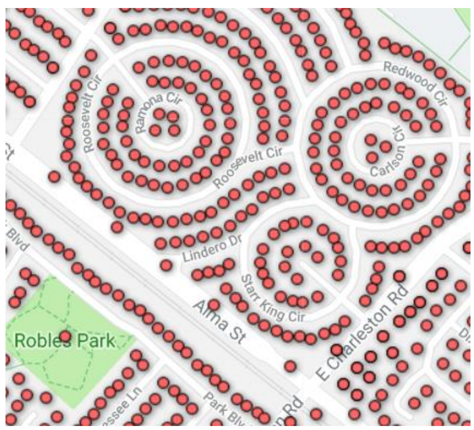
For the City of Palo Alto Utilities (CPAU), acquiring meter data in each region can be broken down into two steps:

- Step 1: Identification of billing addresses within the region of interest
- Step 2: Collection of monthly data for a calendar year for all gas and electric meters associated with each address using internal billing management system[7]

3.1 Identification of Billing Addresses

The city of Palo Alto maintains an Open Data portal, which contains some of the hundreds of layers of data stored in Palo Alto's Geospatial Information System (GIS)[8]. One layer, *Location Data*, contains every distinct, named location in Palo Alto. The data includes a latitude and longitude, as well as the full address.

Figure 3*:* Appearance of Location Data in the City of Palo Alto's GIS Database



Using this database, which is presented to the public as a Google Fusion Table, one can filter the data and download the addresses for the zone(s) of interest. In Downtown Palo Alto, this involved collecting building addresses between 100 and 600 for Lytton Avenue, University Avenue, Hamilton Avenue, and Forest Avenue, as well as addresses from 400 to 700 for the perpendicular streets. The addresses were then downloaded in both CSV and KML format. They appear as follows when plotted in Google Earth and QGIS, an open-source GIS application[9].

[7] Please note that CPAU currently does not have Advance Metering Infrastructure (AMI) and energy usage data is only available at a monthly time-interval. Palo Alto is considering rolling out AMI meters in coming years - https://www.cityofpaloalto.org/civicax/filebank/documents/64784

[8] http://xmap.cityofpaloalto.org/OpenGisData/

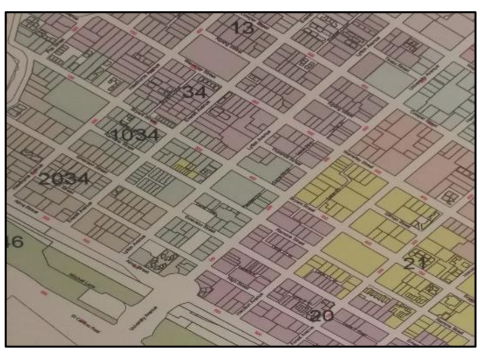
[9] https://qgis.org/en/site/

Figure 4: Downtown Palo Alto addresses in city's GIS database plotted in Google Earth and QGIS

3.2 Collection of Monthly Gas and Electricity Usage

CPAU maintains an internal database for its Billing Information (BI) system, containing information related to monthly bills for each customer account number, including breakdowns of electricity and gas usage. To collect **monthly** consumption data for the zones of interest, the database can be queried by meter reading zone. Meter reading zones are still used due to Palo Alto only having interval meters installed at its largest facilities (key accounts). A subset of the meter reading zone map is shown in Figure 5.

Figure 5: Portion of the meter-reading map for downtown Palo Alto



In one data request from the BI system, all account data from multiple meter reading zones, for the months of interest, can be requested, generating one large Excel file. The data can then be filtered by address number and street name to collect the subset of each meter reading zone that is within the region of interest. Without this database capability, the process of collecting utility data for any neighborhood would be extremely tedious.

For the corporate campus, electricity data acquisition was simpler, as accounts connected to interval meters have their data stored online through a vendor's website. However, monthly gas and water consumption data had to be collected through Palo Alto's internal database.

Since the corporate campus has higher resolution load data, only a *Feasibility* study using CEPOM is presented. The corporate campus study is presented in Section 8.

4 Feasibility Study for Downtown Region – Using Monthly data in RETScreen

This section goes over a step-by-step process for assessing the feasibility of a thermal microgrid in downtown Palo Alto.[10] In this report, emphasis is placed on site-specific parameters; and some experience with modeling tools – RETScreen 4 and CEPOM – is assumed.

4.1 System Design and Load Assumptions

The following assumptions are made about the thermal microgrid system design in downtown Palo Alto:

- Building clusters are largely defined by city block (see Figure 6).
- Cluster load is determined using monthly utility meter data (as discussed in Section 3 above).
- We have not considered any constraints for the Central Energy Facility location (e.g. environmental impact, aesthetics, etc.)
- All thermal loads except restaurant cooking loads are assumed to be connected to the thermal microgrid system
- Natural gas loads for cooking in restaurants are separated and accounted for (as explained in Section 4.1.3)
- All building square footage is assumed to be heated and cooled[11]: We have made this assumption for the sake of simplicity for the preliminary feasibility assessment. For further consideration and system design, this assumption could be refined.
- Majority of buildings are assumed to be heated using natural gas; except some residential buildings. Residential buildings are assumed to have some electric space and water heating. These details are discussed in section 5.

4.2 Data Inputs to RETScreen

A feasibility assessment of a thermal microgrid system in RETScreen requires the following main inputs:

- Building Area by Cluster
- Monthly Energy Loads per Cluster
- Pipe Network
- Central Energy Facility Equipment
- Financial Assumptions

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10 Step-by-step process is similar to section 3 of the Tools Assessment report; *Thermal Microgrids: A Tool Suite Guide for Feasibility Assessment, 2018* http://www.edf-innovation-lab.com/thermal-microgrids/

11 However, not all buildings in Palo Alto have cooling loads. This is reflected by the low cooling load density identified in Section 4.

Inputs for each of these parameters are discussed in subsequent sections (4.2.1 to 4.2.5). Please note that RETScreen does not have the capability to model thermal energy storage. Therefore, we have only considered cooling and heating equipment and network without storage for the feasibility determination exercise by RETScreen.

4.2.1 Data input: Building Area by cluster

Using GIS to Calculate Building Size

As mentioned in Section 3.1, Palo Alto maintains a GIS database. Using this database, parcel sizes and parcel building square footages were collected for the entire downtown region, as well as for each cluster[12]. Any properties that reported no building square footage were cross-referenced through an online real estate search engine[13]. The approximate total building area in the downtown region is **3 million square feet** (280,000 square meters). The building square footage of each cluster is listed in the next Section (Table 1) and Appendix B. Maps of the building clusters and utility accounts is shown in Figure 6.

Figure 6: Building clusters (1 to 7) and utility accounts (represented by dots) in downtown Palo Alto

4.2.2 Data input: Monthly Energy Loads per cluster

Thermal Load Estimation

Each downtown cluster has a different mix of building types, thus representing a different ratio of buildings. We have estimated thermal load fractions of each building type using data from the 2006

[12] For feasibility determination exercise we have assumed that each building cluster is largely defined by a city block.

[13] https://www.realquest.com/

California Commercial End-Use Survey[14] (see Appendix C) and the 2015 Residential Energy Consumption Survey (RECS)[15]. The load fractions and building type fractions were used to calculate the monthly cooling, heating, and hot water loads for each cluster. Table 7 (pg. 13) represents the final inputs to the RETScreen tool: cooling, heating, and hot water load in watt/m^2 for each cluster. Table 1 to 6 represent intermediate steps to estimate the thermal loads for each cluster.

Table 1 represents total annual electricity (kWh), annual natural gas use (therm) and building area (sq. feet or sq. meters) for each cluster in the downtown region.

Table 1: Annual electricity and natural gas demand and building area by cluster

Cluster	Annual Electricity Use [kWh]	Annual Gas Use [therm]	Building Area (ft^2) or (m^2)
1	8,667,197	174958	603964 *(56110)*
2	9,064,992	430602	467419 *(43425)*
3	7,554,736	295203	293857 *(27300)*
4	34,567,849	277299	488029 *(45339)*
5	6,370,091	194599	472287 *(43877)*
6	8,620,201	224432	517838 *(48109)*
7	3,011,893	64052	246095 *(22863)*
Total	**77,856,959**	**1,661,146**	**3,019,489** ***(280520)***

Accounting for Restaurant Loads

There are over fifty restaurants in downtown Palo Alto. As such, restaurants make up a large portion of natural gas consumption. However, the original dataset did not categorize them separately from other commercial or office space. Restaurant data was identified by manually cross-referencing all known restaurant addresses with BI system account data. Most restaurants (45) were found to have their own gas and electric meters; these accounts were categorized as restaurants. A plot of the electricity and gas usage for a subset of 10 restaurants in FY 2018 is shown in Figure 7 and Figure 8. The monthly averages for all 45 identified restaurants are also provided in Figure 9.

[14] http://www.energy.ca.gov/ceus/

[15] https://www.eia.gov/consumption/residential/data/2015/

Figure 7: Electricity consumption for a random subset of downtown Palo Alto restaurants[16]

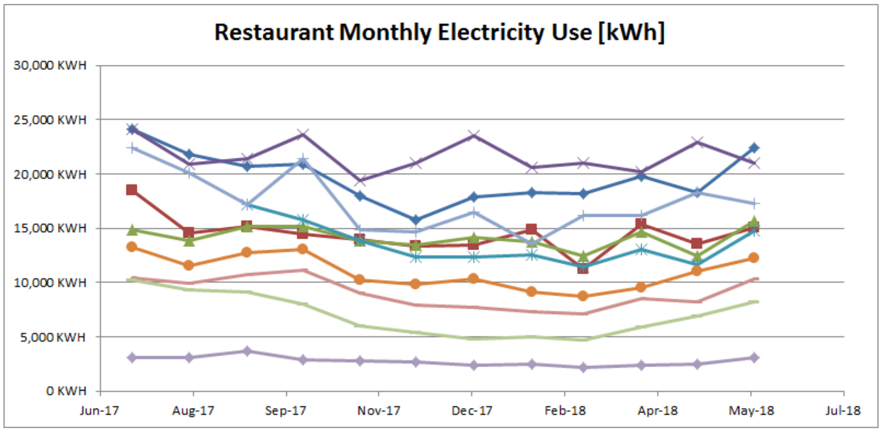


Figure 8: Natural Gas consumption for a random subset of downtown Palo Alto restaurants[17]

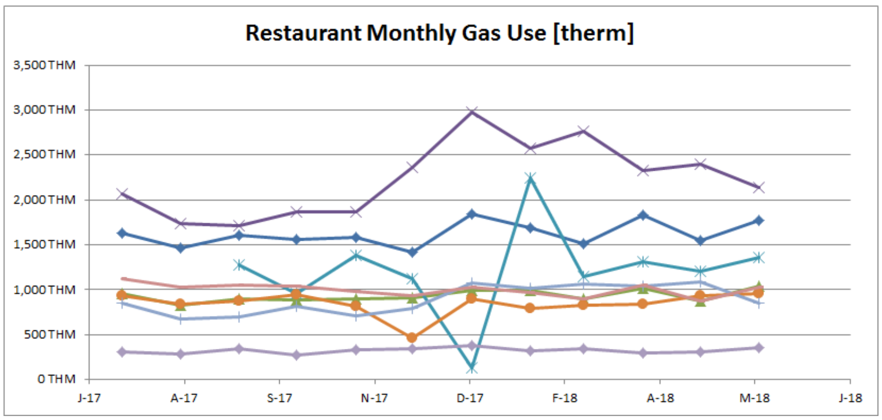
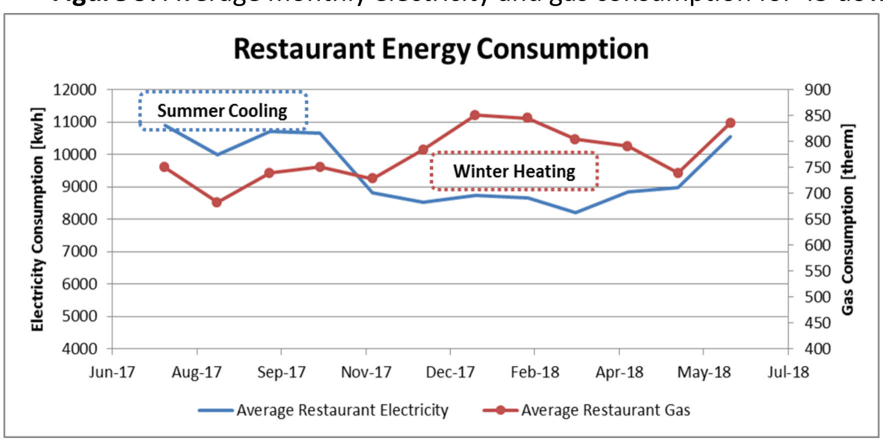


Figure 9: Average monthly electricity and gas consumption for 45 downtown Palo Alto restaurants



The average shape of the natural gas and electricity profiles are used to develop hourly load profiles and end-use ratios in the next Section (5).

16 Note that the loads vary widely, demonstrating the difficulty of establishing a restaurant archetype.

17 Note that 2 of the 10 random restaurants selected did not have a standalone natural gas meter associated with their account. In the total set of 50 restaurants, 7 did not have separate natural gas meters.

Estimating Load Fractions by Building Type: Restaurants, Office Buildings, and Residences

Table 2 and Table 3 show a summary of the end-use load fraction data for electricity and natural gas by building type. The full tables can be viewed in Appendix C. Small office data was chosen to represent commercial office space in the downtown, due to the average building area being under 30,000 square feet. Office and restaurant data was obtained from the 2006 California Commercial End-Use Survey (CEUS)[18]. Residential energy data was obtained through the 2015 Residential Energy Consumption Survey (RECS)[19]. Data for large offices were chosen to represent city (public) buildings, due to the large size of the City Hall in downtown Palo Alto.

Table 2: End-use electric load fraction for various building types

Electricity End-Use	**Small Office (Commercial)**	**Restaurant**	**Residential**	**Large Office (City)**
Cooling	22%[20]	17%	17%	17%
Space Heating	1%	<1%	15%	<1%
Hot Water	2%	1%	14%	2%
Other end-uses (e.g. lighting, plug load)	75%	>81%	54%	>80%
Total	*100%*	*100%*	*100%*	*100%*

Table 3: End-use natural gas load fraction for various building types

Gas End-Use	**Small Office (Commercial)**	**Restaurant**	**Residential***	**Large Office (City)**
Space Heating	67%	3%	50%	82%
Hot Water	29%	24%	42%	13%
Cooking	4%	**72%**	8%	2%
Total	*100%*	*~ 100%*	*100%*	*97%*

* Natural Gas end-use data assumes Marine climate region[21]

[18] http://www.energy.ca.gov/2006publications/CEC-400-2006-005/CEC-400-2006-005.PDF

[19] https://www.eia.gov/consumption/residential/

[20] This means that 22% of annual commercial electricity consumption in the selected climate region is used for cooling

[21] https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce4.5.pdf

Estimating Energy End-Use Fractions by Cluster

To gain more understanding of each cluster's building type, and thus its thermal loads, the total energy consumption by type and cluster was calculated. This data, for electricity and gas, is presented in Tables 4 and 5.

Table 4: Electricity End Use Fraction

Cluster	Small Office (Commercial)	Restaurant	Residential	City (Public)	*Total*
1	0.74	0.05	0.18	0.03	*1.0*
2	0.59	0.33	0.08	0.00	*1.0*
3	0.33	0.07	0.18	0.42	*1.0*
4	0.93	0.02	0.03	0.02	*1.0*
5	0.70	0.00	0.30	0.00	*1.0*
6	0.90	0.04	0.06	0.00	*1.0*
7	0.68	0.04	0.20	0.08	*1.0*

Table 5: Natural Gas End Use Fraction

Cluster	Small Office (Commercial)	Restaurant	Residential	City (Public)	*Total*
1	0.70	0.06	0.24	0.00	*1.0*
2	0.32	0.63	0.05	0.00	*1.0*
3	0.10	0.11	0.21	0.58	*1.0*
4	0.72	0.18	0.10	0.00	*1.0*
5	0.80	0.01	0.19	0.00	*1.0*
6	0.80	0.16	0.04	0.00	*1.0*
7	0.39	0.25	0.36	0.00	*1.0*

Next, using the energy end-use fractions of electricity and heating for each building type (Tables 4 and 5), along with the ratio of consumption by building type for each cluster (Tables 2 and 3), the cooling and heating load fractions for each cluster are calculated (as shown in Table 6).

Table 6: Cooling and Heating Load Fractions for each Building Cluster

Cluster	**Cooling Load Fraction (Electric)**	**Electric Space Heating Load Fraction**	**Gas Space Heating Load Fraction**	**Electric Hot Water Heating Load Fraction**	**Gas Hot Water Heating Load Fraction**
1	0.21	0.03	0.59†	0.04	0.32
2	0.20	0.02	0.26	0.03	0.27
3	0.19	0.03	0.65	0.04	0.22
4	0.22	0.01	0.54	0.02	0.29
5	0.21	0.05	0.63	0.06	0.31
6	0.22	0.02	0.56	0.03	0.29
7	0.20	0.04	0.45	0.04	0.32

† For example, 0.59 means that 59% of the gas consumed in cluster one was used for space heating

Finally, using the cooling and heating load fractions information from Table 6 and total annual electricity and gas consumption of each cluster and the cluster building size (Table 1), the annual average cooling and heating loads ($watt/m^2$) are calculated (as shown in Table 7). This is the required input into the RETScreen model.

Table 7: Cooling and Heating Loads (inputs into RETScreen model)

Cluster	**Total Cooling Load [W/m2]**	Space Heating Load [W/m2]	Hot Water Load [W/m2]	**Total Heating Load [W/m2]**
1	9.49	6.77	4.04	10.82
2	12.35	8.99	9.42	18.41
3	15.31	24.63	9.21	33.84††
4	48.98†	12.22	8.05	20.27
5	8.84	10.23	5.59	15.82
6	11.44	9.12	5.03	14.15
7	7.98	4.77	3.69	8.47

† Cluster 4 contains the buildings with the highest electricity loads; these loads are many times those of all other buildings in the downtown region

†† Cluster 3's heating load is primarily from City Hall, which is one of the largest natural gas users

Data Appearance, Calculations in RETScreen

RETScreen requires inputs for the heated and cooled floor area of each building cluster, as well as the heating and cooling loads shown above. The software uses these values to calculate the total annual fuel consumption, as well as the peak heating and cooling loads, which are necessary for district energy system design and accurate pipe sizing. The cluster building square footages shown in Table 1, and the thermal loads shown in Table 7, are inputs into RETScreen. RETScreen generates the resulting annual heating and cooling loads.

