PATHWAYS TO CARBON NEUTRALITY IN CALIFORNIA

Decarbonizing the Commercial Buildings Sector

May 2022

About

About the Stanford Center for Carbon Storage

Carbon Capture, Utilization, and Storage is a key technology for achieving net-zero greenhouse gas emissions. The Stanford Center for Carbon Storage (SCCS) uses a multidisciplinary approach to address critical questions related to flow physics, monitoring, geochemistry, geomechanics and simulation of the transport and fate of CO_2 stored in partially- to fully depleted oil & gas fields and saline reservoirs. SCCS is an affiliates program associated with the Stanford University School of Earth, Energy and Environmental Sciences.

About the Stanford Carbon Removal Initiative

The Stanford Carbon Removal Initiative (SCRI) seeks to create science-based opportunities and solutions for gigaton-scale negative emissions and atmospheric carbon removal. The initiative helps to enable removal of atmospheric greenhouse gasses at scale by generating and integrating knowledge, creating scalable solutions, informing policies for technology deployment and governance, and demonstrating approaches and solutions with industry collaborators. All of this is done with a focus on social acceptance and equity, as well as environmental, economic, and social costs. SCRI is an affiliates program associated with the Precourt Institute for Energy and the Woods Institute for the Environment.

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California State Building and Construction Trades Council

International Brotherhood of Boilermakers

Western States Petroleum Association

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Acronyms

AEERG	Advanced Energy Efficiency Retrofit Guide
CARB	California Air Resources Board
CHP	combined heat and power
COP	coefficient of performance (HVAC)
CCS	carbon capture and storage
EE	energy efficiency
EER	energy efficiency ratio (HVAC)
EGRID	Emissions & Generation Resource Integrated Database (EPA)
EIA	U.S. Energy Information Administration
EPA	Environmental Protection Agency
GHG	greenhouse gas
GO Bond	general obligation bond
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HVAC	heating, ventilation, and air conditioning
LCOC	levelized cost of carbon
LLNL	Lawrence Livermore National Laboratory
LPG	liquefied petroleum gas
MRR	California regulation for the Mandatory Reporting of Greenhouse Gas emissions (CARB)
NAICS	North American Industry Classification System
NREL	National Renewable Energy Laboratory
OSM	Open Street Map
PCD	personal comfort device
PG&E	Pacific Gas & Electric Company
PHU	packaged heating unit
UTO	useful thermal output

Key Findings

General

- Gas heating is the largest contributor to direct emissions from natural gas in the commercial sector (75% of non-CHP consumption). Water heating and cooking are also major contributors (9.5% and 16%, respectively).
- Natural gas consumption by end-use differs greatly by location and by subsector.
- Fugitive emissions from refrigerants are of growing concern as we add more heat pumps to the commercial sector. 38% of emissions from the commercial sector in 2018 are from refrigerants.
- Heating and water heating loads, along with the EIA's costs and efficiencies for commercial appliances, suggest that heat pumps are more cost efficient than electric heaters and water heaters. Increases in installation costs from changing electric power distribution systems in commercial buildings may change this.
- It is economical to retrofit building envelope at the same time as electrifying or replacing HVAC equipment, as increasing building thermal efficiency can allow for smaller HVAC equipment to fulfil HVAC demand.
- In most cases, electrification will result in higher ($) energy bills for a facility despite energy-efficiency improvements. This is a result of the relatively high cost of electricity in California compared to natural gas.
- It is most likely not economical to abate combined heat and power emissions using carbon capture and storage in facilities emitting less than 25,000 tCO_2e/yr due to high capture costs and lack of incentives.
- There are a limited number of retailers for large commercial heat pumps. Significant growth in manufacturing and retail supply of heat pumps will be needed if they are to be installed widely.
- There are a limited number of professionals who are trained in installing heat pumps. Technical vocational training programs need to be developed and expanded.

Subsector findings

- **Schools (K-12)** in California already have decarbonization efforts underway. These facilities can be decarbonized with an added benefit of providing a learning opportunity for students.
- There are several large **College** CHP facilities (over 25,000 tCO_2e/yr) that can be economically decarbonized using CCS, however most college CHP facilities will likely need to decarbonize through retirement of natural gas heating and electrification.
- **Restaurants** are one of the largest groups of consumers of natural gas, primarily for cooking. Alternate stove technologies can abate 1.33 $MtCO_2e$/yr in emissions, but there are major public opinion and cost barriers.
- In the **Food and Liquor** subsector, leakage from refrigeration equipment and heating demand can be reduced by adopting newer, more thermally efficient refrigerators in

supermarkets, grocery stores, and convenience stores with the co-benefit of reducing electricity for refrigeration.

- **Retail** Sector energy consumption is dominated by interior lighting. Improving lighting efficiency in the Retail subsector while electrifying heating will decarbonize this subsector without too much burden on the grid.
- The largest energy end-use in the **Hotel** subsector is water heating. Investment in high-efficiency electric water heaters and heat pump water heaters and laundry appliances can help decrease costs and energy consumption in this subsector as it decarbonizes.
- In the **Office** Sector, "interior equipment" or electricity plug-load is the largest end-use category. However, some natural gas is used for heating and water heating in offices. Electrifying heating and water heating and retrofitting office buildings for energy efficiency will decarbonize this subsector with limited additional burden on the grid.
- CHP installations in **Healthcare** will be difficult to decarbonize. Many hospitals with CHP fall below the 25,000 tCO_2e/yr threshold, making them uneconomical to retrofit with CCS. Decarbonization options for these facilities will need to provide the same level of reliability as natural gas CHP facilities, or these facilities will need to be offset with negative emissions.

Introduction

In 2019, the Commercial Buildings sector emitted 24.2 Mt CO_2e, or 5.8% of California's total GHG emissions (Figure 1) [1]. California's SB100 policy sets a goal of 100% clean energy by 2045. This study reports current energy consumption and emissions, explores decarbonization options and costs, and projects 2045 electricity consumption of a fully decarbonized system for the Commercial Buildings sector in California.

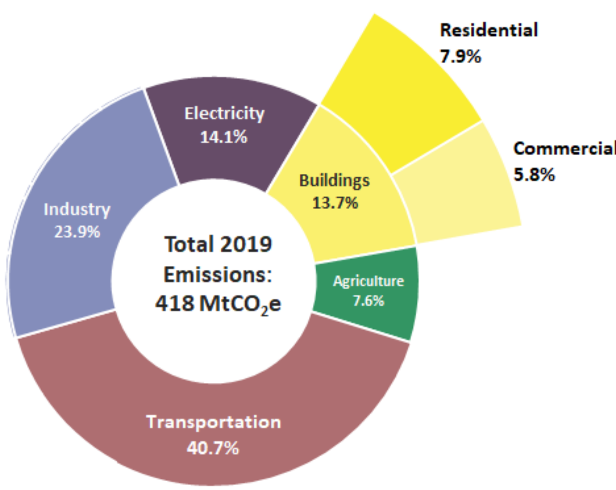


Figure 1: California 2019 Emissions. Adapted from CARB GHG Emissions Inventory (2021) [1].

12.28 $MtCO_2e$ (53.3%) of the 2019 Commercial sector emissions in California are from the combustion of natural gas, and the remainder are primarily from refrigeration and air conditioning, distillate, LPG, aerosols, and gasoline. Emissions from electricity use in buildings is included in the Electricity sector emissions. Figure 2 shows the emissions profile by fuel type from California's Commercial Buildings sector since 2000.

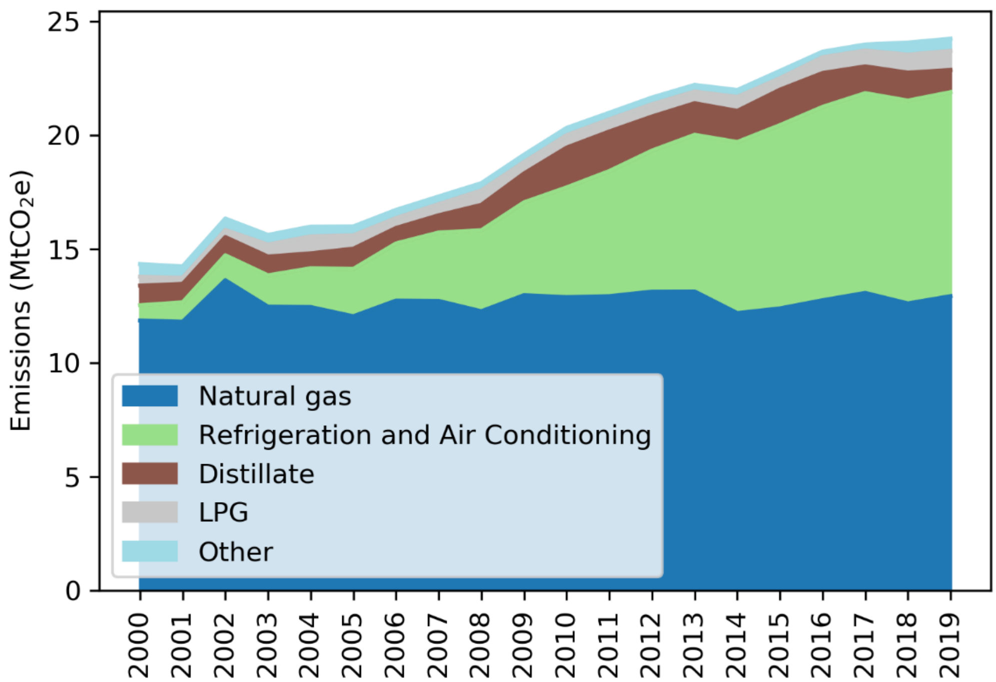


Figure 2: Emissions (excluding electricity) over time for the commercial sector in California based on data from CARB Emissions Inventory [1].

Natural gas is and has consistently been the largest contributor to commercial emissions in this sector. However, emissions from refrigeration and air conditioning are of increasing concern. In 2019, Natural gas, Hydrofluorocarbons, Distillate, and LPG made up 97.8% of total commercial emissions. Figure 3 shows the breakdown of the "other" fuel type, which makes up the remaining 2.2% (0.53 $MtCO_2e$).

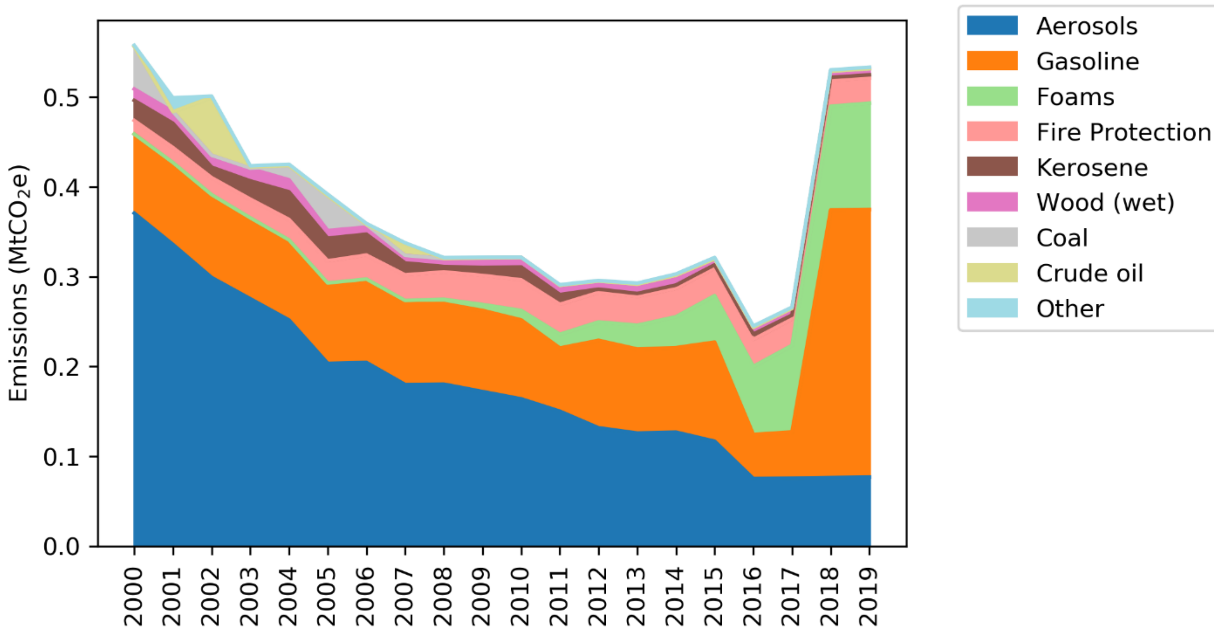


Figure 3: emissions over time for the "other" fuel type in the commercial sector in CA. the "Other" category in this figure consists of digester gas, residual fuel oil, jet fuel, landfill gas, ethanol, and propane [1].

This study focuses on decarbonizing natural gas emissions in the Commercial Building sector in California because natural gas is the largest contributor to the sector emissions and load profile data is available for analysis. Although not the primary subject of this report, fugitive emissions of hydrofluorocarbons (HFCs) from refrigerants should be addressed as California introduces more heat pumps and air conditioners in the Commercial Buildings sector.

The Commercial Buildings sector in California is large and diverse, with around 600,000 buildings [2] which can be categorized into the following subsectors:

- School (K-12)
- College
- Restaurant
- Food and Liquor
- Retail
- Hotel
- Office
- Healthcare
- Miscellaneous Commercial

Commercial buildings have varying natural gas loads depending on subsector, time of day, season, and climate zone. For this study a bottom-up approach was used to develop natural gas consumption load curves (and resultant emissions) for each subsector using building stock data for each region.

The methodology for this study was adapted from Venereau et al.'s (2019) approach to determining the energy consumption of the residential sector from the National Renewable Energy Laboratory (NREL) Commercial and Residential Hourly Load profiles [3]. The same general approach was used for each subsector in this study, with some changes to the methods depending on the characteristics of the subsector and availability of building stock and load profile data. The general five-step approach was as follows:

1. Estimate the floorspace of each subsector in each county in California (see: **Floorspace Analysis Overview** section).
2. For each subsector, calculate current energy consumption (natural gas and electricity) and emissions in each county in California using the floorspace and either the NREL Hourly Load Profiles or the MRR and eGRID databases, or both [4]–[6] (see: **Energy Consumption and Emissions** section).
3. Determine a set of appropriate decarbonizing and electrifying technology options for the subsector based on facility size, facility purpose, and consumption profiles (see: **Technology Options Overview** section).
4. Compute the cost, energy efficiency improvements, and payback period for implementing the technology options on an example facility in the subsector, including energy-efficiency retrofit information if possible (see: **Technoeconomics Overview** section).
5. Estimate the 2045 sector and subsector electricity consumption for 100% electrification scenarios (see: **Methods for Determining 2045 Electricity Demand from the Commercial Sector** section).

Floorspace Analysis Overview

Floorspace for each subsector in each county was determined using either Open Street Map (OSM), Reonomy (reonomy.com), or another source specific to the individual subsector [7], [8]. For example, floorspace for outpatient healthcare was calculated from the number of doctors per county provided by IQVIA healthcare [9]. Reasonable floorspace information for offices in California was not available, so the floorspace for the Office subsector was calculated from the total office floorspace in the United States from the EIA's Commercial Buildings Energy Consumption Survey (CBECS) [10] and then scaled by county population.

OSM data were used in the Restaurant, Retail, Food & Liquor, and Hotel subsectors. In instances where OSM data were used, it became apparent that while OSM provides detailed location information on the businesses it includes, OSM does not include all of the businesses in California of every subsector. Counts of businesses included in OSM were found to have gross underestimates of the total number of businesses in the restaurant, retail, and grocery industries (analogous information was not available for hotels). The number of buildings in each county for these subsectors was rescaled from the OSM numbers to match the total number of businesses of that type in California if such information was available. For these subsectors, it was assumed that the OSM data was underestimating the building stock for a particular subsector by the same percentage in every county. Finally, the average square footage per building was found for each subsector and multiplied by the building stock to get the total floorspace for each subsector in every county in California.

Table 1 details the different approaches used in this study for each subsector. Different techniques were employed due to the different datasets available. Each subsector will be discussed in a later section of this report.

Subsector	**Floorspace Assessment**
School (K-12)	K-12 enrollment by county from the **CDE**. Assumed 50% primary school students and 50% secondary school students. CDE also notes an average of 167 ft^2 per student in secondary school and 122 ft^2 per student in primary school. [11], [12]
College	Number of students per college in California found from **Google searches**. Emissions from larger colleges and universities found from **MRR/eGRID** [5], [6]. Remaining colleges assumed to have consumption profile per student similar to that of a secondary school.
Restaurant	**OSM** [7] used to find as many locations as possible. Number of locations rescaled by total number of restaurants in California according to the **National Restaurant Association** avg square footage per restaurant obtained from **CEUS**.
Food & Liquor	**OSM** [7] used to estimate number of grocery, bakery, and convenience stores. Rescaled in the same manner as restaurants.
Retail	**OSM** [7] used to estimate number of retail locations. Rescaled in the same manner as restaurants.
Hotels	Hotels >100k ft^2 determined using **Reonomy** [9]. Remaining hotels found from **OSM** [7].
Office	Square footage of offices for all of the US from the **CBECS** [10] . Assumed that since California is responsible for 14.62% of US GDP, office floor space in California would scale proportionately. Office floor space in each county calculated based on population.
Health Care	Outpatient Care: Number of doctors per county was obtained from **IQVIA healthcare** [9]. Assumed 1200 ft^2 per doctor [13]. Hospitals: Number of beds per hospital came from the **American Hospital Directory** [14]. Top-down approach was used for hospitals, so no square-footage was calculated.
Miscellaneous	Top-down approach was used to find energy load profile for miscellaneous, assuming a retail load shape.

Table 1: Methods for obtaining floorspace to estimate energy consumption loads by subsector.

Energy Consumption and Emissions

CARB's MRR database provides emissions information from entities in California with emissions greater than 10,000 tCO_2e/yr. The MRR database was used for information on emissions for the largest facilities in the Office, Healthcare (hospitals only), and College subsectors. There were a number of CHP facilities included in both MRR and eGRID which were considered as part of this study [5], [6].

For the vast majority facilities in the commercial sector of California, the current fuel consumption and emissions were calculated from the floorspace and the NREL Commercial and Residential Hourly Load Profiles [4]. The commercial hourly load profiles have been developed for a single building of each type for many cities across California. For each subsector included the NREL Commercial and Residential Hourly Load Profiles, a single building load profile for each county in California was found using a representative city whose data was included in the commercial hourly load profiles. If there were no cities in a particular county included in the NREL Commercial and Residential Hourly Load Profiles, a city was included from the same California Natural Resources Agency climate zone. Representative cities for each county were adapted from a residential buildings study with a similar approach [3], [4].

The energy consumption profile per square foot in each county in California was then determined by dividing the single-building consumption profile provided by the NREL Commercial Hourly Load dataset by the DOE reference building sizes that were used by NREL to create the dataset. The consumption profiles were multiplied by the floorspace in each county to get the total load profiles by county and subsector [4], [15].

The total natural gas consumption and resultant emissions were compared to those provided by CARB [1]. Where necessary, the gas loads were scaled to match those provided by CARB. With this bottom-up approach and detailed load curves, it was then possible to assess the technology options and costs associated with decarbonizing the Commercial Buildings sector.

Table 2 compares the natural gas consumption for each subsector from this study and the CARB GHG inventory. The Retail, Food and Liquor, and Hotels subsectors were all rescaled from the bottom-up calculated totals to match the CARB totals as a result of the limitations of available building stock data. The “Miscellaneous Commercial” subsector includes the Commercial Building sector consumption outside of the subsectors used in this study (and specifically includes the following: wholesale, communications, domestic utilities, landscape, national security, ‘not specified’, and transportation services). The totals for the Miscellaneous Commercial subsector were calculated from the difference between the bottom-up totals of the subsectors and the CARB GHG inventory total gas consumption for the commercial sector [1]. The load shape of the Miscellaneous Commercial subsector was assumed to be the same as for the Retail subsector.

Subsector	This Study (TBTU)	CARB (TBTU)	% Difference
K-12 School	8.84	8.36	5.73%
College	25.25	10.81	133.58%
Restaurant	30.38	30.51	0.41%
Food and Liquor	15.25	15.25	0.00%
Retail	15.29	15.29	0.00%
Hotel	13.94	13.94	0.00%
Office	8.57	8.78	2.39%
Health Care	28.85	28.85	0.00%
Miscellaneous	78.74	93.34 (includes all commercial CHP)	15.88%
Total	225.11	225.11	0.00%

Table 2: Total gas consumption for the Commercial sector in California. Retail, Food & Liquor, and Hotels are rescaled to match CARB [1], [4]–[7].

Figure 4 and 5 show the total monthly gas consumption by subsector and by usage for the Commercial Buildings sector [1], [4]–[7]. Gas consumption in the Commercial Buildings sector in California is strongly winter peaking due to heating demand. Therefore, it is important to take a close look at reducing and shifting heating loads when assessing how to decarbonize the Commercial Buildings sector.

The largest emitting subsectors in the Commercial Buildings sector in California (excluding Miscellaneous) are Restaurant, Healthcare, and College. Note that the total gas consumption and emissions differs greatly from CARB in the College subsector (which includes universities). The College subsector contains a large number of combined heat and power (CHP) facilities. This study accounts for CHP facilities in the subsectors in which they occur, while CARB accounts for CHP emissions in a separate "Commercial CHP" subsector.

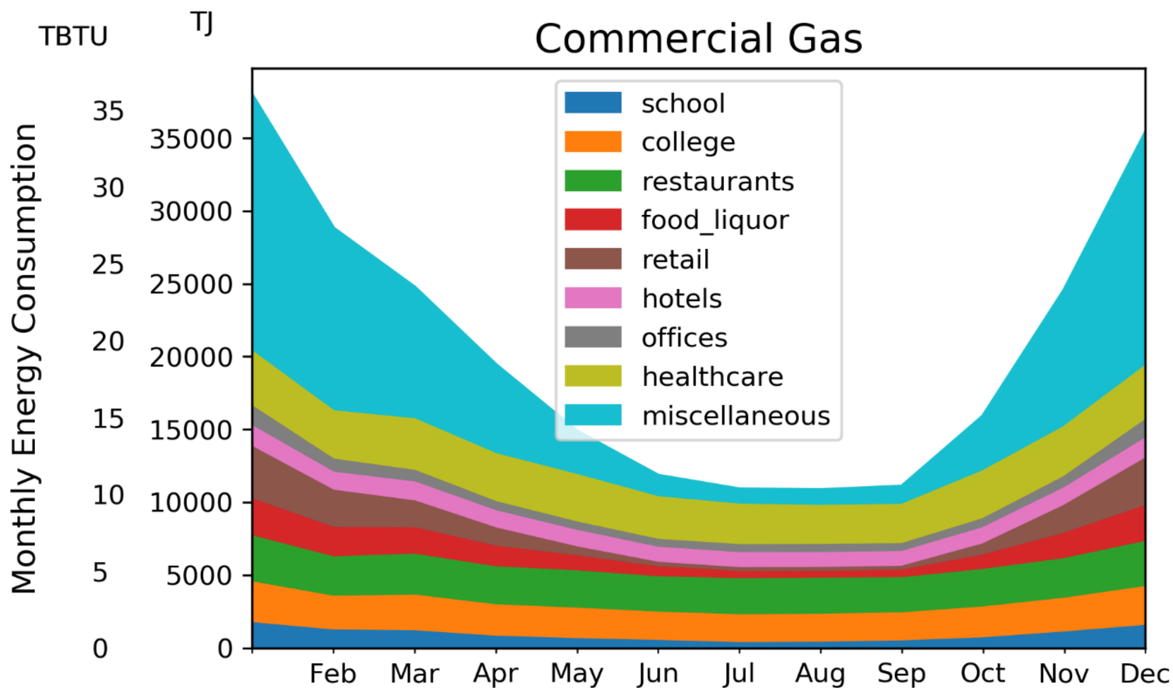


Figure 4: Total 2019 monthly gas consumption by subsector in the Commercial Buildings sector in California. The total 2019 gas consumption for the commercial sector in California is 225.11 TBTU [1], [4]–[7].

Figure 5 shows the total gas consumption for the Commercial Buildings sector by end-use (excluding CHPs). Heating is the largest and most seasonably variable end-use, while water heating and interior equipment show much less seasonal variation.

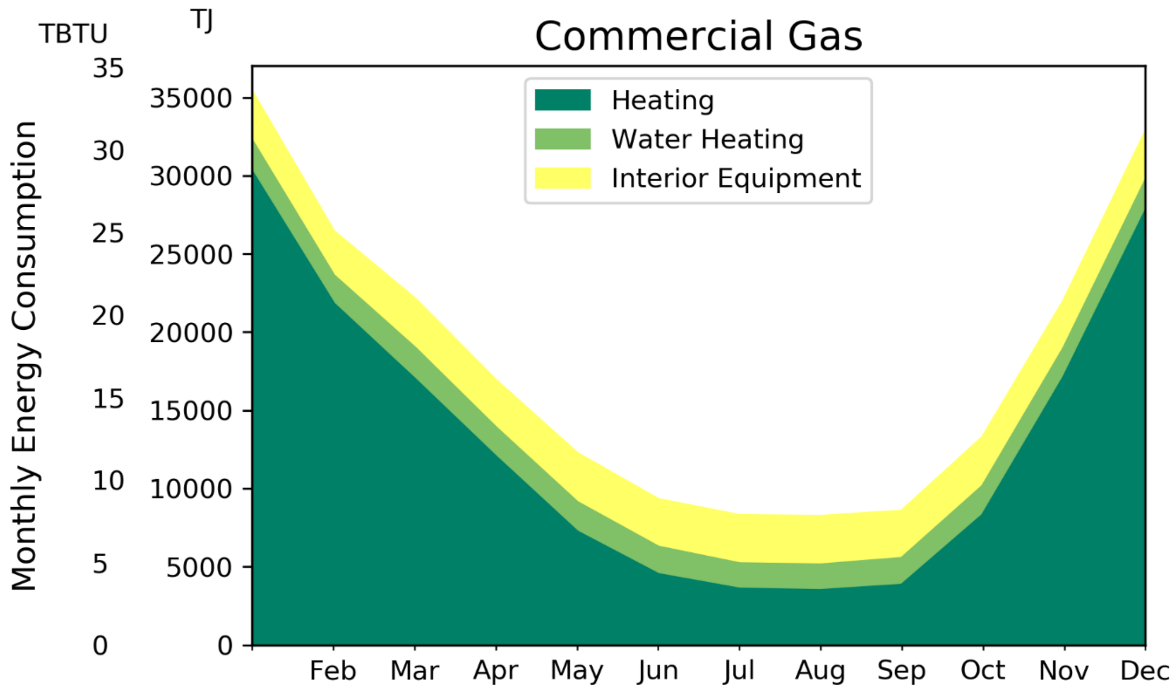


Figure 5: Total 2019 monthly gas consumption by end-use in the Commercial Buildings sector in California, excluding CHPs and "Miscellaneous Commercial" [1], [4]–[7].

Table 3 shows the direct emissions from burning natural gas from the bottom-up approach for each subsector estimated in this study, as well as CARB's totals, and Figure 6 compares both emissions and natural gas consumption estimated in this study to the values provided by CARB [1].

Subsector	This Study (MtCO2e)	CARB (MtCO2e)
K-12 School	0.48	0.48
College	1.38 (0.78 CHP, 0.59 non-CHP)	0.55 (non-CHP)
Restaurant	1.66	1.58
Food/Liquor	0.83	0.82
Retail	0.83	0.85
Hotel	0.76	0.72
Office	0.47	0.56
Health Care	1.57 (0.12 CHP)	1.54 (non-CHP)
Miscellaneous	4.30	5.19 (includes all CHP)
total	12.28	12.28

Table 3: Total 2019 GHG emissions from combustion of natural gas for the Commercial Buildings sector in California. Retail, Food & Liquor, and Hotels were rescaled to match CARB [1], [4]–[7].

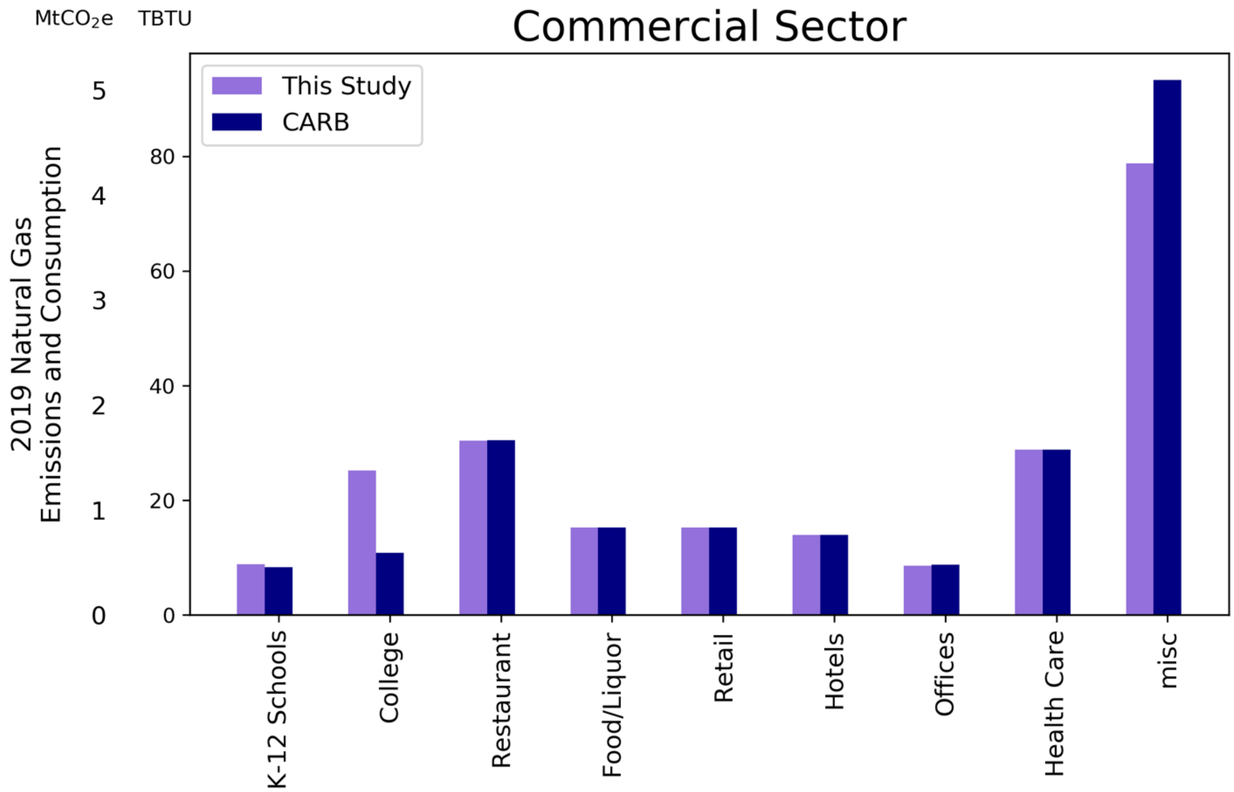


Figure 6: Total natural gas related emissions and consumption for the Commercial Buildings sector in California. Retail, Food & Liquor, and Hotels were rescaled to match CARB [1], [4]–[7].