Figure 10: Heating and Cooling load inputs into RETScreen (highlighted in yellow)

RETScreen Load & Network Design - Combined heating & cooling project

Heating project	Unit								
Base case heating system	Multiple buildings - space heating								
See technical note on heating network design			Building clusters						
			1	2	3	4	5	6	7
Heated floor area per building cluster	ft²	3,089,489	603,964	467,419	293,857	488,029	472,287	517,838	246,095
Number of buildings in building cluster	building	468	58	100	21	82	89	64	54
Fuel type			Natural gas - therm	Natural gas - therm	Natural gas - therm	Natural gas - therm	Natural gas - therm	Natural gas - therm	Natural gas - therm
Seasonal efficiency	%	-	80%	80%	80%	80%	80%	80%	80%
Heating load calculation									
Heating load for building cluster	W/m²	-	10.82	18.41	33.84	20.27	15.82	14.15	8.47
Domestic hot water heating base demand	%	20%							
Total heating	MWh	9,171	1,156	1,522	1,759	1,749	1,321	1,296	369
Total peak heating load	kW	4,818	607	799	924	919	694	681	194
Fuel consumption - unit		-	therm	therm	therm	therm	therm	therm	therm
Fuel consumption - annual		-	49,292	64,907	75,007	74,616	56,357	55,269	15,722
Fuel rate - unit		-	$/therm	$/therm	$/therm	$/therm	$/therm	$/therm	$/therm
Fuel rate		-	1.290	1.290	1.290	1.290	1.290	1.290	1.290
Fuel cost		$ 504,610	$ 63,586	$ 83,731	$ 96,759	$ 96,255	$ 72,700	$ 71,297	$ 20,282
Proposed case energy efficiency measures									
End-use energy efficiency measures	%	5%	5%	5%	5%	5%	5%	5%	5%
Net peak heating load	kW	4,577	577	759	878	873	659	647	184
Net heating	MWh	8,713	1,098	1,446	1,671	1,662	1,255	1,231	350

Cooling project	Unit								
Base case cooling system	Multiple buildings - space cooling								
See technical note on cooling network design			Building clusters						
			1	2	3	4	5	6	7
Cooled floor area per building cluster	ft²	3,089,489	603,964	467,419	293,857	488,029	472,287	517,838	246,095
Number of buildings in building cluster	building	468	58	100	21	82	89	64	54
Fuel type			Electricity	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity
Coefficient of performance - seasonal		-	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Cooling load calculation									
Cooling load for building cluster	W/m²	-	9.49	12.35	15.31	48.98	8.84	11.44	7.98
Non-weather dependant cooling	%	20%							
Total cooling	MWh	15,614	1,722	1,734	1,352	7,182	1,254	1,780	590
Total peak cooling load	kW	4,828	532	536	418	2,221	388	550	182
Fuel consumption - unit		-	MWh	MWh	MWh	MWh	MWh	MWh	MWh
Fuel consumption - annual		-	574	578	451	2,394	418	593	197
Fuel rate - unit		-	$/kWh	$/kWh	$/kWh	$/kWh	$/kWh	$/kWh	$/kWh
Fuel rate		-	0.140	0.140	0.140	0.140	0.140	0.140	0.140
Fuel cost		$ 728,652	$ 80,361	$ 80,936	$ 63,078	$ 335,146	$ 58,537	$ 83,059	$ 27,534
Proposed case energy efficiency measures									
End-use energy efficiency measures	%	5.0%	5%	5%	5%	5%	5%	5%	5%
Net peak cooling load	kW	4,587	506	509	397	2,110	368	523	173
Net cooling	MWh	14,833	1,636	1,648	1,284	6,823	1,192	1,691	561

4.2.3 Data input: Pipe Network Topology

Primary and Secondary Pipe Network Topology

Ideally, to reduce system losses, pipe insulation requirements, and costs, the plant should be situated close to the anchor loads within the system. For downtown Palo Alto, the following locations were identified as the four biggest electricity and natural gas consumers.

Table 8: Location of Top Energy Consumers in Downtown Palo Alto

Rank	Top Electricity Users	Cluster	Top Gas Users	Cluster	Notes
1	*** Bryant St	4	City Hall	3	Highest gas loads in winter
2	*** Hamilton Ave	4	*** University Ave	6	Highest electric loads usually in September
3	City Hall	3	*** University Ave	4	
4	*** University Ave	5	*** Cowper St	5	

*** Addresses removed for privacy

Next, the average load of each cluster was considered. Given the high consumption within clusters 3 and 4, the hypothetical plant was placed in a parking lot adjacent to cluster 3.

Number of Buildings in Each Cluster

The number of buildings in each cluster was estimated in the following manner:

1. The billing data was filtered to remove any accounts with no gas or electric meter
2. Duplicate building addresses (not including unit number) were removed

Table 9 presents the estimated number of buildings in each cluster. An accurate number of buildings is important for estimating the cost of energy transfer stations that connect the district energy system to each building.

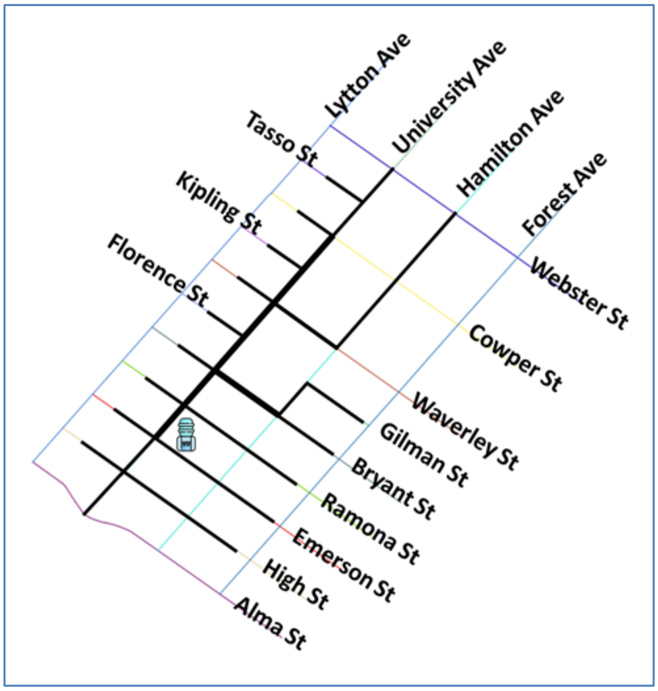
Table 9: Estimated number of buildings in each downtown cluster

Cluster	Number of Buildings
1	58
2	100
3	21
4	82
5	89
6	64
7	54
Total	*468*

Constraints

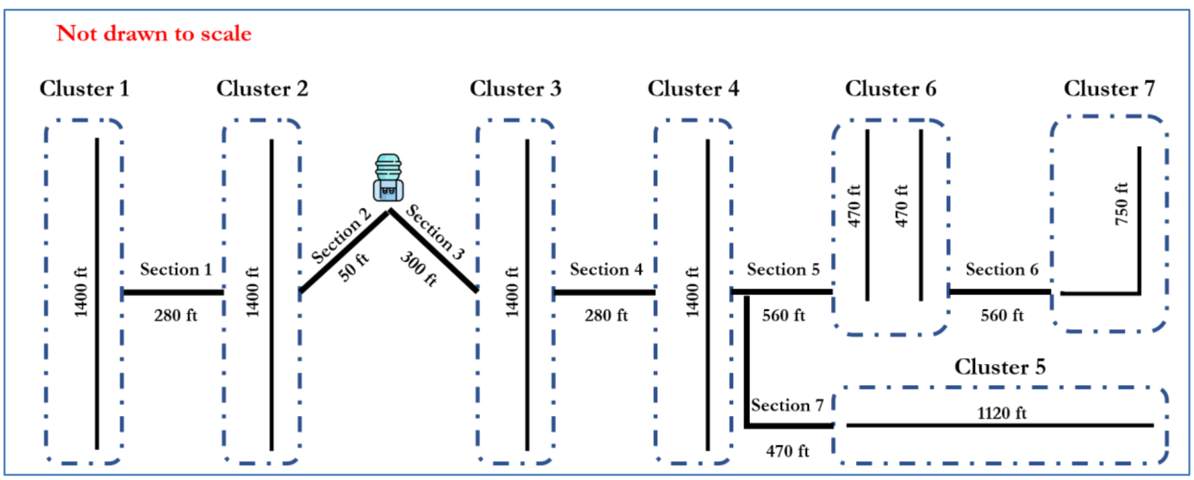
To minimize costs, while maintaining the aesthetic quality of the downtown, the piping system would likely be placed underneath the city streets. The proposed main pipe runs beneath University Ave, with secondary pipes running under each cross street. The proposed network is shown in Figure 11.

Figure 11: Proposed downtown Palo Alto thermal microgrid pipe network



A second schematic is provided to show the pipe lengths and approximate lengths of primary and secondary pipe sections in the network.

Figure 12: Pipe network topology



The schematic shows primary and secondary pipes that will run underneath each street. However, it does **not** show or include the lengths of pipe that connect from the secondary pipe to each building. These *tertiary* pipes do not need to be considered in a *Pre-Feasibility* study, as it is not known which buildings will want to connect to the system. In RETScreen, the second schematic is entered as shown in Figure 13.

Figure 13: Pipe network input into RETScreen

Proposed case district heating network		**Estimate/Total**								
Heating pipe design criteria										
Design supply temperature	°C	80								
Design return temperature	°C	50								
Differential temperature	°C	30								
Main heating distribution line										
Main pipe network oversizing	%	20%								
Pipe sections	**Load**	**Length**	**Pipe size**	**Is the building cluster supplied by this pipe section? (yes/no)**						
	kW	**ft**	**mm**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Section 1	402.4	280	DN 80	Yes	No	No	No	No	No	No
Section 2	1,356.6	50	DN 125	Yes	Yes	No	No	No	No	No
Section 3	1,708.2	300	DN 125	No	No	Yes	Yes	Yes	Yes	Yes
Section 4	1,050.2	280	DN 125	No	No	No	Yes	Yes	Yes	Yes
Section 5	349.1	560	DN 80	No	No	No	No	No	Yes	Yes
Section 6	58.4	560	DN 40	No	No	No	No	No	No	Yes
Section 7	301.0	470	DN 65	No	No	No	No	Yes	No	No
Section 8										
Section 9										
Section 10										
Section 11										
Section 12										
Section 13										
Total pipe length for main distribution line	m	762								
Secondary heating distribution lines										
Secondary pipe network oversizing	%	20%		**Secondary distribution pipes length per building cluster**						
Length of pipe section	m	2,563	ft	1,400	1,400	1,400	1,400	1,120	940	750
Pipe size	mm			DN 32	DN 32	DN 32	DN 32	DN 32	DN 32	DN 32

Note: For entering the cooling data, the square footage is assumed to equal the heating square footage. While many buildings in Palo Alto do not have central A/C, this is already accounted for in the cooling load density value, which considers all buildings and all electricity consumption within the district.

Building Connection and Cost Factors

The energy transfer station (ETS) connection types were chosen to be indirect for both heating and cooling, meaning that the heating and cooling loop within the building are connected to the district system via a heat exchanger. Therefore, the working fluid of the district energy system does not enter the pipes within each building.

The cost factors for the energy station, main distribution piping, and secondary distribution piping were set to 2.0, reflecting the higher cost of construction in Palo Alto, as well as the time that has passed since the model was developed. Finally, an exchange rate of $0.76/CAD was used[22].

4.2.4 Data input: Central Energy Facility Equipment

We have used equipment per-unit cost estimates as listed in Appendix D[23]. Since the RETScreen model does not support heat recovery chillers, the district heating and cooling system equipment were considered separately[24]. This section describes the baseload and peak heating and cooling equipment used in the downtown Palo Alto analysis. An analysis of equipment which includes heat recovery chillers is discussed in Section 6 (feasibility assessment using CEPOM).

22 CAD to USD exchange rate observed in August 2018

23 These estimates are provided by Colin Moyer from Affiliated Engineers Inc (AEI); based on their experience to design both the Stanford main campus (SESI) and Redwood City campus thermal microgrids

24 This is a limitation of RETScreen tool for thermal microgrid pre-feasibility assessment; any potential savings in energy costs from simultaneous heating and cooling needs are not captured.

Base and Peak Load Cooling Systems

An air-source heat pump was selected to be the district cooling baseload system. A fuel rate of $75/MWh was chosen, to match the average cost to Palo Alto of purchasing electricity from the California market. A coefficient of performance of 3.0 was used. The equipment costs were estimated as a function of the rated capacity, shown in Table 10, and are presented thereafter. An electric compressor was selected to be the district cooling peak load system. The same fuel rate and coefficient of performance were used. The capacity of the peak compressor is designed to be less than that of the baseload heat pump.

Base and Peak Load Heating Systems

An air-source heat pump was also selected for the heating base load system. A fuel rate of $75/MWh was used, as well as a seasonal efficiency of 200% (or COP of 2.0). A natural gas boiler was selected for the peak load heating system. The natural gas fuel rate is set to $4.5/MMBtu[25] to match current natural gas purchasing costs. The seasonal efficiency of the natural gas boiler is set to 85%, which is in the range of new medium and high-efficiency boiler systems[26]. For simplicity, RETScreen model costs are not broken down by equipment type. An estimate of **$6,000 per ton** of capacity was assumed as the total cost of a heating and cooling plant. This value includes the cost of labor.

Table 10: Estimated equipment capacity

	Base Load Cooling (Air-Source HP)	Peak Load Cooling (Compressor)	Base Load Heating (Air-Source HP)	Peak Load Heating (Nat. Gas Boiler)
Capacity	3400 kW (960 ton)	1400 kW (400 ton)	2600 kW (740 ton)	2100 kW (600 ton)

The total heating and cooling capacity of the facility is 2,700 tons. Using a value of $6,000 per ton, the estimated cost of the energy plant is **$16.2M**. These equipment costs, electricity costs, and natural gas costs are used in the financial analysis section.

4.2.5 Data input: Financial Assumptions

Financial Analysis

The following financial parameters were used for the RETScreen model.

Table 11: Financial parameters input into RETScreen

Parameter	**Value**	**Notes**
Inflation Rate	3%	3% also used for hourly analysis using CEPOM
Project Lifespan	50 yr	Usually at least 30 years; up to 80-100 years
Debt Ratio	20%	

[25] This is the approximate commodity purchase price for Palo Alto's natural gas

[26] https://www.energy.gov/energysaver/home-heating-systems/furnaces-and-boilers

Debt Interest Rate	5%	Cities with high credit ratings can borrow debt at much lower interest rates for capital projects than many private entities.
Debt Term	50 yr	Typically, equal to the project lifespan

4.3 Data Output: Results

This section describes the results from the RETScreen model.

Installation Costs

The total costs for the district heating network and district cooling network are broken down in Table 12.

Table 12: RETScreen itemized cost data for thermal microgrid

	Energy Transfer System Cost ($)	Main Distribution Pipe	Secondary Distribution Pipe	Total
District Heating	$1.78M	$0.57M	$1.80M	**$4.1M**
District Cooling	$1.22M	$0.87M	$2.55M	**$4.6M**

The estimated cost of the system, including the central energy facility, is **$25M.**

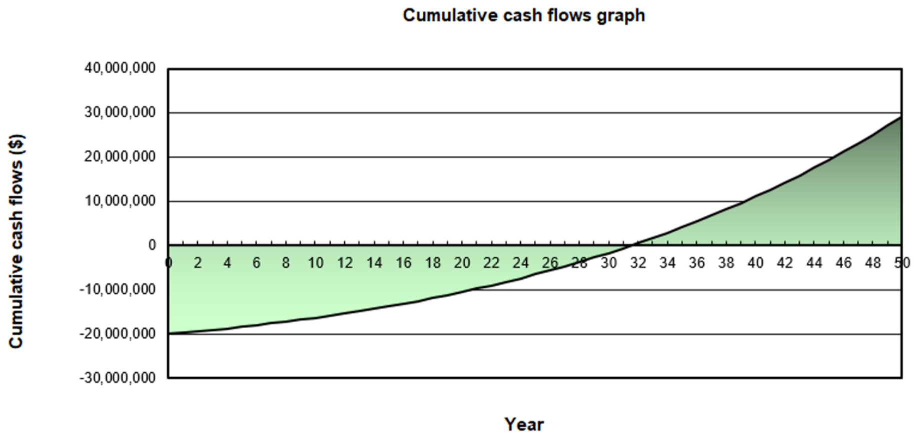
Financial Viability

RETScreen provides four metrics that help determine the financial viability of a project: pre-tax IRR – equity, pre-tax IRR – assets, simple payback period, and equity payback period. The software also generates a cumulative cash flow graph to provide a visualization of these parameters and breaks down the savings by category. The metrics and graph are shown in Table 13 and Figure 14, respectively.

Table 13: Financial feasibility metrics provided by RETScreen

Pre-tax IRR - equity	**Pre-tax IRR - assets**	**Simple Payback Period**	**Equity Payback Period**
3.0%	2.2%	46 yr	32 yr

Figure 14: Cumulative cash flow graph for downtown Palo Alto thermal microgrid project



This analysis shows a low IRR and a long payback period. A private developer would likely be unable to finance a project with these values. Fortunately, a municipality can issue bonds to fund infrastructure projects.

Table 14: Savings, costs, and other parameters of the RETScreen model

O&M Savings	Fuel Cost - Proposed Case	Debt Payments	Total Annual Savings
$0§	$690,000	$275,000	$1,200,000

§This is a conservative estimate, as O&M costs would likely decrease via the installation of a district energy system[27].

Emissions Reduction

RETScreen reports the annual GHG emission reduction as well as the equivalent number of cars and light trucks not used. The GHG reduction is a function of the base case electricity system, which has its GHG emission factor and transmission and distribution losses. The average GHG emission factor of the California grid is approximately 239 kg/MWh. When this value is used, RETScreen estimates that the district heating and cooling system would reduce GHG emissions by **950 metric tons** annually. This is a reduction of 27**%**. They estimate this to be the equivalent of removing approximately 160 cars from the road. When Palo Alto's carbon-neutral electricity is considered, the GHG emissions avoided increases to 2000 metric tons annually (or the equivalent of removing 340 cars from the road for a year).[28]

Takeaways

The *Pre-Feasibility* analysis using RETScreen 4 suggests that installing a thermal microgrid in downtown Palo Alto would greatly reduce energy costs, but that high initial capital costs would offset most of these savings. However, the system would have a sizeable impact on reducing the carbon intensity of thermal loads. Importantly, as renewable energy penetration continues to increase, the district energy system's

[27] Sandvall, A., *Cost Efficiency of Urban Heating Strategies - Modelling scale effects of low-energy building heat supply*
[28] https://www.cityofpaloalto.org/gov/depts/utl/residents/sustainablehome/carbon_neutral/default.asp

GHG emissions will continue to decrease. This demonstrates the long-term value of installing the fourth-generation district energy systems that are the topic of this project. The value of the project would also increase if a carbon tax was implemented in the future or if natural gas prices rose. Overall these estimates are conservative as thermal microgrid system design is not optimized for heat recovery potential (with heat recovery chillers) and considerations for storage.

4.4 Sensitivity Analysis

The following parameters of the RETScreen model were varied to observe the effect on cost, energy use, and financial metrics.