The 2019 electricity consumption profiles were estimated for this study to examine the effect of decarbonizing the Commercial Buildings sector on the grid. CARB does not provide electricity consumption broken down into sectors or subsectors. It is important to note that these numbers are also rescaled from the bottom-up approach. Table 4 and Figure 7 show total electricity consumption by subsector in TWh and TJ [1], [4]–[7].

Subsector	Electricity (TWh)	Electricity (TJ)
K-12 School	7.58	27,304
College	4.57	16,456
Restaurant	5.26	18,923
Food & Liquor	9.96	35,859
Retail	12.19	43,891
Hotel	4.87	17,548
Office	17.59	63,338
Health Care	11.19	40,280
Miscellaneous	41.09	147,240
Total	114.3	411,489

Table 4: Total Electricity consumption for the Commercial Buildings sector in California. Numbers are rescaled from the bottom-up approach detailed above [1], [4]–[7].

The largest consumers of electricity are retail and offices (due to lighting and air conditioning), as well as the miscellaneous subsector.

Box 1

A Note About Electricity

NREL's commercial and residential hourly load profiles provide 8760 hour (every hour for a year) load profile information (natural gas and electricity) for buildings of most types included in this study. Using the methods outlined in this study, with some top-down rescaling as a result of limitations of floorspace and building stock data, the natural gas numbers from this study were remarkably similar to those estimated by CARB. However, using the exact same approach with the same load profiles resulted in a gross overestimate in the total electricity consumption for the Commercial Buildings sector compared to those provided by the Lawrence Livermore National Laboratory[B]. Note that CARB does not provide electricity consumption broken down by sector or subsector. This electricity consumption overestimate is likely because of assumptions made when the NREL Hourly Load Profiles were simulated from a collection of historical local weather trends and national building codes.

As a result, in this study the electricity consumption profiles were calculated from the NREL loads and building stock information. Excluding the Miscellaneous Commercial subsector (which is calculated as the difference from the total consumption from LLNL), the remaining subsectors were scaled down such that the ratio of Miscellaneous Commercial to total electricity in this study would be the same as the ratio of Miscellaneous Commercial to total gas in this study.

Figure 7 shows the seasonal variations in electricity consumption for the Commercial Buildings sector in California.

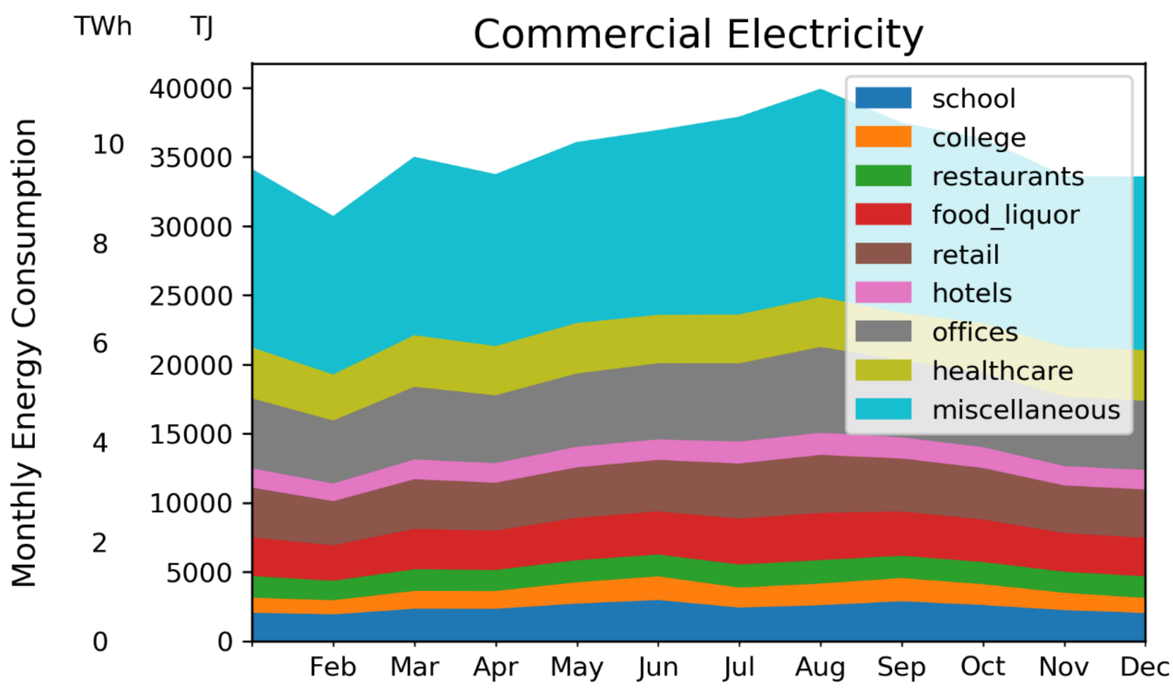
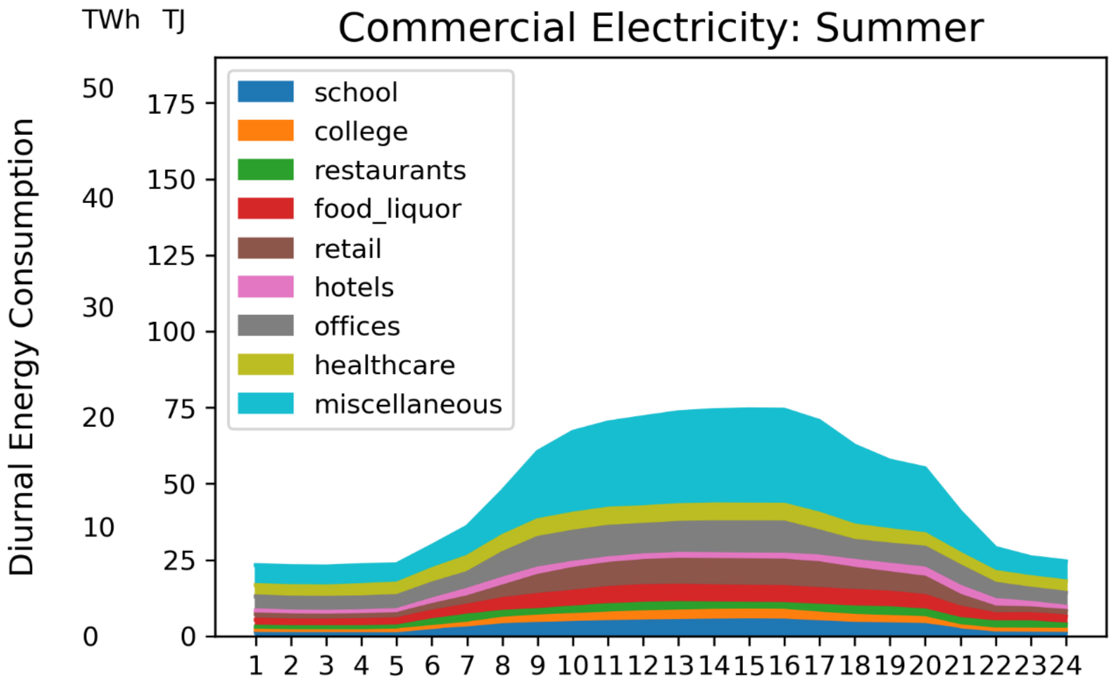
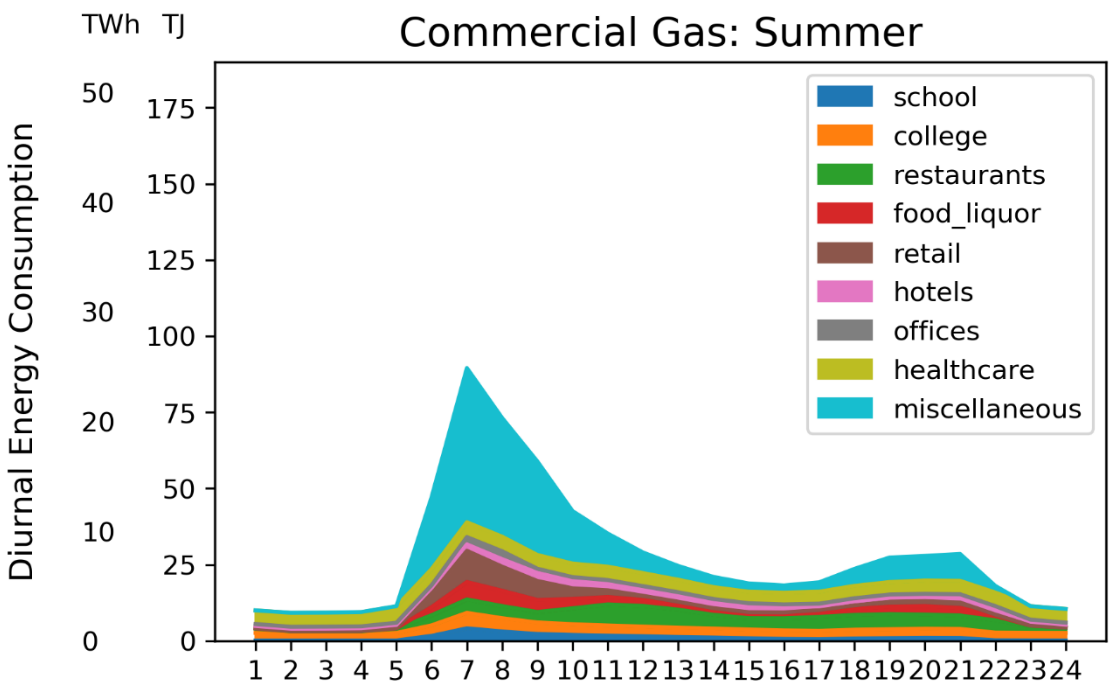


Figure 7: Total current monthly electricity consumption by subsector in the Commercial Buildings sector in California. [1], [4]–[7]

Electricity consumption in the Commercial Buildings sector is generally non-varying but with a modest summer peak. Furthermore, diurnal load information was calculated through this

B https://flowcharts.llnl.gov/commodities/energy study. Figure 8 shows both the diurnal gas and electricity consumption for an average winter and summer day.





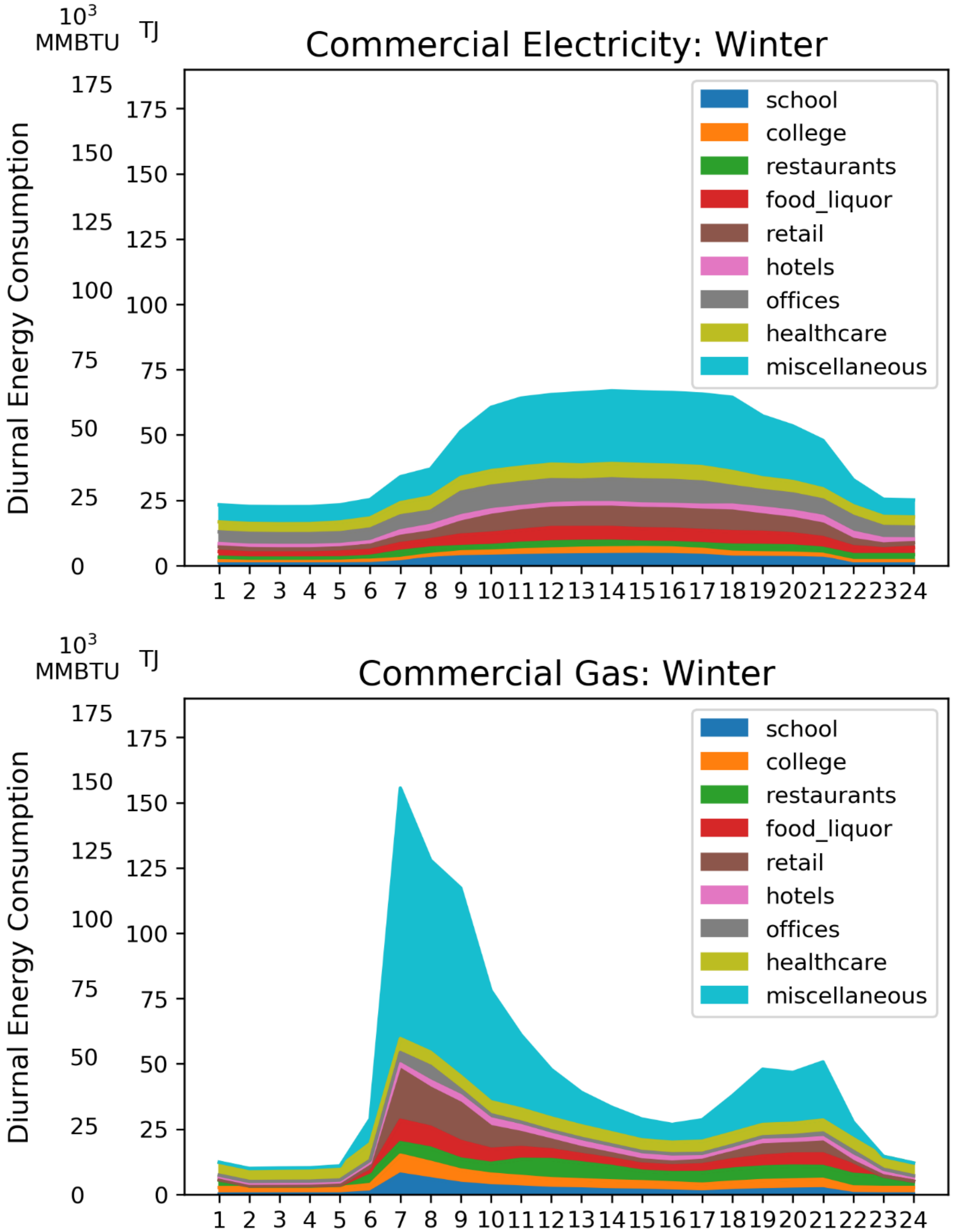


Figure 8: Total 2019 diurnal gas consumption by subsector in the Commercial Buildings sector in California [1], [4]–[7].

Energy consumption and emissions also vary across the 58 counties of California. In colder regions, heating dominates the gas consumption. However, population, tourism, and economy also drive energy consumption across counties.

For this study, ten climate regions in California were identified to show regional variations in energy consumption and emissions across the state. The climate regions were taken from Venereau et al. (2019). Figure 9 is a map of the climate regions referenced in this study [3].

Figure 9: Map of California climate regions used in this study. Adapted from Venereau et al (2018)[3].

Figure 10 shows the total natural gas consumption by end-use in each climate region, as well as total gas consumption per capita, according to the calculations outlined above.

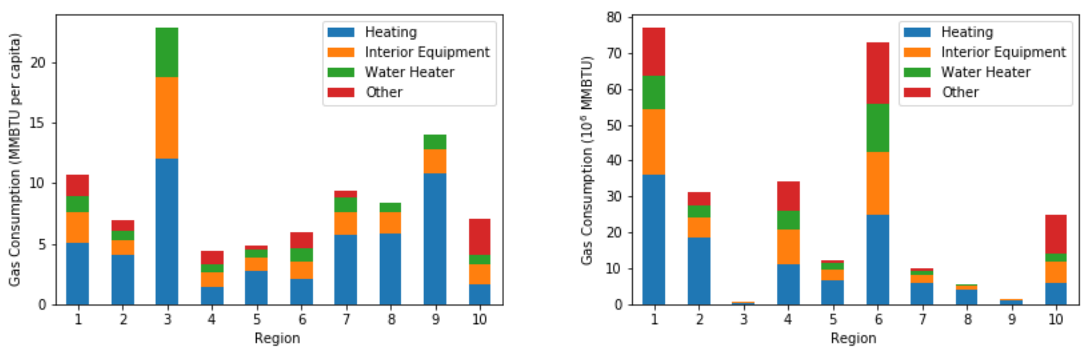


Figure 10: Total gas consumption and consumption per capita by end-use for the 9 climate regions in California [1], [3]–[7].

The regions with the largest total natural gas consumption do not correspond to the regions with the largest consumption *per capita*. For regions 3 and 9, heating alone is responsible for more gas consumption than the total gas per capita for other regions. Region 3, which is made up of Inyo and Mono counties, has both the lowest total gas consumption and highest consumption per capita. This is because of the harsh winter experienced by the people in this region. The regions with the highest total gas usage are regions 1 and 6, which contain San Francisco and Los Angeles, respectively, along with their surrounding areas. Note that region 6 (Los Angeles area), although high in gas consumption, is low on a per capita basis reflecting the temperate climate of that region.

Technology Options Overview

The primary goal of this study is to assess options to eliminate direct emissions from natural gas in the Commercial Buildings sector. In this sector, natural gas is mainly used for space heating, water heating, and cooking.

The US Department of Energy provides Energy Efficiency Retrofit Guides for offices, healthcare, retail buildings, grocery stores, and K-12 schools. For the subsectors included in the DOE's Advanced Energy Retrofit Guides, or to which the information in the retrofit guide could reasonably be extended (i.e. small colleges), information on retrofitting for energy-efficiency was included in this study. [16]–[20]

Specific options applicable to each subsector are discussed in more detail in later sections of this report. Capital and maintenance costs, as well as typical equipment sizes for energy-consuming equipment in commercial buildings are from the Energy Information Administration (EIA) [21]. The technology options and associated costs utilized in this study are listed below.

Electric Resistive Heaters

Commercial electric resistive heaters are typically 100% efficient, meaning 100% of the electricity consumed by electric heaters is converted to usable heat. Assumptions for electric resistive heaters used in this study are listed in Table 5.

	Capacity (kBTU/hr)	Cost (2020)	Installation Cost (2020)
Small	17	$850	$200
Large	170	$5,375	$975

Table 5: 2020 costs for a commercial electric resistive heater, according to the EIA. 17-170 kBTU/hr is the typical range in the market for these heaters. Maintenance costs are negligible. This equipment is expected to have a typical lifetime of 18 years. [21]

Electric Boilers

Commercial electric boilers are typically 98% efficient. According to the EIA, the typical capacity for a commercial electric boiler is 165 kW (563 kBTU/hr). Boilers work by generating steam to distribute through pipes in a building for heating and hot water [22]. According to the EIA [21], a typical 165 kW boiler will cost about $9850, with $1900 in installation costs,.

Air Conditioning and Chillers

This study focuses its decarbonization plan on eliminating natural gas consumption in the Commercial Buildings sector, with little focus on cooling. We assume all commercial cooling is currently done using rooftop air conditioning units. Many larger buildings, however, have chillers to satisfy their cooling loads. We expect energy consumption to remain the same given this simplification, however this may skew costs associated with cooling equipment projected in this study.

One co-benefit of heat pumps is that they can satisfy part or all of the cooling load in a building as well as the heating load. As heat pump penetration increases, the need for rooftop air conditioning and chillers will decrease.

Air-source heat pump

Air-source heat pumps are electric-run HVAC equipment which move heat from the outside to the inside (to satisfy part or all of a heating load) or move heat from the inside to the outside (to satisfy all or part of a cooling load). This technology becomes much less efficient at heating when ambient temperatures are below freezing [22]. Assumptions for air-source heat pumps used in this study are listed in Table 6.

	Capacity (kBTU/hr)	Energy Efficiency Ratio (EER)	Coefficient of Performance (COP)	Cost (2020)	Installation Cost (2020)
Typical	90	11.2	3.3	$7,750	$3,400
Efficient	90	13.1	3.7	$11,000	$5,050

Table 6: 2020 costs for a commercial rooftop air-source heat pump, according to the EIA. Maintenance costs are approximately $310/year per unit. This equipment is expected to have a typical lifetime of 21 years. Although this analysis only looked at small (90 kBTU/hr) packaged heat pumps, there is a large range of sizes of commercial heat pumps available on the market. [21]

Ground-source heat pumps

Ground-source heat pumps (also called geothermal heat pumps) can provide heating, cooling and/or water heating. They can have a typical COP (coefficient of performance) range of 3.1-4.0 for commercial use [21]. Geothermal heat pumps run on underground loops that can be installed vertically (perpendicular to the ground) or horizontally (parallel to the ground below the surface). Horizontal loops are cheaper to install, however the choice between the vertical or horizontal heat pump depends on the amount of open space available to dig beneath the ground and install the loop. [23]

Ground-source heat pumps are ideal for some larger commercial facilities because they are "quieter, last longer, need little maintenance, and do not depend on the temperature of the outside air," according to the DOE [23]. This technology also can free-up space in buildings which was previously used to store HVAC equipment [23]. Ground-source heat pumps are also more efficient at cooling than typical commercial rooftop heat pumps and air conditioners, with a typical energy efficiency ratio (EER) of 17.4 [21]. Drawbacks to geothermal heat pumps include requiring outdoor space, invasive construction, and relatively large upfront costs compared to other technology options.

The current typical installation cost range for ground source heat pumps is between $4750-$6700 per 48 kBTU/hr unit, with total installed costs between $21,750-$23,700. The EIA expects these costs to remain constant through 2050 [21].

Heat pump water heaters

Heat pump water heaters are typically air-source heat pumps which heat water rather than air space. There is very low market penetration for commercial heat pump water heaters, with only 3 manufacturers as of 2018 [21]. Heat pump water heaters can also be installed indoors in warm climates, where they are able to displace some cooling load by moving heat from inside a building and using it to heat water [21]. Furthermore, commercial dishwashing often requires water temperatures at 180 F, which is not often feasible for commercial heat pump water heaters. For this reason, commercial heat pump water heaters may not be a feasible choice for some commercial buildings. Assumptions for heat pump water heaters used in this study are listed in Table 7.

	Capacity (kW)	Water Flow Rate (gal/min)	COP	Cost (2020)	Installation Cost (2020)
Typical	50	34	3.9	$47,100	$3,850

Table 7: 2020 costs for a typical commercial heat pump water heater, according to the EIA. Maintenance costs are approximately $100/year per unit. This equipment is expected to have a typical lifetime of 15 years. There is currently little federal regulation of commercial heat pump water heaters [21].

Rooftop Solar
According to the LA100 study (a study on the potential for rooftop solar for Residential and Commercial Building sectors), rooftop solar will be an "economic choice for nearly all households and businesses" by 2045 [24]. Rooftop solar is not included in technoeconomic analysis for this study, however it will be a likely option for many businesses, especially in conjunction with electrification. Rooftop solar was not included in this study due to the focus on decarbonizing natural gas and associated emissions.

District Energy (Heating and/or Cooling)
In district energy systems, central facilities supply thermal energy to multiple buildings via piping. District energy systems are typically built where many buildings are concentrated, such as in cities and downtown areas, or where multiple buildings have the same owner . While district energy systems were traditionally supplied by CHP, the Stanford University campus is an example of an almost fully electrified district energy system. In that system, heat recovery chillers are used to meet the bulk of the campus' simultaneous heating and cooling needs, while the remainder are met with electric chillers and gas boilers [25], [26]

Carbon Capture and Storage (for CHPs)
Combined heat and power (CHP), or cogeneration, is a commonly used technology in California, where a fuel (typically natural gas in the Commercial Buildings sector) is burned to create both electricity and useful thermal output (UTO), which is used to heat buildings [22]. Excess power from some CHPs is sold to the large energy utilities in the state. The options for decarbonizing CHP are to displace the heating and power load elsewhere, or to add carbon capture and storage (CCS) to the facility.

Electric Stoves
For the School, Restaurant, Hotels, and Food and Liquor subsectors, technoeconomic analysis included one new stove for each facility to electrify cooking. According to the EIA, a commercial-grade electric stove costs $9,700 [21].

Efficiency Improvements
Improving energy efficiency can both reduce the carbon footprint of a facility and reduce costs, along with other co-benefits. For many electric technologies, switching from a natural gas fired unit to an electric unit comes with inherent energy efficiency improvements. For

example, electric heaters are typically 100% efficient[C] compared to the typical 80% thermal efficiency for commercial gas-fired furnaces [21].

There are also options for improving energy efficiency that do not include fuel-switching. Examples include improving insulation, changing air conditioner and heater set-points, upgrading windows, and upgrading lighting. [16]–[20]

This study evaluates at energy-efficiency retrofits from NREL's Advanced Energy Retrofit Guides for K-12 Schools, retail buildings, healthcare, offices, and grocery stores [16]–[20].

Flexible Loads

It will be favorable to shift electricity loads to match peak renewable energy generation during certain times of the day, since the carbon intensity of the grid changes by the hour. For example, smart storage water heaters can heat water during times of increased renewable generation to be used later in a building. Similar options exist for thermostats and electric vehicle chargers. Solar power generation peaks midday, while wind power production is more volatile. The Commercial Buildings sector primarily operates during daylight hours, therefore load shifting is not as big of a problem as it may be with the Residential sector. However, the Commercial Buildings sector has larger buildings with the capacity to shift greater loads, allowing for larger impact on the grid. Shifting electricity loads can reduce the peak demand on the grid, which will be especially important as California moves towards electrifying services that are now met by natural gas consumption. [27]

Personal Comfort Devices

Personal comfort devices (PCDs) are small devices for individuals inside a building which typically work to maintain thermal comfort. Examples of PCDs include:

- Cooling or heating office chairs
- Personal fans
- Foot warmers
- Space heaters

PCDs have the potential to greatly reduce energy waste by focusing on the thermal comfort of individuals within a building, rather than focusing on maintaining a temperature in an entire space.

A summary of decarbonization technologies assessed for each subsector in the Commercial Buildings sector is outlined in Table 8.

Subsector	Energy Consumption Assessment	Technology Options for Decarbonization
School	NREL	Retrofit according to standard package from NREL Advanced Energy Retrofit Guide for Schools. Electrification of heating, water heating, and stoves
College	NREL, MRR/EGRID	College and University CHP facilities retrofitted with CCS or retired and electrified. Retrofit smaller colleges by same method as K-12 schools.

[C] 100% efficiency refers to the efficiency of converting electricity into useable energy (i.e. heat), and therefore does not include the efficiency of electric power generation, distribution, or transmission.

Restaurant	NREL	Electrification of space heating, water heating, and stoves.
Food & Liquor	NREL. Bakeries treated as small restaurants, and convenience stores rescaled to meet a 52.5 kWh/ft^2 electricity consumption.	Retrofit grocery stores and convenience stores according to standard package from NREL Advanced Energy Retrofit Guide for Grocery. Electrification of heating, water heating, and stoves. Bakeries can reference the restaurants section.
Retail	NREL	Retrofit options according to standard package from NREL. Electrification of space heating and water heating
Hotel	NREL	Compare retrofitting for efficiency improvements according to Energy retrofit guide for offices to just electrifying (heating, water heating, one new stove)
Office	NREL	Retrofit according to standard package from NREL Advanced Energy Retrofit Guide for Offices. Electrify heating and water heating.
Health Care	Outpatient Care: NREL Hospitals: Remaining gas consumption from CARB not covered by outpatient and MRR/EGRID was distributed evenly by number of beds per county * consumption/ft^2	Outpatient Care: Retrofit options from NREL Advanced Energy Retrofit Guide for Healthcare. Electrification of space heating and water heating Hospitals: CCS for hospitals with CHPs. Retrofit remaining hospitals according to standard package from NREL with electrification of heating and water heating.

Table 8: Overview of energy consumption and technology options that were examined by subsector for this study.

Technoeconomics Overview

Technoeconomic analysis was done for both the existing commercial building stock as well as for new (future buildings) in each subsector. An adjusted electricity load for the average building in each subsector was estimated based on energy efficiency improvements from electrification and building envelope retrofits for each subsector, if such information was available from the National Renewable Energy Laboratory's Advanced Energy Retrofit Guides. Assuming an inflation rate of 2%, fuel costs were projected over a 20 year period for a single building in the subsector [16]–[20].

After determining whether financing or up-front payment for new equipment and/or building retrofits is more common for a particular subsector, yearly loan payments and capital costs were added to the fuel costs to show the cash flow for a single building in each Commercial Building subsector. Heating and water-heating equipment was sized based on 100% of the peak load for the building, and costs were scaled linearly from the costs from the EIA Buildings Sector Appliance Costs [21]. Incentives were ignored. Variations from this standard approach are detailed in the subsector analysis portion of this report.

CHP facilities over 25,000 tCO_2e/yr in emissions were retrofit with carbon capture equipment and assessment of cost of CO2 abatement followed the methodology outlined in a study recently completed by Stanford and the Energy Futures Initiative [28]. The 45Q tax incentive was assumed to apply to facilities emitting 25,000 tCO_2e/yr or more.

Limitations to Technoeconomics

- *Installation Costs*. When retrofitting buildings, it is important to examine the existing technology to figure out how to decarbonize the building. For this reason, installation costs may vary from those reported in this study. For example, the most reasonable decarbonization options for distributed heating technologies such as boilers and PHUs are likely electrified distributed heating technologies. It may be financially optimal to replace a commercial gas-fired boiler with an electric boiler, leaving the distribution system for the building intact.
- *Equipment costs.* The EIA provides cost information for electric technologies for buildings of a particular size. In the technoeconomic analysis for this report, costs for heating and water heating technologies were scaled linearly by peak demand for the average building of each type in California. For small buildings with lower heating demand, this approach may result in an underestimate of costs, as heating technologies below a certain size may not be available or their costs may not scale linearly with larger technologies' costs.