Table 15: RETScreen financial model sensitivity study

Parameter, Variation	Resulting Pre-tax IRR (equity)	Resulting Equity Payback	50 year Savings
Capital Cost Doubled	-1.0%	N/A	Costs of >$10M
Inflation Rate Doubled	6.5%	23 yr	>$100M
Natural Gas Costs Doubled	2.9%	32 yr	>$20M
Electricity Costs Doubled	negative	N/A	Costs of >$40M
Cooling Load Density Doubled	5.0%	23 yr	>$60M
Heating Load Density Doubled	4.5%	25 yr	>$50M

Sensitivity Study Interpretation

As expected, doubling the capital cost makes the project infeasible. Doubling the electricity cost does as well, since the thermal microgrid with air-source heat pumps is much more reliant on electricity for heating. Doubling the natural gas cost has little effect on the project's financials since gas use is minimal. However, it is important to note that this would dramatically increase the business-as-usual heating costs. Doubling the cooling and heating load density have similar effects due to the project cost of $6,000 / ton being applied to both cases.

In the next section (5), the method for estimating hourly loads for downtown Palo Alto is described. These hourly loads are then used as inputs to the feasibility analysis using CEPOM.

5 Estimating Hourly Loads (input to CEPOM)

Moving from RETScreen's pre-feasibility study to CEPOM's feasibility study requires the estimation of hourly load profiles for each account number in the downtown zone, as well as identification of the use type associated with each meter. The original data from the city database split the meters into the following account classes: City (public buildings), Commercial, Public Facilities Non-City, Residential Multi-Family, Residential Multi-Family Master Meter, and Residential Single Family. As described in Section 4.2, another building type classification of 'Restaurants' was created manually.

We have used commercial reference building data from the Department of Energy (DOE) to calculate hourly load ratios for each building type for each month of the year[29]. Afterward, these hourly ratios are multiplied by the recorded electricity and gas consumption of each building type for each month of the year. Finally, these ratios were multiplied by the end-use ratios for each building type for each month of the year. The end-use ratios varied each month to account for different behaviors during the different seasons. For example, while 25% of a home's electricity may go towards cooling in September, it is unlikely that the same is true in January. This is handled in RETScreen via the knowledge of heating and cooling-degree-days[30]. However, for the CEPOM analysis, these ratios were estimated using the actual monthly data.

5.1 Methodology and Assumptions for estimating hourly load profiles

The following assumptions are made when estimating the hourly load profiles in downtown Palo Alto:

- *'City'* and '*Public Facilities Non-City'* are combined into one category: The combined category for public buildings was assumed to fit the *Large Office* profile
- *'Residential Multi-Family*', '*Residential Multi-Family Master Meter*', and '*Residential Single Family'* were combined into one category. The combined category for residential buildings is assumed to fit the *Mid-rise Apartment* profile
- Restaurants are assumed to fit the *Full-Service Restaurant* profile
- Commercial loads are assumed to fit the *Medium Office* profile[31]
- Medium offices, large offices, and restaurants are assumed to have no electric water or space heating
- Cooking loads are assumed to be constant throughout the year for all building types
    - This amount was a fraction of the lowest monthly gas consumption
    - 8% for housing; 2% for large office; 7% for medium office / commercial

[29] https://openei.org/datasets/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states; These hourly load profiles for a typical metrological year are developed by DOE based on results from building simulation software.

[30] https://www.weather.gov/key/climate_heat_cool

[31] This was classified as small office for the RETScreen analysis. The OpenEI dataset follows a different definition for building sizes

The following sub-sections describe the hourly load calculation process in greater detail. For this project, the required Excel data was imported into MATLAB to perform these estimates.

5.1.1 Step 1: Calculate Monthly Consumption for Cooling, Space Heating, and Water Heating using OpenEI database

The Office of Energy Efficiency & Renewable Energy (EERE) has provided OpenEI with hourly load profile data for 16 different commercial building and residential building types[32]. The commercial profiles are based off simulations run using the Department of Energy's EnergyPlus software[33]. The load profiles have been run for all TMY3 locations, making this an excellent reference for any location in the United States. An example portion of the data (for a Medium Office) is shown in Figure 15.

Figure 15: Sample of hourly data available in OpenEI database

Date/Time	Month	Electricity:Facility [kW](Hourly)	Fans:Electricity [kW](Hourly)	Cooling:Electricity [kW](Hourly)	Heating:Electricity [kW](Hourly)	InteriorLights:Electricity [kW](Hourly)	InteriorEquipment:Electricity [kW](Hourly)	Gas:Facility [kW](Hourly)	Heating:Gas [kW](Hourly)	Water Heater:WaterSystems:Gas [kW](Hourly)
01/01 01:00:00	01	239.6169864	1.674349	0	0	24.92036353	149.522181	6.723134712	6.703134712	0.02
01/01 02:00:00	01	239.4296611	1.48831	0	0	24.92036353	149.522181	8.359083012	6.170367852	2.18871516
01/01 03:00:00	01	239.8063105	1.860388	0	0	24.92036353	149.522181	10.6992357	8.510519112	2.188716592
01/01 04:00:00	01	239.4317018	1.48831	0	0	24.92036353	149.522181	9.566371971	7.377464498	2.188907472
01/01 05:00:00	01	252.0310113	1.860388	0	0	24.92036353	149.522181	12.23980676	10.05089764	2.188909125
01/01 06:00:00	01	276.1014578	1.48831	0	0	24.92036353	149.522181	10.7153814	8.523948164	2.191433241
01/01 07:00:00	01	325.3670161	1.860388	0	0	24.92036353	149.522181	14.05669349	11.8677524	2.18894109
01/01 08:00:00	01	315.2598156	1.48831	0	0	24.92036353	149.522181	11.6671729	9.478229621	2.188943282
01/01 09:00:00	01	298.540148	1.860388	0	0	24.92036353	149.522181	9.404088712	7.215143519	2.188945192
01/01 10:00:00	01	261.4958279	1.48831	0	0	24.92036353	149.522181	6.389602222	4.20065516	2.188947062

One valuable component of the OpenEI data set is its ability to shed light on how heating and cooling equipment is typically operated in buildings. While heating loads are either modeled as electric or gas loads, depending on the location and building type, what is most important for a district energy system is understanding when the thermal loads occur. Robust hourly heating and cooling demand estimates help improve the accuracy of system piping and storage sizing while minimizing the use of secondary equipment that utilizes natural gas.

The total consumption for cooling, space heating, and water heating was found for each month for each building type. Next, for each hour of each month, the load at that hour was divided by the monthly load for its respective month. This provides one with the **Hourly Load Ratios.**

5.1.2 Step 2: Multiply Hourly Ratios by Palo Alto Monthly Consumption

The total electricity and gas consumption for each building type in downtown Palo Alto is shown in Figure 16. These values were calculated during the RETScreen analysis (section 4.1).

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[32] https://openei.org/datasets/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states

[33] https://energyplus.net/

Figure 16: Monthly electricity and natural gas consumption, by building type, for downtown

Month	Commercial Electricity [kwh]	Restaurant Electricity [kwh]	Housing Electricity [kwh]	City Electricity [kwh]	Commercial Gas [thm]	Restaurant Gas [thm]	Housing Gas [thm]	City Gas [thm]
January	4529516	393562	716720	340638	103253	38271	30910	28309
February	5053952	389185	709487	374092	95181	38006	25495	31587
March	4533655	368547	690334	329432	95387	36187	26665	24498
April	4723202	398205	606595	344085	85274	35592	19647	23074
May	4718229	404292	580654	338985	75552	33240	18267	13889
June	5352184	474884	581392	398815	66074	37600	14797	14569
July	5558995	490850	736317	406647	51216	33723	13981	5591
August	5239000	449376	695708	392626	46881	30692	13026	3691
September	5694037	482096	729191	415066	47811	33245	13025	6513
October	5013878	479640	696530	326982	47610	33795	13390	3000
November	4978162	396398	580282	358392	58501	32756	15317	6712
December	5022008	383803	618930	361403	74113	35286	20554	12553

The Hourly Load Ratios for each building type and month, which were calculated in Step 1, were multiplied by the Palo Alto consumption data for each building type and month. This provides the hourly Palo Alto gas and electricity consumption for each building type. However, this assumes all natural gas and electricity consumption is being used for heating and cooling equipment. Therefore, one must multiply by the appropriate end use ratios for each month to calculate the heating and cooling demands of the system.

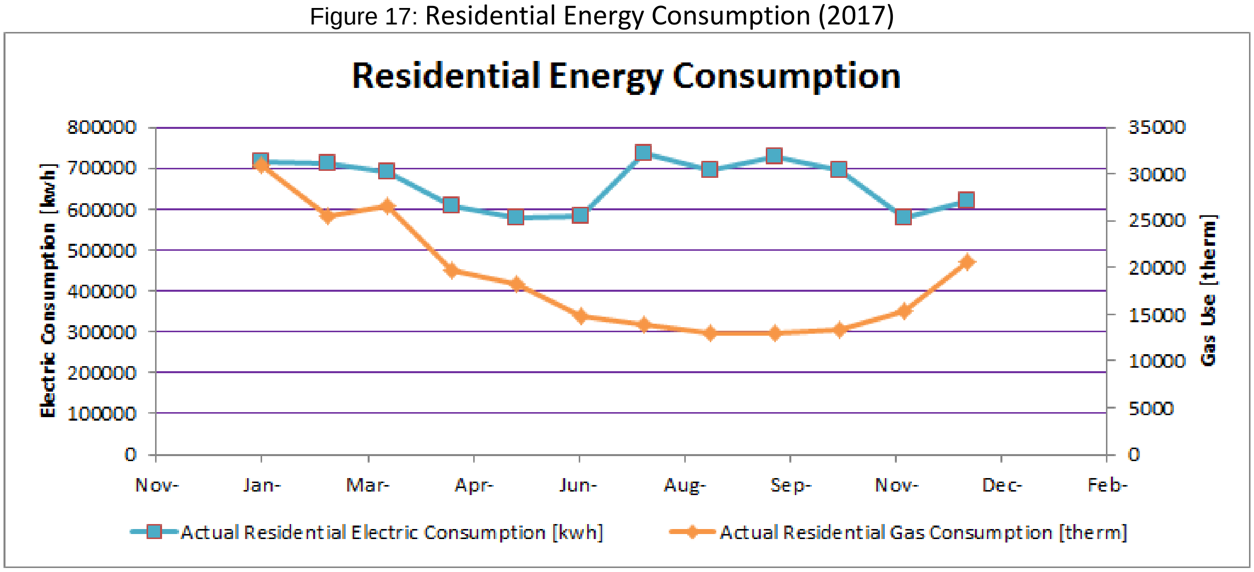
5.1.3 Step 3: Calculate Monthly End-Use Ratios for each Building Type

For an accurate estimate of hourly loads for an entire calendar year, the end-use ratios should vary with each month. For downtown Palo Alto, these ratios were calculated for each building type and end use. The assumptions made when calculating these ratios are presented in this section. The energy data shown in this section is the original meter data. When calculating heating and cooling needs, the appropriate heating efficiency and cooling COP must be used.

End-Use Ratio Calculation: Housing

The monthly energy use for residential meters in downtown Palo Alto is shown in Figure 17.

Figure 17: Residential Energy Consumption (2017)



Natural Gas End Uses

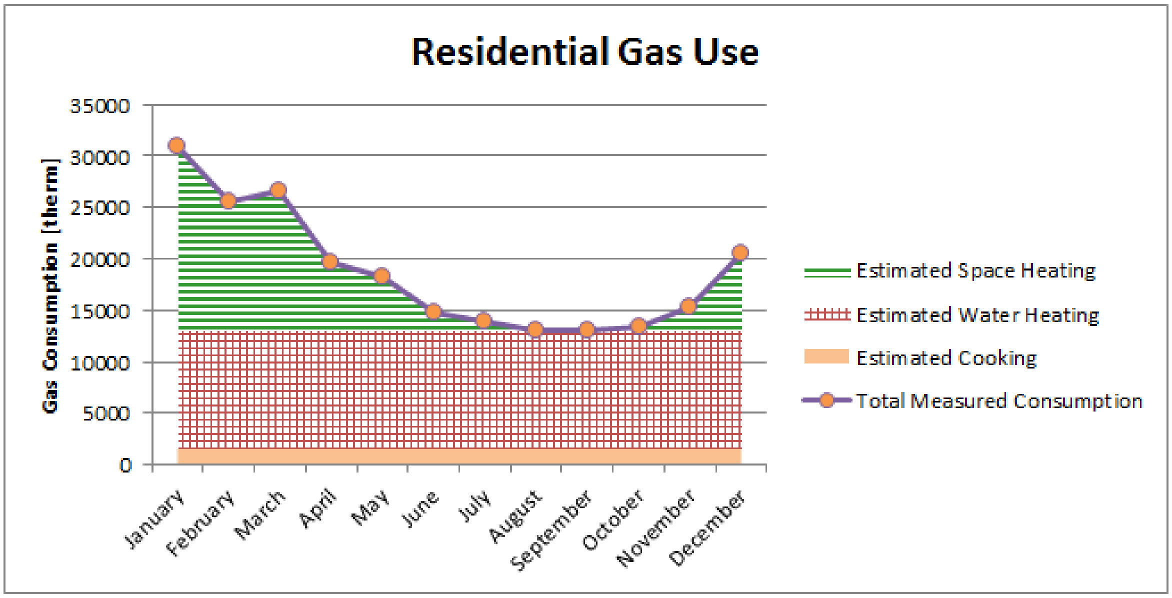
- Space heating was assumed to make up the portion of the natural gas consumption that is higher than the total consumption during the summer months.
- Cooking demands were assumed to make up a constant monthly value such that the annual cooking load equaled 8% of the total annual residential gas consumption (September). This was done to match data from the 2015 RECS.
- Water heating was assumed to make up the remaining natural gas consumption. Thus, both cooking loads and water heating loads are held constant throughout the year, matching typical OpenEI results.

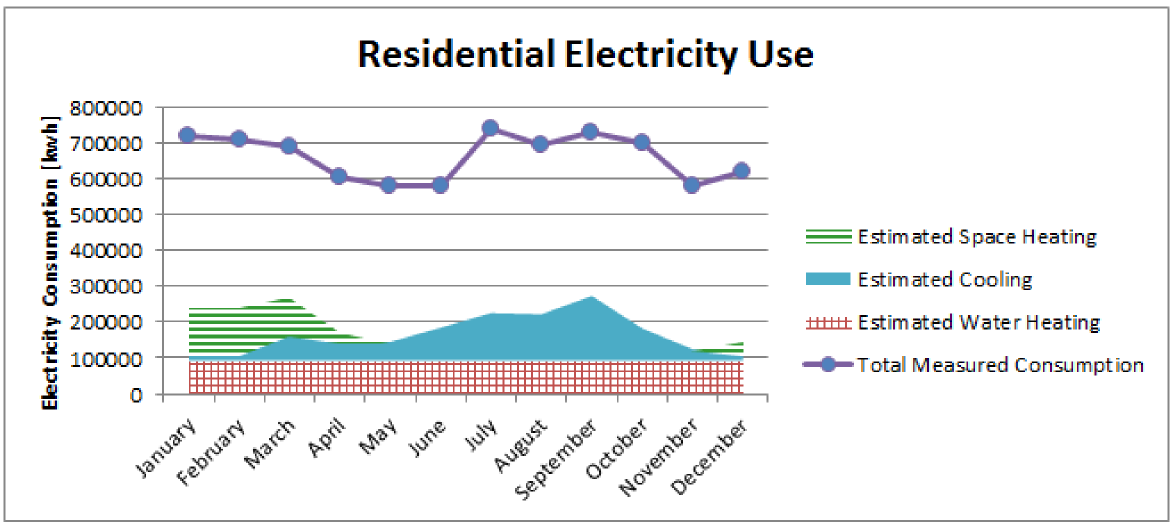
Electricity End Uses

- Cooling load ratios were taken directly from the OpenEI dataset. This entailed dividing the electricity used for cooling each month by the total monthly electricity consumption (both values from the OpenEI simulation).
- Electric water heating was assumed to consume a constant amount of each electricity each month such that it equaled 14% of annual household electricity use, matching 2015 RECS data.
- Electric space heating was assumed to make up the amount of electricity used that was greater than the lowest monthly electricity use (November). Electric space heating was assumed to be 0 during June to October.

This breakdown can be visualized as follows.

Figure 18: Breakdown of Residential Gas and Electricity Consumption

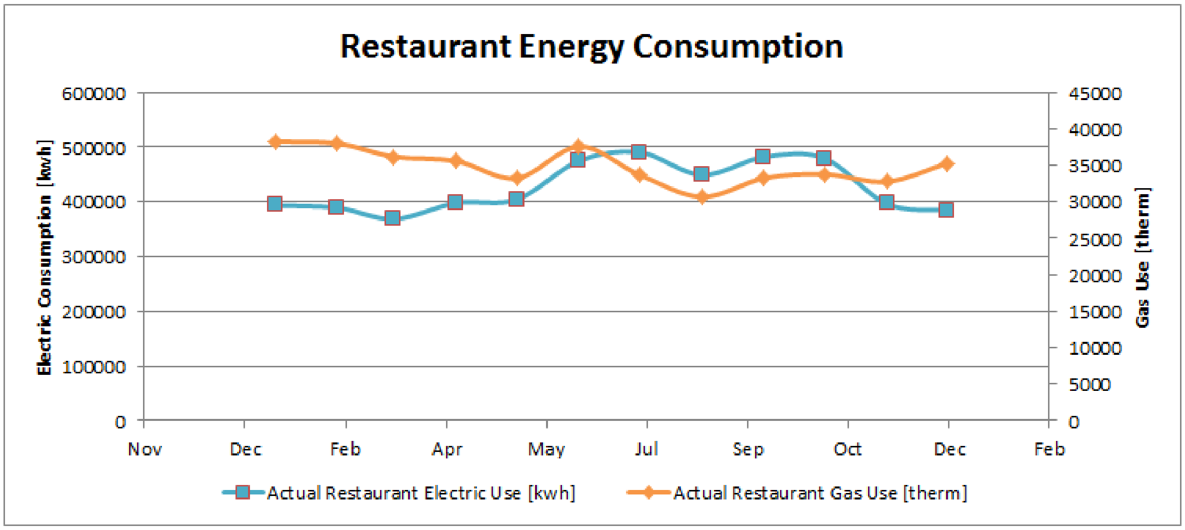




End-Use Ratio Calculation: Restaurants

The monthly energy use for restaurant meters in downtown Palo Alto is shown in Figure 19.

Figure 19: Restaurant Energy Consumption (2017)



Natural Gas End Uses

- Space heating loads for each month were assumed to make up any heating loads greater than the amount recorded in the month with the lowest natural gas use.
- Cooking loads were held constant each month and totaled 72% of the total annual restaurant natural gas consumption, in order to match CA Commercial End-Use Survey data (Appendix C).
- Water heating was assumed to make up the remaining natural gas consumption.

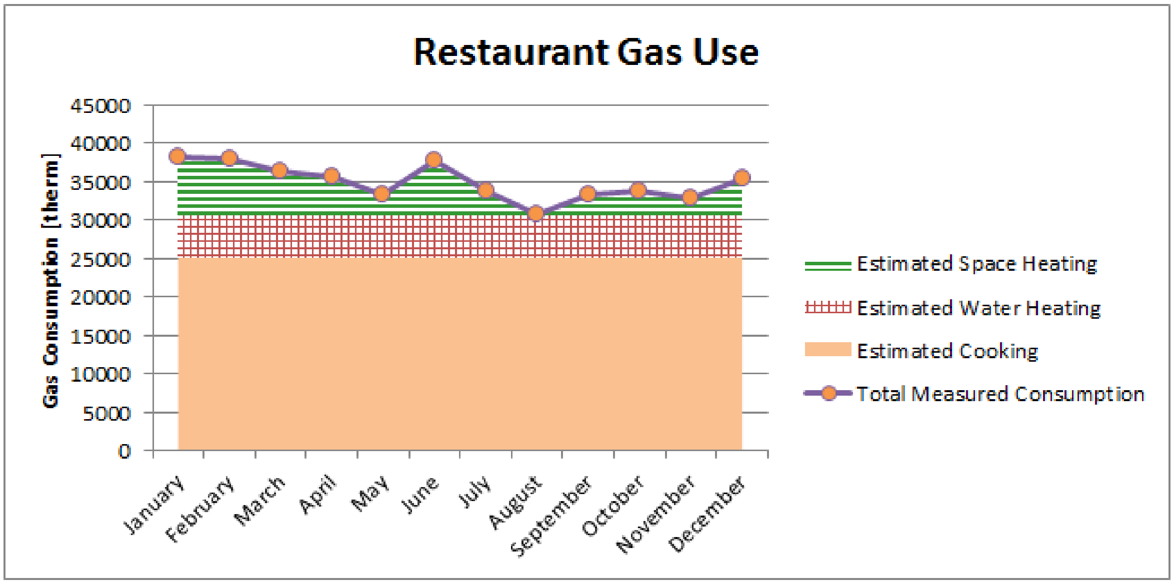
Electricity End Uses

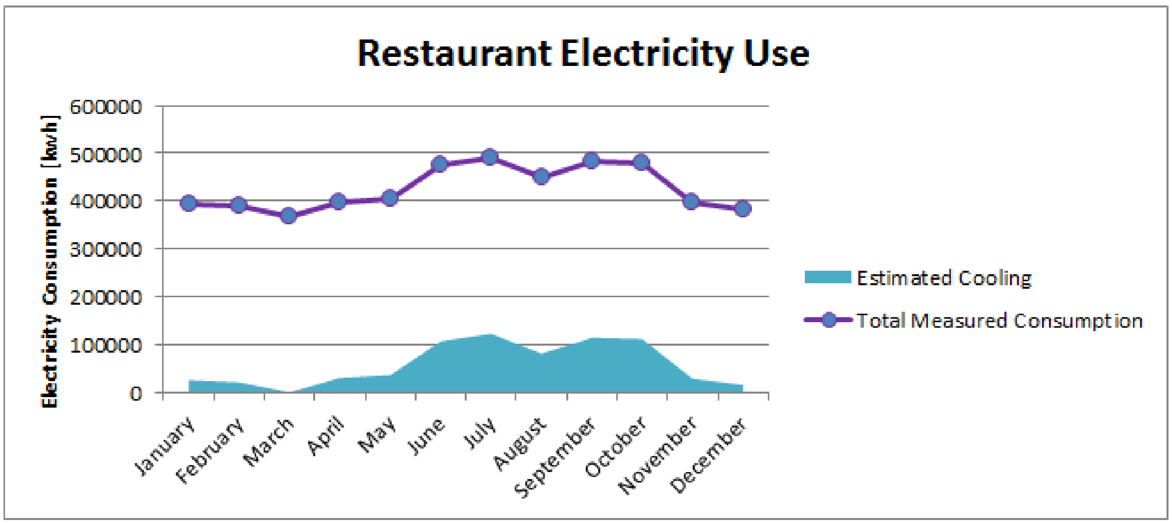
- Cooling loads were assumed to be all electric loads greater than the value recorded in the month with the lowest electricity consumption. This led to an annual average of 14% of electricity going to cooling loads.
- Electric water heating and space heating was assumed to be zero. End-Use surveys suggest the true value to be approximately 1%, but no electric heating data was used in the OpenEI model.

Cooking loads were held constant because cooking loads vary by less than 10% throughout the year in the OpenEI data set, and no additional data was known about monthly variations in cooking demand.

The end-use ratio for restaurants can be visualized as follows.

Figure 20: Breakdown of Restaurant Gas and Electricity Consumption

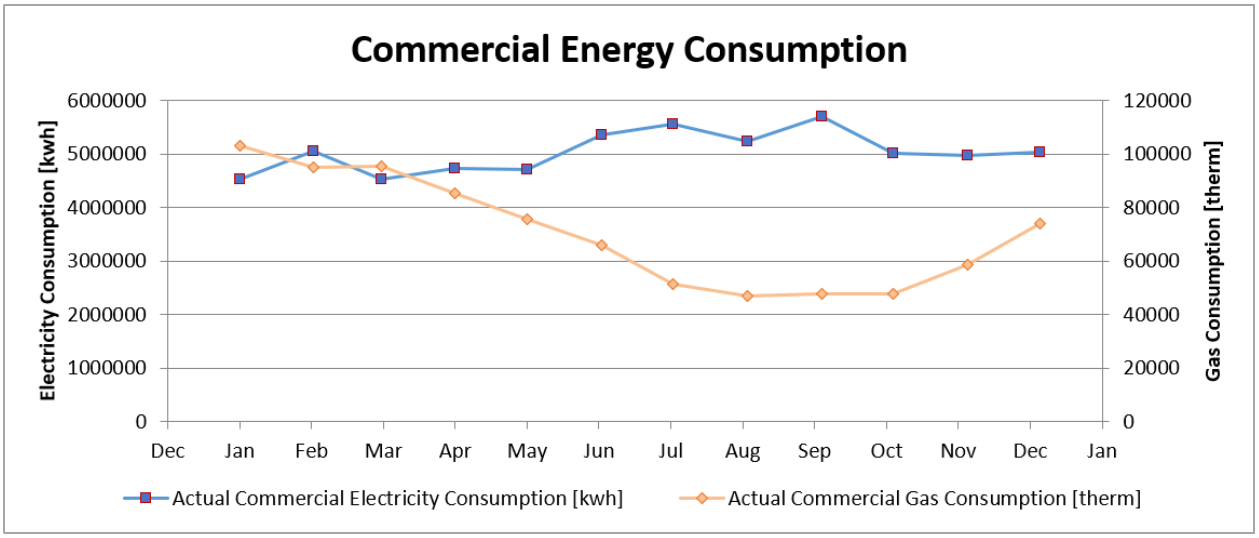




End-Use Ratio Calculation: Commercial

The monthly energy use for commercial meters in downtown Palo Alto is shown in Figure 21.

Figure 21: Commercial Energy Consumption (2017)



Natural Gas End Uses

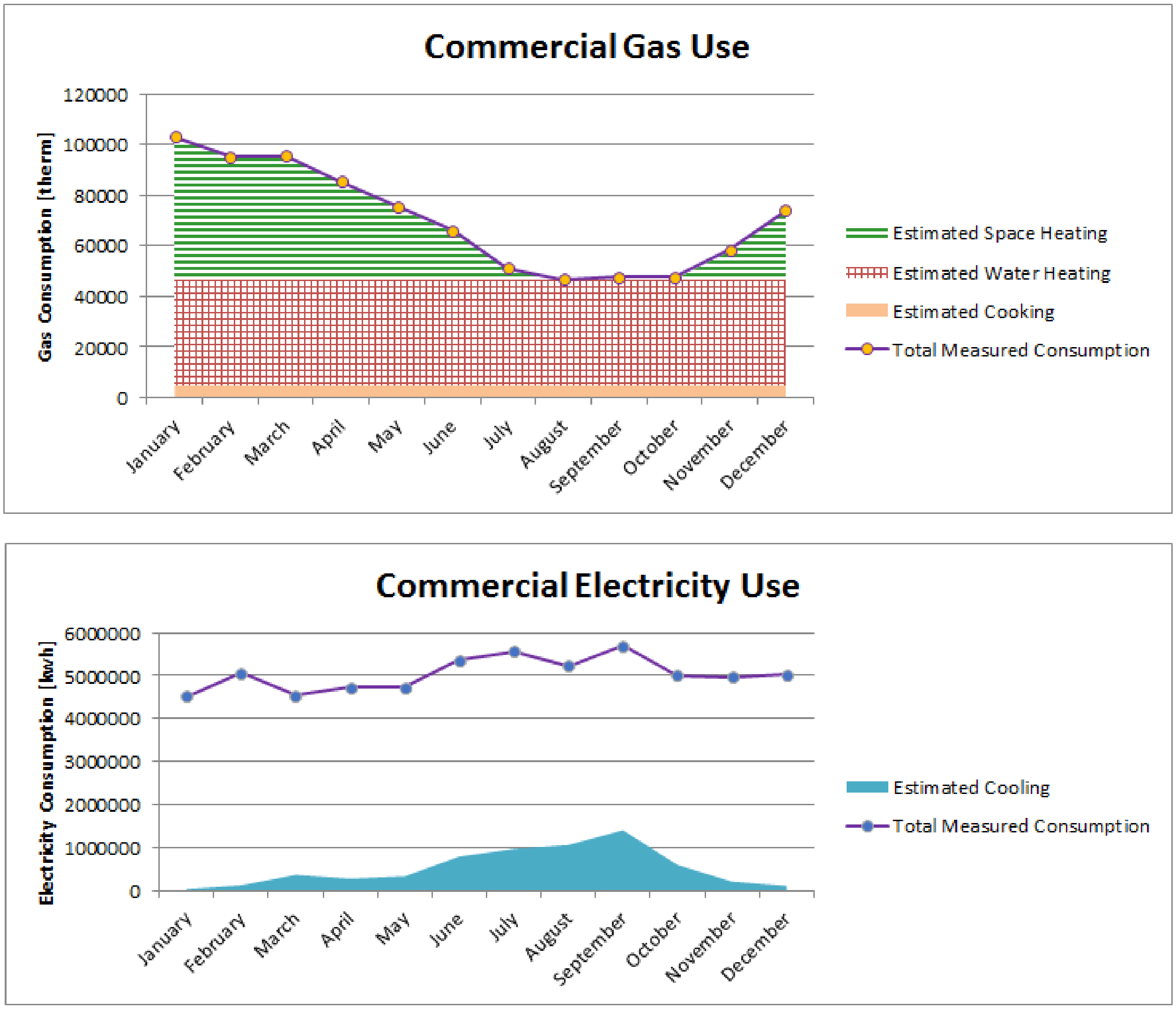
- Space heating loads were assumed to make up all natural gas use greater than the use in the month with the lowest demand (August).
- The cooking load was held constant throughout the year and adjusted such that it equaled 7% of the total annual natural gas consumption. This is slightly higher than the ratio found in the End-Use survey, and accounts for restaurants that may not have been captured during the manual restaurant identification process.
- Water heating was assumed to make up the remaining natural gas consumption.

Electricity End Uses

- To calculate cooling loads, the end use ratios from OpenEI were used. However, before calculating the cooling load ratio, the energy consumption from electric space heating was removed. This satisfies the assumption that no electric heating occurs in commercial buildings.

The end-use ratio for commercial buildings can be visualized as follows.

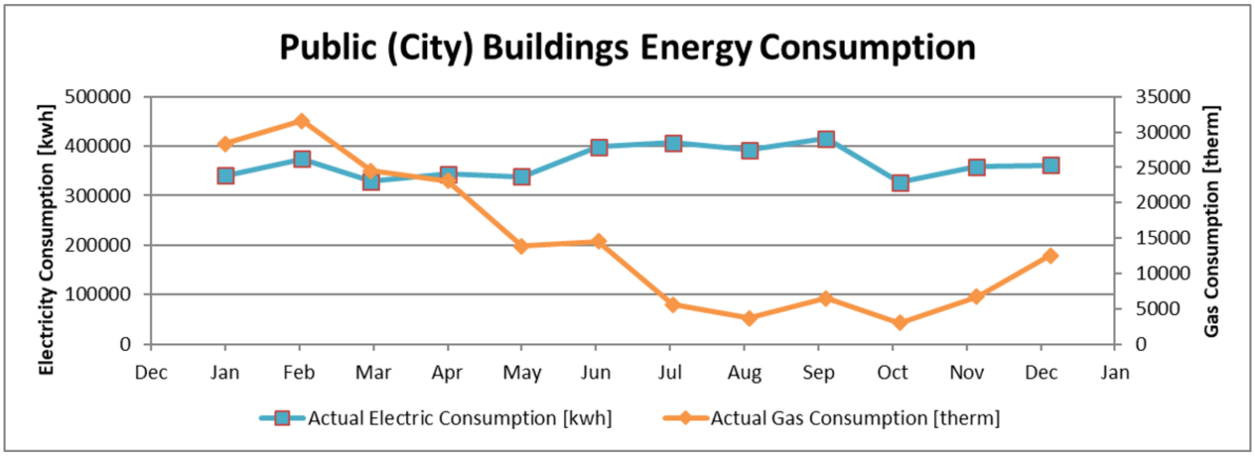
Figure 22: Breakdown of Commercial Gas and Electricity Consumption



End-Use Ratio Calculation: City Buildings

The monthly energy use for city building meters in downtown Palo Alto is shown in Figure 23.

Figure 23: Public (City) Buildings Energy Consumption



Natural Gas End Uses

- Space heating loads were assumed to make up any month's gas usage greater than the amount recorded in the second lowest month[34].
- Cooking loads were held constant throughout the year, equaling 2% of the annual gas consumption.
- Water heating was assumed to make up the remaining natural gas consumption.

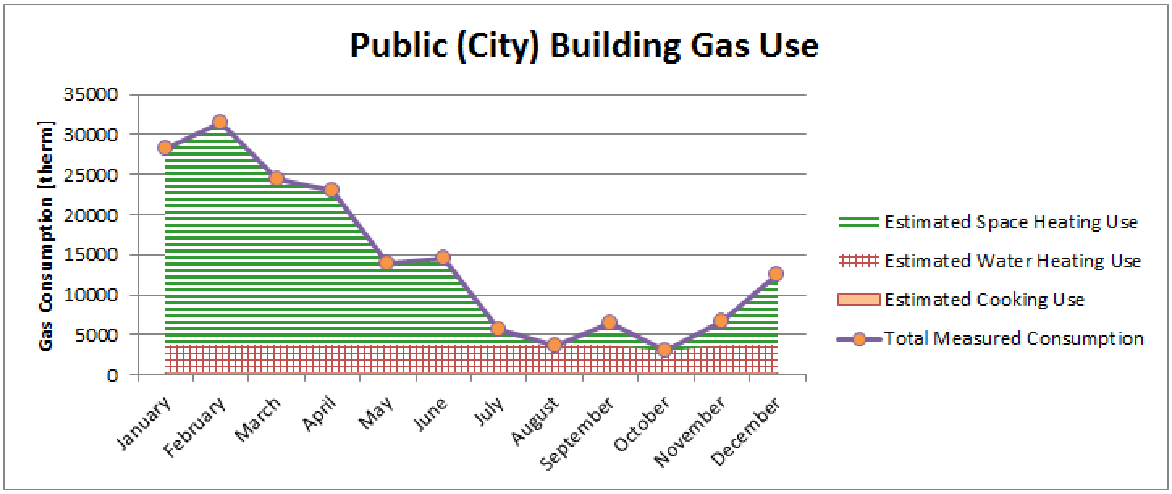
Electricity End Uses

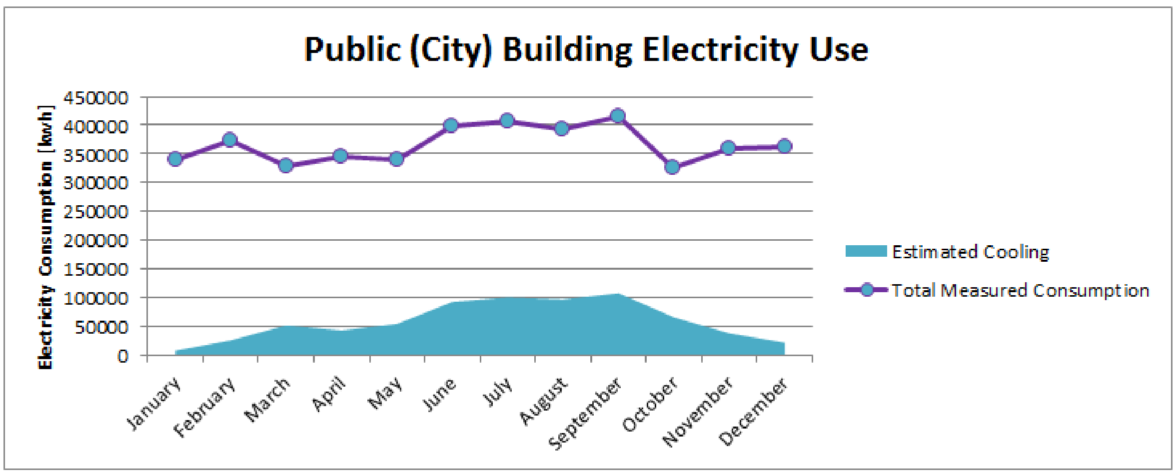
- The cooling ratios from OpenEI were directly used to calculate the cooling load for public buildings. No correction was needed to account for electric space heating, as the OpenEI model assumed all heating was supplied by gas.

[34] The second lowest consumption value was used due to an outlier consumption value near 0 that was recorded

The end-use ratio for public buildings can be visualized as follows.

Figure 24: Breakdown of Public (City) Gas and Electricity Consumption





The following table presents the end-use ratios that were calculated for downtown Palo Alto. As expected, the ratios for space heating tend to be higher in the winter, and the ratios for cooling tend to be higher in the summer.