Future Energy Consumption Overview

For each subsector, 2045 electricity demand forecasts were developed which assume 100% electrification of current load profiles with 0.5% projected yearly growth in energy consumption in each subsector. Each gas end-use was treated differently as follows:

Space Heating and Water Heating

For each scenario, space heating for 2045 was calculated assuming 100% heating electrification. An 80% and 82% thermal efficiency for gas furnaces and water heaters was assumed [21].

Interior Equipment

No efficiency improvements were assumed when replacing gas stoves with commercial electric stoves.

Efficiency Improvements

If NREL provided an Advanced energy retrofit guide for a subsector, the standard efficiency improvements were assumed for that sector if indicated. Forecasted "new" electrification loads were added to the current electricity load for the Commercial Buildings sector to produce the 2045 forecasts.

Two scenarios have been included in 2045 forecasts:

Scenario 1

- 50% heat pumps and heat pump water heaters
- 50% electric boilers and electric water heaters
- 50% penetration of energy efficiency improvements (where applicable).

Scenario 2

- 30% heat pump and heat pump water heaters
- 70% electric boilers and electric water heaters
- 10% penetration of energy efficiency improvements (where applicable).

Scenario 1 corresponds to both high electrification (100%) and high penetration of energy efficiency improvements. Scenario 2 is also high electrification (100%) but has lower penetration of energy efficiency improvements resulting in the need for more electricity. The rationale for scenario 2 is that (1) heat pump penetration is currently very low and future adoption rates are uncertain and (2) energy efficiency improvements create the barrier of upfront costs.

School (K-12) Subsector

In 2019 natural gas consumption in K-12 schools was responsible for 0.48 $MtCO_2e$ of emissions. There are about 13,000 K-12 schools in California, with over 6.2 million students enrolled [11]. Investing in reducing the energy consumption of K-12 schools in the near-term will reduce energy costs for the long-term as California moves toward its zero-energy goals. Schools may also be easier to decarbonize than some other types of commercial buildings because the retrofits are often directly funded by policy.

The EPA's guide to Energy Efficiency Programs in K-12 Schools [29] details the costs, benefits, and options for reducing energy consumption in educational facilities. According to the EPA, benefits of reducing energy consumption in schools include environmental benefits, job creation, educational opportunities, and improved health and safety conditions for students. Some energy technology upgrades have the co-benefit of improving air quality for students, which according to the EPA can reduce the incidence of certain illnesses [29].

Methodology

The California Department of Education (CDE) provides information on the primary and secondary school enrollment in each county in California. The CDE also reports a median square footage per student in California of 122 ft^2 for elementary and 167 ft^2 for high schools. Assuming 6 out of 12 students in the state are enrolled in primary school, and 6 out of 12 students are enrolled in secondary school in each county, this computes to about 900 million square feet of building space in the School subsector.[11], [12]

The NREL Commercial Hourly Load dataset provides electricity and natural gas load information by month and by region for primary and secondary schools for cities across California and the US [4]. Using the square footage information from the California Department of Education [11], [12], the total natural gas usage for schools in California was calculated to be 8.84 TBTU which is very close to the CARB estimated fuel usage of 8.36 TBTU [1]. 56% of natural gas used in schools is for space heating, 19% for water heating, and 25% for interior equipment [4], [11], [12].

Figure 11 shows the total monthly natural gas and electricity usage by end use for all California schools. Gas heating varies seasonally, while water heating and interior equipment consumption do not show significant seasonal variations. Gas consumption in schools in California is winter-peaking as a result of fluctuations in heating demand. Alternatively, electricity consumption in schools is summer-peaking as a result of cooling demand.

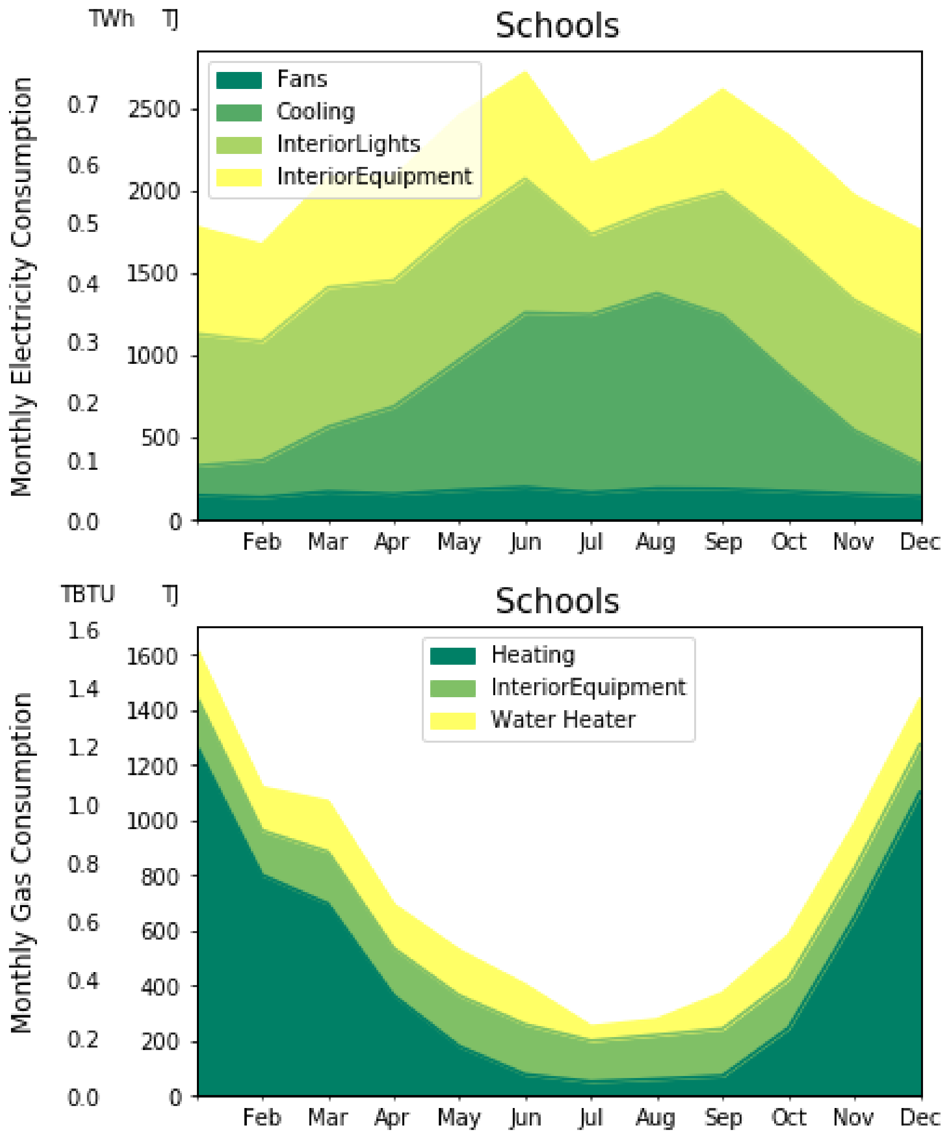
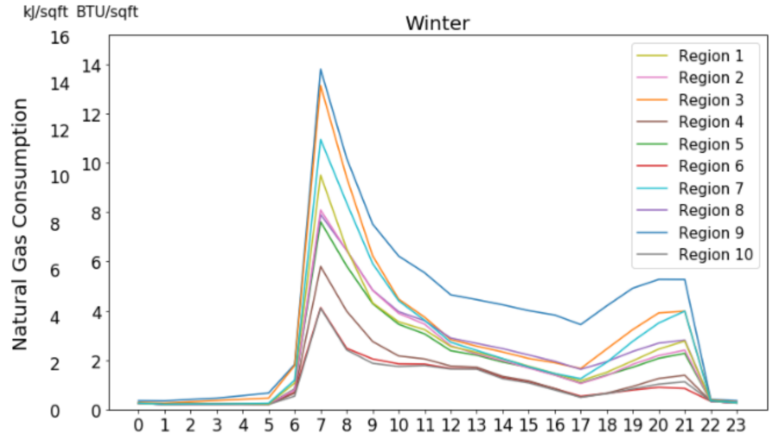
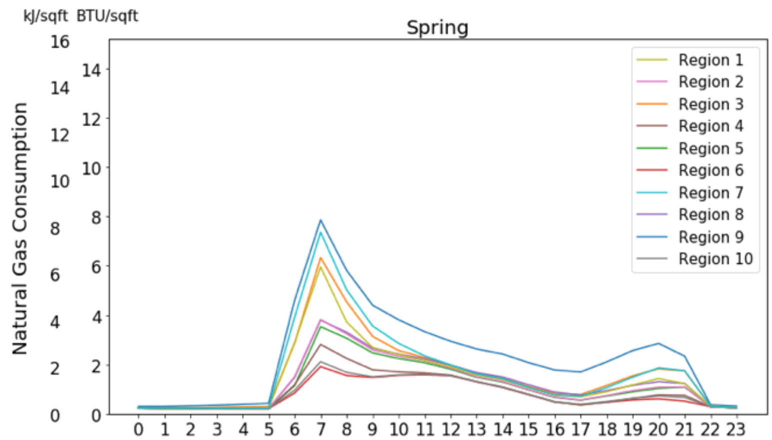


Figure 11: Total current monthly electricity (top) and gas (bottom) usage for all schools in California, by end-use. [4], [11], [12].

The NREL Commercial Hourly Load dataset provides 8760 hours (every hour for a year) of load information. Figure 12 shows the gas consumption per square foot for an average winter and summer day across the different climate regions (Figure 9) of the state.


kJ/sqft BTU/sqft
Winter
Natural Gas Consumption
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Region 9
Region 10


kJ/sqft BTU/sqft
Spring
Natural Gas Consumption
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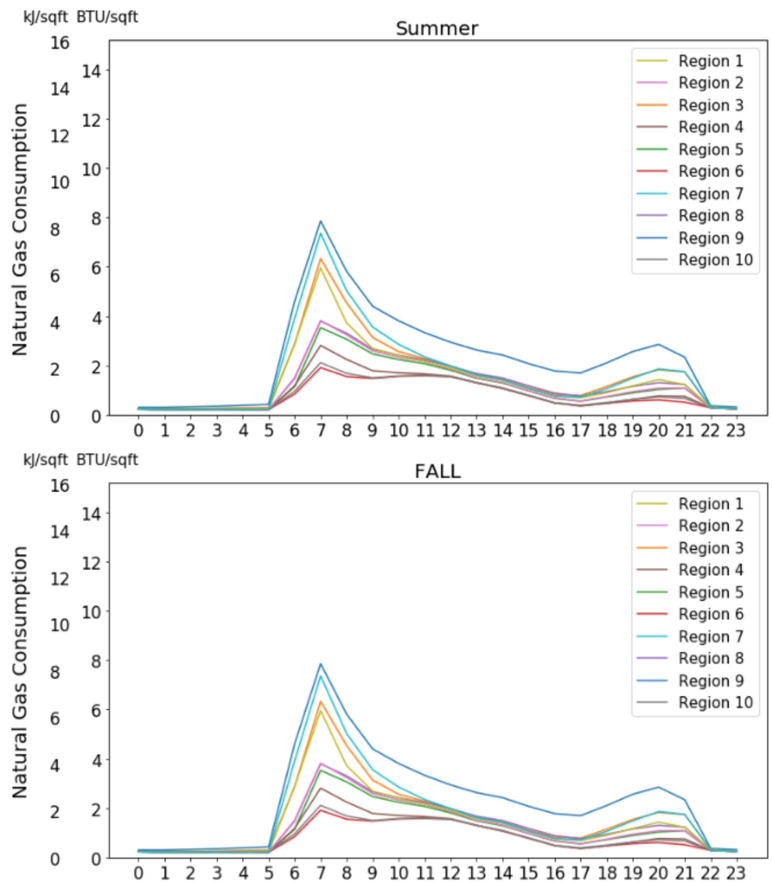


Figure 12: Diurnal variations in natural gas consumption per square foot for a primary school in California, by climate region [4], [15].

Heating in schools peaks during the mornings, shows usage during school hours and is largest in the winter. In the summer, gas consumption for heating is minimal in most regions of California.

Primary schools in California tend to have a different energy usage load profile per square foot than secondary schools. Figure 13 compares the monthly gas consumption profile per square foot across the 10 different climate regions in California for primary and secondary schools. While the exact reasons for the higher energy usage in secondary schools was not disclosed, it is surmised that secondary schools contain more large additional spaces that require space heating (auditoriums, libraries, etc).

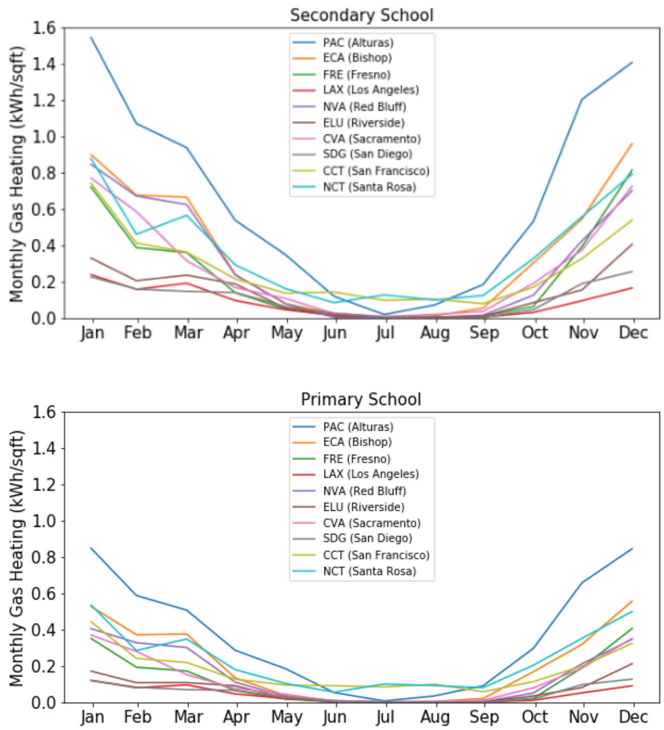


Figure 13: Gas heating consumption per square foot in primary and secondary schools in California by climate region [4]*.*

Given the different energy load profiles, primary and secondary schools were treated separately for current-state energy consumption and emissions analysis. Using the CDE's information on school square-footage per student, number of schools per county, and enrollment per county [11], [12], the total square footage of primary and secondary schools was calculated for each county in California. This analysis finds that the average primary school in California is about 46,000 ft^2, and the average secondary school is about 98,000 ft^2.

Using the calculated square-footage of primary and secondary schools per county and the energy consumption profiles from the NREL Commercial Hourly Load dataset, the energy consumption by schools was calculated for each county [4]. Counties with a larger number of enrolled students tended to have greater total emissions (Figure 14). The largest emissions per square foot were in the northeastern regions of California, as shown in Figure 14. Heating is the main driver for differences in natural gas consumption per square foot across counties, while gas consumption for water heating and interior equipment does not vary significantly by location.

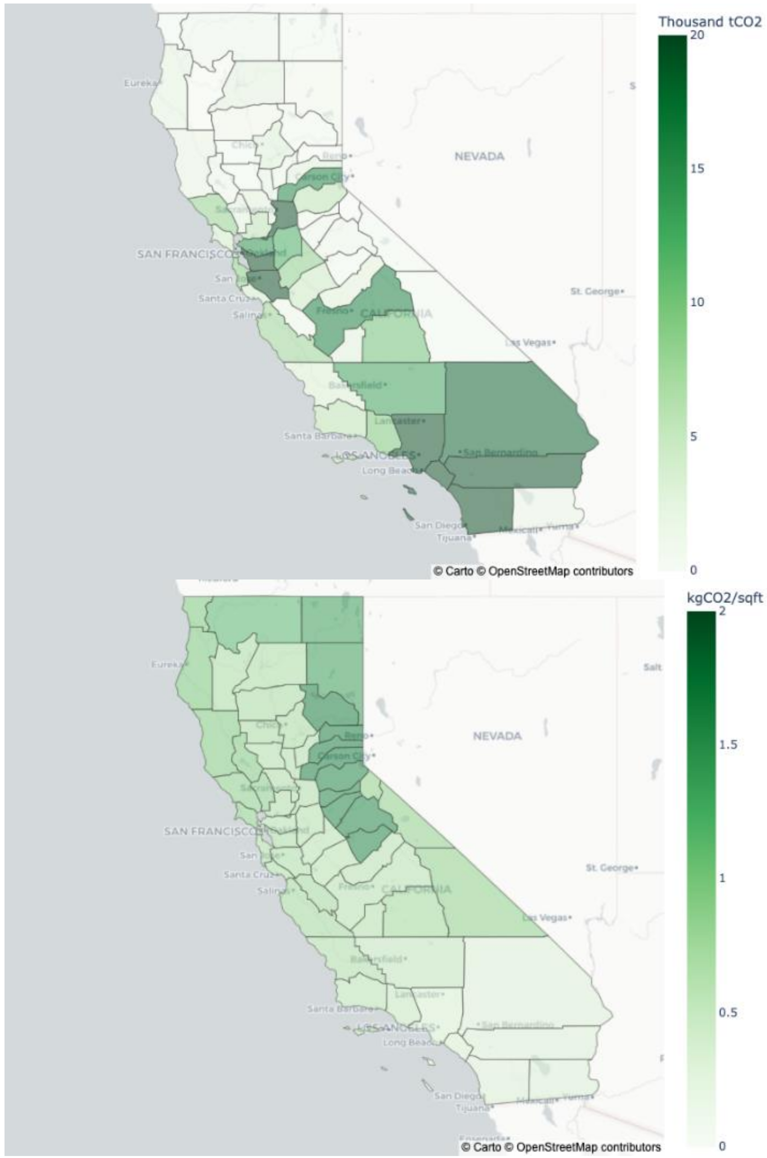


Figure 14: Maps of emissions from natural gas consumption by schools in California. Top: Total emissions by county. Bottom: Emissions per ft². Top map calculated from the NREL Commercial Hourly Load dataset and total square footage of schools per county based on 167 ft² and 122 ft² per secondary and primary school student, respectively [4], [11], [12].

Technology Options

Schools are among the larger commercial buildings in the state, and therefore they may see larger returns on investments with packaged investments in both energy efficiency improvement and decarbonization retrofits, since energy efficiency improvements can reduce the capacity of heaters and water heaters needed in the retrofit as well as reduce fuel costs post-retrofit.

According to the EIA's Commercial Buildings Energy Consumption Survey, the most common heating technologies for educational facilities in the United States today are packaged heating units (PHUs) and boilers (Figure15). [10]

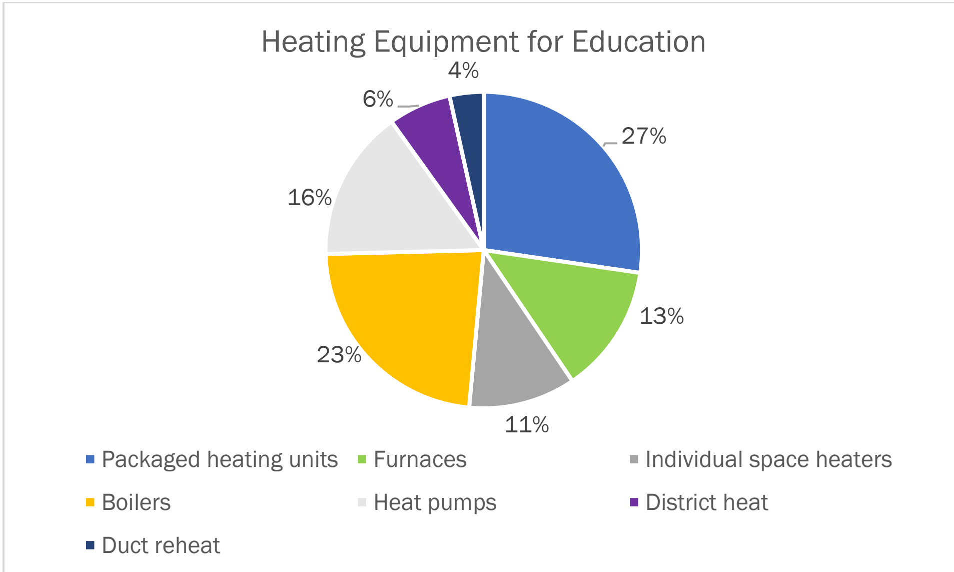


Figure 15: Shares of heating technology in the education sector in the US [30].

Technology options for schools include:

- Electric Heating
- Heat Pump Heating
- Electric Boilers
- Heat Pump Water Heating
- Efficiency
- Rooftop Solar
- Alternate stoves
- Passive Solar Water Heating

Technoeconomic Analysis

Since most schools are publicly funded it is important to understand how schools finance large energy-related projects to find the best decarbonization pathway for the School subsector. The most common ways of funding energy-related or decarbonization projects for schools is using general obligation (GO) bonds and lease agreements [31]. The average municipal bond interest rate as of 2021 is 2.28%. [32]

The recommended retrofit packages from the Advanced Energy Retrofit Guide for K-12 Schools for the marine climate, which includes most of California [18] was readjusted for the size of the average primary and secondary school in California based on the square footage analysis (see Table 1, Table 9 below shows the cost of energy-efficiency retrofits in California *before electrification.*

Secondary School	Primary School	Total End-Use Energy Savings
$473,719	$225,123	25.5%

Table 9: Retrofit package (excluding electrification) costs and savings for the average primary and secondary school in California [18].

In this study it was assumed that energy efficiency (EE) improvements are uniform across end uses, e.g. a 26% total energy efficiency improvement for a building implies a 26% reduction in heating load.

Next, an adjusted total and peak electricity load was estimated based on efficiency improvements from the retrofit and efficiency improvements associated with electrifying heating and water heating, in order to size heating and water heating equipment for the average school building in the state. The costs of new electric equipment for heating, water heating, and cooking, as well as the energy-efficiency retrofit were included in the GO bond financing. Cost details are shown in Table 10 below.

SECONDARY SCHOOL	Without EE retrofit			With retrofit			Payback period for retrofit (years)
	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	
Electric heaters	$393,798	$4	2.77%	$769,572	$8	28%	9
Heat pumps	$283,970	$3	11%	$687,750	$7	34%	8
Electric boiler	$277,864	$3	2.58%	$683,202	$7	27%	8

PRIMARY SCHOOL	Without EE retrofit			With retrofit			Payback period for retrofit (years)
	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	
Electric heaters	$135,196	$3	2.20%	$328,319	$7	27%	10
Heat pumps	$104,186	$2	9%	$305,216	$7	32%	10
Electric boiler	$96,869	$2	2.07%	$299,765	$6	27%	9

Table 10: Capital costs and energy savings for electrification technologies for the average school building with and without energy efficiency retrofits. Costs include electrifying cooking and replacing air conditioners in the building. Payback periods are for adding a retrofit to the system[4], [11], [12], [18], [21].

Costs and savings differ slightly for primary and secondary schools because their end-use consumption profiles differ [4]. For both secondary and primary schools, the most cost-effective option overall is to invest in heat-pumps, as the upfront costs are similar to other electrification technologies, but their energy savings are much greater. Actual costs will depend on location, available technologies, and equipment and labor availability. Rooftop solar PV was ignored for the purposes of this analysis.

Incentives and rebates can further improve the costs of upgrades. California's Proposition 39 allocated $1.7B over 2015-2021 for energy upgrades in K-12 schools [33]. The California Energy Conservation Assistance Act also provides zero interest loans to school districts and charter schools for energy-related upgrades, allowing for an opportunity for greater savings [34]. The California Bright Schools Program is also available to fund consultation services to determine the best pathway to energy efficiency for schools [35].

Mountain View Elementary School in Fresno, California is a 53,000 square foot school which performed energy-efficiency upgrades on its facilities. The school is part of the Clovis Unified School District, which received over $100,000 in rebates from PG&E, reducing the costs of the upgrade down to $0.52/ft^2, with a payback period of only 1.2 years [18].

The Orange County School District also performed an aggressive retrofit on over 1 million ft^2 of school buildings. Before incentives, the project cost $22.40/ft^2, with a payback period of 17 years [18].

Future Energy Consumption

Figure 16 is a forecast of the total electricity consumption by schools in 2045 for a fully electrified system, assuming a 0.5% growth rate in electricity consumption in the subsector from new building construction. Both scenario 1 and scenario 2 (defined in the introduction) assume electrifying all services provided currently by natural gas consumption in California schools. Scenario 1 assumes 50% heat pumps with heat pump water heater upgrades and 50% electric boilers, assuming 50% of schools upgrade their building envelope efficiency. Scenario 2 (less energy efficient) assumes 30% heat pumps and 70% electric boilers, with 10% penetration on energy efficiency upgrades. Energy efficiency upgrades were assumed to reduce total electricity consumption by 25.5% in each upgraded school in accordance with the Advanced Energy Retrofit Guide for K-12 Schools [4], [11], [12], [18], [21].

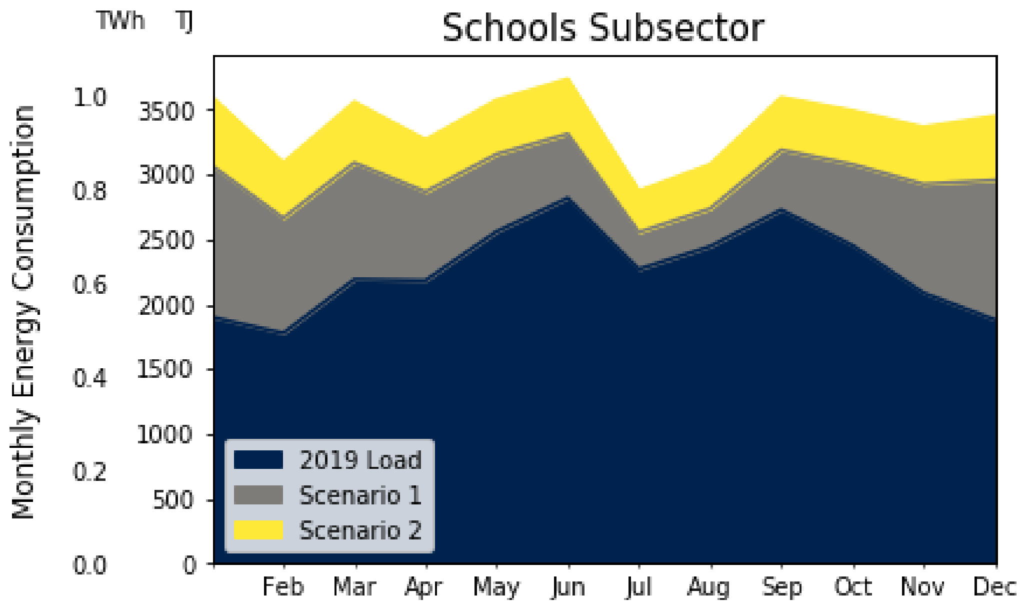


Figure 16 Forecast of electricity consumption by schools in 2045 in a fully electrified system [4], [11], [12], [18], [21].

College Subsector

According to CARB, in 2019 the College subsector was responsible for approximately 0.6 $MtCO_2e$, not including CHP emissions associated with the subsector. When CHP emissions are included, the 2019 College subsector accounts for a total of 1.38 $MtCO_2e$ in direct emissions from natural gas [1], [5], [6]. According to collegestats.org, there are approximately 752 colleges and universities in the state of California with a total of 3.6 million students enrolled. There are 285 colleges with over 1,000 students [36].

Methodology

CARB'S MRR database provides information on large facilities that emit over 10,000 tCO_2e/yr. There are 27 large colleges and universities included in the MRR and EGRID databases. 13 are powered and heated by CHP facilities, responsible for .8 M tCO_2e in emissions [5], [6].

For all colleges and universities not included in MRR or EGRID, this study assumes an energy consumption profile per student similar to that of a secondary school, and the load profile was calculated using the same methods as outlined in the previous section. Figure 17 shows the current monthly gas and electricity consumption for the entire College subsector.

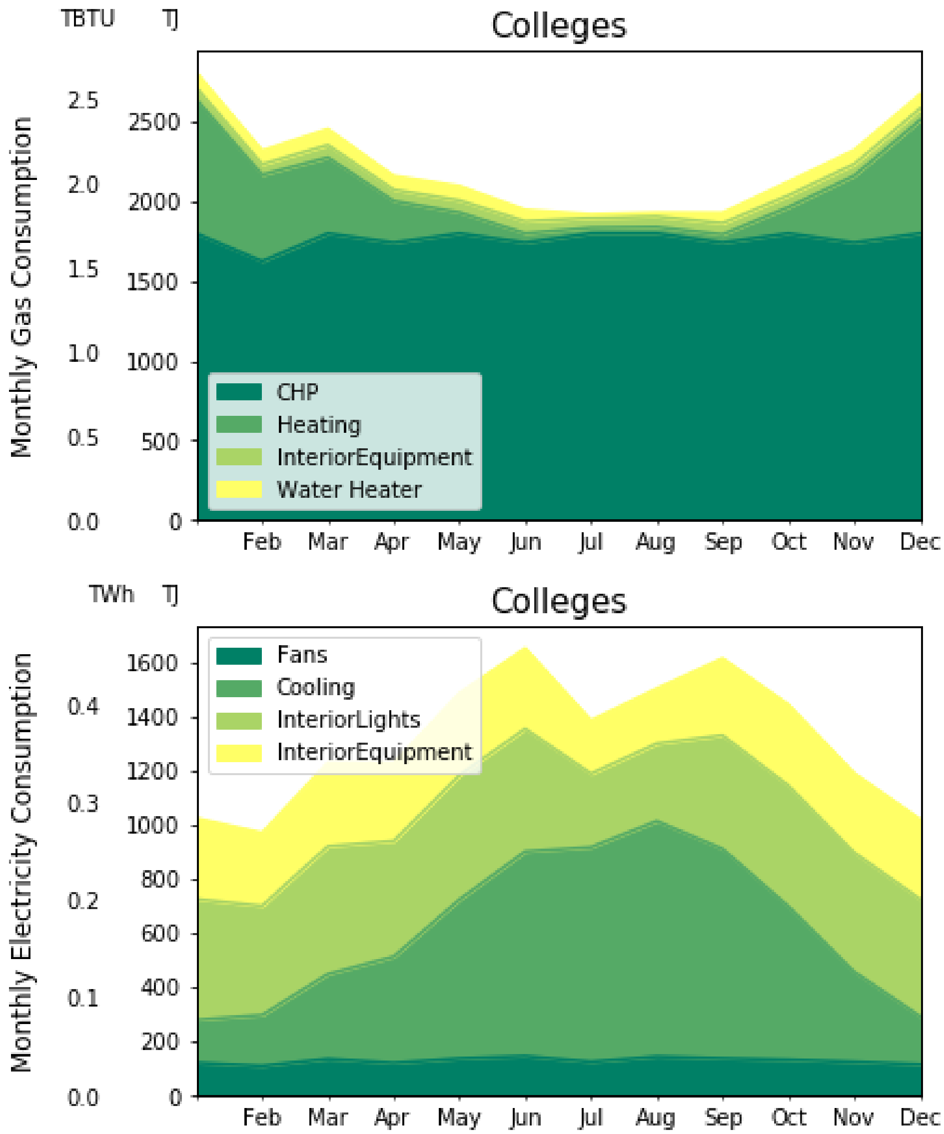


Figure 17: Total current monthly gas and electricity usage for the Colleges subsector in California, split by end-use. [1], [4]–[6]

Figure 17 shows that CHPs are the source for a significant portion of emissions within the College subsector. A flat load profile was assumed for natural gas consumption for CHP facilities in this subsector (note: dark green on Figure 17 appears bumpy due to different numbers of days in each month).

Figure 18 shows the regional variations in emissions from the College subsector, including CHPs.

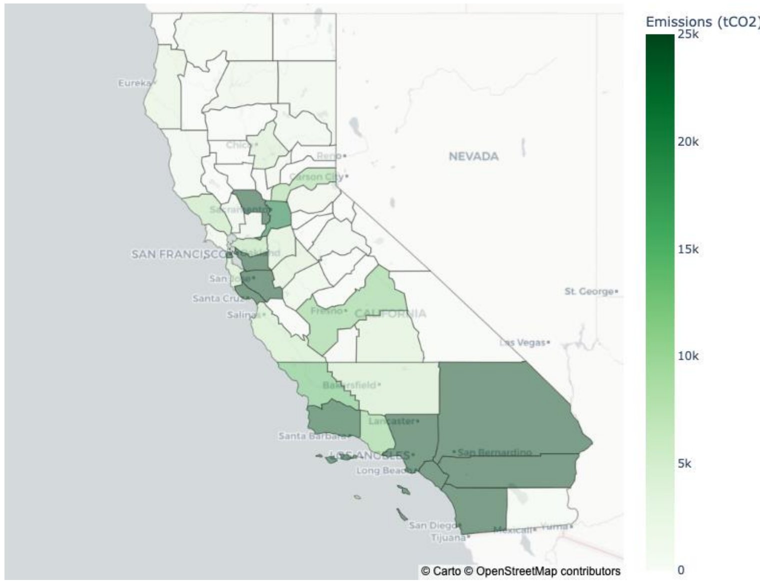


Figure 18: Map of total emissions from natural gas consumption by the College subsector in California. Calculated from the NREL Commercial and Residential Hourly Load Profiles and emissions from large facilities from MRR and EGRID [4]–[6], [15].

Counties with the largest consumption by this subsector include Los Angeles (6.8 TBTU) and San Diego (4.7 TBTU). The majority (79%) of these emissions come from CHP facilities in large universities.

Technology Options

For more information on technology options for decarbonizing small colleges and universities, see the previous section for Schools.

The options for decarbonizing CHP facilities in this College subsector include:

1. Carbon Capture and Storage (CCS)
2. Retiring the infrastructure and replacing the heat and power load with electricity

Note that a number of colleges and universities in California are publicly funded. This allows for a direct line of regulation between California policymakers and these colleges and universities.

Technoeconomic Analysis

Based on this analysis, 79% of emissions from colleges and universities are from CHP facilities at a few larger campuses. Technoeconomics for this subsector explores the costs and benefits of: (1) adding carbon capture equipment to these facilities so that emissions can be captured, transported, and stored in permanently in suitable geologic storage sites, and (2) retiring the infrastructure and opting for an upgrade to all-electric.

Table 11 shows the current emissions and LCOC in $/tCO_2e$ for a representative large, medium and small university-owned CHP.

CHP Facility	Emissions (tCO_2e)	NPV	LCOC ($\$/tCO_2e$)
Small University CHP	7,000	($9,275,838.77)	$166.24
Medium University CHP	55,000	($37,255,947.59)	$87.19
Large University CHP	160,000	($90,596,740.98)	$70.92

Table 11: Emissions for CHP facilities in the College subsector and costs of decarbonization using CCS [28].

The assumptions for the analysis in Table 11 are shown below in Table 12.

Assumption	Value	Unit
Inflation Rate	2	%
Discount Rate	10	%
NG Price (for capture equipment)	7.28	$/MMBTU
Electricity Cost (for capture equipment)	144.20	$/MWh
Feed Duration	3	Years
Capex Duration	2	Years
CO2 Storage Cost	10	$\$/tCO_2e$
CO2 Transport Cost	5	$\$/tCO_2e$
45Q Incentive	50	$\$/tCO_2e$
45Q Duration	12	years

Table 12: Assumptions used in technoeconomic analysis for CHPs. 45Q tax credit was assumed for facilities with greater than 25,000 tCO_2e in emissions [28].

As can be seen in Table 11, the cost of CCS retrofits becomes less economic for smaller CHPs. Below 25,000 tCO_2e, levelized costs of carbon exceed $100/$tCO_2e$. It is likely not a viable choice to decarbonize CHP facilities below this threshold with CCS. For some larger campuses, it also may not be reasonable to implement CCS due to the complexity of capturing CO_2 and transporting it to a storage site. Furthermore, as more natural gas infrastructure is retired, it is likely that the costs of the existing infrastructure will fall on those facilities which still burn natural gas.

Future Energy Consumption

Figure 19 shows the total electricity consumption by colleges and universities in 2045 for a fully electrified system (excluding CHPs), assuming a 0.5% growth rate in electricity consumption in the subsector from new building construction. Both scenario 1 and scenario 2 assume electrifying all energy services in the subsector. Scenario 1 assumes 50% heat pumps with heat pump water heater upgrades and 50% electric boilers, assuming 50% of schools upgrade their building envelope efficiency. Scenario 2 is a less aggressive approach, assuming 30% heat pumps and 70% electric boilers, with 10% penetration on energy efficiency upgrades. Energy efficiency upgrades were assumed to reduce total electricity consumption by 25.5% in each upgraded school in accordance with the Advanced Energy Retrofit Guide for K-12 Schools [4]–[6], [18], [21], [36].

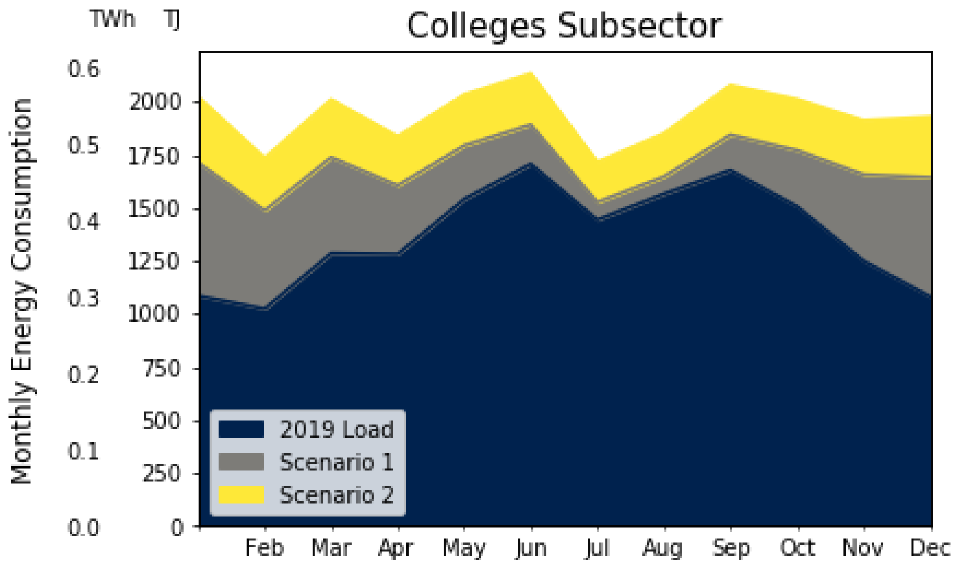


Figure 19: projections for electricity consumption by colleges and Universities in 2045 (excludes electrifying services currently fulfilled by CHP). [4], [11], [12], [18], [21]

Restaurant Subsector

According to CARB, in 2019 the natural gas combustion in the Restaurant subsector was responsible for 1.61 $MtCO_2e$ [1].

Restaurants are among the more difficult subsectors to decarbonize, because:

- Many restaurants are small businesses that do not have the ability to pay for equipment upgrades upfront.
- There are approximately 76,000 restaurants in California, and they are among the smallest buildings in the Commercial Buildings sector. It is more difficult to regulate, monitor and enforce policy with large numbers of small buildings [37].
- Many chefs are unwilling or unable to switch away from natural gas cooking, which is responsible for the bulk of natural gas consumption in restaurants.

The restaurant industry is heavily impacted by the move towards decarbonization in California. There are approximately 1,830,000 restaurant and foodservice jobs in California, with $97 billion spent at California restaurants in 2018 [37].

Methodology

The total square footage in the Restaurant subsector was estimated starting with the number of restaurants in each county found in the OSM database [7]. This source indicates that there are 41,681 restaurants in the state, which is an underestimate (Figure 20). The total number of restaurants was therefore rescaled by county to match the National Restaurant Association's estimate of the number of restaurants in California (76,201) [37]. The average size per restaurant was assumed to be 3280.5 ft^2 [2].

The NREL Commercial and Residential Hourly Load Profiles [4] were used to calculate the energy consumption profile for restaurants in California. The total natural gas consumption in restaurants in California was found to be 30.38 TBTU, which is very close to the 2019 CARB estimate of 30.51 TBTU [1]. Figure 21 shows stacked plots of monthly gas and electricity consumption for the entire Restaurant subsector [4].

The NREL Commercial and Residential Hourly Load Profiles [4] include an energy consumption profile for both quick service and full-service restaurants.the NREL Commercial and Residential Hourly Load Profiles [4] includes an energy consumption profile for both quick service and full-service restaurants. The load profile for quick and full-service restaurants per square foot is extremely similar, therefore quick and full-service restaurants were combined for this study. Figure 20 shows the distribution of quick and full-service restaurants across CA. According to California Downtown[38], 70% of restaurants in the state are quick service and 30% are full-service.

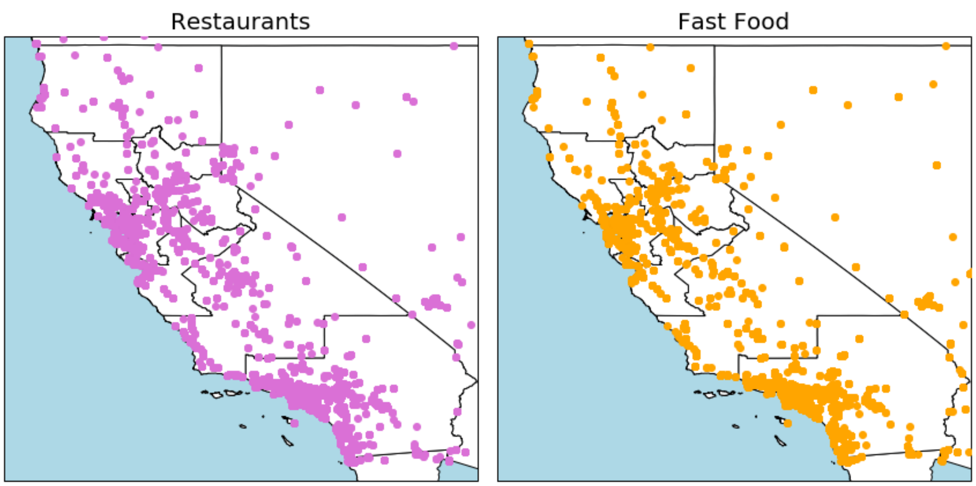


Figure 20: Locations of fast food and full-service restaurants in California, based on data found in OSM [7].

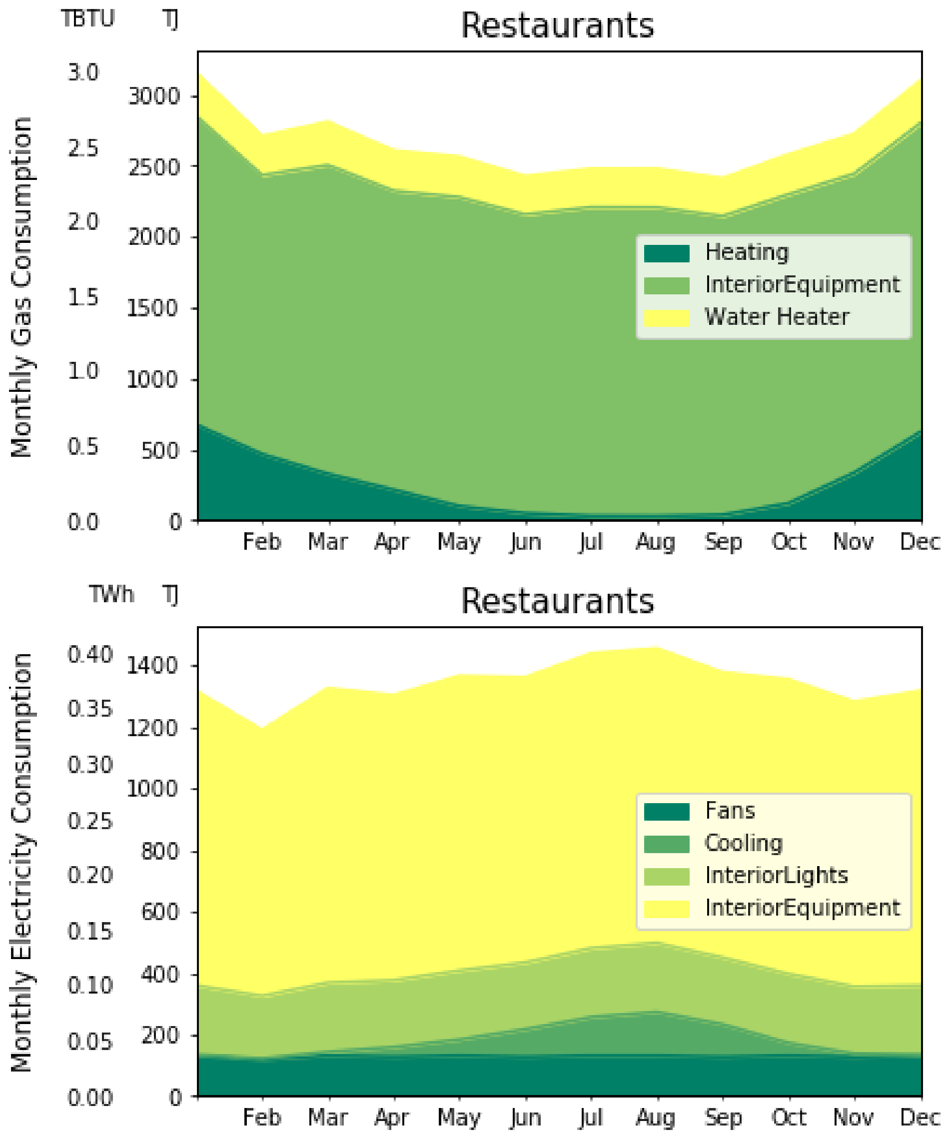
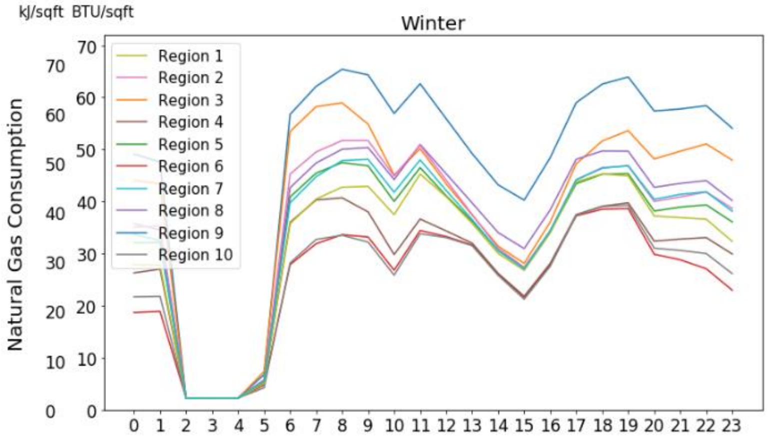


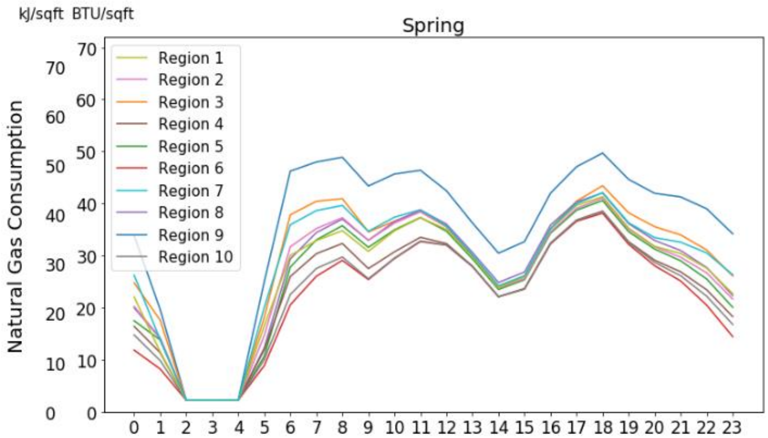
Figure 21: Total 2019 monthly gas and electricity usage for all restaurants in California, by end-use. Based on data from [2], [4], [7], [37].

The Restaurant subsector's energy consumption does not have strong seasonal variations and shows only slightly elevated gas consumption in the winter and slightly elevated electricity consumption in the summer. Gas consumption and electricity consumption are relatively similar in magnitude in this subsector, unlike in some other subsectors in which electricity is the dominate energy consumed. The pivotal end-use of gas in restaurants is interior equipment, which is mainly comprised of fuel use for cooking. Interior equipment is also the dominating electricity end-use category.

Diurnal load information is also available for restaurants via the NREL Commercial and Residential Hourly Load Profiles [4]. Figure 22 shows the estimated diurnal load profiles for gas consumption per square foot in restaurants by climate region and season.



kJ/sqft BTU/sqft
Winter
Natural Gas Consumption
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Region 9
Region 10



kJ/sqft BTU/sqft
Spring
Natural Gas Consumption
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Region 9
Region 10

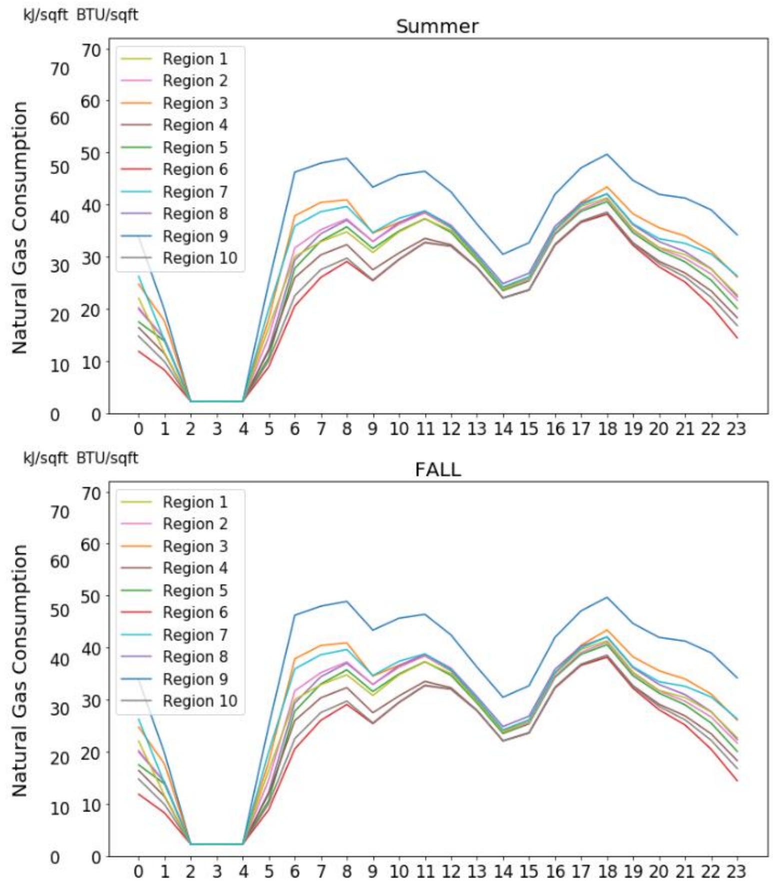


Figure 22: Diurnal variations in natural gas consumption per ft^2 by climate region for a full-service restaurant in California, according to NREL hourly load profiles [4], [15].

The diurnal load profile for restaurants peaks during mealtimes in all four seasons, with slightly higher gas consumption in the winter as a result of heating.

Figure 23 shows the regional variations in emissions from restaurants. Gas consumption in restaurants does not show as strong a regional variation as other subsectors in which heating is the dominant end-use for gas.

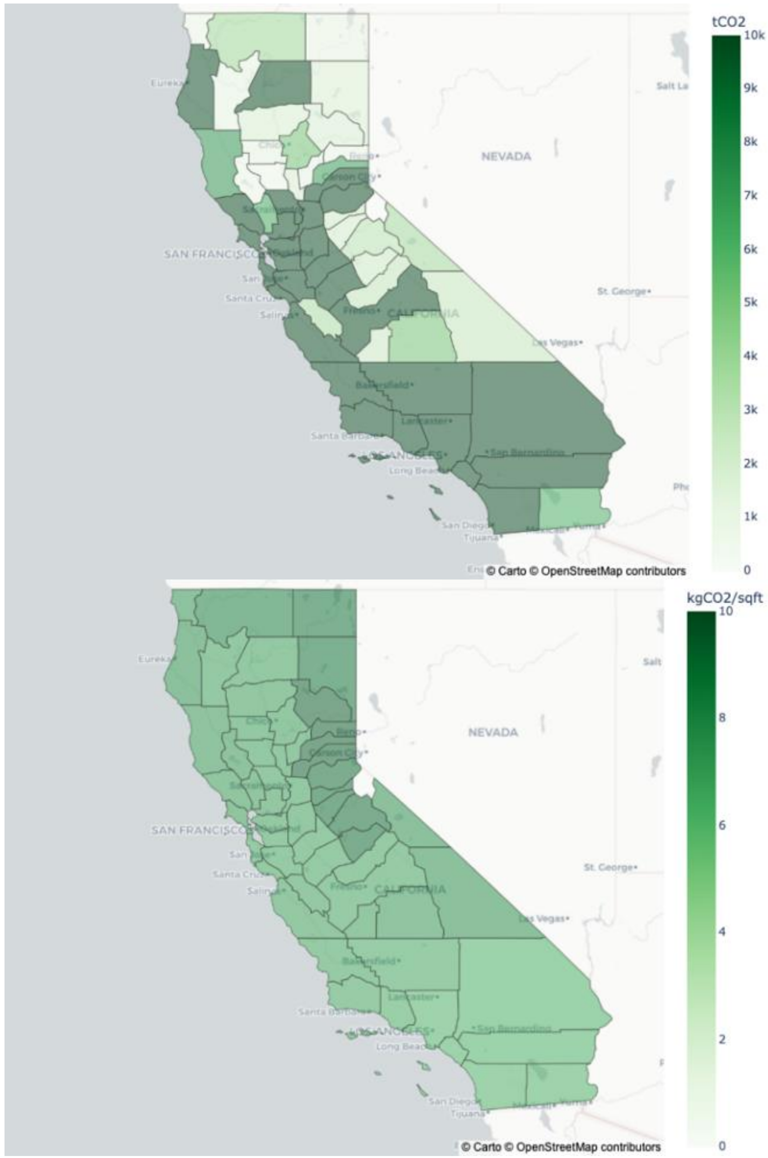


Figure 23: Maps of emissions from natural gas consumption by restaurants in California. Top: Total emissions by county. Bottom: Emissions per ft². Top map calculated from the NREL Commercial and Residential Hourly Load Profiles and total square footage of restaurants per county based on OSM data and data from the National Restaurant Association [2], [4], [7], [37].

Technology Options

The primary source (80%) of emissions from the Restaurant subsector is direct emissions from natural gas cooking. Therefore, finding a suitable alternative to natural gas cooking is the most important way to decarbonize the Restaurant subsector. In addition, 9% of natural gas consumption in restaurants is from heating, and 11% is from water heating [4], [7], [37].

Technology options to decarbonize restaurants include:

- Electric and Induction Stoves
- Electric Heaters
- Electric Water Heaters

- Electric Boilers
- Heat Pump Water Heaters
- Air-Source Heat Pumps

While natural gas for cooking is the dominating energy end-use in restaurants, it may be difficult to decarbonize because of industry opinion and cost barriers for small businesses. There is a possibility of replacing cooking in some restaurants with green or blue hydrogen stoves, in order to maintain a cooking style more akin to that of natural gas. However, there is little evidence today that hydrogen cooking will be an economically or logistically sound option in the future.

Technoeconomic Analysis

Technoeconomic analysis assumed no energy efficiency programs from technology upgrades other than from upgrading heating and water heating equipment (Table 12). Capital expenditures are the upfront costs to upgrade heating, water heating, and air conditioning equipment, and to add one new electric stove to a 10,000 or 2,000 ft^2 restaurant in California.

Large Restaurant (10,000 ft^2)	Without energy efficiency retrofit		
	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings
Electric heaters + Electric water heaters + Electric stove	$24,981	$2.5	1.8%
Heat pumps + Heat pump water heaters + Electric stove	$18,585	$1.9	7.8%
Electric boilers + Electric water heaters + Electric stove	$31,552	$3.2	1.7%

Small Restaurant (2,000 ft^2)	Without energy efficiency retrofit		
	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings
Electric heaters + Electric water heaters	$12,756	$6.4	1.8%
Heat pumps + Heat pump water heaters	$11,477	$5.7	7.8%
Electric boilers + Electric water heaters	$14,070	$7.0	1.7%

Table 12: Capital costs and energy savings for electrification technologies for a small and large restaurant in California. Costs include electrifying cooking and replacing air conditioners in the building. A new commercial electric stove costs $9700. This analysis omits upgrading hot food holding cabinets [2], [4], [21].

Since energy consumption is dominated by cooking, upgrading heating equipment in restaurants does not result in major efficiency gains. The most cost-effective option for both small and large restaurants is heat pumps, which is also the most energy-efficient option. However, depending on what type of HVAC system is currently in place in a particular restaurant, as well as equipment and labor availability, it may be more favorable to choose a different technology.

Future Energy Consumption

Figure 24 shows the total electricity consumption by restaurants in 2045 in a fully electrified system, assuming a 0.5% growth rate in electricity consumption in the subsector from new building construction. Both scenario 1 and scenario 2 assume all current natural gas consumption in California restaurants is replaced with electricity. Scenario 1 assumes 50% heat pumps with heat pump water heater upgrades and 50% electric boilers. Scenario 2 is a lower efficiency approach, assuming 30% heat pumps and 70% electric boilers.

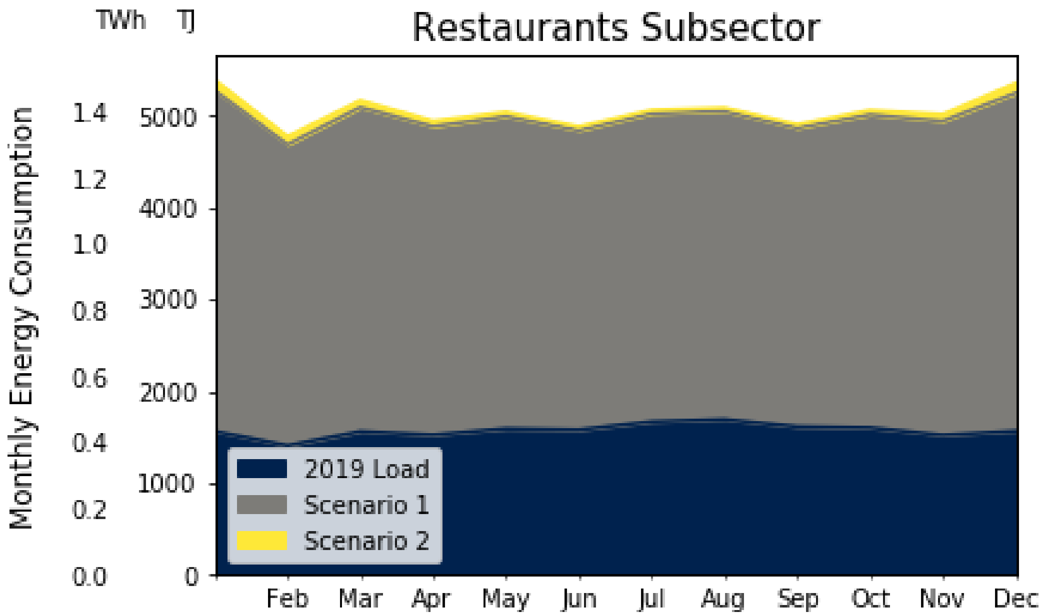


Figure 24: Forecast of electricity consumption by restaurants in 2045 in a fully electrified system [4], [11], [12], [18], [21].

There is a 1.3% difference in the total yearly electricity consumption for scenario 1 vs. scenario 2. This is because the primary energy end-use for restaurants is cooking, and no energy efficiency improvements were assumed for cooking for the purposes of this analysis. It is possible that technology improvements and will result in the increased availability of energy efficient commercial stoves, allowing for the 2045 electricity consumption for restaurants to be lower than forecast [4]. Since restaurant energy consumption is dominated by cooking, there is very little seasonal variation in either the 2019 load or the 2045 projections, as shown in Figure 24.

Food & Liquor Subsector

The Food and Liquor subsector is comprised of grocery stores, convenience stores, and bakeries. According to CARB, in 2019 natural gas combustion in this this subsector was responsible for 0.84 $MtCO_2e$[1]. According to our analysis, the subsector also consumes 9.6 TWh of electricity per year.