Figure 25: End-use ratios for downtown Palo Alto

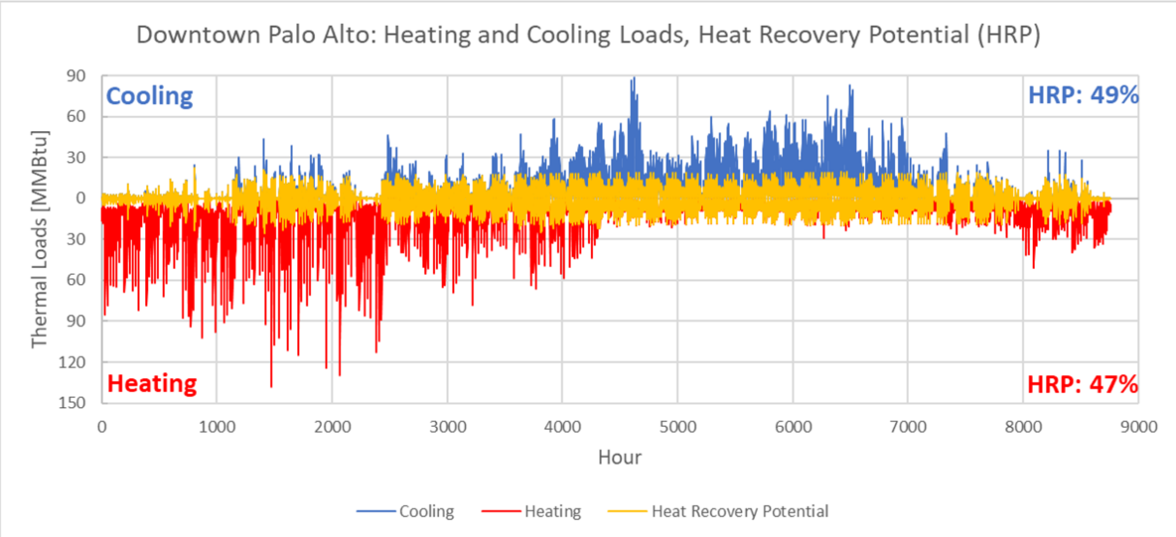
Month	Restaurant Space Heating (gas)	Restaurant Water Heating (gas)	Restaurant cooling (electric)	Large Office Space Heating (gas)	Large Office Water Heating (gas)	Large Office Cooling (electric)	Residential Space Heating (gas)	Residential Water Heating (gas)	Residential Cooling (electric)	Residential Space Heating (electric)	Residential Water Heating (electric)	Medium Office / Commercial Space Heating (gas)	Medium Office / Commercial Water Heating (gas)	Medium Office / Commercial Cooling (electric)
January	0.198	0.146	0.064	0.870	0.119	0.022	0.579	0.373	0.023	0.190	0.129	0.546	0.406	0.008
February	0.192	0.147	0.053	0.883	0.107	0.067	0.489	0.452	0.034	0.182	0.131	0.507	0.441	0.023
March	0.152	0.154	0.000	0.849	0.137	0.156	0.512	0.432	0.103	0.159	0.134	0.509	0.440	0.080
April	0.138	0.157	0.074	0.840	0.146	0.124	0.337	0.587	0.089	0.043	0.153	0.450	0.492	0.058
May	0.077	0.168	0.088	0.734	0.242	0.159	0.287	0.631	0.091	0.001	0.160	0.379	0.555	0.070
June	0.184	0.149	0.224	0.747	0.231	0.232	0.120	0.779	0.158	0	0.159	0.290	0.635	0.147
July	0.090	0.166	0.249	0.340	0.602	0.245	0.068	0.824	0.181	0	0.126	0.085	0.819	0.174
August	0.000	0.182	0.180	0.000	0.912	0.246	0.000	0.885	0.186	0	0.133	0.000	0.895	0.202
September	0.077	0.168	0.236	0.433	0.517	0.259	0.000	0.885	0.247	0	0.127	0.019	0.877	0.246
October	0.092	0.165	0.232	0.000	0.891	0.200	0.027	0.861	0.129	0	0.133	0.015	0.881	0.118
November	0.063	0.171	0.070	0.450	0.501	0.105	0.150	0.752	0.055	0.000	0.160	0.199	0.717	0.041
December	0.130	0.158	0.040	0.706	0.268	0.059	0.366	0.561	0.030	0.062	0.150	0.367	0.566	0.021

5.2 Generation of 8760 Hourly Thermal Profiles and Heat Recovery Potential

With the hourly thermal load ratios identified, Palo Alto monthly data acquired, and end-use ratios identified, the 8760 loads for heating and cooling in downtown Palo Alto are calculated. The thermal loads, in MMBtu, for downtown are shown in Figure 26 below.

It is very important to account for the coefficient of performance of the cooling system as well as the efficiency of the heating system. For this report, a COP of 2.6 and an efficiency of 80% were assumed for the cooling and heating systems, respectively.

Figure 26: Downtown Palo Alto hourly thermal load profile and heat recovery potential



The **heat recovery potential**, shown in orange, represents the quantity of heating and cooling loads that overlap for each hour. As described in the Thermal Microgrid Whitepaper, heat recovery chillers can harness waste heat from cooling operations to provide heat when the loads overlap. For downtown, 49% of the cooling loads could be provided using heat recovery chillers. At the same time, 47% of the heating loads could be met using waste heat recovery from heat recovery chillers. When the heat recovery potential is low, such as in the winter for downtown, other heat sources, such as renewable heat recovery from the ground, surface water, or air, can be implemented.

The following section will describe how the hourly loads are modeled in CEPOM, providing an estimate for the required thermal energy storage, plant capacity, and annual operating cost.

6 Feasibility study for the downtown region – Using hourly loads in CEPOM

In this section, we discuss the feasibility determination of a thermal microgrid system for downtown Palo Alto using the CEPOM tool. CEPOM has certain advantages over RETScreen. For example, it can model thermal storage and heat recovery chillers (to capture heat recovery potential). However, CEPOM modeling is a bit more complex. It requires hourly heating and cooling energy needs for a year as input. In section 5, we discussed an approach to derive hourly loads from monthly utility energy data. This section describes the data inputs required for CEPOM, the annual energy costs output from the model, the equipment sizing that is inferred from the model, and the emissions reductions achieved.

6.1 Data Inputs to CEPOM

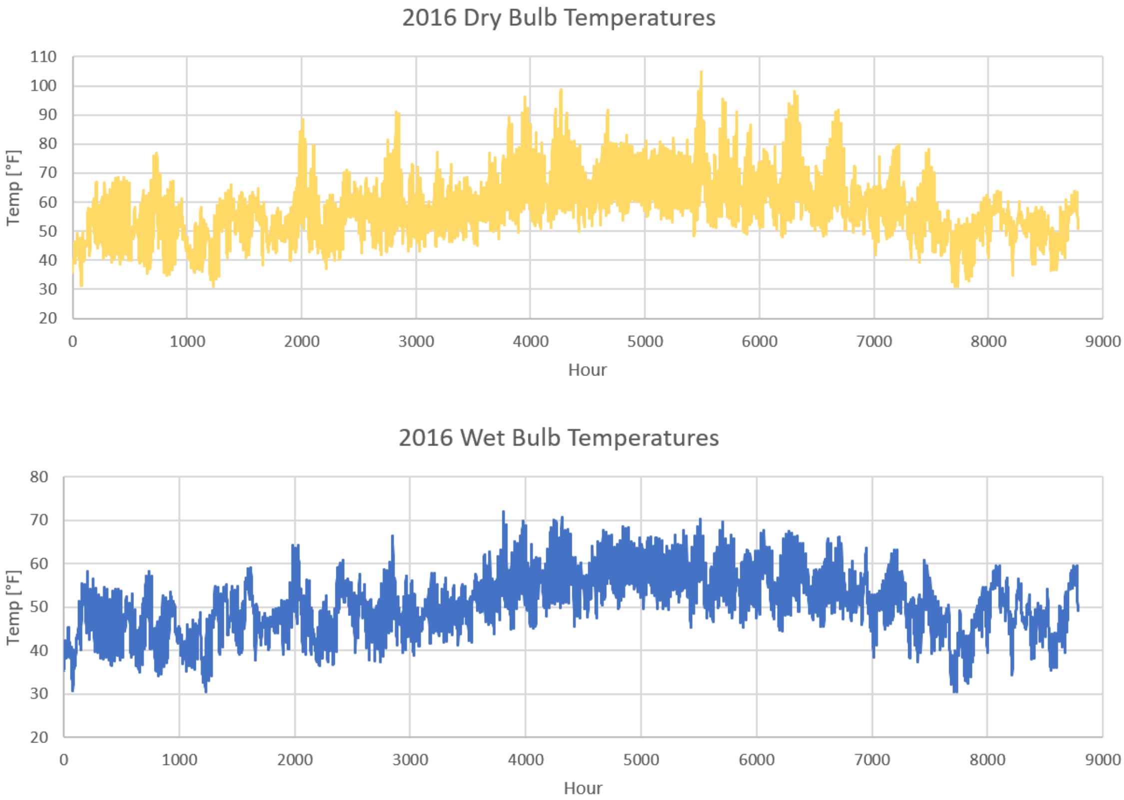
The CEPOM tool requires the following main inputs. Each of these inputs are discussed in greater details in following subsections. Another main input into CEPOM is hourly cooling and heating demand. This has already been discussed in section 5.

- Data Input: Temperatures
- Data Input: Electricity and Natural Gas Rates
- Data Input: Central Energy Facility Equipment Energy Consumption
- Data Input: Other Initial Model Parameters

6.1.1 Data Input: Temperatures

The following 8760s for dry-bulb and wet-bulb temperature were used. CEPOM requires knowledge of both temperatures due to the wet bulb temperature's effect on chiller efficiency.

Figure 27: Temperature input data for CEPOM model



6.1.2 Data Input: Electricity and Gas Rates

For the CEPOM analysis of Downtown Palo Alto, gas rates and electricity rates were held constant for all hours of the year.

Electricity rates were held constant because Palo Alto currently only offers time-of-use rates to customers in a pilot program[35]. If time-of-use rates do occur within the municipality being studied, it is important to include the price variations in the CEPOM model, as the model will attempt to optimize the chiller, hot water generator, and storage capacity to avoid consuming power during on-peak times. Since these times typically correspond to the highest cooling demands, significant cost savings may be realized.

The total electricity use of the downtown region was assumed to be constant throughout the year. Since time-of-use rates are not currently used and a demand charge was not a primary concern, attempting to find an accurate profile for total electricity consumption would not affect the total annual operating cost. However, future work or more detailed engineering analyses should attempt to develop this profile.

6.1.3 Data Input: Central Energy Facility Energy Consumption

When modeling the Stanford Central Energy Facility (SESI), the facility is assumed to maintain a base load of 250 kW. For modeling other facilities, this value needs to be scaled according to the amount of

[35] https://www.cityofpaloalto.org/gov/depts/utl/residents/rates.asp

thermal load required. For initial analyses, simply scaling the power demand linearly will suffice. SESI produces about 1.5 million MMBTu per year of heating and cooling[36]. Since the Palo Alto project could potentially produce about 180 thousand MMBTu per year of heating and cooling, we have estimated the base load for the new Central Energy Facility as follows:

$$\frac{250}{1.5 * 10\text{^}6} = \frac{x}{180{,}000}; \quad x = 30\ kW$$

6.1.4 Data Input: Other Initial Model Parameters

Storage Parameters

For the initial model run, the hot and cold thermal energy storage parameters were kept equal to those used on the Stanford University main campus (SESI). While these storage parameters are much larger than what downtown Palo Alto would use, using the original values guarantees that the model achieves a feasible solution. In the following model runs, we lowered the thermal storage values incrementally.

HRC Capacity, Chiller Capacity, Hot Water Heater Capacity

As with the storage parameters, the capacities of the HRCs, chillers, and hot water heaters was kept identical to the Stanford model for the initial model run. What is most important for sizing the equipment is observing the peak usage of each type during the year.

Peak Demand

The maximum power demand allowed (non-cooling loads + central energy facility equipment) was set at 15 MW. Since the non-cooling loads were estimated to be 7.7 MW for every hour of the year, this allows the central energy facility to use up to 7.3 MW of power before causing demand charges.

6.2 Data Output: Total Annual Energy Costs (BAU vs New System)

Business-as-Usual Cost Estimation

In 2017, the customers in downtown Palo Alto consumed 77,856,959 kWh of electricity and 1,661,146 therms of natural gas, for a total cost of approximately **$10.9 million** and **$2.14 million**, respectively. The average price paid for electricity and gas was 14 cents per kWh and $1.29 per therm, respectively.

Assumptions

From the results of the 8760 generation (Section 5), heating and cooling loads are assumed to make up 77% and 13% of downtown natural gas and electricity consumption in 2017, respectively. Therefore, the business-as-usual thermal load costs are as follows[37]:

Electric Thermal Load Costs: Approx. $1.42 Million
Natural Gas Thermal Load Costs: Approx. $1.65 Million

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[36] According to part 2 report, Stanford's annual thermal load was 1.33 million MMBtu. - http://www.edf-innovation-lab.com/wp-content/uploads/2018/06/2018_SESICaseStudy_FINAL.pdf

[37] Recall that for the downtown CEPOM study, some electric loads were for space and water heating, in addition to cooling

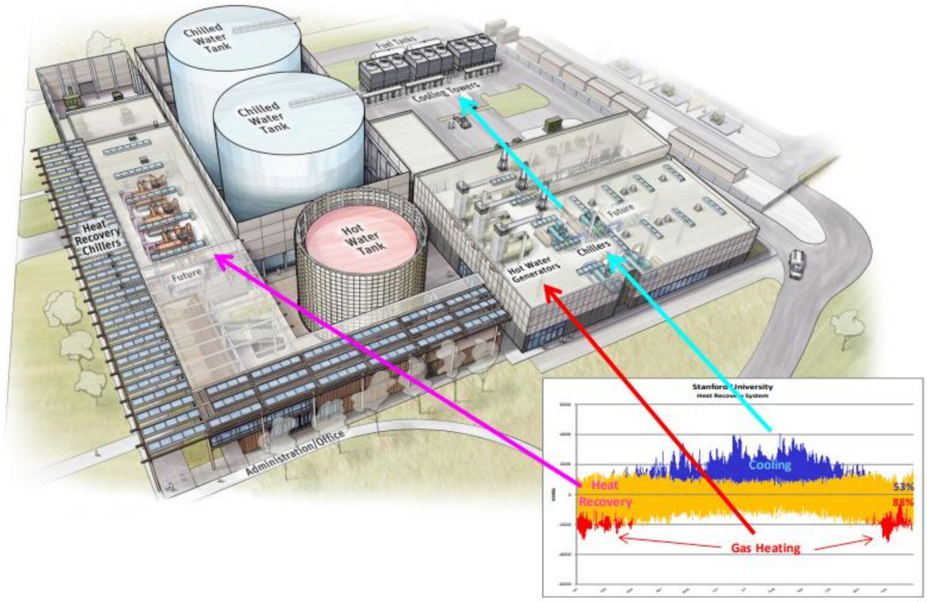
CEPOM Model Outputs

The total electricity cost to run each piece of equipment and supply the required loads, using 2018 cost data, is shown in Table 16. Figure 28 visualizes what each piece of equipment handles, as well as its relative size at the Stanford CEF.

Table 16: Estimated electricity costs for the downtown thermal microgrid equipment

Heat Recovery Chiller (HRC)	Chillers	Heaters	CEF	Distribution
$572,354	$197,237	$15,886	$36,893	$97,665

Figure 28: Thermal Microgrid Equipment Diagram at SESI [38]



The estimated annual consumption and cost of natural gas (for space and water heating) was found to be 66,749 MMBtu and $861,061, respectively. This corresponds to a **48%** decrease in natural gas used for heating, and a **37%** decrease in overall gas use within the district.

Thermal Microgrid Heating and Cooling Costs (assuming 50-50 HRC split)[39,40]

Heating: Approx. $1,200,000
Cooling: Approx. $570,000

[38] http://www.edf-innovation-lab.com/wp-content/uploads/2018/06/2018_SESICaseStudy_FINAL.pdf

[39] This means that half of the HRC electricity cost is counted as a cooling cost, and half as a heating cost.

[40] The model was run for scenarios with no initial storage and full initial storage. Cost variations were negligible.

Therefore, the total energy cost to run the downtown Palo Alto thermal microgrid is estimated at **$1,770,000** for 2018 costs. This is a **42%** decrease in total heating and cooling cost.

Cost Saving Breakdown (Downtown Palo Alto)

Table 17: Source and Quantity of various cost savings associated with the thermal microgrid

Saving Source	Saving Amount	Fraction of Total Savings
Heat recovery	$820,000	66%
Chiller efficiency[41]	$400,000	32%
HRC efficiency	$10,500	1%
Improved Natural Gas Boilers Efficiency	$4,000	< 1%

Note: Cost saving sources will vary depending on the unique characteristics of the district being studied

It is important to note that the cost of natural gas makes up almost 50% of the remaining cost, which suggests that the modeled system will be very sensitive to changes in natural gas cost. This also suggests that additional heat recovery methods, such as ground source heat exchange, heat recovery from the San Francisco Bay, or installation of air-source heat pumps at the building level may be able to further reduce natural gas consumption in the district.

6.3 Data Output: Required Central Energy Facility Equipment and Thermal Storage Capacities

Hot Water Storage

From the initial, unconstrained model run, the minimum value of remaining hot water storage was identified. The difference between the minimum storage value and the defined storage capacity was **35 MMBtu**. This value will be used in the detailed cost estimate.

Cold Water Storage

From the initial, unconstrained model run, the difference between the minimum cold-water storage reached and the defined storage capacity was found to be **40,000 ton-hr**.

HRC Capacity

The maximum combined hot water production from the heat recovery chiller was **2,000 tons**.

Chiller Capacity

The maximum combined cold-water production from the electric chillers was **8,000 tons**.

41 The new, high-efficiency chillers have an efficiency of 0.5 kW/ton, which is much better than the HRC (1.33-1.5 kW/ton)

Boiler Capacity

The maximum combined hot water production from the boiler was **160 MMBtu/hr**. Note that this value is highly sensitive to the *peakiness* of the heating load estimates.

Table 18: Summary Table for Recommended System Parameters

HW Storage	CW Storage	HRC Capacity	Chiller Capacity	Boiler Capacity
35 MMBtu	40,000 ton-hr	2,000 tons	8,000 tons	160 MMBtu/hr

6.4 Capital Costs of New System

System Cost Estimation Model

We have developed capital cost estimates for a new thermal microgrid system using equipment and storage size estimates from the CEPOM tool (Section 6.3) and capital cost per equipment as listed in Appendix D. This approach is referred to as the "detailed costing" analysis in this section. We have also attempted to estimate capital costs using a few other benchmarks and refer to them as "simplified analysis".

- Detailed costing analysis, where each equipment size and per unit cost is entered
- Simplified costing analysis, where total gross square feet (GSF) of building space is entered
- Simplified costing analysis, where total plant capacity is entered
- Simplified costing analysis, where total heat delivered is compared to Stanford SESI system

By presenting different costs, a range of likely costs for the project is developed, which can help build further confidence in the model. The cost spreadsheet for this case study can be found using the OneDrive link in the footnote[42].

Using the cost data presented in Appendix D and the storage and capacity parameters in Section 6.3, the four cost estimates for the downtown Palo Alto system were calculated and are shown in Table 19.