Many supermarkets and convenience stores are owned by large corporations. Therefore, they have the potential to mitigate some carbon quickly by mass-decarbonizing markets with multiple locations across California. They also have the potential to increase decarbonization outside of California, as many of these companies are national or international. This subsector also has great potential for energy efficiency improvements.

Methodology

The number of grocery stores, convenience stores, and bakeries in each county was assessed using OSM. The total for each county was then rescaled to match the actual total number of businesses in California from IBISWorld and Statista [39], [40]. Table 13 shows the results for the Food & Liquor subsector.

Business Type	Grocery Store	Convenience Store	Bakery
OSM total	3,617	4,280	960
Total in CA	4,701	12,074	N/A
ft^2 per unit	45,000	2,500	1,420

Table 13: Summary of bottom-up rescaling numbers for the Food & Liquor subsector. Reliable information was not available on the total number of bakeries in California. [1], [2], [7], [15], [39]–[41]

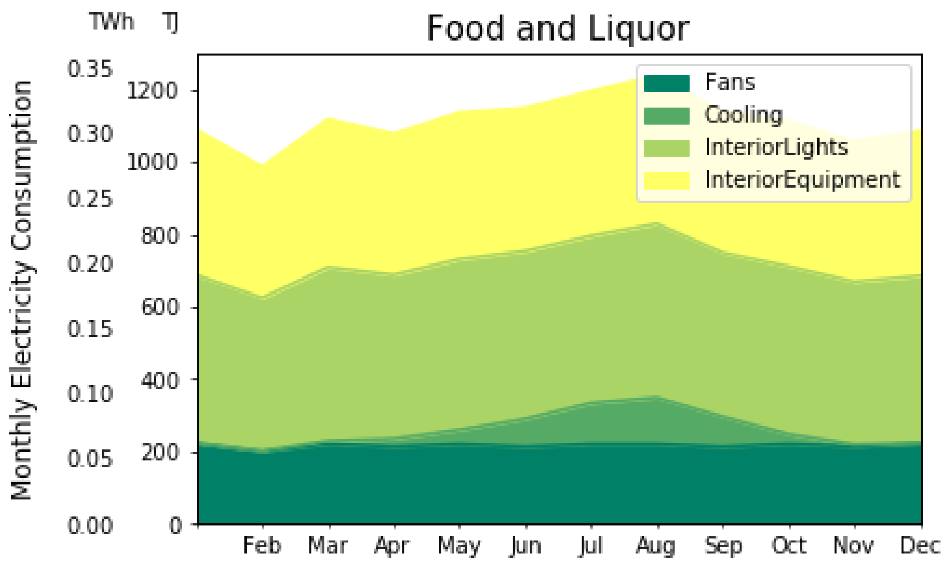
Grocery Stores. The NREL Commercial and Residential Hourly Load Profiles provides load information for a typical supermarket across different locations in California. Using the total floorspace for grocery stores calculated from Table 13 as well as NREL's hourly load profiles, the total energy consumption for grocery stores was calculated. The average electricity consumption in grocery stores in California was calculated to be 37.3 kWh/ft^2 [4].

Convenience Stores. While the NREL Hourly Load profiles do not include convenience stores, the load shape for convenience stores was assumed to be similar to that of a supermarket. The actual electricity consumption for convenience stores is 52.5 kWh/ft^2 per year [41].The load profile for grocery stores per square foot was rescaled to match 52.5 kWh/ft^2 per year on average to calculate the energy consumption for convenience stores in California.

Bakeries. Reliable information was not available on the total number of bakeries in California. Furthermore, there is concern regarding overlap with coffee shops, which are counted under the Restaurant subsector. Therefore all bakeries that were not also listed as coffee shops in OSM were counted in the food & liquor category. For this reason, the total floorspace for bakeries in California is likely an underestimate. The energy load profile for bakeries was assumed to be the same load per square foot as a restaurant, as the NREL Commercial and Residential Hourly Load Profiles does not include load info specifically about bakeries (see Restaurant section).

Using this bottom-up approach, the total gas consumption per year by the Food & Liquor subsector was calculated to be 8.86 TBTU, a 41.9% difference from CARB's estimate for the yearly gas consumption in the food & liquor category of 15.25 TBTU. For the sake of future projections, energy consumption in food & liquor in this study was rescaled proportionally such that the total gas consumption in the subsector summed to 15.25 TBTU per year [1], [4], [7], [41].

Figure 25 shows rescaled monthly gas and electricity consumption, respectively, for the entire Food & Liquor subsector.



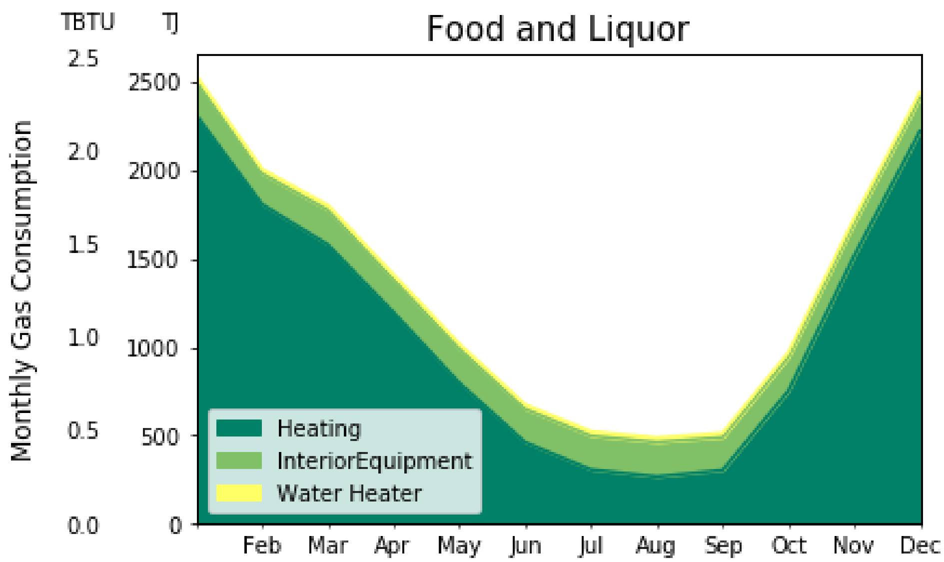
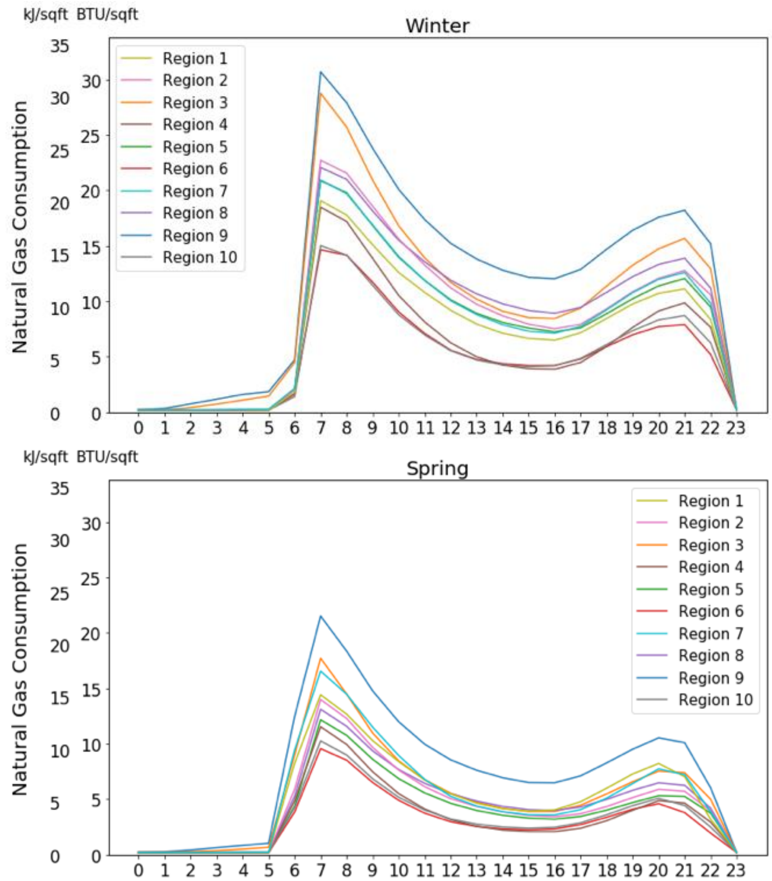


Figure 25: Total current monthly gas and electricity usage for the Food and Liquor subsector in California, by end-use. These numbers are rescaled to match CARB's fuel inventory totals [1], [2], [4], [7], [15], [41].

The primary source of direct emissions in the Food & Liquor subsector is natural gas space heating, which varies seasonally by nearly an order of magnitude, peaking in the winter. Electric cooling also varies seasonally in this subsector, however the overall electricity consumption in the food and liquor subsector does not show strong seasonal variations. Interior lighting and interior equipment such as refrigerators and freezers are the largest contributors to electricity consumption in this subsector.

The Food and Liquor subsector also shows a surprisingly large heating demand, likely a result of refrigeration equipment reducing the internal temperature of these facilities. Leakage from cooling equipment can be reduced by adopting more thermally efficient refrigerators in supermarkets, grocery stores, and convenience stores. This also has the added co-benefit of reducing electricity for refrigeration.

Diurnal load information is also available for supermarkets via the commercial hourly load profiles [4]. Figure 26 shows the diurnal load profiles for gas consumption per square foot in supermarkets by climate region.



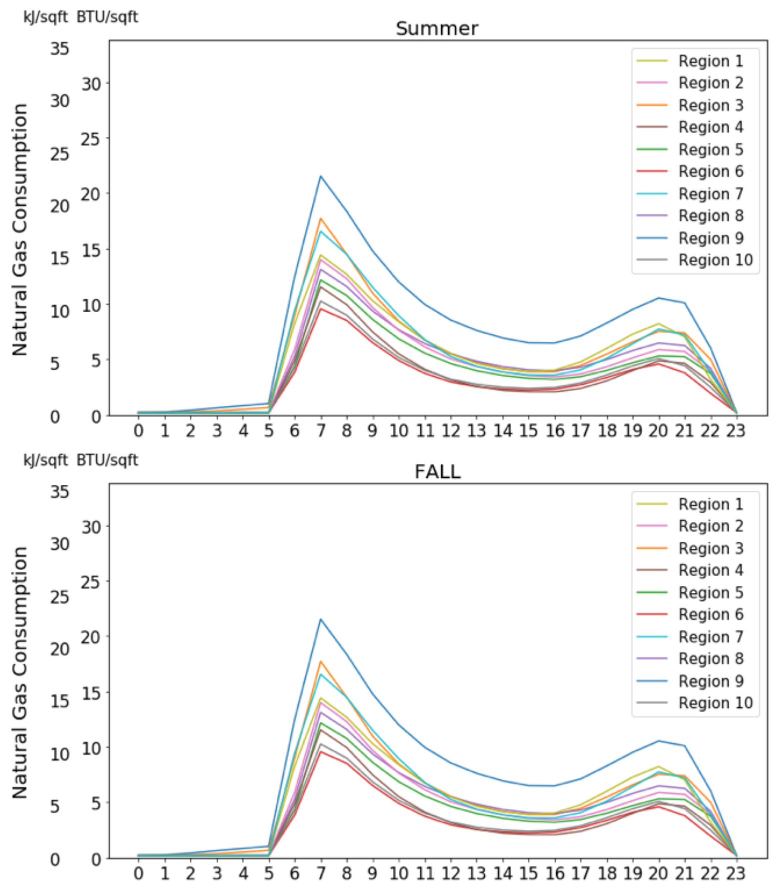


Figure 26: Diurnal variations in natural gas consumption per square foot by climate region in California supermarkets. [4], [15]

Diurnal gas consumption in supermarket follows a duck curve, with a larger peak in the morning. Gas consumption is minimal before 5am.

Figure 27 shows how total emissions and emissions per square foot vary across locations in California.

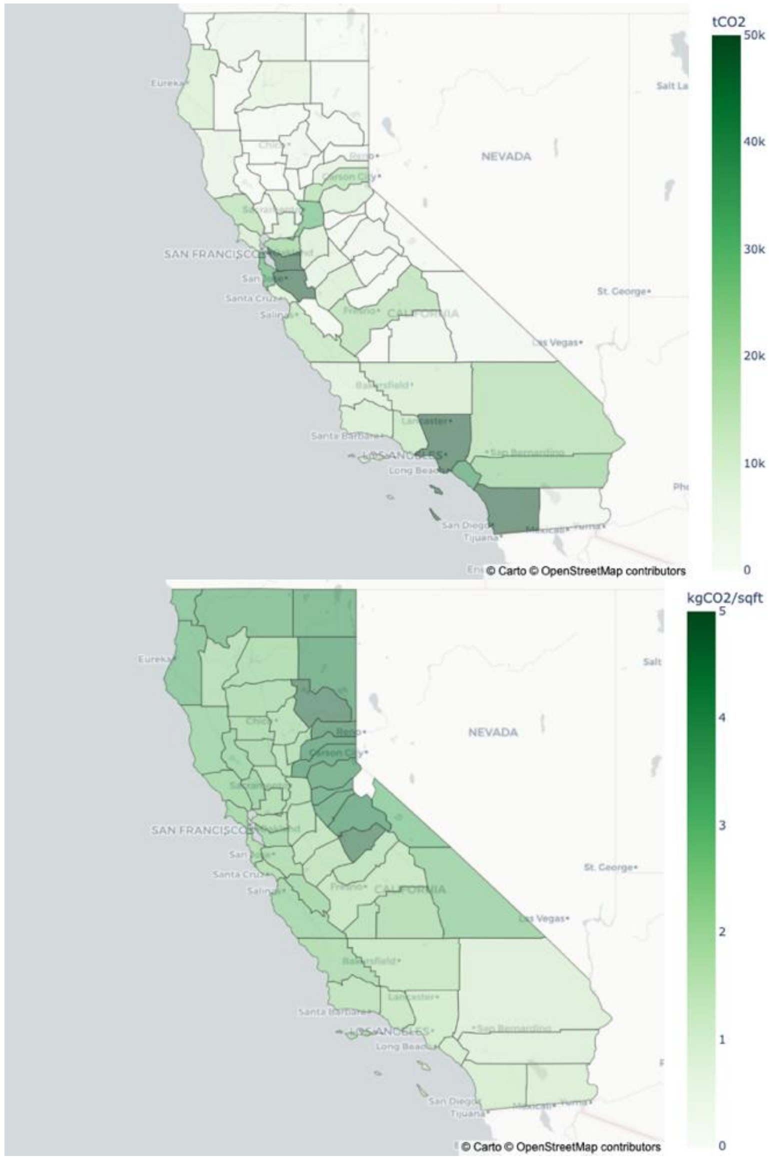


Figure 27: Maps of emissions from natural gas consumption in the Food and Liquor subsector in CA. Top: total emissions by county. Bottom: Emissions per ft^2. Top map calculated from the NREL Commercial and Residential Hourly Load Profiles and total square footage of food and liquor per county based on OSM data and total counts of grocery stores and convenience stores [1], [2], [4], [7], [15], [39]–[41].

Alameda, Santa Clara, Los Angeles, and San Diego counties show the highest total direct emissions from natural gas in the Food and Liquor subsector. These numbers are most heavily influenced by grocery stores, which are the largest of the buildings included in the Food and Liquor subsector.

Technology Options

Grocery and convenience stores use natural gas primarily for space heating. Many groceries also use some gas for cooking, though typically convenience stores do not use gas for cooking. For more information on decarbonizing technology options for bakeries, see the previous discussion on Restaurants.

The technology options for the Food & Liquor subsector include:

- Electric Heaters
- Electric Water Heaters
- Electric Boilers
- HPWHs
- Air-Source Heat Pumps
- Alternate Stoves

Since many supermarkets and convenience stores in California are chain markets, it may be valuable to implement a standard procedure for decarbonizing these facilities.

Technoeconomic Analysis

Technoeconomic analysis on a small grocery (10,000 ft^2), large grocery (45,000 ft^2) and convenience store (2,500 ft^2) are shown in Table 14 below. The grocery stores were expected to need a new electric stove, while a new stove was not included in technoeconomic analysis for convenience stores.

Large Grocery Store (45,000 ft^2)	Without EE retrofit			With retrofit			Payback period for retrofit (years)
	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings	
Electric heaters	$46,920	$1.0	6.4%	$503,157	$11.2	36.7%	5.25
Heat pumps	$35,886	$0.8	24.4%	$495,698	$11.0	48.9%	6.40
Electric boiler	$71,234	$1.6	5.9%	$519,593	$11.5	36.4%	5.39
Small Grocery Store (10,000 ft^2)	**Without EE retrofit**			**With retrofit**			**Payback period for retrofit (years)**
	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings	
Electric heaters	$17,971	$1.8	6.4%	$119,357	$11.9	36.7%	5.60
Heat pumps	$15,519	$1.6	24.4%	$117,700	$11.8	48.9%	6.84
Electric boiler	$23,374	$2.3	5.9%	$123,010	$12.3	36.4%	5.74
Convenience Store (2,500 ft^2)	**Without EE retrofit**			**With retrofit**			**Payback period for retrofit (years)**
	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings	

Electric heaters	$5,548	$2.2	1.6%	$29,767	$11.9	33.5%	0.42
Heat pumps	$3,884	$1.6	6.0%	$28,642	$11.5	36.4%	0.43
Electric boiler	$9,155	$3.7	1.4%	$32,205	$12.9	33.4%	0.46

Table 14: Capital costs and energy savings for electrification technologies for a large and small grocery and convenience store with and without energy efficiency retrofits from NREL's Advanced Energy Retrofit Guide for Grocery Stores (Source). Costs include replacing HVAC and water heating in the building, as well as a new electric stove (grocery stores only). Payback periods are for adding a retrofit to the system [1], [2], [4], [7], [15], [41].

The payback period for energy efficiency retrofits in convenience stores is particularly short because convenience stores use a relatively large amount of electricity. In grocery stores and supermarkets, heat pumps with energy efficiency retrofits can mitigate as much as 49% of the current energy consumption in these buildings [1], [2], [4], [7], [15], [19], [21], [41].

Future Energy Consumption

Figure 28 shows the total electricity consumption in the Food and Liquor subsector in 2045 for a fully electrified system, assuming a 0.5% growth rate in electricity consumption in the subsector from new building construction. Both scenario 1 and scenario 2 assume electrifying all energy services in the subsector. Scenario 1 assumes 50% heat pumps with heat pump water heater upgrades and 50% electric boilers, assuming 50% of buildings in the subsector upgrade their building envelope efficiency. Scenario 2 is a less aggressive approach, assuming 30% heat pumps and 70% electric boilers, with 10% penetration on energy efficiency upgrades. Uniformity across facilities was assumed for these projections, unlike technoeconomic analysis and the current-state energy consumption, where the subsector was split into convenience stores, grocery stores, and bakeries. Energy efficiency upgrades were assumed to reduce total electricity consumption by 34% in each upgraded facility in accordance with the Advanced Energy Retrofit Guide for Grocery Stores [1], [2], [4], [7], [15], [19], [21], [39]–[41].

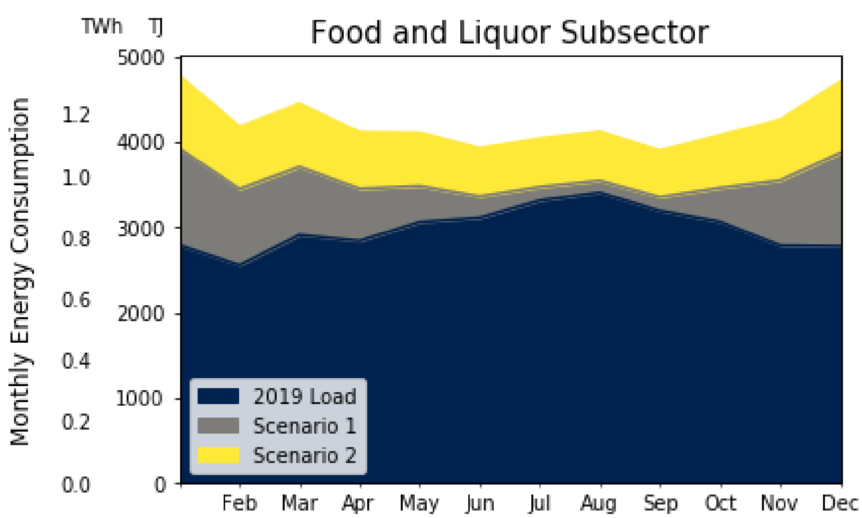


Figure 28: projections for electricity consumption by food and liquor stores in 2045 [1], [2], [4], [7], [15], [19], [21], [41].

The resulting 2045 energy consumption projections (Figure 28) show a slightly winter-peaking electricity load in 2045. The large difference between consumption in scenario 1 and 2 implies large potential for saving money and energy in the Food and Liquor subsector. While this analysis assumes proportional scaling of heating demand, building envelope improvements and efficient refrigeration would likely dampen the seasonal variations in energy demand in the Food and Liquor subsector.

Retail Subsector

There are approximately 164,200 retail stores in California [42]. According to CARB, in 2019 natural gas combustion in this this subsector was responsible for 0.87 $MtCO_2e$.

Methodology for Assessing Retail Subsector

The number of retail stores in each county was assessed using OSM. The total for California using this approach is 45,109, which is significantly less than 164,200, The per county OSM estimates were scaled up to the state total, and an average size per retail store of 8392 ft^2 [2] was used to get total square footage for the state and each county.

NREL Commercial and Residential Hourly Load Profiles were used to calculate the energy consumption profile for retail stores in California from the total square-footage per county. Using this bottom-up approach, the total gas consumption per year by the Retail subsector was calculated to be 12.51 TBTU, a 18.2% difference from CARB's estimate for the yearly gas consumption in the retail category of 15.29 TBTU. For the sake of future projections, energy consumption in the Retail subsector in this study was rescaled proportionally such that the total gas consumption in the subsector summed to 15.29 TBTU per year. [1], [2], [4], [7], [15], [42]

Figure 29 shows rescaled monthly gas and electricity consumption, respectively, for the entire Retail subsector. The NREL Commercial and Residential Hourly Load Profiles assume 100% of gas usage in retail is for gas heating.

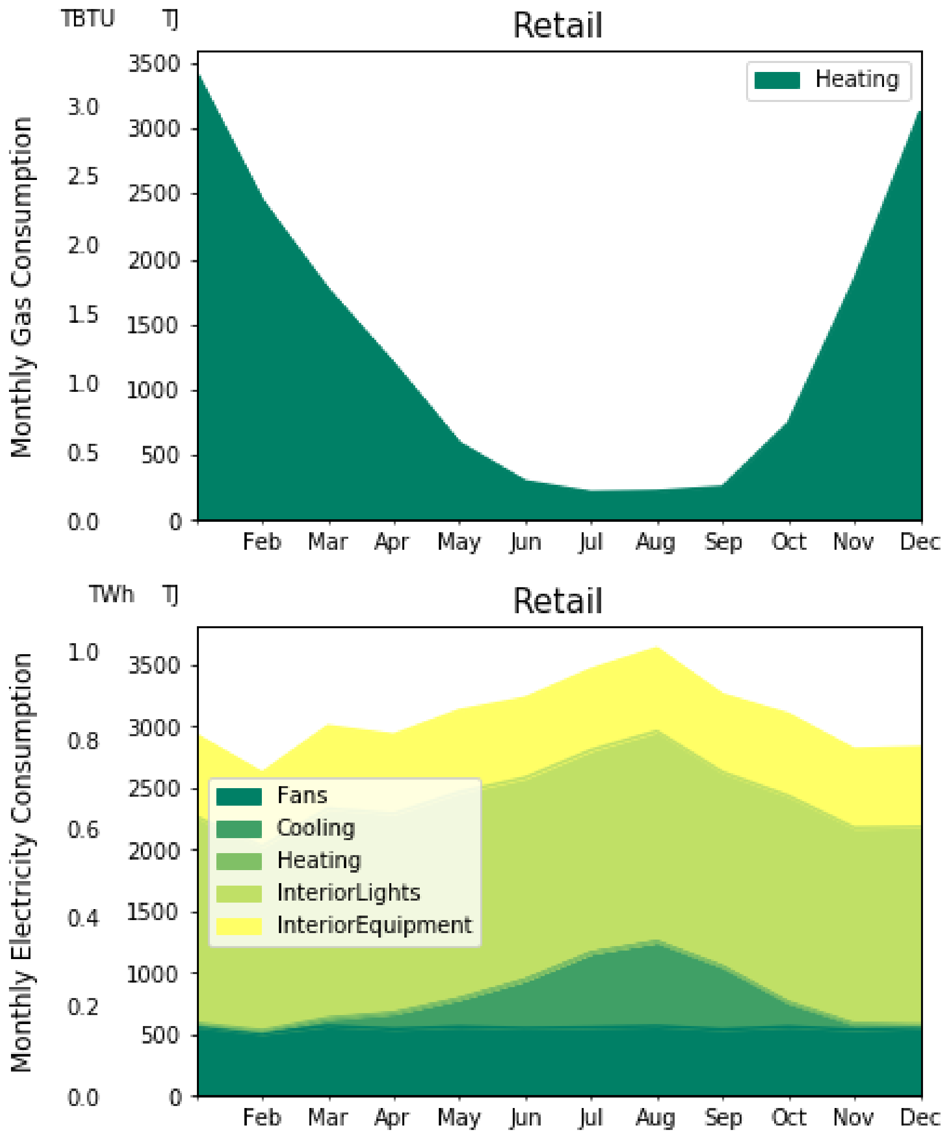
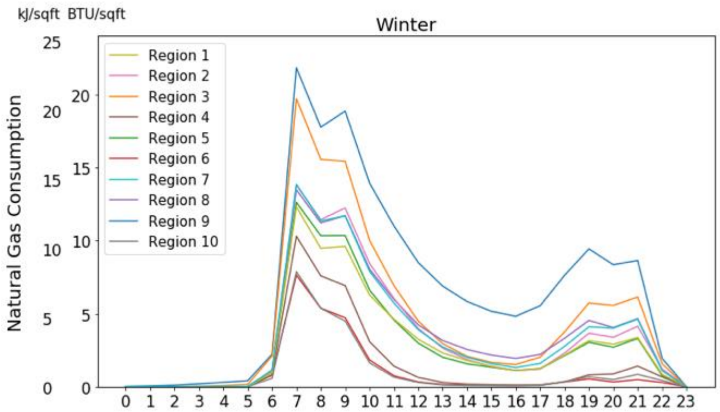
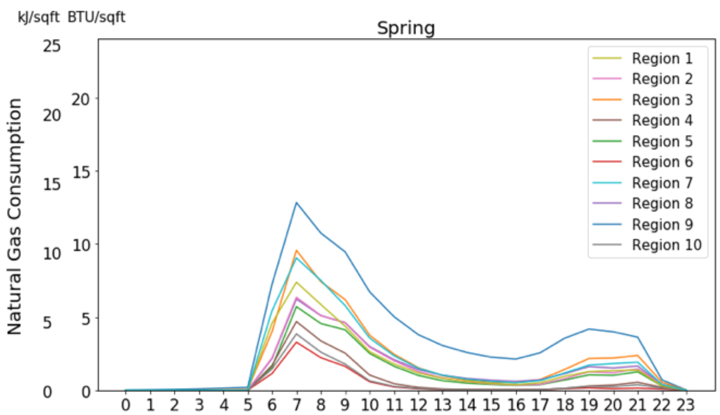
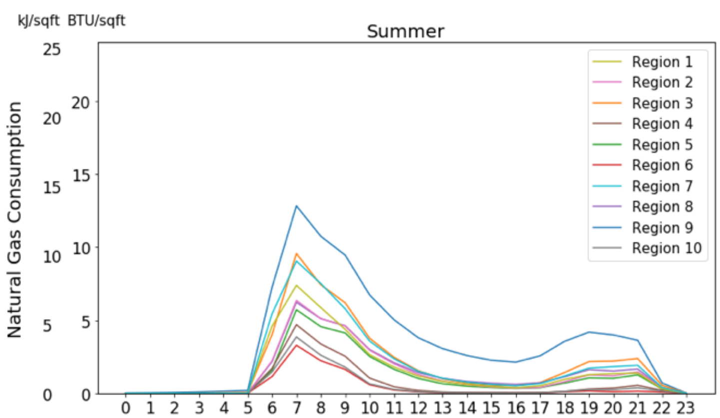


Figure 29: Stacked plot, showing total current monthly gas and electricity usage for the Retail subsector in California, by end-use. These numbers are rescaled to match CARB's fuel inventory totals [1], [2], [4], [7], [15], [42].

Diurnal load information is also available for retail stores via the commercial hourly load profiles [4]. Figure 30 shows the diurnal load profiles for gas consumption per square foot in retail by climate region.


kJ/sqft BTU/sqft
Winter
Natural Gas Consumption
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Region 9
Region 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23


kJ/sqft BTU/sqft
Spring
Natural Gas Consumption
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Region 9
Region 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23


kJ/sqft BTU/sqft
Summer
Natural Gas Consumption
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Region 9
Region 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

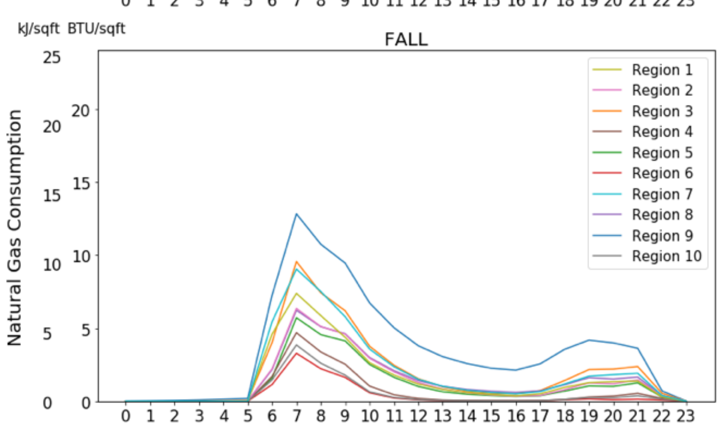

kJ/sqft BTU/sqft
FALL
Natural Gas Consumption
Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Region 9
Region 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

Figure 30: Diurnal variations in natural gas consumption per square foot by climate region in California stand-alone retail stores [4], [15].