Table 19: Cost estimates for the downtown Palo Alto thermal microgrid project

Detailed Costing	GSF-based Costing	Capacity-based Costing	Stanford-based Costing
$113M	$48M	$60M	$144M

System Cost: Sensitivity to Capacity

The peak loads estimated in this analysis are much higher than the average load. While the average hot water heating at the CEF is 10 MMBtu annually, the 10 highest hourly consumptions range from 100 to 140 MMBtu. If these loads are lower than predicted, significant cost savings could be realized.

[42] https://office365stanford-my.sharepoint.com/:f:/g/personal/spragg_stanford_edu/Ei2iomo_zvpHgWVqohDu-bUBBOia8DGh9E6T4fZjkwEHmw?e=SdsuD5 (both the downtown and corporate site spreadsheets are shared)

Further engineering analyses should develop models using building management system data specific to large buildings in the downtown region.

6.5 Estimated Emissions Reduction

As stated in Section 6.2, installation of the downtown thermal microgrid would decrease natural gas consumption by 37%. Assuming carbon-free electricity from the city of Palo Alto, this corresponds to a 37% reduction in total district carbon dioxide emissions. The emissions associated with natural gas consumption are 13.446 lbs per therm[43]. From Section 6.2, the total natural gas consumption in 2017 was 1,661,146 therms. Therefore, the thermal microgrid would result in 8,264,235 lbs or over **3,700 metric tons** of avoided greenhouse gas emissions annually[44].

43 https://www.pge.com/includes/docs/pdfs/about/environment/calculator/assumptions.pdf

44 For reference, Palo Alto has about 100,000 metric tons of annual GHG emissions from natural gas usage in the city https://www.cityofpaloalto.org/civicax/filebank/documents/64462

7 Comparison of RETScreen and CEPOM Load Results for Downtown Palo Alto

This section discusses the differences between the RETScreen and CEPOM results for downtown Palo Alto. The RETScreen and CEPOM results are compared with the results of two other methods that utilize data for the entire City of Palo Alto, as well as data for the two Stanford thermal microgrid facilities.

7.1 Peak and Annual Load Comparison

Table 20 shows the annual and peak heating and cooling demand estimates by RETScreen, 8760 hourly estimates (as described in section 6) by CEPOM, and the Business-As-Usual (BAU) case. These values represent end-use demands and not the electricity or natural gas required to meet said demands. For reference, we have also listed the thermal loads for the Stanford campus and Redwood City campus.

The RETScreen model outputs both annual and peak loads that are **less** than what the utility BAU and CEPOM data suggests. To account for the discrepancy between models, further tuning of the ratios was performed, and the variations were discussed with a RETScreen engineer. It was determined that, given RETScreen's focus as a *Pre-Feasibility* tool, that little emphasis should be placed on their peak load calculation. Therefore, two other estimation methods, using the City of Palo Alto's ratio of peak load to average electricity load, as well as the hourly electricity load profile for the entire city, were performed to better estimate the peak cooling loads.

Table 20: Heating and Cooling Load Comparisons using different methods

	Heating Load (Annual)	Heating Load (Peak)	Cooling Load (Annual)	Cooling Load (Peak)
RETScreen Estimate	31,000 MMBtu	16,000 MBH	53,000 MMBtu	43,000 MBH
Estimate using Design Temperatures (RETScreen)	420,000 MMBtu	--	350,000 MMBtu	--
Downtown 8760 Estimate	107,545 MMBtu	138,000 MBH	75,527 MMBtu	89,000 MBH
BAU Downtown Estimate[45]	102,327 MMBtu	--	89,725 MMBtu	--
Estimate Using Palo Alto Peak Load Data	--	--	--	67,000 MBH
Estimate Using Palo Alto Hourly Data	--	--	--	34,000 MBH
Redwood City Campus	10,701 MMBtu	100,000 MBH	21,024 MMBtu	300,000 MBH
Stanford Campus	610,205 MMBtu	3,000,000 MBH	723,187 MMBtu	4,000,000 MBH

[45] Heating: 166,115 MMBtu * 77% heating * 80% eff. = 102,327 MMBtu; **Note:** does not include electric space heating
Cooling: 77.86 million kWh * 13% * 0.0034MMBtu/kWh * 2.6 (COP) = 89,725 MMBtu; Overestimates

7.2 Alternate Peak Cooling Load Estimation Methods

7.2.1 Cooling Peak Load Estimation using City of Palo Alto Utilities Peak versus Average Electricity Loads

Table 21: Average versus peak electricity load for each month (City of Palo Alto Utilities, 2017)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Total Demand [MWh]	80,066	72,129	79,696	76,418	80,101	80,543	84,332	85,139	81,101	81,840	77,163	79,252
Peak Load [MW]	134	135	140	150	156	168	168	167	165	155	142	136
Peak: Avg Ratio	1.25	1.26	1.31	1.41	1.45	1.50	1.48	1.46	1.46	1.41	1.32	1.28

The ratio of peak load versus average load is highest during the summer months. Assuming the max ratio (1.50) for the downtown region, and that the peak load consists **only of cooling** demands in September[46], the downtown peak cooling load can be estimated as follows:

Total and average electricity consumption in downtown (Sep. 2017): 7,320 MWh (average = 10.17 MW)
Approximate peak electricity consumption in downtown (Sep. 2017): 15.26 MW

Estimated average cooling load in downtown (September 2017): 1,803 MWh (2.5 MW)
Estimated cooling peak load in downtown: 2.5 MW (base) + (15.26 MW - 10.17 MW) = **7.59 MW**[47]

Given that this estimate assumes all peak load is for cooling, uses the highest peak to average load ratio, and considers the month where the portion of electricity that goes to cooling is the highest, this value is likely an *overestimate* of peak cooling demand in downtown Palo Alto. This suggests that RETScreen is providing a reasonable peak cooling load. However, when compared with the other facilities, it appears to underestimate the heating load. The data also suggest that the hourly load estimate is providing a higher-than-expected peak load (10 MW). Since the hourly loads are defined such that they sum up to the actual consumption, having high peak loads means that the OpenEI data has peaks that are higher than those in downtown. Future analyses could attempt to use smoothing algorithms to reshape the peak load.

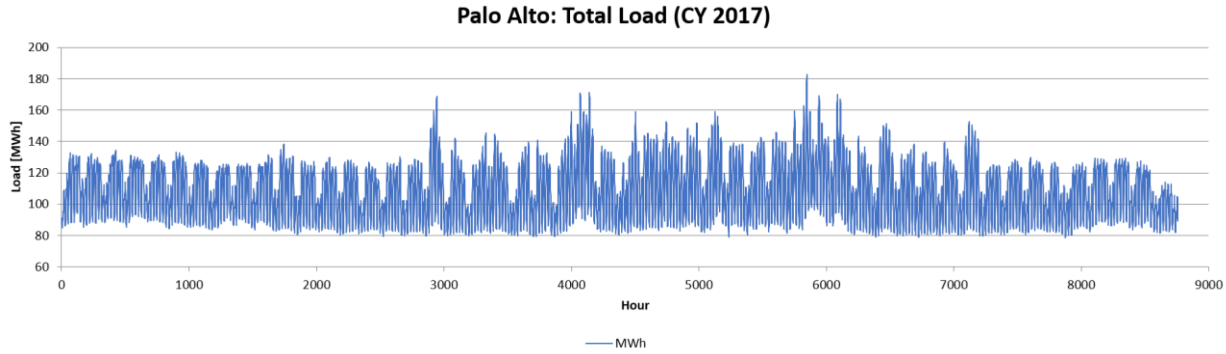
[46] In 2017, all four building types report their highest cooling ratio in September. The total electricity consumption was also highest in September for all four types.

[47] This is the electricity consumption of cooling at the peak. The actual cooling load is 67,000 MBH (assuming COP of 2.6)

7.2.2 Peak Load Estimation Using Palo Alto Hourly Load Data

While hourly electric load data is not available for downtown Palo Alto, it is available for the city as a whole. Hourly load data for calendar year 2017 is shown in Figure 29. Hourly load data can complement peak to average ratio data to better estimate peak cooling loads for a region.

Figure 29: Palo Alto city-wide hourly load data (2017)



During the spring and fall, the base load is lowest, at about 80 MW. The peak loads during this time are approximately 130 MW. During times of high cooling demand, the load is around 170 MW. This suggests that the peak cooling load is about 40 MW, or 25% of the total electric load for the peak hours[48]. Here, we assume that the *peakiness* of the hourly load data for the entire city is likely similar to the profile in downtown Palo Alto. Therefore, the peak cooling load for downtown Palo Alto can be estimated as follows.

Average electricity consumption in downtown (Sep. 2017): 10.17 MW
Approximate peak electricity consumption in downtown (Sep. 2017): 15.26 MW
Approximate cooling peak load assuming 25% ratio: **3.8 MW**

The following table shows how the downtown peak cooling load varies with different assumptions for its end use ratio.

Table 22: Peak downtown cooling load vs cooling load ratio

20%	25%	30%	35%
3.1 MW	3.8 MW	4.6 MW	5.3 MW

7.2.3 Comparison Takeaways

The data suggest that 25% is a reasonable cooling ratio for the peak load. The data also suggest that the peak load is approximately 150% of the average load for the hottest month. Therefore, the peak cooling load is approximately **4 MW**. These estimates, along with the results from the RETScreen and CEPOM models, should be considered when performing an engineering design of the system capacity.

48 This estimate assumes no cooling loads during the times when the base load is lowest

7.3 Equipment Size Comparison

Table 23: RETScreen downtown Palo Alto equipment size estimates (identical to Table 10)

	Base Load Cooling (Air-Source HP)	Peak Load Cooling (Compressor)	Base Load Heating (Air-Source HP)	Peak Load Heating (Nat. Gas Boiler)
Capacity	3400 kW (960 ton)	1400 kW (400 ton)	2600 kW (740 ton)	2100 kW (600 ton)

Table 24: CEPOM downtown Palo Alto equipment size estimates (identical to

Table **18**)

HW Storage	**CW Storage**	**HRC Capacity**	**Chiller Capacity**	**Boiler Capacity**
33 MMBtu	20,000 ton-hr	1,600 tons	6,000 tons	170 MMBtu/hr

The CEPOM model predicts a necessary cooling capacity that is many times greater than RETScreen. It also predicts a heating capacity that is many times greater than RETScreen. This is in line with the much lower peak load predicted by RETScreen, as discussed in Section 7.1.

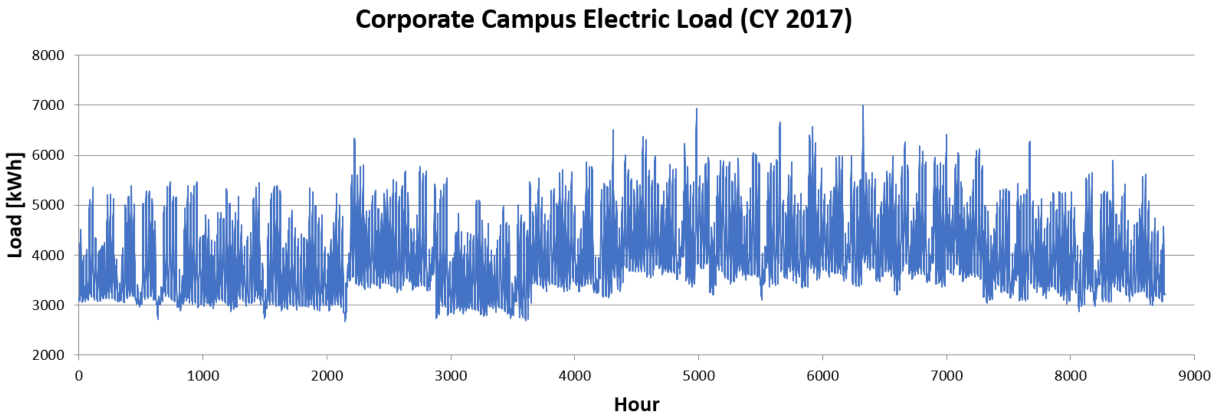
8 Feasibility study for a Corporate Campus – Using hourly loads in CEPOM

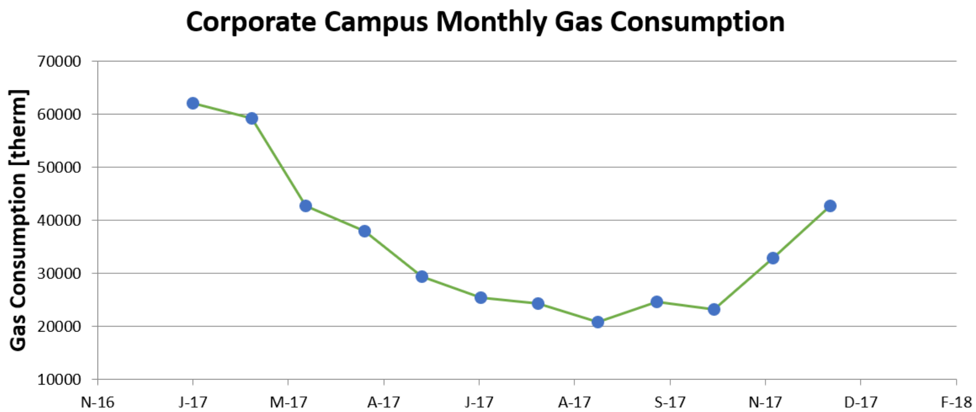
A corporate campus in the Stanford Research Park had previously expressed their interest in researching the potential for an electric microgrid. After reaching out to Stanford, they were interested in learning the scope of a thermal microgrid on their campus as well. An initial scoping study of the campus is performed, and the heat recovery potential, capital costs, emissions, and profitability are estimated.

8.1 Data Inputs to CEPOM

As discussed in Section 3, 15-minute resolution electricity data was available for each building in the campus. Using this data, the hourly electric profile for the campus was generated. Like the downtown region, only monthly loads for natural gas usage were available.

Figure 30: Campus Energy Consumption: 15-minute interval electricity usage and monthly natural gas usage





8.1.1 Heating Load Assumptions

For heating loads, the hourly profile was developed in a similar manner to the downtown study (Section 5), whereby publicly available hourly load ratios (on OpenEI), generated using building energy modeling software, were multiplied by the campus total monthly gas consumption[49]. All heating loads were assumed to be from natural gas.

8.1.2 Cooling Load Assumptions

For cooling loads, a new method was developed which takes advantage of the hourly load data. For each month, the average campus load was identified. Then, for each hour, all loads greater than a certain percentage of the monthly average load were assumed to be cooling loads. In Table 25, this is described as the cooling threshold. The threshold is lower in the summer because the percentage of electricity going to cooling loads is likely higher in that period. A base cooling load was also applied to every hour of each month. This was done to match the higher base loads observed during the summer.

Table 25: Cooling Load Assumptions for Corporate Campus

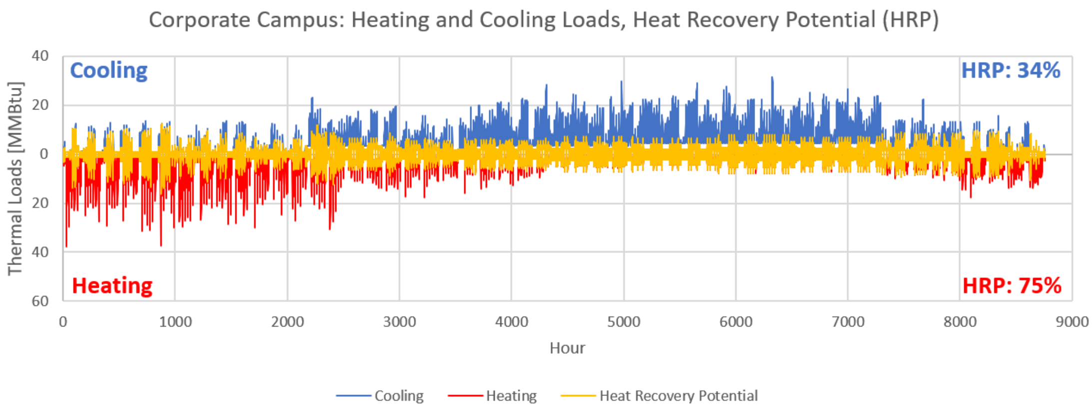
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Cooling % Threshold	110	110	110	100	100	90	90	90	90	90	100	110
Base [kw]	100	100	100	400	200	400	400	500	500	500	200	100

Since data was provided at the building level, knowledge of each building's use case or information from the building management system would help improve the accuracy of the load profiles. Future work could likely entail this, specifically working with the building manager to access building management system data. Correlations could also be generated between high and low outdoor temperature and hourly load.

8.1.3 Hourly (8760) profile of Heating and Cooling Loads

The 8760 for the campus heating and cooling loads, developed using the method described in Section 8.1, is shown in

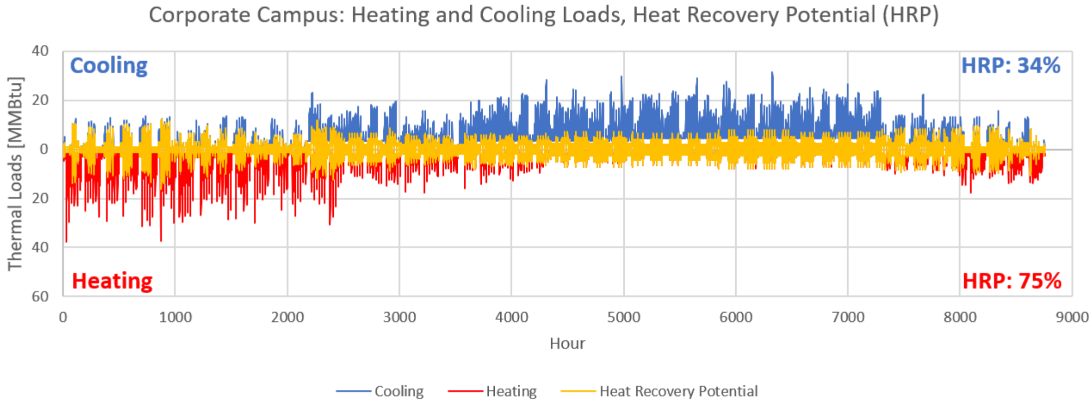
Figure **31:** Heating and cooling loads and heat recovery potential at the corporate campus



[49] https://openei.org/datasets/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states

. Heat recovery potential implies that 75% of campus heating needs could be met by HRCs.

Figure 31: Heating and cooling loads and heat recovery potential at the corporate campus



8.2 Data Output: Total Annual Energy Costs (BAU vs New System)

In 2017, the campus spent approximately $4.6M on electricity and $487,000 on natural gas. The average price paid for electricity and gas was 13.5 cents per kWh and $1.15 per therm, respectively[50]. Demand charges were set at $15.5 per kW peak demand.