Gas consumption in retail stores follows a duck curve, with minimal gas usage before 5am. In most locations in California, there is little to no gas consumption in the summer.

Figure 31 shows the regional variations in emissions from the Retail subsector

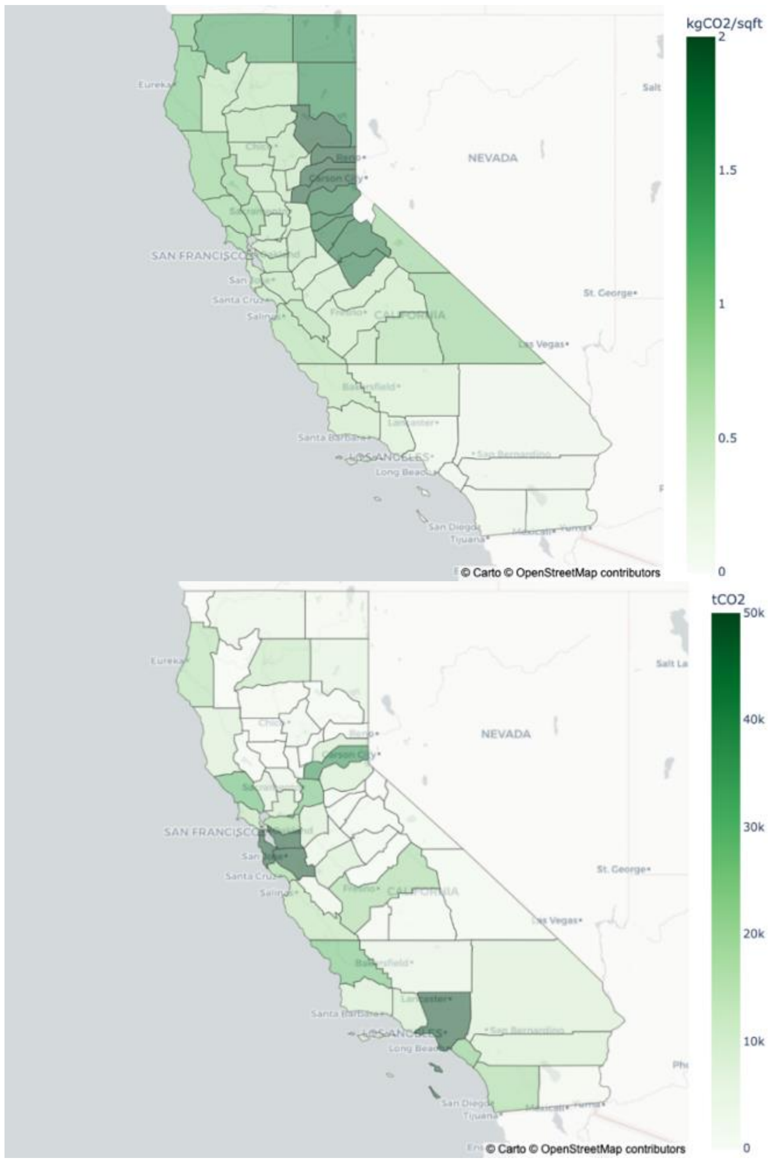


Figure 31: Maps of emissions from natural gas consumption by the Retail subsector in CA. Top: total emissions by county. Bottom: Emissions per ft². Top map calculated from the NREL Commercial and Residential Hourly Load Profiles and total square footage of retail establishments per county based on OSM data and total counts of retail stores from Team California [1], [2], [4], [7], [15], [42].

Tourist destinations and highly populated areas such as Los Angeles County and the San Francisco Bay Area show the highest direct emissions from retail. San Francisco County emits approximately 69,000 tCO_2e from the Retail subsector, while Los Angeles County emits around 55,000 tCO_2e. Although San Francisco County is smaller, with fewer retail establishments, the yearly gas consumption per square foot by retail establishments is more than three times that of retail stores in Los Angeles County as a result of differences in heating demand.

Technology Options

NREL Commercial and Residential Hourly Load Profiles [4] assume 100% of the gas consumption in retail establishments is from heating.

The technology options for the Retail subsector include:

- Electric Heaters
- Electric Water Heaters
- Electric Boilers
- HPWHs
- Air-Source Heat Pumps
- Flexible Loads
- Efficiency

Efficiency. Since retail stores in California primarily use gas for heating, thermal efficiency gains would result in reduced emissions and cost improvements. Coupling improvements in the thermal efficiency of retail establishments, such as upgrading insulation, with upgrading to all-electric heating appliances can lead to relatively short payback periods. Retail establishments also use a large amount of electricity for lighting, therefore lighting efficiency upgrades have great potential for returns.

Flexible loads. Gas consumption for heating in retail stores typically peaks in the morning and evening, therefore there is great potential for load-shifting in this subsector. Upgrading the retail sector to not only electric appliances, but smart appliances which can pre-heat retail spaces at low-demand times can help flatten California's duck curve.

Technoeconomic Analysis

Technoeconomic analysis for a small (8,392 ft^2) and large (100,000 ft^2) retail store with average gas consumption in California is shown below in Table 15.

Small Retail (8,392 ft^2)	**Without EE retrofit**			**With retrofit**			**Payback period for retrofit (years)**
	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	
Electric heaters	$9,604	$1.1	3.8%	$51,439	$6.1	37.5%	6.18
Heat pumps	$5,508	$0.7	14.3%	$48,777	$5.8	44.3%	6.58
Electric boiler	$14,784	$1.8	3.5%	$54,807	$6.5	37.3%	6.56

Large Retail (100,000 ft²)	Without EE retrofit			With retrofit			Payback period for retrofit (years)
	Capital Expenditures ($)	Capital Expenditures ($/ft²)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/ft²)	Total end-use energy savings	
Electric heaters	$114,437	$1.1	3.8%	$612,955	$6.1	37.5%	6.18
Heat pumps	$65,632	$0.7	14.3%	$581,232	$5.8	44.3%	6.58
Electric boiler	$176,172	$1.8	3.5%	$653,082	$6.5	37.3%	6.56

Table 15: Capital costs and energy savings for electrification technologies for a 100 kft² retail store with and without energy efficiency retrofits from NREL's Advanced Energy Retrofit Guide for Retail Buildings. Costs include replacing HVAC upgrades. Payback periods are for adding a retrofit to the system [2], [4], [7], [16], [21], [42].

Energy consumption was scaled linearly by square foot. Equipment and maintenance costs were scaled linearly with peak demand. Heat pumps were found to have the lowest up-front cost and highest energy efficiency improvement. However, costs may change depending on whether a building would need to replace its existing heating distribution system in order to upgrade to electric appliances.

Future Energy Consumption

Figure 32 shows the total electricity consumption by the Retail subsector in 2045 for a fully electrified system, assuming a 0.5% growth rate in electricity consumption in the subsector from new building construction. Both scenario 1 and scenario 2 assume electrifying all energy services in the subsector. Scenario 1 assumes 50% heat pumps with heat pump water heater upgrades and 50% electric boilers, assuming 50% of buildings in the subsector upgrade their building envelope efficiency. Scenario 2 is a less aggressive approach, assuming 30% heat pumps and 70% electric boilers, with 10% penetration on energy efficiency upgrades. Energy efficiency upgrades were assumed to reduce total electricity consumption by 35% in each upgraded facility in accordance with the Advanced Energy Retrofit Guide for Retail Buildings [1], [3], [5], [8], [15], [33].

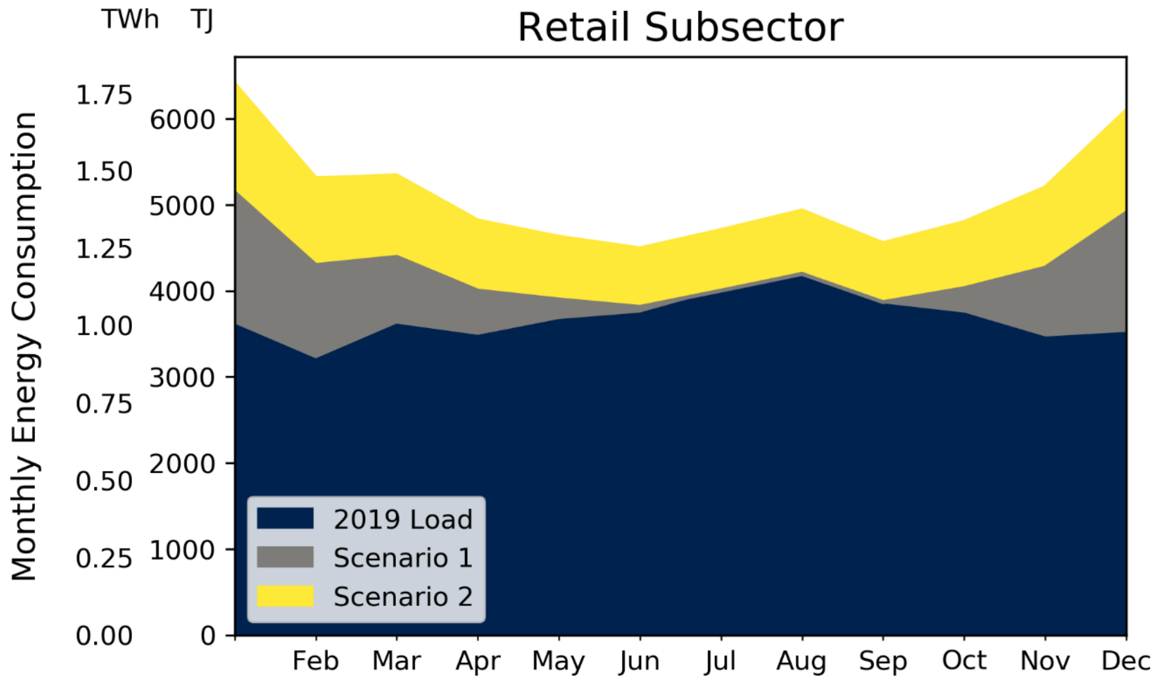


Figure 32: Projections for electricity consumption from retail stores in 2045 [2], [4], [7], [16], [21], [42].

2045 projections from this study predict a switch from a summer-peaking electricity load to a winter-peaking load in the Retail subsector between 2019 and 2045. Note that efficiency gains from the scenario 1 actually result in lower electricity demand in 2045 than in 2019 during July and August.

Hotel Subsector

The Hotel subsector in California is responsible for emissions of approximately 0.73 $MtCO_2e$ in direct emissions from natural gas. OSM includes 6,917 hotels and motels. Although we were unable to find a reliable source for the total number of buildings in the Hotel subsector in California, it is expected there are more than those included in OSM. This study includes hotels and motels, but excludes Airbnb and other homestay services, as they are included in the residential sector.

Methodology for Assessing Hotel Subsector

NREL Commercial and Residential Hourly Load Profiles [4] contain energy load information for small and large hotels. There is no reliable information available on the total number of or the total floor space of hotels in California. Reonomy [8] is a database which provides real-estate information such as lot-size and building square footage for commercial buildings. Data from Reonomy for hotels over 100,000 ft^2, was used along with OSM to estimate the total floorspace of hotels in California. There are 387 such hotels, with an average of 234,287 ft^2 per hotel [8]. The total number of hotels per county was estimated using OSM and subtracting out the hotels in each county previously captured in the Reonomy analysis. According to this method, there are 6,530 small hotels in California [7]. Square-footage per hotel building for small hotels was assumed to be 43,200 ft^2, from the DOE commercial reference building size for small hotels [15]. In total, this analysis estimates there are approximately 6,917 hotels in California, with a total floorspace for hotels of 373 million ft^2. It is likely that these numbers are an underestimate, because OSM does not include every business in California.

In order to estimate the energy consumption from the Hotel subsector in California, small and large hotel profiles from the NREL Commercial and Residential Hourly Load Profiles [4] were combined with the small and large hotel floorspace estimated in this analysis. Using this bottom-up approach, the total gas consumption per year by the Hotel subsector was calculated to be 9.9 TBTU, a 29% difference from CARB's estimate for the 2019 gas consumption in the hotels category of 13.94 TBTU. For the sake of future projections, energy consumption in the Hotel subsector in this study was rescaled proportionally by county, such that the total gas consumption in the subsector summed to 13.95 TBTU/y [1], [4], [7], [8], [15].

The primary use for gas in hotels is for hot water heating. Space heating and cooling drive seasonal variations in gas and electricity consumption, respectively as shown in Figure 33.

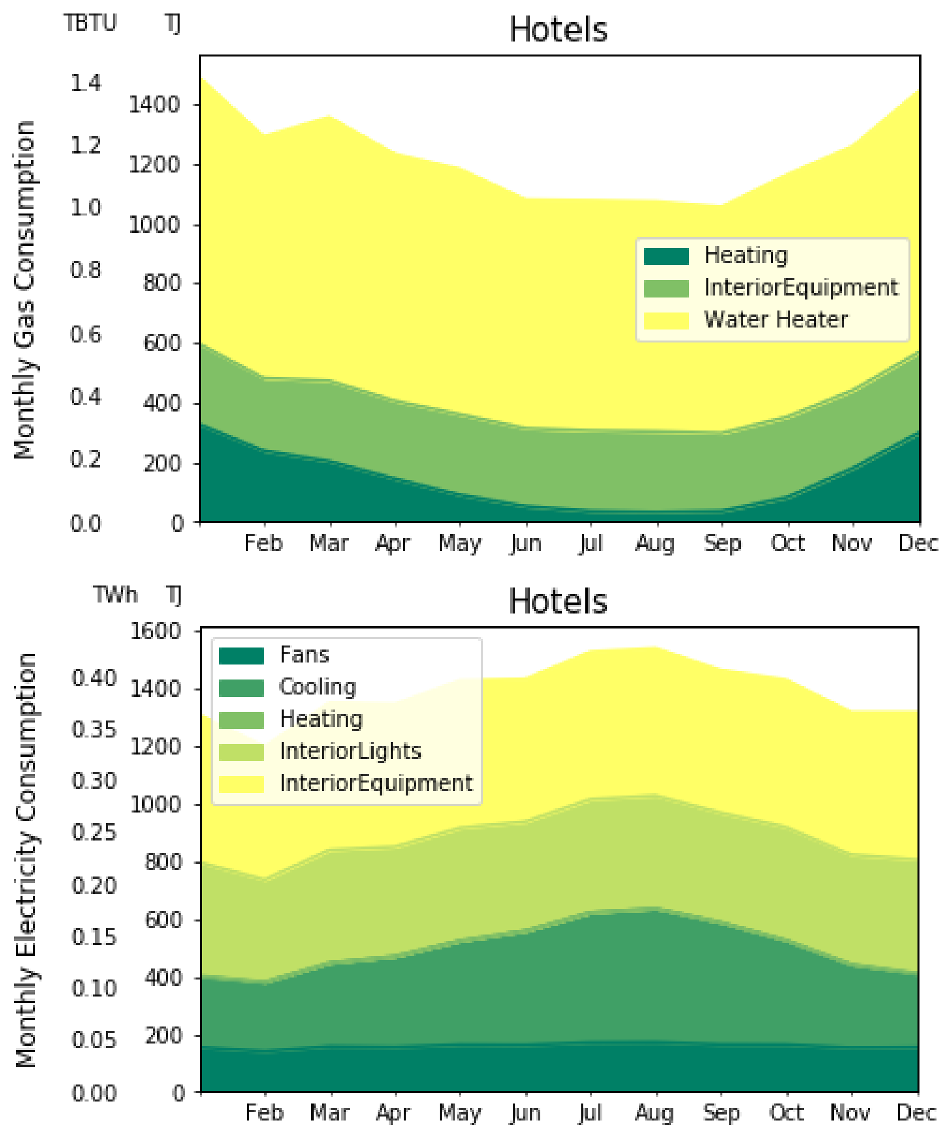


Figure 33: Total current monthly gas and electricity usage for the Hotel subsector in California by end-use. These numbers are rescaled to match CARB's fuel inventory totals [1], [4], [7], [8], [15].

Furthermore, the energy consumption profiles per square foot are much larger for large hotels than for small hotels, according to the NREL Commercial and Residential Hourly Load Profiles [4], as shown in Figure 34 below.

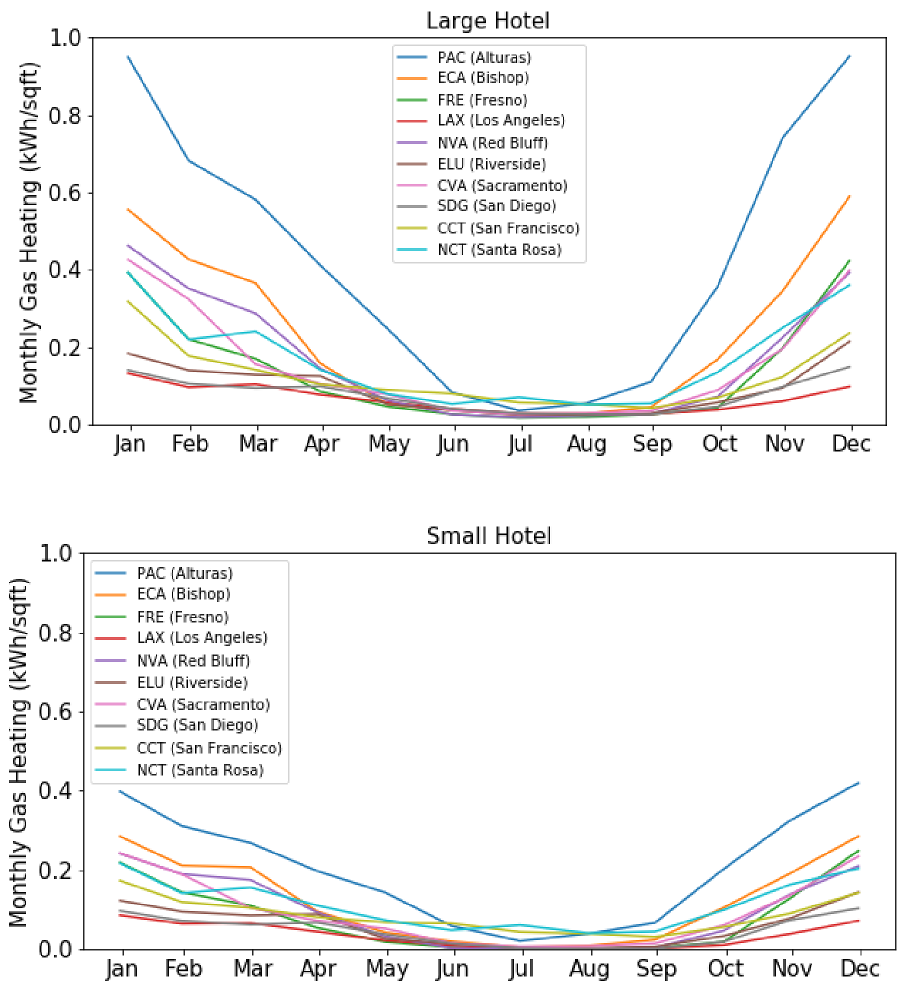


Figure 34: Natural gas consumption per square foot by climate region in California small hotels and large hotels. [4], [15]

Therefore it was important to treat small and large hotels differently for this analysis.

Diurnal load information is also available for hotels via the commercial hourly load profiles [4]. Figure 35 shows the diurnal load profiles for gas consumption per square foot in large hotels by climate region.

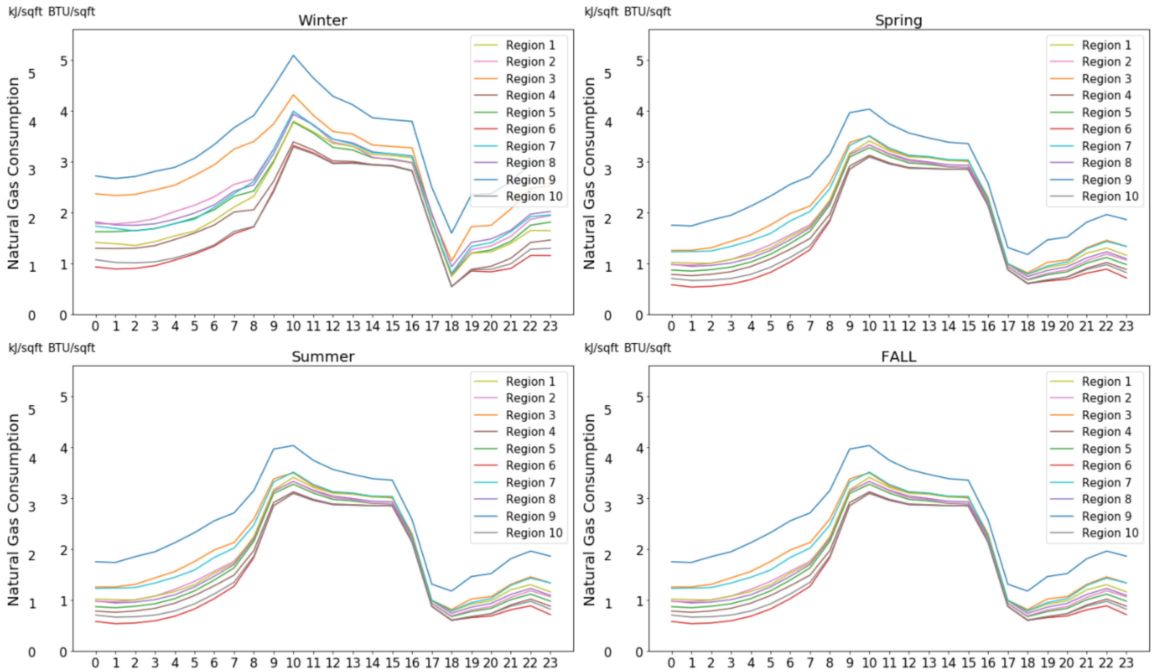


Figure 35: Diurnal variations in natural gas consumption per square foot by climate region in California small hotels. [4], [15]

Note that the gas consumption does not vary as widely across regions and seasons as other subsectors in the Commercial Buildings sector. This is because water heating is the primary gas end-use in the Hotel subsector as seen in Figure 33. Furthermore, unlike other subsectors, gas consumption in hotels peaks and remains steady throughout the middle of the day. For this reason, electrification in hotels may help flatten the duck curve in California.

Figure 36 shows the regional variations in emissions from the Hotel subsector.

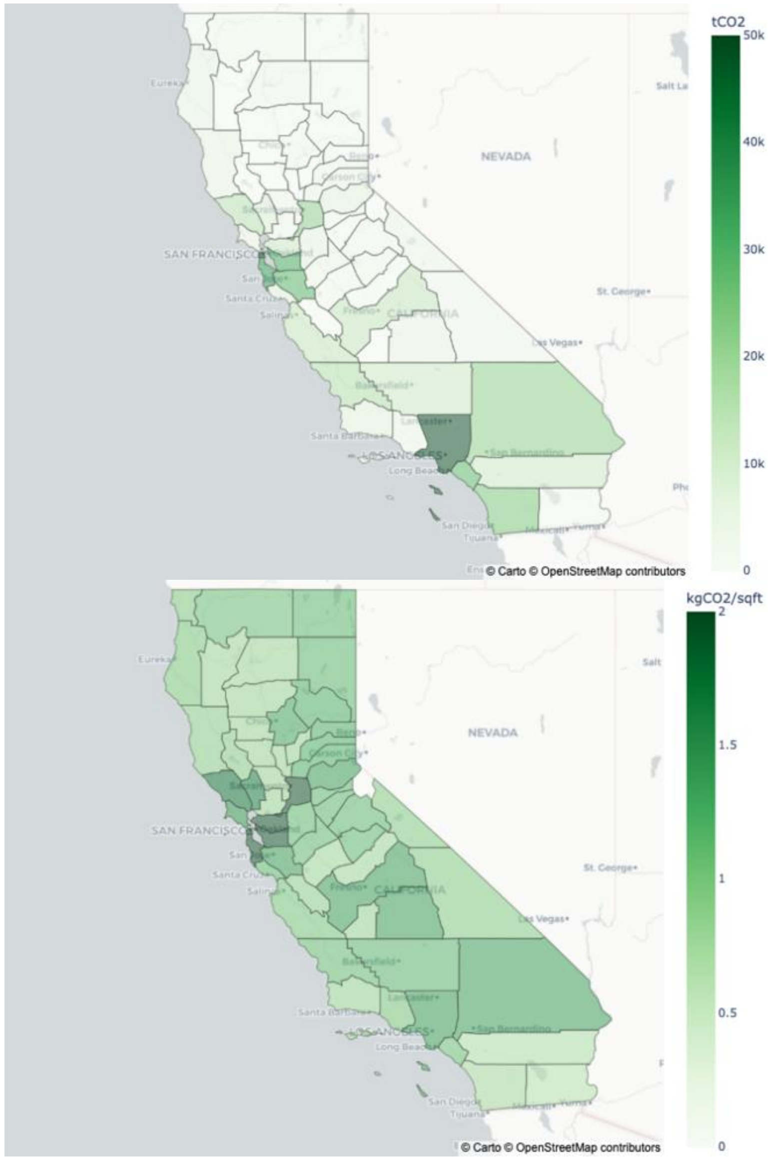


Figure 36: Maps of emissions from natural gas consumption by the Hotel subsector in California. Top: total emissions by county. Bottom: Emissions per ft². Top map calculated from the NREL Commercial and Residential Hourly Load Profiles and total square footage of hotels per county based on OSM data and Reonomy data [1], [4], [7], [8], [15].

According to this analysis, Los Angeles County is responsible for 0.28 $MtCO_2e$ in direct emissions from hotels, by far the greatest emissions from hotels by any county. Counties with high tourism rates or large cities have the most hotels, such as Los Angeles, San Francisco, San Mateo, Alameda, and San Diego Counties.

Technology Options

Hotels have a particularly high gas water heating load. Electrifying both water heating and space heating will be necessary for decarbonizing this subsector.

The technology options for the Hotel subsector include:

- Electric Heaters
- Electric Water Heaters
- Electric Boilers
- HPWHs
- Air-Source Heat Pumps
- Alternate stoves
- Efficiency

There is no Advanced Energy Efficiency Retrofit Guide applicable to hotels, however there is space for energy efficiency improvements and cost-savings in this subsector.

Technoeconomic Analysis

Table 16 shows technoeconomic analysis for a small (43,200 ft^2) and large (234,287 ft^2) hotel with and without stove electrification. Since the consumption profile per square foot from NREL's hourly load profiles [4] are noticeably different for small and large hotels, they were treated separately for technoeconomic analysis.

Large Hotel (with stove)	**Without EE retrofit**		
	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings
Electric heaters	$32,551	$0.8	6.4%
Heat pumps	$19,998	$0.5	30.2%
Electric boiler	$35,104	$0.8	5.8%
Small Hotel (with stove)	**Without EE retrofit**		
	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings
Electric heaters	$34,008	$0.8	2.9%
Heat pumps	$20,394	$0.5	13.3%
Electric boiler	$36,847	$0.9	2.7%
Small Hotel (without stove)	**Without EE retrofit**		
	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings
Electric heaters	$24,308	$0.6	2.9%
Heat pumps	$10,694	$0.2	13.3%
Electric boiler	$27,147	$0.6	2.7%

Table 16: Capital costs and energy savings for electrification technologies for a small (with and without stove) and large (with stove) hotel in California. Costs include replacing HVAC and water heating. A new commercial electric stove costs $9700, according to the EIA. This analysis omits upgrading hot food holding cabinets [4], [7], [15], [21].

Note that technoeconomic analysis for heat pumps includes heat pump water heating. Although very low market penetration poses a barrier to widespread implementation of HPWHs, applying this technology in the water-heating intense Hotel subsector has the potential to offset thousands of tonnes in CO_2 emissions while keeping costs low.

Future Energy Consumption

Figure 37 shows the total electricity consumption by hotels in 2045 for a fully electrified system, assuming a 0.5% growth rate in electricity consumption in the subsector from new building construction. Both scenario 1 and scenario 2 assume electrifying all energy services. Scenario 1 assumes 50% heat pumps with heat pump water heater upgrades and 50% electric boilers. Scenario 2 is a less aggressive approach, assuming 30% heat pumps and 70% electric boilers. There is a 4.1% difference in the total yearly electricity consumption for scenario 1 vs. scenario 2, since electricity consumption far exceeds the efficiency improvements from more efficient heating and water-heating devices. The projection also assumes no efficiency improvement from electrifying interior equipment in this subsector. Furthermore, although there is no Advanced Energy Efficiency Retrofit Guide from NREL for the Hotel subsector, building envelope efficiency improvements could significantly reduce 2045 consumption in the Hotel subsector below the projected scenarios [1], [4].

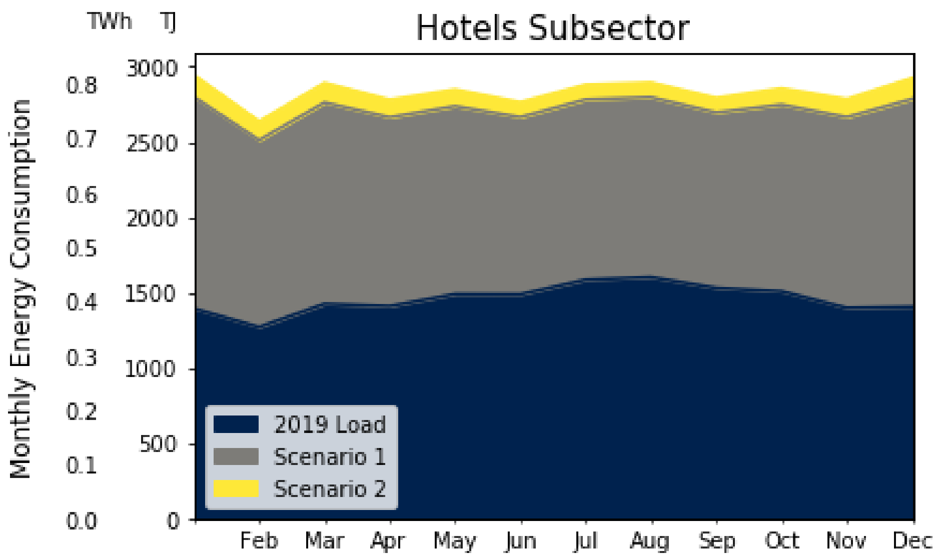


Figure 37: Projections for electricity consumption from hotels in 2045 [2], [4], [7], [16], [21], [42]..

Since no energy efficiency retrofits were used to project the 2045 Hotel subsector loads, there is very little difference in 2045 energy consumption between scenario 1 and scenario 2. Heat pumps are more efficient than electric boilers, resulting in a slightly lower demand in scenario 1, as shown in Figure 37.

Office Subsector

In California, office buildings are responsible for 0.47 $MtCO_2e$ emissions. Offices have relatively low gas consumption per square foot compared to some other commercial buildings. However, there is great potential for energy savings in the Office subsector. The hourly load profiles from NREL assume no gas consumption for interior equipment in offices [4].

Methodology

There is little reliable information on the total amount of office space in California. However, according to the DOE's Commercial Buildings Energy Consumption Survey, there are 16.9 billion square feet of office space in the United States [10]. While California is 12% of the US population, it is responsible for 14.62% of the total US gross domestic product. Therefore, for this study it was assumed that California's office buildings are 14.62% of the total floorspace of offices in the US, or 2.46 billion square feet. The total floorspace for offices in California was then scaled by population to estimate the floorspace in each county [43].

The NREL Commercial and Residential Hourly Load Profiles [4] were used to calculate the energy consumption profile for offices in California. The total gas consumption by offices was calculated to be 7.0 TBTU/year from this analysis. There are also some facilities in this subsector 1.5 TBTU of facilities in the Office subsector which reported to MRR or EGRID. The total from the bottom-up approach to calculating gas consumption in the Office subsector was 8.57 TBTU/year, which is 21.5% less than the CARB estimate 8.78 TBTU for 2019. [1], [4]

Figure 38 shows monthly gas and electricity consumption, respectively, for the entire Office subsector.

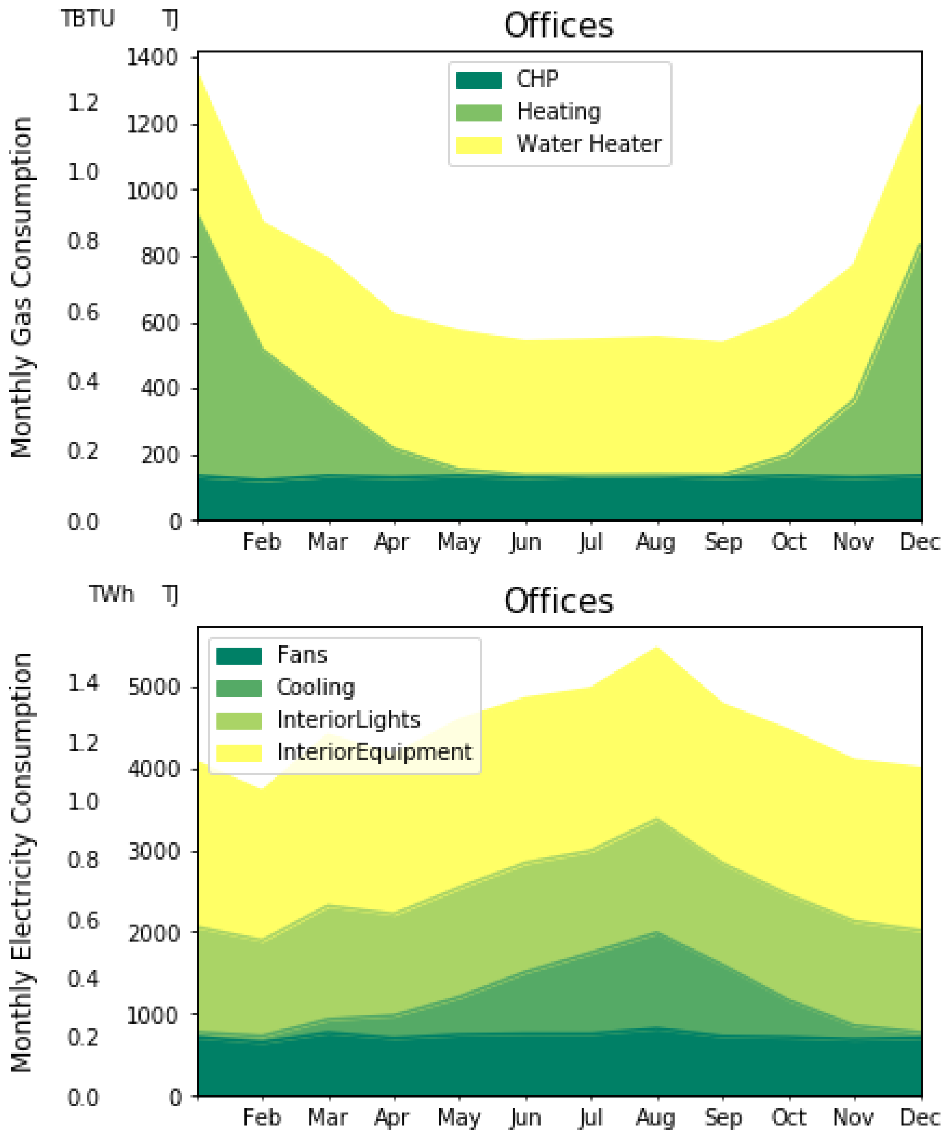
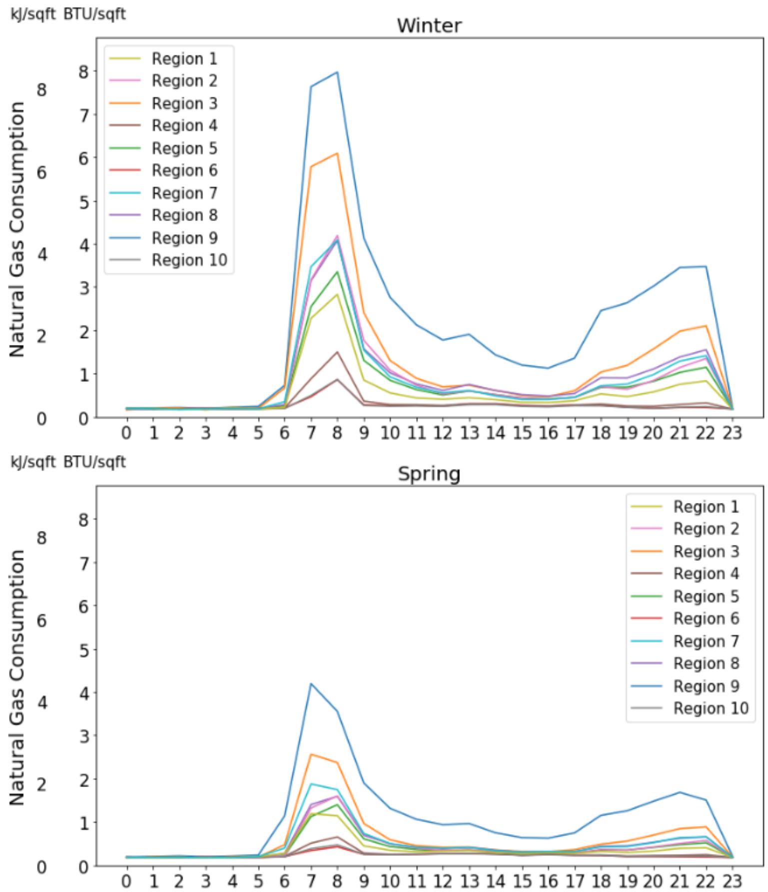


Figure 38: Total current monthly gas and electricity usage for all offices in California, by end-use [4], [10], [43].

Gas consumption in offices is strongly winter peaking as a result of seasonal variations in heating demand. Furthermore, there is very little heating demand in California from offices during the summer months. Alternatively, electricity usage is summer peaking as a result of increased cooling demand. In terms of total energy demand, electricity consumption dominates over natural gas in offices.

According to the NREL commercial and residential hourly load profiles, water heating is more than 65% of gas consumption in offices. This is not supported by other sources on energy consumption in commercial buildings, such as the California commercial end-use survey, which records 16% and 12% of gas consumption for water heating in small and large offices, respectively [2]. The large proportion of water heating in office buildings in California is likely a result of limitations to the simulated data. As a result of this limitation, technoeconomic analysis and future projections for offices may be skewed.

Diurnal load information is also available for offices via the NREL Commercial and Residential Hourly Load Profiles [4]. Figure 39 shows the diurnal load profiles for gas consumption per square foot in a small office by climate region and season.



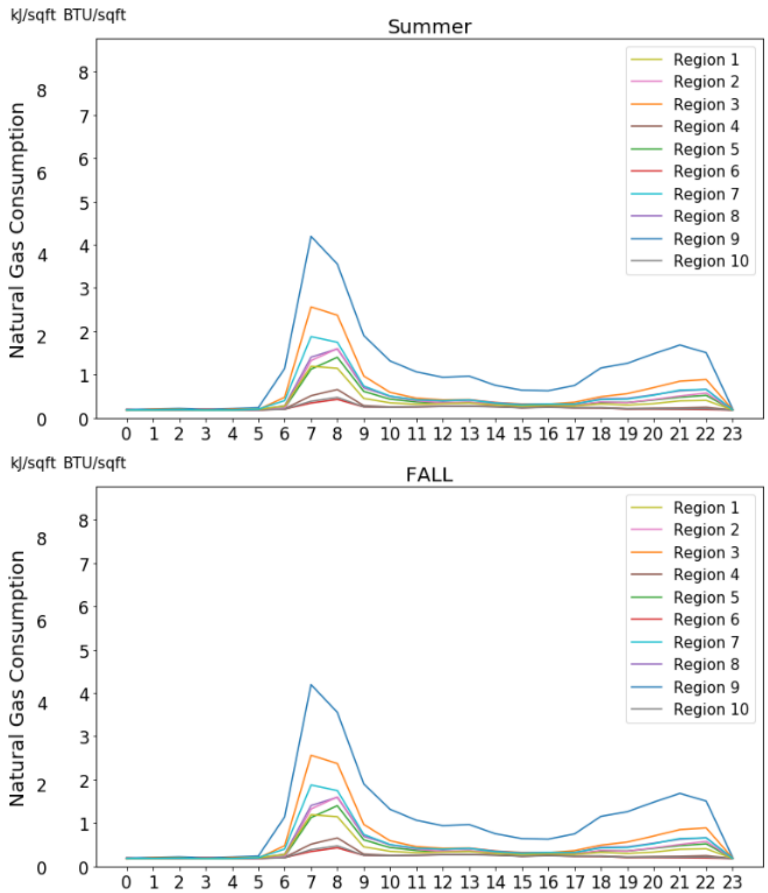


Figure 39: Diurnal variations in natural gas consumption per square foot by climate region. [4], [15]

Gas consumption in offices peaks at around 7am, with a smaller peak at around 9pm which is most prominently observed in the winter and fall. Figure 40 shows the regional variations in emissions from offices across California counties.[4]

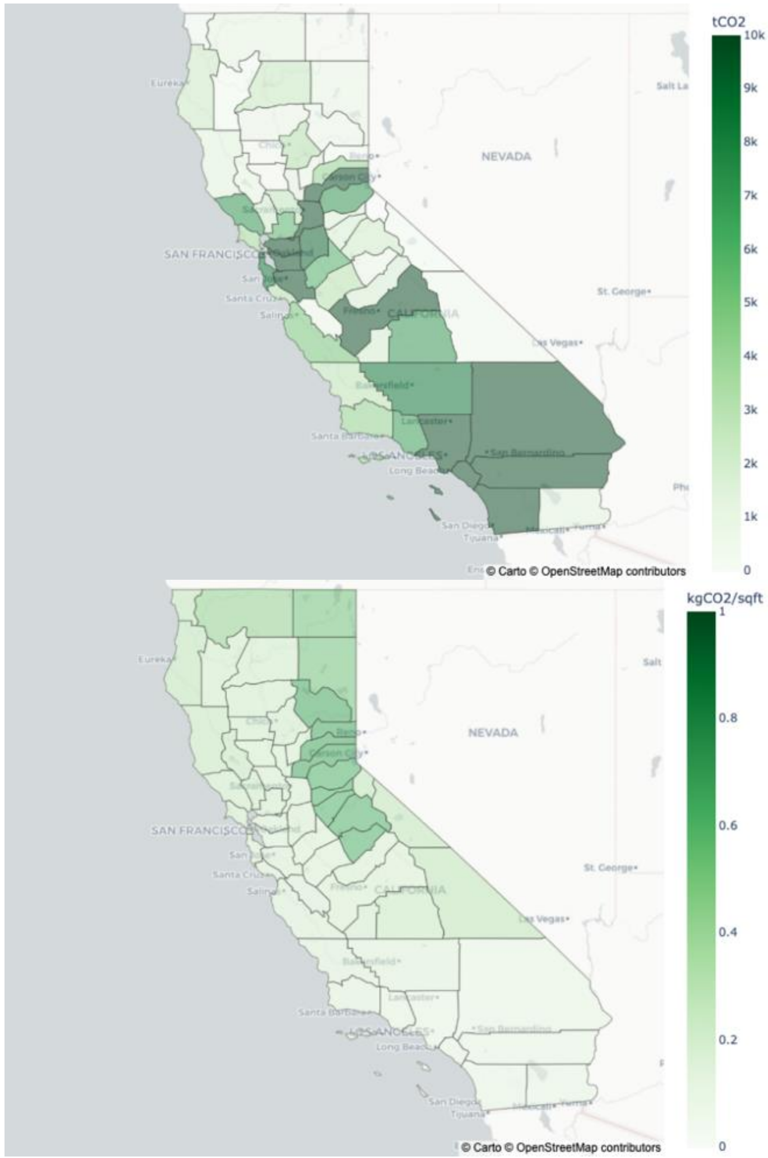


Figure 40: Maps of emissions from natural gas consumption by Offices in California. Top: total emissions by county. Bottom: Emissions per ft². Top map calculated from the NREL Commercial and Residential Hourly Load Profiles and total square footage of offices per county based on scaling the total floorspace of offices in the US from (source) by county population [2], [9], [27].

Larger and more populated counties tend to have higher total emissions, while the emissions per square foot are highest in colder regions. Therefore, total emissions from offices in a county is more heavily influenced by number of offices than by climate.

Technology Options

According to the NREL Commercial and Residential Hourly Load Profiles [4] there is little to no gas usage in offices for anything other than heating and water heating. Offices also consume a large amount of electricity compared to other commercial buildings. Therefore, the technology options for decarbonization include:

- Electric Resistive Heating

- Electric WH
- Heat Pumps
- Heat Pump WHs
- Electric Boilers
- Ground-Source heat pumps (larger buildings)
- Efficiency
- Personal Comfort Devices
- Flexible Loads

Since offices follow a duck curve, with peaks in the morning and at night, it may be favorable to the electricity grid to implement some diurnal load shifting. Larger offices may be able to make a significant impact on the load shape for the Commercial Buildings sector.

Personal comfort devices also may be able to reduce energy waste in office buildings, and have potential for load shifting.

Technoeconomic Analysis

Technoeconomic analysis was done for a small (5,000 ft^2) and large (100,000 ft^2) office building in California with average energy consumption. The recommended retrofit packages from the Advanced Energy Retrofit Guide for Office Buildings costs $439,000 for a 200,000 ft^2 office [17] (Table 17). Readjusting for the size of the small and large office buildings, Table 17 shows the cost of energy-efficiency retrofits for offices in California *before electrification.*

Small Office (5,000 ft^2)	**Large Office (100,000 ft^2)**	**Total End-Use Energy Savings**
$10,975	$219,500	26%

Table 17: Retrofit package (excluding electrification) costs and savings for a small (5,000 ft^2) and large (100,000 ft^2) office building in California [17].

It was assumed that energy efficiency improvements were uniform across end uses, e.g. a 26% total energy efficiency improvement for a building implies a 26% reduction in heating load. Table 18 shows technoeconomic analysis for a large and small office with and without energy efficiency retrofit.

Large Office (100,000 ft^2)	**Without EE retrofit**			**With retrofit**			**Payback period for retrofit (years)**
	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/$ft^2$)	Total end-use energy savings	
Electric heaters	$66,222	$0.7	1.2%	$268,504	$2.7	26.9%	4.1
Heat pumps	$25,717	$0.3	5.2%	$238,531	$2.4	29.8%	3.8

Electric boiler	$87,164	$0.9	1.1%	$284,001	$2.8	26.8%	4.4
Small Office (5,000 ft²)	**Without EE retrofit**			**With retrofit**			**Payback period for retrofit (years)**
	Capital Expenditures ($)	Capital Expenditures ($/ft²)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/ft²)	Total end-use energy savings	
Electric heaters	$3,311	$0.7	1.2%	$13,425	$2.7	26.9%	4.1
Heat pumps	$1,286	$0.3	5.2%	$11,927	$2.4	29.8%	3.8
Electric boiler	$4,358	$0.9	1.1%	$14,200	$2.8	26.8%	4.4

Table 18: Capital costs and energy savings for electrification technologies for a small and large office building with and without energy efficiency retrofits. Costs include replacing HVAC and water heating in the building.. Payback periods are for adding a retrofit to the system [4], [17], [21] ,[9], [27].

While electrification is necessary to move office buildings in California to net zero carbon emissions, energy-efficiency improvements to the building envelope have the greatest ability to reduce the energy load for offices.

Future Energy Consumption

Figure 41 shows the total electricity consumption by offices in 2045 for a fully electrified system, assuming a 0.5% growth rate in electricity consumption in the subsector from new building construction. Both scenario 1 and scenario 2 assume electrifying all energy services in California offices. Scenario 1 assumes 50% heat pumps with heat pump water heater upgrades and 50% electric boilers, assuming 50% of offices upgrade their building envelope efficiency. Scenario 2 is a less aggressive approach, assuming 30% heat pumps and 70% electric boilers, with 10% penetration on energy efficiency upgrades. Energy efficiency upgrades were assumed to reduce total electricity consumption by 33% in each upgraded office in accordance with the Advanced Energy Retrofit Guide for Offices [4], [17], [21] ,[9], [27].

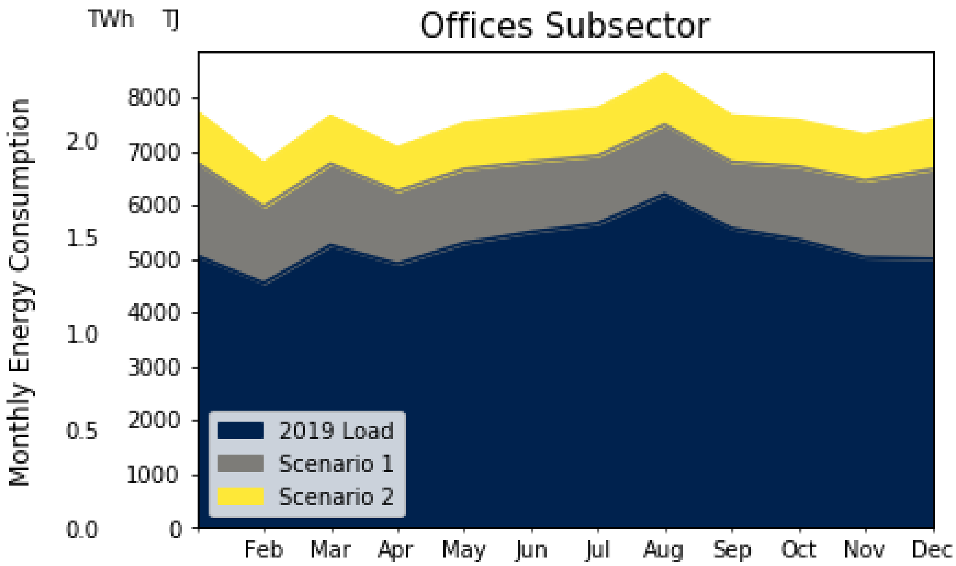


Figure 41: Projections of electricity consumption by offices in 2045 [2], [9], [27].

We also expect an increased electricity load during the day in offices beyond these scenarios as a result of EV charging, which will likely not show large seasonal variations. The 2045 load projections do not show large seasonal variations in energy consumption. The large difference between consumption in scenario 1 and 2 implies large potential for saving money and energy in the Office subsector.

Healthcare Subsector

In 2019 the Healthcare subsector was responsible for approximately 1.57 $MtCO_2e$ in direct emissions from natural gas, not including CHP emissions associated with the subsector. CHP emissions from the Healthcare subsector total 0.12 $MtCO_2e$ (TBTU). All CHP emissions found were from hospitals. Non-CHP emissions from hospitals total 1.37 $MtCO_2e$ (25.05 TBTU of natural gas), while outpatient facility emissions from natural gas are 0.21 $MtCO_2e$ (3.8 TBTU of natural gas).

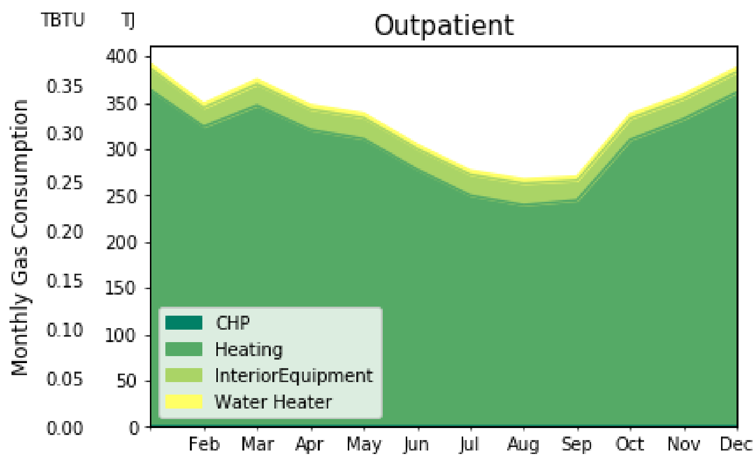
Methodology

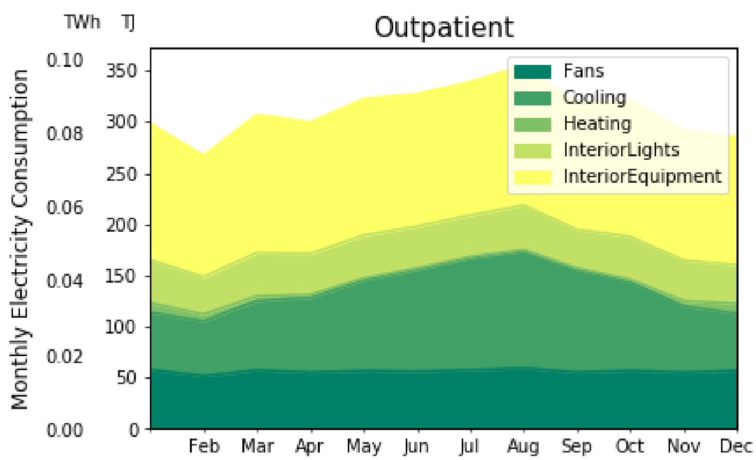
According to the NREL Commercial Hourly Load Profiles [4], electricity and gas consumption per square foot differs between outpatient care facilities and hospitals. Therefore, due to the complexity of this subsector, outpatient care facilities (physician offices, etc) were assessed separately from hospitals.

Outpatient Care. The total square footage for outpatient facilities in California was estimated using a count of the total number of doctors in each county in California from IQVIA healthcare [9], and assuming 1,200 ft^2 per doctor [13]. The NREL hourly load profiles include an energy consumption profile for an outpatient facility [4]. These load profiles were combined with the total square footage of outpatient facilities calculated in this study to obtain energy load information for outpatient facilities in the entire state.

Hospitals. CARB's MRR database and eGRID provide information on large facilities that emit over 10,000 tCO_2e per year [5], [6]. 29 large hospitals with CHP facilities were included in the MRR and EGRID databases. A list of all the hospitals in California was obtained from the American Hospital Directory including information on the number of beds per hospital [14]. The total natural gas consumption for each hospital was extrapolated from the number of beds and hospital energy load per square foot from Commercial and Residential Hourly Load Profiles [4], such that the total gas consumption from the Healthcare subsector minus CHP would be equivalent to CARB's total of 28.84 TBTU natural gas. [1], [4]

Figure 42 shows the total current energy consumption for the Healthcare subsector.





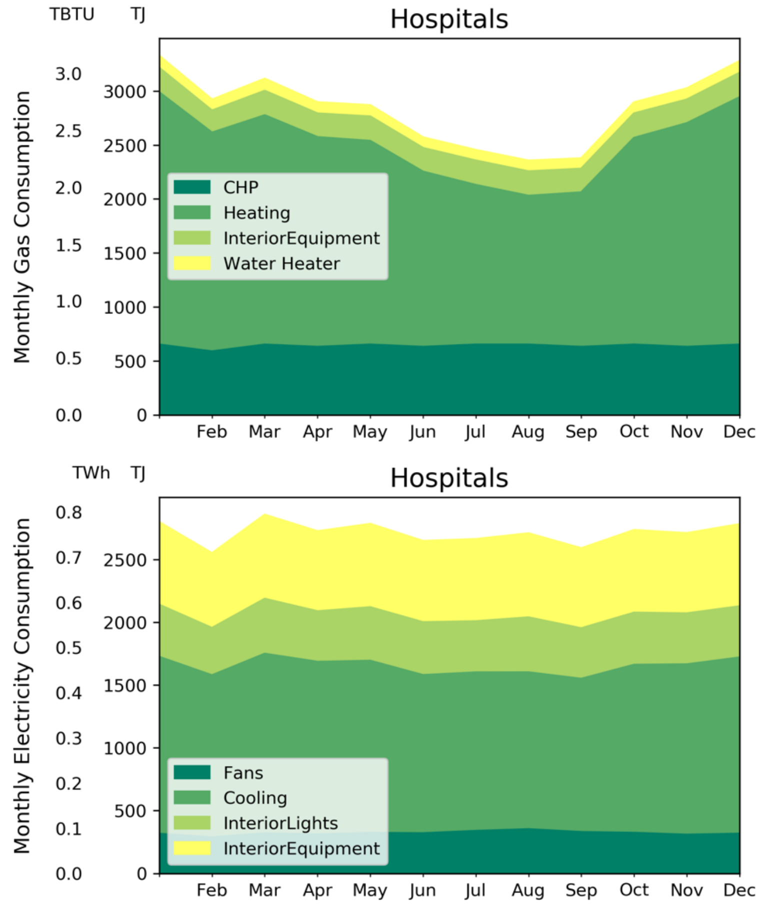


Figure 42: Total current monthly gas and electricity usage for the Healthcare subsector in California, by end-use [1], [4]–[6], [14].

Gas consumption in the Healthcare subsector is winter peaking. Electricity consumption does not show seasonal variations in hospitals, though some excess demand from cooling in the summer for outpatient facilities is observed. Figure 42 also shows that combined heat and power is a significant portion of emissions for the Healthcare subsector. A flat load profile for natural gas consumption for CHP facilities was assumed for this analysis.

A limitation of the simulated NREL Hourly Commercial Load Profiles is that the shares of end-uses for natural gas in the health sector may be inaccurate. According to NREL's Advanced Energy Retrofit Guide for Healthcare, water heating is responsible for 30% of gas consumption in healthcare facilities, however analysis with the NREL hourly profiles implies a water heating share of more like 30%, excluding CHPs. The California Commercial End-Use Survey also reports the 2006 share of water heating in healthcare facilities to be 41.5% of the total gas consumption. [2], [20]

Figure 43 and 44 show the diurnal gas consumption per square foot in outpatient facilities and hospitals.

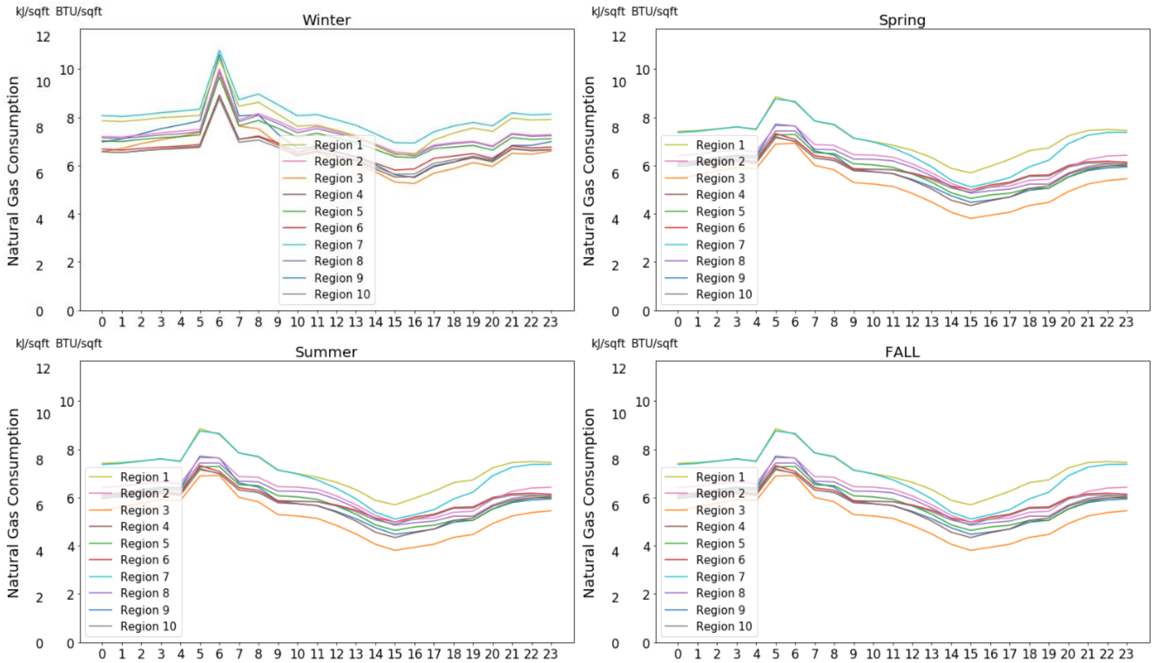


Figure 43: Diurnal variations in natural gas consumption per square foot by climate region in California hospitals [4], [15].