Assumptions

Heating and cooling were assumed to make up 87% and 16% of the campus natural gas and electricity consumption in 2017, respectively. Therefore, the business-as-usual (BAU) heating and cooling costs are as follows:

BAU Heating: Approx. $425,000
BAU Cooling: Approx. $740,000

Using Stanford's Central Energy Facility (SESI) as a reference, the proposed new central system at corporate campus was assumed to always consume 13.7 kW of power.[51]

The campus electricity use input into CEPOM did not include the portion attributed to cooling loads, as these loads would not exist under the new system. As with the downtown Palo Alto study, the initial model run did not vary any of the equipment capacities or efficiencies[52]. Finally, due to the proximity to Stanford, the same temperature data was used. The natural gas rate, demand charge, and electricity rate were assumed to be constant throughout the year.

---

50 The average electricity cost of 13.5 cents per kWh includes the demand charge, as it was calculated by dividing total cost by total consumption

51 Stanford SESI Energy Consumption: 250kW (assumed to be constant throughout the year)

Stanford SESI Total Heating and Cooling Production: 1.5 million MMBtu

Corporate campus total Heating and Cooling Production = 82,000 MMBtu

Energy Consumption by Corporate Campus Central Facility = 250/1.5 million = x/82,000; **x = 13.7 kW**

52 Multiple model runs were completed. The equipment capacity was decreased each run until the solution became infeasible

The estimated electricity costs of the thermal microgrid equipment are shown in Table 26.

Table 26: Electricity costs for the corporate campus thermal microgrid equipment

Heat Recovery Chiller	Chillers	Heaters	CEF	Distribution
$257,004	$162,097	$2,159	$16,246	$53,095

The estimated annual cost of natural gas (for hot water heating) was estimated to be $108,163. This corresponds to a **65%** decrease in the total campus natural gas consumption.

Thermal microgrid heating and cooling costs (assuming 50-50 HRC split[53]):

Heating: $250,000
Cooling: $340,000

The total annual energy cost savings for heating and cooling of the corporate campus are **$575,000**. This is a **50%** reduction in annual energy cost.

8.3 Data Output: Required Central Energy Facility Equipment and Thermal Storage Capacities

Estimates for the recommended equipment sizing were completed by observing the maximum capacity demanded of the HRC, chiller, and boiler during the year, as well as observing the minimum hot and cold-water storage reached. These values will change as the parameters are adjusted; therefore, subsequent model runs should be completed to ensure feasibility.

Table 27: Equipment sizing for the corporate campus thermal microgrid project

HW Storage	CW Storage	HRC Capacity	Chiller Capacity	Boiler Capacity
16 MMBtu	25,000 ton-hr	1,000 tons	6000 tons	40 MMBtu/hr *(40,000 MBH)*

The assumed efficiencies of the thermal microgrid equipment are listed in Appendix F.

Approximate Thermal Energy Storage Tank Size[54]
Hot Water Storage: 8,500 ft^3 (approx. 64,000 gallons)
Cold Water Storage: 240,000 ft^3 (approx. 1,800,000 gallons)

8.4 Capital Costs of New System

The system sizing parameters from the CEPOM model run, the total annual thermal load identified in the 8760 generation, and the campus square footage were all used in a cost spreadsheet that follows

[53] This means that half of the HRC electricity cost is counted as a cooling cost, and half as a heating cost

[54] Storage size is a function of the differential between the supply and return temperatures for hot and cold water

the same form as the downtown Palo Alto project (Section 6.4). All per unit equipment costs were left unchanged from the downtown project. The resulting four cost estimates are shown in Table 28.

Table 28: Cost estimates for the corporate campus thermal microgrid project

Detailed Costing	GSF-based Costing	Capacity-based Costing	Stanford-based Costing
$68M	$26M	$36M	$66M

It is likely that the corporate campus can achieve lower per unit costs than the thermal microgrid systems that were used to generate cost models. This is because Stanford University, which owns the Redwood City campus that was studied, does not usually engage in lowest-bid contract awards and has strict aesthetic, construction, and physical requirements.

In Section 9, the financial feasibility of both the downtown and the corporate campus project are discussed.

8.5 Estimated Emissions Reduction

As stated in Section 6.8, the GHG emissions associated with natural gas consumption are 13.446 lbs CO2 per therm.[55] Thus, the business-as-usual carbon dioxide emissions are approximately 2580 metric tons. A 65% decrease in natural gas consumption (through use of thermal microgrid) represents **1680 metric tons** of avoided carbon dioxide emissions annually.

Since 2013, Palo Alto has provided 100% carbon neutral electricity[56]. Secondly, California's electricity grid emissions are expected to continue to decline as renewable penetration increases[57]. Therefore, the increased electricity consumption associated with building electrification and thermal microgrids does not negatively impact GHG emissions.

Thus, under the assumption of carbon free electricity, the campus can reduce its *direct* GHG emissions by **65%**. For comparison, Stanford's campus achieved a 68% reduction in emissions via their central energy facility SESI[58].

Water Use
The CEPOM model estimates that the thermal microgrid would consume approximately 3,300,000 gallons of water per year. The campus consumed approximately 45 million gallons of water during fiscal year 2018. Therefore, the thermal microgrid would make up **7.4%** of future campus water use.

55 https://www.pge.com/includes/docs/pdfs/about/environment/calculator/assumptions.pdf
56 Current emissions associated with CA electric grid emissions are approximately 0.238 kg per kWh
57 https://www.pge.com/includes/docs/pdfs/shared/environment/calculator/pge_ghg_emission_factor_info_sheet.pdf
58 https://news.stanford.edu/features/2015/sesi/ (grid electricity portion includes offsets due to renewables PPAs)

9 Financial Analyses of Proposed Thermal Microgrid Projects

This section describes how the studied thermal microgrid projects can be compared financially against the business-as-usual scenario.

9.1 Independent Financial Model

9.1.1 Internal Rate of Return (IRR)

The internal rate of return (IRR) is calculated to assess the financial feasibility of the project. The IRR is defined as the interest rate corresponding to a net present value of 0.

Assumptions

- Both 30-year and 50-year project lifespans are modeled
- Initial investment of $91 and $49 million is modeled for the downtown and campus projects, respectively
    - These are the average costs of the four estimates for each project (as discussed in sections 6.4 and 8.4)
- Inflation Rate of 3% is assumed[59]

Future Load Trajectory

Load growth was assumed to remain flat (zero) for the lifetime of the district energy system. During the past decade, Palo Alto's total electricity load has slightly decreased[60]. However, the adoption of electric vehicles, combined with a growth in new building construction, could offset future load loss due to efficiency improvements. Other parameters that will affect a city's load growth include the age of the existing building stock, future local, state, or federal building code changes, and population growth rates.

Cost Factors

The following table shows the different prices for electricity and natural gas that were used for the 30 years that were modeled. Customer costs for 2018 were estimated from billing data in Downtown Palo Alto. For future years, customer costs are based on average rates increase observed.[61]

Table 29: Energy cost data for downtown Palo Alto

Year	Customer Electricity Cost ($/kWh)	Customer Gas Cost ($/MMBtu)
2018	0.140	12.9
2023	0.162	15.0

[59] This is slightly higher than the 2.5% annual increases in electricity and gas costs that Stanford used for their system design

[60] 963,000 MWh (2015), 947,000 MWh (2017)

[61] https://www.cityofpaloalto.org/civicax/filebank/documents/64474

2028	0.188	17.3
2033	0.218	20.1
2038	0.253	23.3
2043	0.293	27.0
2048	0.340	31.3

9.2 Results

Financial Model

The internal rate of return (IRR) was calculated for both the downtown and the corporate campus projects. Both projects were assumed to have a lifespan of 30 years. The IRR is estimated to be -**1.83%** and **-2.63%** for the downtown and campus projects, respectively (assuming average capital costs). The IRR for a range of initial capital cost estimates of each project (as summarized in Tables 19 and 28) is shown in the following Figures.

Figure 32: IRR analysis for downtown Palo Alto thermal microgrid (30-year lifespan)

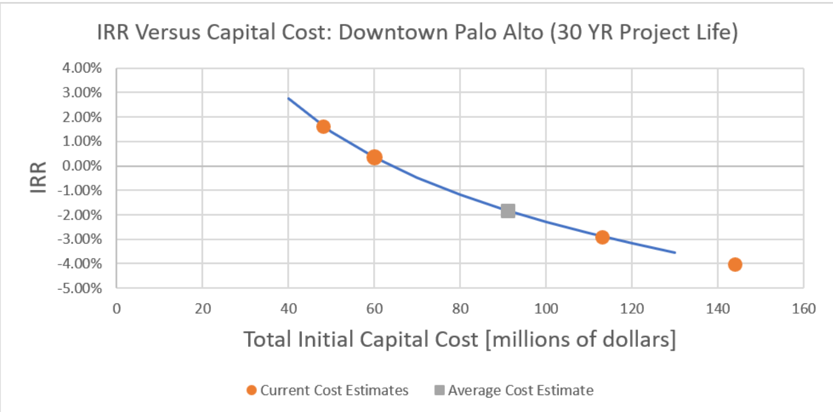
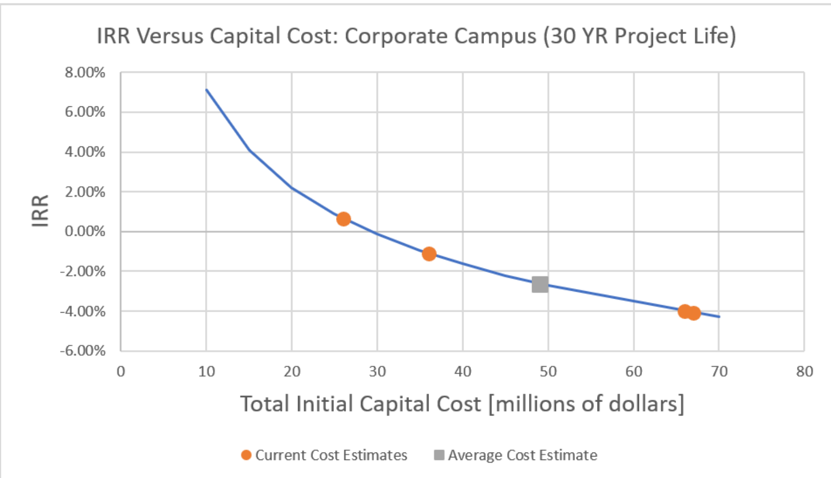


Figure 33: IRR analysis for corporate campus thermal microgrid (30-year lifespan)



The campus project has a slightly lower average IRR, as well as a smaller range of cost estimates. The higher downtown IRR could be due in part to its larger size (economy of scale). The smaller range in cost estimates for the campus project can be attributed to its smaller size, more accurate cooling load data, and lower peak heating load.

Please note that a project lifespan of 30 years is likely conservative. Some components for infrastructure deployed, such as pipelines for hot and cold water, has lifespan greater than 30 years. When Stanford installed their SESI thermal microgrid, the pipe network was assumed to have a lifespan of 50 years. Therefore, the financial model was also run with the assumption of a 50-year project life. The resulting average IRR was **1.55%** and **1.09%** for the downtown and campus projects, respectively.

Figure 34: IRR analysis for downtown Palo Alto thermal microgrid (50-year lifespan)

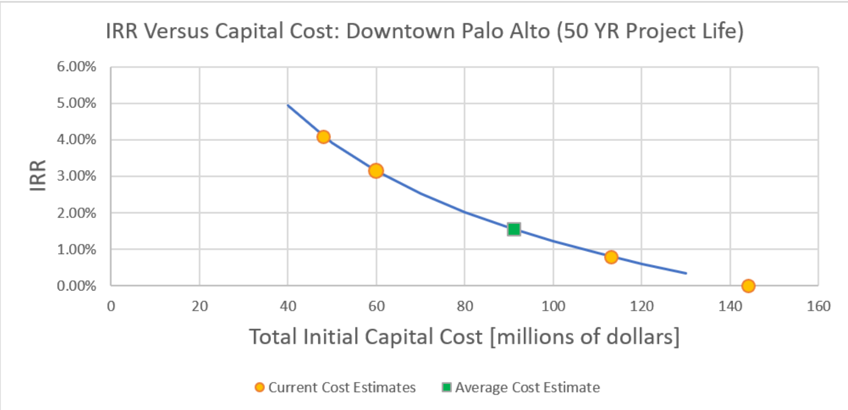
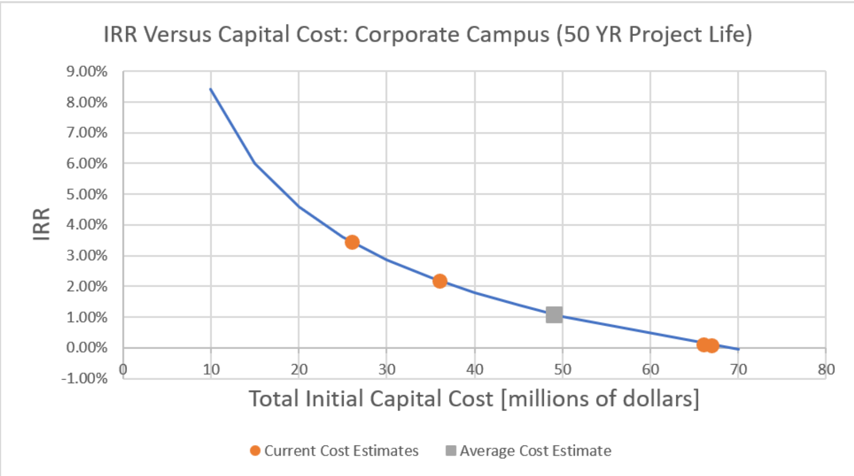


Figure 35: IRR analysis for corporate campus thermal microgrid (50-year lifespan)



Discussion

We believe that both IRR figures estimated above are conservative estimates for the feasibility of the thermal microgrid. This analysis does not consider O&M savings, improved resiliency benefits, reduced exposure to variability in natural gas prices, additional heat sources (i.e. ground-source heat exchange), a future carbon tax, or any grants or incentives. It also does not consider future equipment cost reductions as the technology becomes commonplace. There are likely additional benefits associated with optimizing thermal and electric microgrids in unison. Finally, the IRR values are highly sensitive to plant equipment capacities, which require more thorough investigation to model with precision. ***Therefore, the low IRR should not be used to discredit the potential for such a system for both downtown Palo Alto and the corporate campus.***

9.3 Comparison of RETScreen and Independent Financial Model (Downtown)

For downtown Palo Alto, RETScreen estimated an IRR of **2.2%** on assets with a 50-year project lifespan. The average IRR for the hourly load analyses is -1.83% for downtown Palo Alto with a 30-year project lifespan. With a 50-year project lifespan, the independently generated IRR increases to **1.55%**. Therefore, both modelling approaches arrive at similar results. This is likely due to the cost and energy consumption of the RETScreen model being a similar fraction of the corresponding parameter of the CEPOM model.

10 Conclusions and Future Work

This section summarizes the results of the two case studies for a potential Thermal Microgrid system in Palo Alto. We also discuss next steps that could expedite feasibility assessments and further practical project considerations to implement a thermal microgrid system. This section also briefly discusses the topic of restaurant electrification and other decarbonized systems.

10.1 Conclusions

10.1.1 Downtown Project

A thermal microgrid project in downtown Palo Alto could deliver significant annual energy cost savings and emissions reductions. We estimate that upon installation of the thermal microgrid, total annual heating and cooling energy costs would decrease by over 42% and overall natural gas consumption would decrease by 37% in the downtown area. Installation capital costs range from $48 to $144 million dollars, with financial profitability achieved at costs below $65 million for a 30-year project lifespan (or below $140 million for 50-year project lifespan). GHG emissions would be reduced by about 3,700 metric tons per year, a decrease of 37% compared to BAU.

10.1.2 Corporate Campus

The feasibility results suggest that, for the corporate campus, installation capital costs of a thermal microgrid could range from $26 to $68 million dollars. Furthermore, the thermal microgrid becomes financially profitable at costs below $30 million for a 30-year project lifespan (or below $70 million for a 50-year lifespan). GHG emissions would be reduced by about 1680 metric tons per year, a decrease of 65% compared to BAU. Finally, annual thermal energy costs decreased by 50 percent. This decrease can be attributed to the following reasons.

- Relatively low cost of electricity provided by CPAU
- Large amount of overlap between cooling and heating needs and heat recovery potential
- Overall efficiency improvement of the thermal microgrid system

The cost and emission savings could potentially be increased if the following occurs:

- Heat recovery potential is greater than predicted
    - Other sources, such as ground source heat exchange, are considered
    - Effect of removing free cooling economizers should be considered (if currently installed)[62]
- Capital costs are found to be lower than predicted. Detailed cost estimates could be provided by an engineering firm

10.1.3 Key Takeaways

For the City of Palo Alto, future thermal microgrid studies should prioritize the assessment of corporate campuses (such as those located at the Stanford Research Park). This is due in part to their structure; corporate campuses are owned by a single entity, and thus can work more efficiently to serve the best interest of the whole campus. Secondly, based off the results of the two studies, corporate campuses have a smaller potential cost range for a given thermal microgrid project. Many of the campuses also have high resolution thermal load data in the form of interval meters, as well as building management

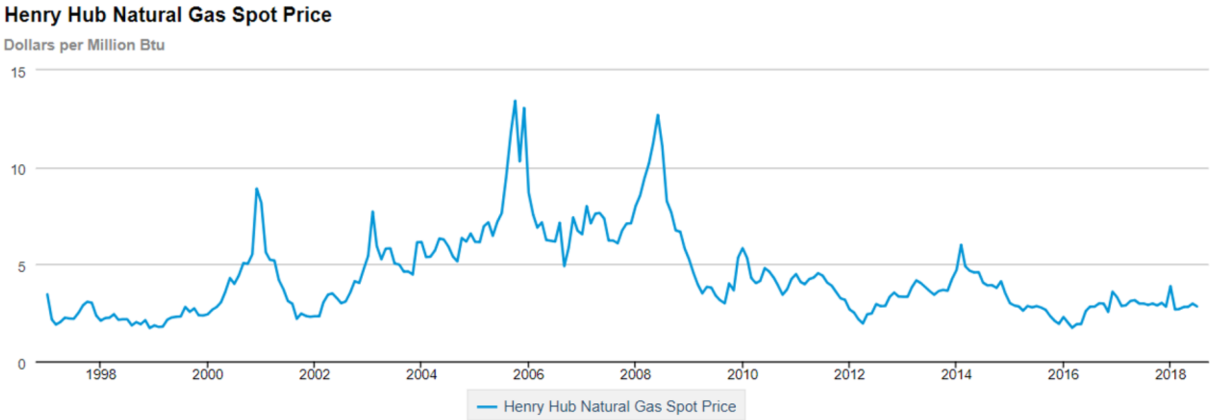
[62] Economizers are often included with building HVAC systems so that when it is cool outside they can use that cold air for cooling. This cooling may not be included in a cooling load estimate based on a chiller output.

system data. Finally, large corporations can dedicate staff time to such projects and can work effectively with the city to streamline permitting processes and engineering challenges that arise.