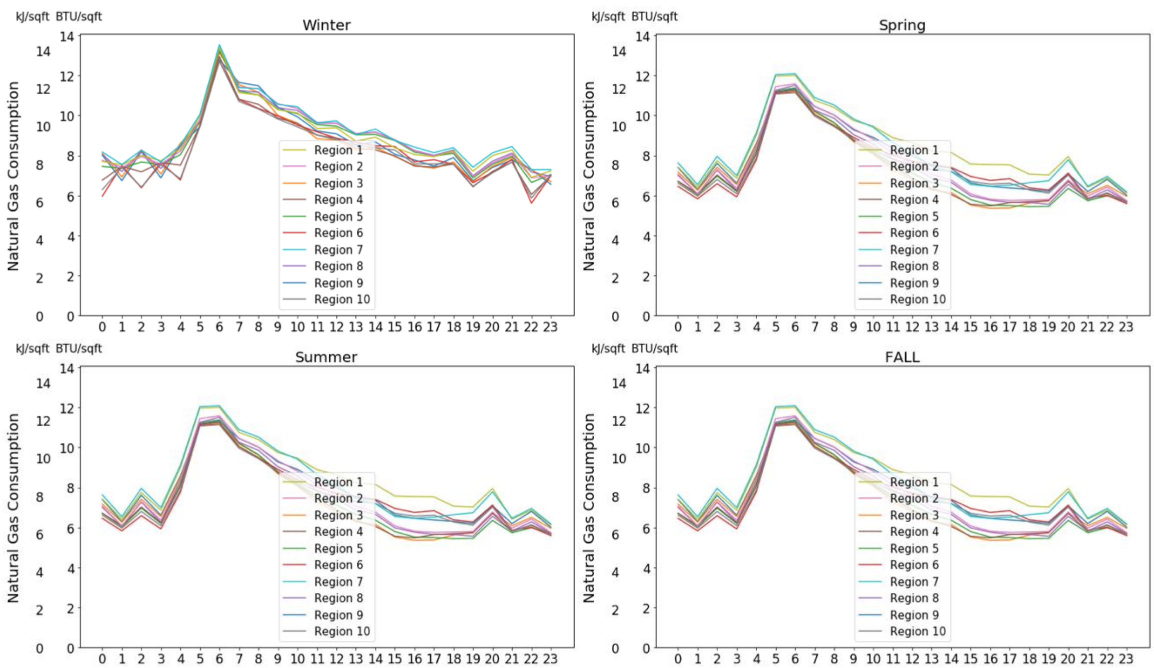


Figure 44: Diurnal variations in natural gas consumption per square foot by climate region in California outpatient facilities [4], [15].

Gas consumption profiles per square foot are remarkably similar for outpatient facilities and hospitals. Furthermore, the load profile does not vary significantly by location or climate. Figure 45 shows the regional variations in emissions from the Healthcare subsector, including CHP.

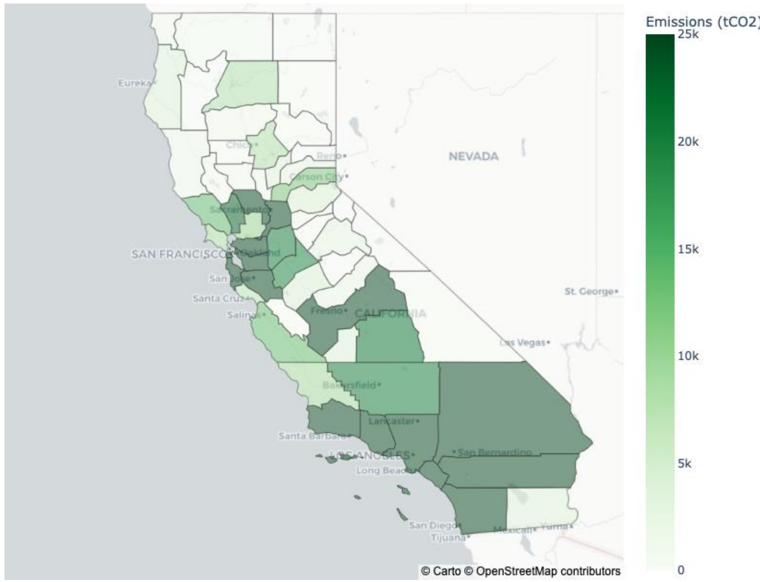


Figure 45: Map of total emissions from natural gas consumption by the Healthcare subsector in California. Calculated from the NREL Commercial and Residential Hourly Load Profiles and emissions from large facilities from MRR and EGRID [1], [4]–[6]

The largest emissions from the Healthcare subsector are from Los Angeles, Orange and San Diego counties, consistent with population density.

Technology Options

Reliable energy is extremely important in the Healthcare subsector, particularly in hospitals where patients can be relying on life-sustaining equipment. Natural gas has proven to be a reliable source of energy, which is why many hospitals have opted for natural gas CHP facilities to supply their energy needs. Decarbonization pathways in this subsector must be reliable. Since CHP facilities can be independent from the grid, the best pathway for decarbonizing these facilities may be CCS. However, the average hospital CHP facility in California reported to MRR and EGRID is emitting 16,000 tCO_2e per year, which is relatively small for implementing CCS, as the cost per ton of mitigating carbon with CCS rises as facilities get smaller.

Furthermore, many hospitals and outpatient facilities in California are not reliant on CHP facilities. The dominating end uses for natural gas in non-CHP healthcare facilities are heating and water heating, as well as interior equipment. Additionally, the Advanced Energy Retrofit Guide for Healthcare outlines costs and energy efficiency improvements from retrofitting healthcare facilities. [20]

Although not the subject of this report, a possible solution to concerns about reliability of energy in healthcare facilities is the use of robust battery energy storage systems (BESS), which would allow facilities to continue running during grid interruptions.

The technology options for this subsector include:

- Electric Heaters

- Electric Water Heaters
- Electric Boilers
- HPWHs
- Air-Source Heat Pumps
- Alternate stoves
- Efficiency
- Carbon Capture and Sequestration (for CHP facilities)

Technoeconomic Analysis

For an outline on the approach to technoeconomic analysis for CHP with CCS retrofits facilities in this study, refer to the College subsector.

Technoeconomic analysis was done for a 100 kft2 non-CHP hospital, including retrofits according to the retrofit package from the Advanced Energy Retrofit Guide for Healthcare Facilities, which shows efficiency improvements at 4.5% [20].

Retrofit information was given for a hospital facility from the AERG, however the cost per square foot and efficiency improvement information could be reasonably extended to outpatient facilities. Results are shown below in Table 19.

Large Hospital	**Without EE retrofit**			**With retrofit**			**Payback period for retrofit (years)**
	Capital Expenditures ($)	Capital Expenditures ($/ft2)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	
Electric heaters	$643,642	$1.3	5.4%	$1,358,813	$2.7	9.6%	43.2
Heat pumps	$250,547	$0.5	20.5%	$983,407	$2.0	24.1%	37.3
Electric boiler	$860,608	$1.7	4.9%	$1,566,015	$3.1	9.2%	49.6

Small Hospital	**Without EE retrofit**			**With retrofit**			**Payback period for retrofit (years)**
	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	Capital Expenditures ($)	Capital Expenditures ($/ft^2)	Total end-use energy savings	
Electric heaters	$128,728	$1.3	5.4%	$271,763	$2.7	9.6%	43.2
Heat pumps	$50,109	$0.5	20.5%	$196,681	$2.0	24.1%	37.3
Electric boiler	$172,122	$1.7	4.9%	$313,203	$3.1	9.2%	49.6

Table 19: Capital costs and energy savings for electrification technologies for small (100kft^2)l and large (500 kft^2) hospitals with and without energy efficiency retrofits. Costs include replacing HVAC and water heating in the building. Payback periods are for adding a retrofit to the system [4], [14], [20], [21].

2045 Projections for Healthcare

Figure 46 shows the total electricity consumption by the Healthcare subsector in 2045 for a fully electrified system, assuming a 0.5% growth rate in electricity consumption in the subsector from new building construction. Both scenario 1 and scenario 2 assume electrifying all energy services in California hospitals, excluding CHP. Scenario 1 assumes 50% heat pumps with heat pump water heater upgrades and 50% electric boilers, assuming 50% of offices upgrade their building envelope efficiency. Scenario 2 is a less aggressive approach, assuming 30% heat pumps and 70% electric boilers, with 10% penetration on energy efficiency upgrades. Energy efficiency upgrades were assumed to reduce total electricity consumption by 4.5% in each upgraded hospital or outpatient facility in accordance with the Advanced Energy Retrofit Guide for Healthcare [4], [20].

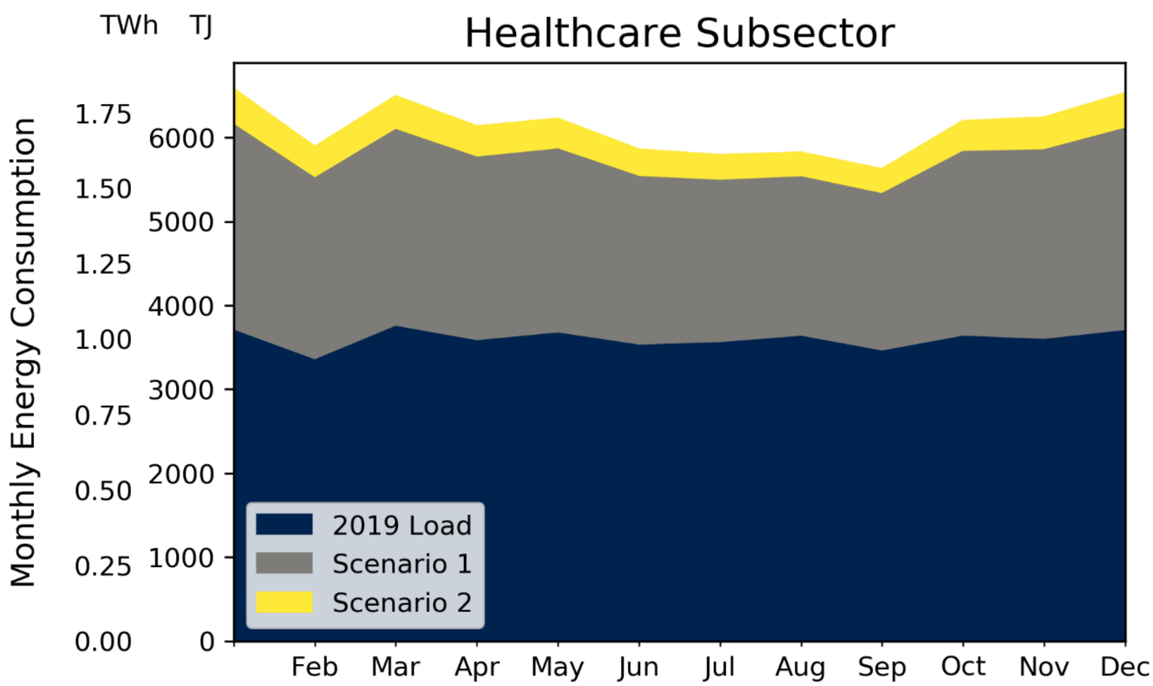


Figure 46: Projections of electricity consumption by healthcare in 2045 [4], [14], [20]

The 2045 load projections do not show large seasonal variations in energy consumption. Because of the very small energy efficiency improvements (4.5%) associated with the advanced energy retrofit [20], there is only a small difference between scenarios 1 and 2. As with the Office subsector, we expect there to be increased electricity consumption in healthcare beyond these scenarios as a result of EV charging, which will likely not show large seasonal variations.

Miscellaneous Subsector

The Miscellaneous Commercial subsector in California is responsible for emissions of approximately 4.3 $MtCO_2e$ in direct emissions from natural gas.

Methodology for Assessing Miscellaneous Commercial Subsector

This study calculated the gas consumption for the Miscellaneous Commercial subsector from the difference between CARB's total gas consumption for the Commercial Buildings sector and the sum of the gas consumption for the other subsectors in this study. CARB estimates the total commercial natural gas consumption to be 225.11 TBTU. The total natural gas consumption from the School, College, Restaurant, Food and Liquor, Retail, Hotel, Office, and Healthcare subsectors combined from this study is 146.37 TBTU. Therefore the total gas consumption for the Miscellaneous Commercial subsector is 78.74 TBTU.

CARB's fuel inventory categorizes commercial entities by the North American Industry Classification System (NAICS). Examples of businesses that fall under the commercial: miscellaneous classification from NAICS include amusement parks, museums, performing arts centers, bowling centers, religious organizations, dry-cleaning and laundry, and marinas. After reviewing the list of businesses included in the commercial: miscellaneous category, we assumed the load shape for the Miscellaneous Commercial subsector to be closest to a retail load shape from the NREL commercial hourly load profiles, and the spatial distribution of emissions to be the same as the Retail subsector in this study. CHP was ignored when finding the load shape, but all miscellaneous CHP was included in the total.

Total miscellaneous electricity consumption was calculated as the difference between the total commercial electricity consumption in California and the sum of the consumption from the School, College, Restaurant, Food and Liquor, Retail, Hotel, Office, and Healthcare subsectors. The load shape was also assumed to match the electric load shape of the retail subsector.

Refrigerants

According to CARB, leakage of Hydrofluorocarbon (HFC) gases from refrigeration and cooling equipment are responsible for 8.96 $MtCO_2e$ in emissions from the Commercial Buildings sector. Other uses for HFC in the Commercial Buildings sector include foams (0.12 $MtCO_2e$), fire protection (0.03 $MtCO_2e$), and aerosols (0.08 $MtCO_2e$) [1].

The primary refrigerants used in the commercial sector in CA today are HFC-125, 134a, 143a, 152a, 236fa, and 32. Table 20 is a summary of the Global Warming Potentials (GWP) of these gases from IPCC's annual report 4 (AR4) [44].

GHG	HFC-125	HFC-134a	HFC-143a	HFC-152a	HFC-236fa	HFC-32
GWP (100-yr AR4)	3500	1430	4470	124	9810	675

Table 20: AR4 100-year GWP values for common HFCs in California's Commercial Buildings sector [44].

GWP refers to how much more potent these GHGs are than CO_2. For example, 1 kg of HFC-125 creates roughly the same warming effect as 3,500 kg of CO_2.

R-404a and R-410a are two common refrigerant blends. R-404A is a blend of 52% HFC-143a, 44% HFC-125, and 4% HFC-134a, with an overall GWP of 3,922 [45]. R-410 is a 50/50 blend of HFC-125 and 32, with a GWP of 2,088 [46] [44] .

Since HFCs can be such potent greenhouse gases, regulating them and limiting their leakage is important, especially in the Commercial Buildings sector where refrigeration demand is high. Figure 47 shows growth in commercial refrigerant and air conditioning emissions from CARB's GHG inventory [1].

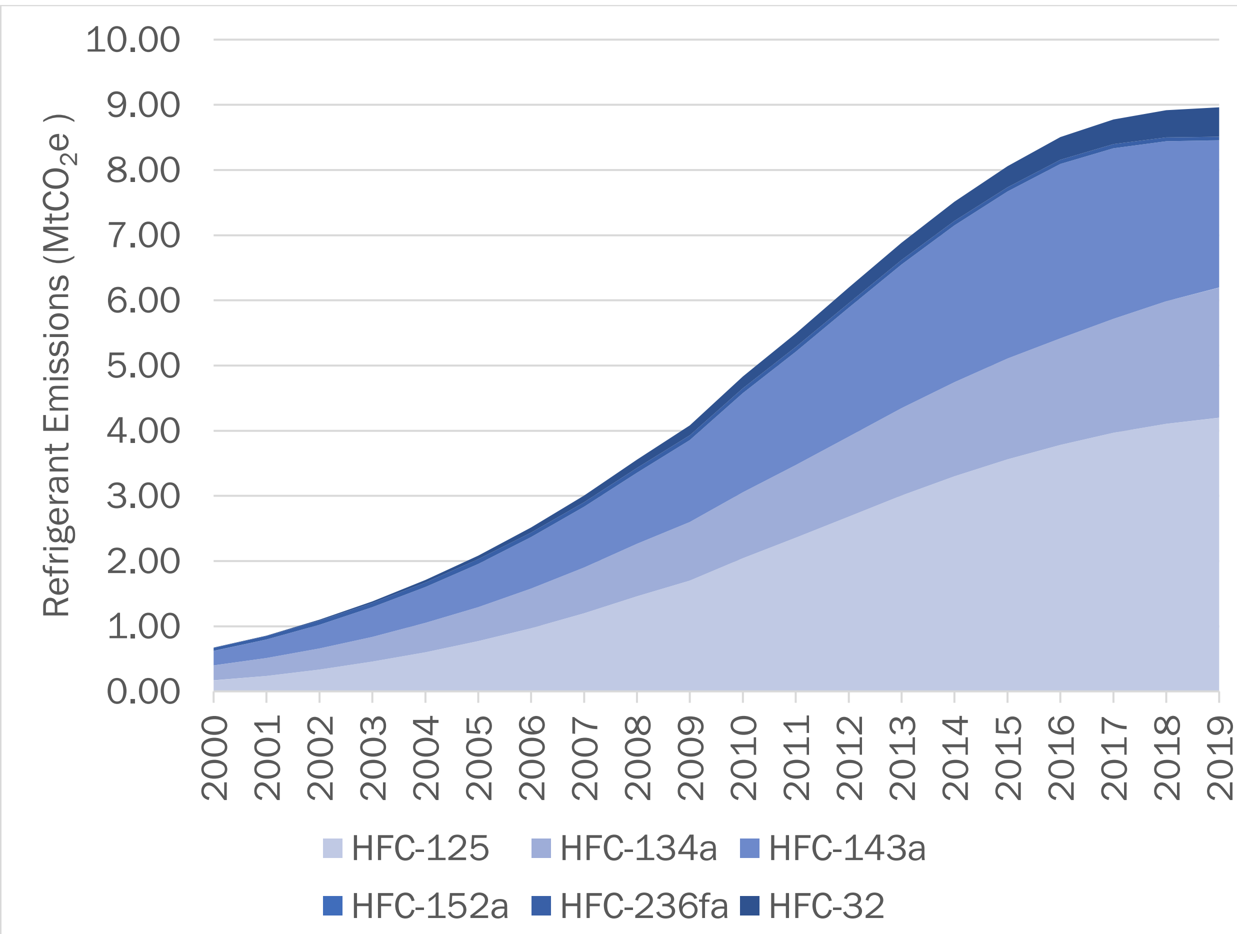


Figure 47: HFC emissions from refrigeration and air conditioning in the Commercial Buildings sector in California [1].

HFC emissions have risen by an order of magnitude in the last 20 years. With the hope of electrifying heating in the Commercial Buildings sector using highly efficient heat pumps, refrigerant emissions are of even greater concern. However, several regulations are underway:

- Senate Bill 1383 requires California to cut HFC emissions down by 40% of 2013 levels by 2030 [47], [48].
- Senate Bill 1013, the "California Cooling Act," prohibits the use of high GWP HFCs and other refrigerants in California took effect on January 1, 2019 [49]. This regulation bans the manufacture of aerosol products using the HFC-125 and HFC-134a refrigerants. The act also bans the use of R-404a in specific uses, such as vending machines, supermarkets, retail refrigeration, and commercial chillers. HFC-134a will be banned for use in chillers and new vending machines, as well as some temperature units, according to CARB. The highly potent HFC-236fa is now banned in new centrifugal chillers [47]. The California Cooling Act also requires manufacturers using refrigerants to use a certain amount of recycled or "reclaimed" HFCs when making new refrigeration and cooling equipment [48], [49].

While HFCs can help California reach its carbon emissions goals through electrification using heat pumps and electric cooling and refrigeration, it will be very important to reduce leakage of HFCs and promote recycling of HFCs, and it will not take relatively large quantities HFCs to undo California's decarbonization efforts. Reaching the 40% reduction goal in refrigerant emissions set by the California cooling act would result in 4.24 Mt reduction in emissions from HFCs in 2030, with HFC emissions increasing from 38% of the Commercial Buildings sector in 2019 to 44% in 2030, provided the sector reaches the SB100 goal of 60% reduction in carbon emissions by 2030. Furthermore, if California is planning on 100% reduction in carbon emissions by 2045, some level of negative emissions will likely be necessary to offset refrigerant leaks, as well as switching to low-GWP refrigerants.

Conclusions

Natural gas emissions in the Commercial Buildings sector in California can be abated by 2045, however decarbonizing this sector will require relatively substantial effort and funding.

2045 Projections for the Commercial Buildings Sector

Forecasted "new" electrification loads were added to the current electricity load for the Commercial Buildings sector to produce the 2045 forecasts.

Scenario 1 includes:

- 50% heat pumps and heat pump water heaters
- 50% electric boilers and electric water heaters
- 50% penetration of energy efficiency improvements (where applicable).

Scenario 2 includes:

- 30% heat pump and heat pump water heaters
- 70% electric boilers and electric water heaters
- 10% penetration of energy efficiency improvements (where applicable).

Both scenario 1 and scenario 2 are 100% electrification scenarios. Scenario 1 includes larger energy efficiency improvements with high heat pump penetration. Figure 48 shows the 2045 electricity profile projections for the entire Commercial Buildings sector.

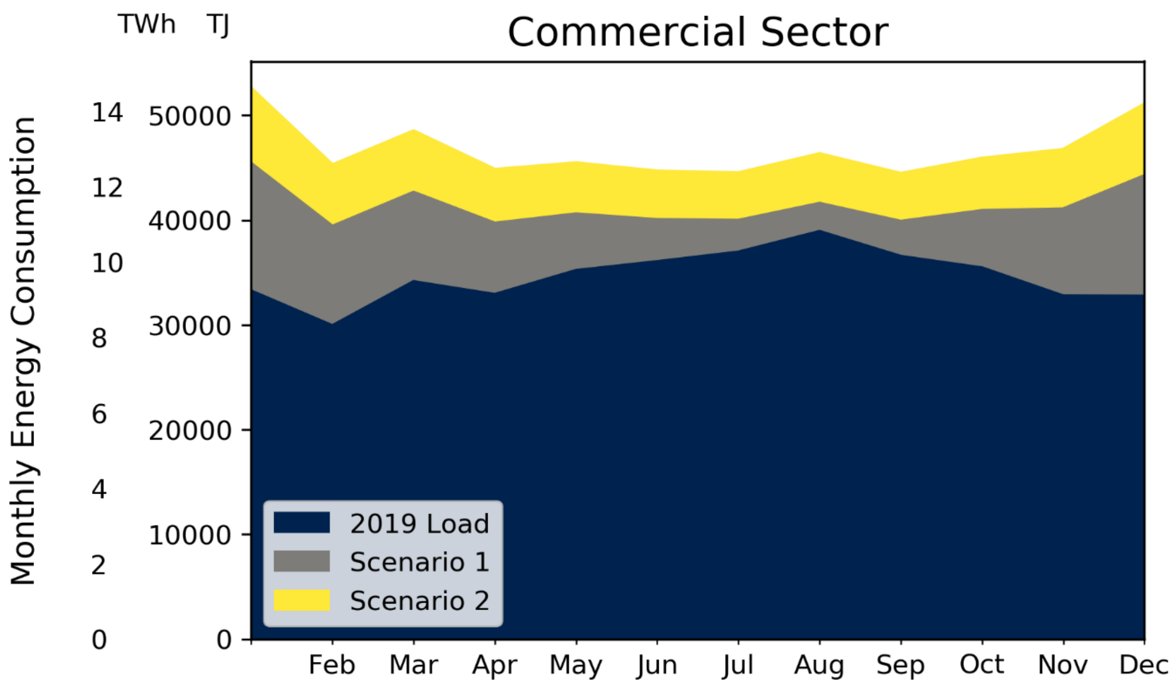


Figure 48: Projections of electricity consumption by the Commercial Buildings sector in 2045 [1], [4], [5], [16]–[21].

Scenario 1 results in a 19.5% increase in electricity consumption from 2019-2045, from 114 TWh to 137 TWh. Scenario 2 results in a 35% increase in electricity consumption from 2019-2045, from 114 TWh to 156 TWh.

One limitation to these projections is that they assume a retail load shape for the Miscellaneous Commercial subsector, while the actual miscellaneous category is much more eclectic. At-work EV charging is likely to increase commercial electricity consumption by 2045, which is ignored for this analysis. The assumptions in this analysis lead to a switch from a summer-peaking electricity consumption profile in 2019 to a winter-peaking electricity system in 2045 from heating electrification.

Figure 49 shows the increase in electricity consumption by subsector from 2019-2045 in scenarios 1 and 2.

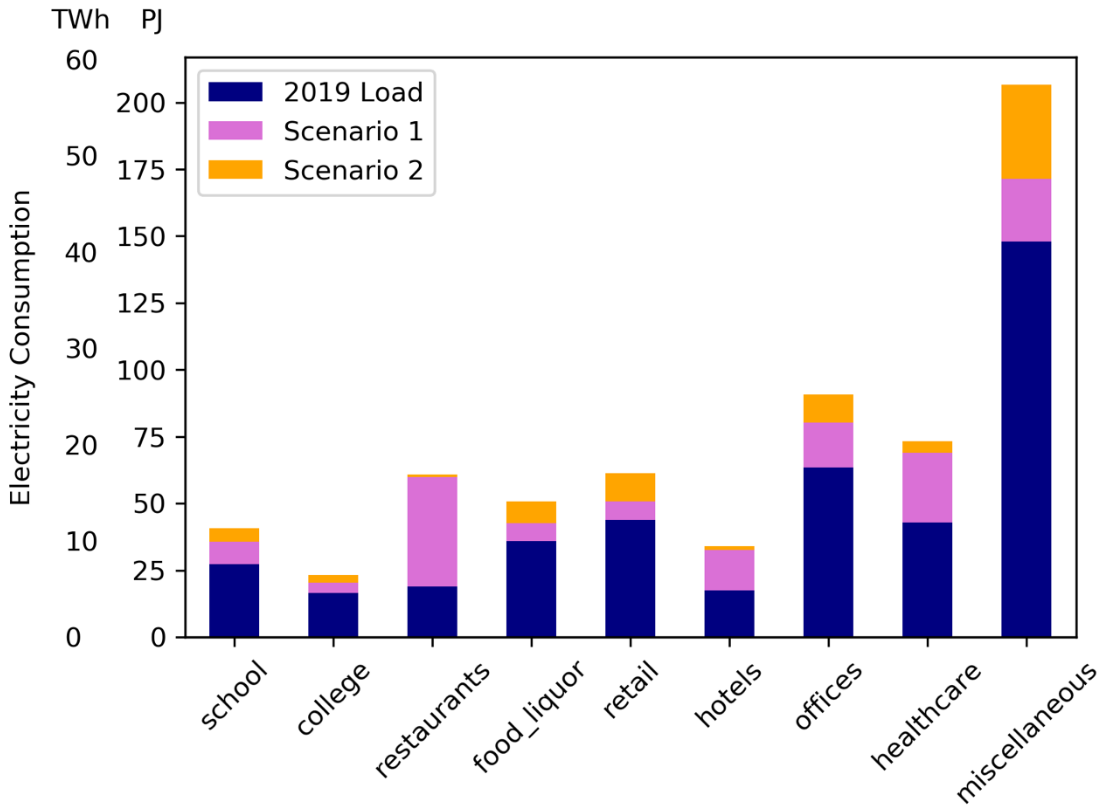


Figure 49: Summary of projections of electricity consumption by the Commercial Buildings sector in 2045 [1], [4], [5], [16]–[21].

Electricity consumption in scenarios 1 and 2 differs for each county because of differences in electricity end-use and energy efficiency retrofit options. Subsectors with large potential for energy efficiency improvements such as retail, food and liquor, offices, and schools show a proportionally smaller projected increase in electricity consumption between 2019 and 2045. Subsectors with lower potential for energy efficiency improvement, such as restaurants, show a proportionally larger projected increase.

Summary of Major Challenges and Benefits to Decarbonizing the Commercial Buildings Sector in California

Expense. Electrifying heating, water heating, and cooking in the Commercial Buildings sector will result in large efficiency gains. However, in most cases, high electricity rates in California will result in higher energy bills after electrifying despite efficiency gains. Replacing equipment before its lifetime is over results in larger overall costs.

Shortage of Skilled Labor. Industry interviews [50] indicated that there is a shortage of electricians trained in installing commercial-sized heat pumps. Heat pumps are more than 3 times as efficient as electric boilers and natural gas heaters and boilers at providing the same heating services. Demand for commercial heat pump installation is extremely likely to rise as California works towards the SB100 goal. We recommend policies to promote and fund vocational programs for electricians to aid this problem.

Equipment Supply. Similarly, Industry interviews [50] also indicated extremely low market penetration for heat pumps and heat pump water heaters for large buildings. According to the EIA, there are only three commercial heat pump water heater manufacturers as of 2018 [21]. This will likely hinder improvements in energy efficiency as demand for commercial heat pumps rises.

Small Businesses. How California reaches its SB100 goal is as important as reaching it. Preserving the small business economy must be part of the plans for California's clean energy transition. Many of the 4.1 million [51] small businesses in California will be unable to bear the upfront costs of electrifying their heating, cooking, and water heating equipment. Furthermore, industry interviews [50] suggest that small businesses are fearful of climate related regulation because of costs. This will pose a challenge for decarbonizing the Commercial Buildings sector in California.

Combined Heat and Power. CHP facilities in the Commercial Buildings sector with below 25,000 tCO_2e /yr in emissions are responsible for a combined 291,491 tCO_2e in emissions. Costs of abating CHP emissions increase above \$100/t CO_2e when CHP plants are smaller than 25,000 t CO_2e. The best decarbonization option for these facilities is likely retirement.

Energy Efficiency. Energy efficiency will be a key factor in reducing costs as the commercial buildings sector decarbonizes. Buildings who choose to upgrade the thermal efficiency their building envelope simultaneously with HVAC electrification can purchase a smaller HVAC system, resulting in lower capital costs and lower energy costs.

The Commercial Buildings Sector in California is unlikely to reach carbon neutrality via business as usual. However, with some reasonable changes, decarbonization is within reach. California is home to a wide range of commercial facilities with a variety of energy end-uses. Therefore, California's commercial decarbonization plan will need to be crafted with the heterogeneity of California's commercial businesses in mind.

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