10.1.4 Price Risk Reduction via Reduced Fossil Fuel Consumption

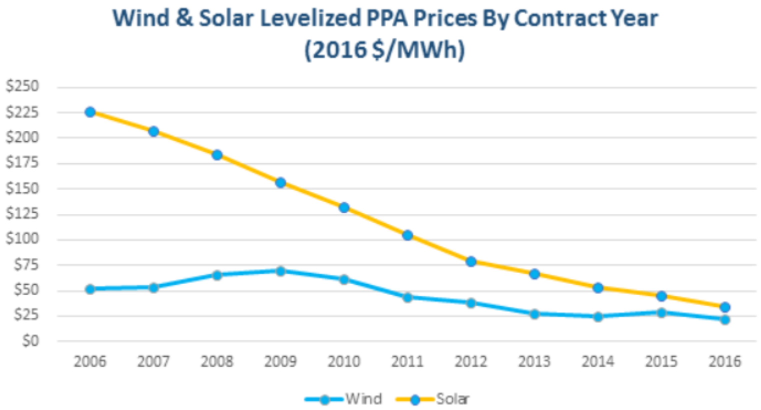
Natural gas prices have varied widely during the past decade, as shown in Figure 36[63].

Figure 36: Natural gas spot prices in the United States since 1997. Note the spikes around 2007.



At the same time, the price for renewable electricity in the form of wind and solar power purchase agreements (PPA) have decreased dramatically in the past decade[64].

Figure 37: Wind & solar PPA prices have fallen steadily over the past decade



Since PPAs are usually established for 10 to 25 years, continued investment in electrification also results in reduced exposure to commodity price shocks in the fossil fuel industry[65]. Therefore, financial models that weigh the value of electrified thermal microgrids should attempt to quantify the value of energy price stability for a community. This is especially relevant for heavily low or fixed income communities.

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63 https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm

64 https://www.epa.gov/greenpower/green-power-pricing

65 https://www.seia.org/research-resources/solar-power-purchase-agreements

10.2 Future Work

10.2.1 Optimizing the Feasibility Assessment Process using Optimal Tool

The third phase of this project (Tools Assessment guide) presented a vision for an optimal tool which could remove the need for utility data when planning a new district energy system. Such a tool would use publicly available datasets for weather, building information, typical energy consumption, and many other parameters to create a platform where the user could simply select a region on a map and determine quickly what its suitability for district energy is.

Currently, the case studies described in this report could not have been completed without direct access to the utility's database. Furthermore, the lack of similar projects in a downtown region makes cost estimates highly uncertain. If new, decarbonized thermal microgrids are to gain popularity in the United States, tools must be developed that help all interested parties study and plan for them.

10.2.2 Identifying Partners for Initial Phase of Construction

In the United States, many contractors are likely unfamiliar with thermal or electric microgrids. Therefore, it is important to document the engineering firms and contractors that have experience with such projects. Entities such as the International District Energy Association (IDEA) maintain a directory of companies that can provide a multitude of services, including thermal microgrids[66].

10.2.3 Sensitivity Studies

Future work should examine how the feasibility of a thermal microgrid varies with different input costs for natural gas and electricity, especially time-of-use rates. Other types of heat recovery systems should also be considered[67]. Sensitivity studies should be completed which vary the amount of heat recovery potential, to identify how much is needed to achieve cost parity. Finally, the resiliency benefits associated with thermal energy storage should be quantified.

10.2.4 Lessons Learned from Austin Energy

Given the size of the downtown Palo Alto project, as well as the large number of restaurants, it is likely that any thermal microgrid in an urban center would be installed in phases.

For example, when Austin Energy developed their downtown district cooling system, they began by building the first cooling plant and partnering with a few key buildings. Afterwards, new customers largely consisted of new construction, repeat customers, and buildings whose existing infrastructure had reached its end-of-life. Presently, their system is better understood and trusted by the community, and new growth is organic; as the demand for connections increases, Austin expands its network[68].

10.2.5 Detailed Engineering Analysis, Sensitivity Studies

If the City of Palo Alto or another municipality decides to pursue a district energy project, they will need to hire an engineering consultant who can perform a more thorough engineering analysis. Before doing this, the municipality should identify multiple buildings with the highest cooling and heating loads that would be interested in participating. The municipality should also identify which buildings with high loads have infrastructure that is nearing the end of its life. Just as with installing conduit for heat pump water heaters, putting the infrastructure in place to enable businesses to connect to the

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[66] https://www.districtenergy.org/home

[67] https://www.c40.org/case_studies/98-of-copenhagen-city-heating-supplied-by-waste-heat

[68] https://austinenergy.com/ae/commercial/commercial-services/on-site-energy-systems/district-cooling

new system when their equipment needs to be replaced is the most cost-effective way to adopt the new technology.

10.2.6 Restaurant Electrification

Currently, most restaurants in the United States use natural gas for cooking[69]. However, in countries such as France, many chefs have made the switch to electric induction stovetops[70]. This switch has also occurred in regions of the United States where gas connections can be unreliable or difficult to access, such as New York City[71]. Since restaurants account for **25%** of the natural gas use in downtown Palo Alto, and approximately 72% of this natural gas is used for cooking, programs which encourage the switch to induction cooking could help drive deeper decarbonization.

Benefits of Induction Cooking

The US DOE estimates the efficiency of heat transfer in induction cooking at 84%[72]. In comparison, only about 40% of the heat in the flame of a gas burner is used for cooking[73]. While this ignores the efficiency losses during electricity production, it is important to remember that electricity generation is becoming less carbon intensive. Induction cooking is also safer than gas cooking, as the glass stovetop does not get hot. Induction cooking also allows for more precise temperature control[74] and reduces the need for ventilation and cooling of kitchens compared to gas systems.

Assuming the current GHG intensity of electricity on the California grid and the efficiency improvements discussed above, the estimated GHG emissions reduction associated by a switch to induction cooking can be estimated as follows:

> Current Palo Alto restaurant natural gas use for cooking: approx. 300,000 therms per year
> Emissions associated with burning one therm of natural gas: 6.10 kg[75]
>
> Total Annual CO2 emissions from restaurant cooking in downtown Palo Alto: **1.83 million kg**
>
> Amount of electricity required to perform same amount of induction cooking: 4,200 MWh
> CO2 emissions if all cooking was switched to induction: **1 million kg**
>
> **Reduction in CO2 emissions:** 830,000 kg annually **(45%)**
>
> Reduction in CO2 emissions (assuming net-zero carbon electricity) **(100%)**

Future Palo Alto Program to Encourage Restaurant Electrification

Palo Alto could encourage restaurant electrification in many ways. To start, the city could host information sessions where business owners can learn from chefs who have made the switch to induction cooking. This will help alleviate many of the concerns associated with switching away from gas, including temperature control, cook time, and cost. Through understanding the hurdles they may

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69 In Palo Alto, only 7 of the 50 restaurants identified did not use natural gas. End-use survey data suggests this as well, as only 1% of electricity is used for space or water heating.

70 https://www.treehugger.com/kitchen-design/induction-stoves-french-cooking-school.html

71 http://www.grubstreet.com/2015/09/restaurants-open-without-gas.html

72 https://www.energy.gov/eere/buildings/appliance-and-equipment-standards-program

73 https://www.centurylife.org/is-induction-more-efficient-than-electric-coil-or-gas-an-energy-efficiency-comparison-between-stoves/

74 https://www.foodabletv.com/blog/how-vollrath-induction-equipment-and-cookware-can-make-your-kitchen-even-more-efficient

75 https://www.pge.com/includes/docs/pdfs/about/environment/calculator/assumptions.pdf

have to overcome as well as the benefits they will gain, many businesses would then consider making the switch.

To further incentivize this switch, Palo Alto could also streamline regulatory processes for businesses that make the switch to induction, such as receiving quicker approval from the fire marshal or lower permitting costs. New residences and restaurants could be required to be **all-electric**. A program could also be established which pays for a portion of the additional cost required to install an induction system.

Finally, if complete electrification becomes more of a priority, mandated retrofits of existing spaces could occur over a span of multiple years. However, such a mandate is unlikely, as restaurants will likely see the benefit of electrification rather quickly.

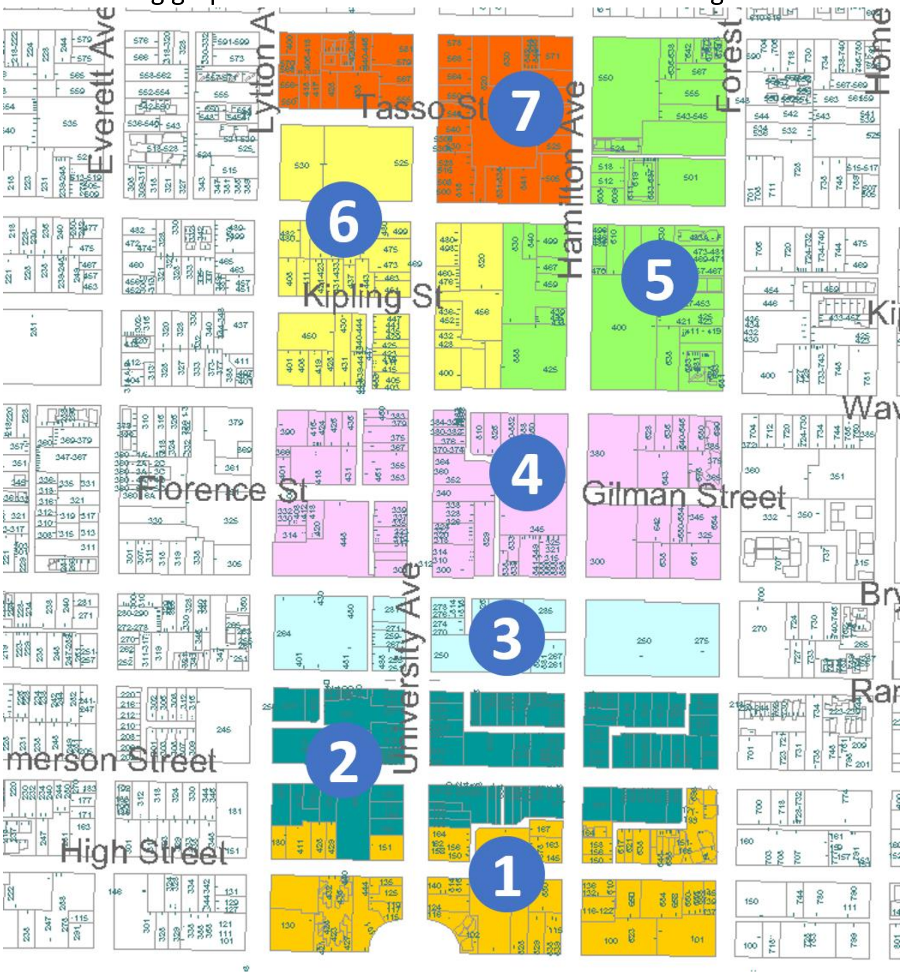
Appendix A: Further Reading

The following references provide additional information on technology and feasibility assessments of district energy systems:

- District Heating and Cooling, Svend Frederiksen and Sven Werner (2013).
- Advanced District Heating and Cooling (DHC) Systems, Edited by R. Wiltshire (2016).
- Austin Energy District Cooling: https://austinenergy.com/ae/commercial/commercial-services/on-site-energy-systems/district-cooling

Appendix B: Palo Alto Building Data

The following graphic shows the boundaries of each building cluster within the downtown region.



Appendix C: California Commercial End-Use Survey Data

Electricity End Use

Note: Data presented is from 2006 survey. California is currently in the process of performing an updated end-use survey[76].

Table 10-8: Small Office Electric EUIs, Fuel Shares, and EIs

End Use	Electric EUI (kWh/End-Use ft^2)	Electric Fuel Share	Electric EI (kWh/ft^2)
Heating	0.23	44.50	0.10
Cooling	3.12	93.30	2.91
Ventilation	1.31	93.90	1.23
Water Heating	0.46	51.40	0.24
Cooking	0.13	92.30	0.12
Refrigeration	0.60	95.50	0.57
Interior Lighting	3.87	100.00	3.87
Office Equipment	1.63	99.90	1.63
Exterior Lighting	1.69	72.70	1.23
Miscellaneous	0.93	92.50	0.86
Process	0.00	0.00	0.00
Motors	1.32	27.80	0.37
Air Compressors	0.74	16.30	0.12
All End Uses			13.25

Table 12-10: Large Office Electric EUIs, Fuel Shares, and EIs

End Use	Electric EUI (kWh/End-Use ft^2)	Electric Fuel Share	Electric EI (kWh/ft^2)
Heating	1.75	84.80	1.49
Cooling	3.57	94.20	3.36
Ventilation	3.57	94.70	3.38
Water Heating	0.34	38.80	0.13
Cooking	0.10	100.00	0.10
Refrigeration	0.28	100.00	0.28
Interior Lighting	4.73	100.00	4.73
Office Equipment	5.04	100.00	5.04
Exterior Lighting	0.39	97.20	0.38
Miscellaneous	0.52	93.40	0.48
Process	4.34	0.90	0.05
Motors	0.55	87.80	0.48
Air Compressors	0.15	34.60	0.04
All End Uses			19.94

76 http://www.energy.ca.gov/ceus/

Table 10-12: Restaurant Electric EUIs, Fuel Shares, and EIs

End Use	Electric EUI (kWh/End-Use ft^2)	Electric Fuel Share	Electric EI (kWh/ft^2)
Heating	0.18	16.40	0.03
Cooling	10.10	77.60	7.83
Ventilation	5.24	78.20	4.10
Water Heating	2.50	17.80	0.45
Cooking	11.25	100.00	11.25
Refrigeration	10.41	100.00	10.41
Interior Lighting	7.12	100.00	7.12
Office Equipment	0.72	99.50	0.71
Exterior Lighting	3.13	87.50	2.74
Miscellaneous	1.30	86.70	1.13
Process	0.00	0.00	0.00
Motors	1.47	26.70	0.39
Air Compressors	0.78	2.60	0.02
All End Uses			46.19

Natural Gas End Use

Table 10-9: Small Office Natural Gas EUIs, Fuel Shares, and EIs

End Use	Natural Gas EUI (kBtu/End-Use ft^2)	Natural Gas Fuel Share	Natural Gas EI (kBtu/ft^2)
Heating	10.46	51.50	5.39
Cooling	0.00	0.00	0.00
Water Heating	5.71	40.70	2.32
Cooking	3.91	7.20	0.28
Miscellaneous	2.47	2.40	0.06
Process	0.00	0.00	0.00
All End Uses			8.00

Table 12-11: Large Office Natural Gas EUIs, Fuel Shares, and EIs

End Use	Natural Gas EUI (kBtu/End-Use ft^2)	Natural Gas Fuel Share	Natural Gas EI (kBtu/ft^2)
Heating	22.61	72.00	16.29
Cooling	0.00	0.00	0.00
Water Heating	5.04	49.50	2.50
Cooking	0.59	40.10	0.24
Miscellaneous	21.71	2.00	0.43
Process	16.46	1.90	0.32
All End Uses			19.78

Table 10-13: Restaurant Natural Gas EUIs, Fuel Shares, and EIs

End Use	Natural Gas EUI (kBtu/End-Use ft^2)	Natural Gas Fuel Share	Natural Gas EI (kBtu/ft^2)
Heating	14.55	57.50	8.36
Cooling	0.00	0.00	0.00
Water Heating	71.28	84.90	60.55
Cooking	195.69	91.80	179.71
Miscellaneous	0.00	0.00	0.00
Process	71.01	0.70	0.52
All End Uses			249.10

Appendix D: Equipment Per Unit Cost Data

Estimates for equipment costs were shared by Affiliated Engineers Inc based of their experience of designing Stanford main campus (SESI) and Redwood City campus thermal microgrid systems[77]. The cost data is presented in Table D.1.

Please note that equipment per unit costs only include materials, not labor.

Table D.1: Per unit cost data for the Redwood City thermal microgrid project

Equipment	**Unit Cost**	**Notes**
Chiller	$400/ton	
Heat Recovery Chiller	$600/ton	
Cooling Tower	$150/ton	
Pumps	$100/ton	
Piping	$250/ton	
Controls	$100/ton	
Electrical	$200/ton	
Boilers	$50/MBH	MBH = Thousands of BTUs per hour
TES	$2.5/gallon	TES = Thermal Energy Storage
Distribution Piping	$50/inch diameter and foot length	
Building	$500/Square Foot	
Building Size	5 Square Feet / ton	For small plants
Entire chiller plant **including labor**	$6000/ton	

[77] www.aeieng.com/

Appendix E: Stanford Redwood City Cost Data

Stanford University is currently constructing its Redwood City campus. The campus, which will eventually house 2,700 employees, marks Stanford's first major expansion outside its original campus[78]. Like the main campus, the Redwood City campus will boast its own Central Energy Facility. Cost data for the Redwood City campus combined heating and cooling system is shown below.

Please note that Redwood City campus costs are total capital costs, including labor. Labor costs were approximately 50% of the Redwood City project, which is similar to the cost breakdown predicted via online resources[79].

Campus Size	Initial Size: **600,000 GSF** Future Expansion to **1,500,000 GSF**

Equipment	**Cost**	**Notes**
Hydronic Piping from Central Facility to Site Buildings	$4.4M	Chilled water pipe is HDPE Hot water pipe is PP-RCT*
Chilled Water TES Tank	$2.6M	
HVAC and Controls for CEF	$4.6M	Includes chiller, boilers, pumps, cooling tower
Building, Site, etc. for CEF	$8.3M	Includes a $2M screen wall around tank, which serves only an aesthetic purpose Building dimensions: 125' by 80'
Estimated Total Cost (with Future Equipment)	$24M ($16/GSF)	GSF = Gross Square Feet

* PP-RCT: polypropylene random copolymer with modified crystallinity and temperature resistance[80]

Initial Redwood City CEF Equipment

- Two 600-ton chillers
  - Each chiller has a heat recovery capability of 8,000 MBH at 110F
  - Includes evaporative cross flow cooling towers
- Two 12,700 ton-hr chilled water tanks
- Two 4 MMBtu hot water tanks
- Two 3,300 MBH condensing hot water generators
  - Natural gas fired; for backup heating

Future Redwood City CEF Equipment

- Additional chiller
- Two hot water tanks

[78] https://redwoodcity.stanford.edu/facts
[79] https://www.rsmeans.com/
[80] https://plasticpipe.org/building-construction/bcd-pp.html

Recommended Heat Recovery Chiller Manufacturers

- Trane
- Carrier
- York

Potential Field-erected TES Tank Manufacturers

- Caldwell Tank
- Pacific Tank
- CB&I

Appendix F: Assumed Efficiency Values for Equipment

Equipment	Efficiency
Heat Recovery Chiller	1.33 kw/ton
Chiller	Varies, but around 0.46 kw/ton
Heater (% HHV)	85% (typical value for new furnaces or boilers)
Heater Electric Efficiency	2.0 kWh/MMBtu (i.e. for every MMBtu of heat, consumed 2 kWh for fans, etc.)
Cold Water Loop	Assumed 15-degree delta between supply and return loop
Hot Water Loop	Assumed 30-degree delta between supply and return loop