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Nexus of Electrification and Energy Efficiency Retrofit of Commercial Buildings at the District Scale

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Abstract

Rapid electrification of buildings at the district scale is needed for cities to achieve climate change mitigation goals. However, most electrification studies focus on either the single building level or the city/region building stock level, and depend on the slow and uncertain process of requesting personally identifiable customer energy usage data from utilities. To answer a key question facing local policymakers: “Where can electrification proceed at scale without first upgrading the grid?” this study aims to quantify and inform building electrification impacts at the district scale using detailed building energy modeling and based on public records datasets. We explore how energy efficiency retrofits can help mitigate increased peak electric demand, and quantify impacts to energy use and carbon emissions. Building energy models of a baseline, and scenarios of simple electrification, energy retrofits, and electrification in combination with retrofits were created and simulated for 54 commercial buildings in two contiguous districts of San Francisco. A simple electrification scenario increased annual electricity consumption but reduced annual site energy usage by 15% to 17%, mainly due to replacing inefficient gas furnaces and boilers with more efficient heat pumps. Peak demand increased 7.4% for Fisherman’s Wharf (e.g. within the capacity of the existing power grid), while the Design District showed a marginal decrease. Annual carbon emissions were reduced by 46% and 37%. Combining electrification with efficiency upgrades reduced peak demand by 26% and 40%, and annual carbon emissions by 63% and 64% for the two districts. These results indicate that impacts of electrification depend on the mix of building uses within a district, and coupling electrification with energy efficiency upgrades is an effective strategy to decarbonize buildings while maintaining or reducing the peak electric demand.

Keywords: electrification, building decarbonization, building simulation, carbon emission, district, energy efficiency

Nomenclature

ASHP	Air-source Heat Pump
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CityBES	City Buildings, Energy, and Sustainability

COP	Coefficient of Performance
CVRMSE	Coefficient of Variation of Root-Mean Squared Error
DER	Distributed Energy Resource
DOE	Department of Energy
DIDF	Distribution Investment Deferral Framework
DX	Direct Expansion
EDV	Energy Data Vault
EDX	Energy Data eXchange
EE	Energy Efficiency
eGRID	Emissions & Generation Resource Integrated Database
EPA	Environmental Protection Agency
ERV	Energy Recovery Ventilation
EUI	Energy Use Intensity
GHG	Greenhouse Gas
HPWH	Heat Pump Water Heater
HVAC	Heating, Ventilation, and Air Conditioning
ICA	Integration Capacity Analysis
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Laboratory
LED	Light-emitting Diode
LPD	Lighting Power Density
NETL	National Energy Technology Laboratory
NMBE	Normalized Mean Bias Error
NREL	National Renewable Energy Laboratory
OSM	OpenStudio Model
PG&E	Pacific Gas & Electricity
PSZ-AC	Packaged Single Zone Air Conditioner
PTAC	Packaged Terminal Air Conditioner
PTHP	Packaged Terminal Heat Pump
PVAV	Packaged Variable Air Volume
SF Environment	San Francisco Department of the Environment
SHGC	Solar Heat Gain Coefficient

1. Introduction

Building operations are responsible for 28% of global carbon emissions (IEA, 2019). This means buildings play a key role in the transition to a low-carbon environment and climate change mitigation. Recent studies present decarbonization pathways for buildings and provide holistic carbon reduction scenarios. Camarasa et al. present pathways to meet the Intergovernmental Panel on Climate Change (IPCC)'s 1.5°C to 2.0°C temperature rise targets from studies of buildings in 32 countries (Camarasa et al., 2022; IPCC, 2022). Bistline et al. discussed actions for reducing United States (U.S.) emissions by at least 50% by 2030 (Bistline et al., 2022). Langevin et al. presented a modeling approach and scenarios to assess the potential to reduce the U.S. building carbon dioxide (CO_2) emissions by 80% by 2050 (Langevin et al., 2019).

Building energy efficiency improvement is the most feasible approach to achieve emission reduction goals and mitigate the worst impacts of climate change (Alam et al., 2019; Barnes & Parrish, 2016; REHVA, 2022). Widely adopted climate action strategies to achieve net zero emissions in the buildings sector includes renewable energy transition, energy efficiency, and electrification of buildings' thermal loads (Allen et al., 2022). The U.S. state of California is a preeminent testing ground for strategies to reduce greenhouse gas (GHG) emissions from energy use. The state has an aggressive economy-wide GHG reduction goal to reduce emissions 40% below the 1990 level by 2030 (*SB-32 California Global Warming Solutions Act of 2006: Emissions Limit*, 2016) and 80% below 1990 levels by 2050 (*Executive Order S-3-05*, 2005). More recently, California set the target of zero-GHG emissions from the electricity sector by 2045 (*SB-100 California Renewables Portfolio Standard Program: Emissions of Greenhouse Gases*, 2018), and the California governor announced a goal of net-zero carbon emissions statewide by 2045 (*Executive Order B-55-18 To Achieve Carbon Neutrality*, 2018). Electrification of gas-based space heating, domestic hot water systems, as well as gas appliances is necessary to rapidly decarbonize the buildings sector (Fournier et al., 2022). These targets are supported in the recent versions of California building energy efficiency standards, Title 24, that encourage residents to electrify their homes; a shift to all-electric and more energy efficient systems, such as heat pump technologies (California Energy Commissions, 2018). Since 60% of existing homes in California were built before the 1980s, and older homes tend to have lower energy efficiency, an electrification retrofit of these homes will bring more benefits in terms of energy, GHG emissions, and cost savings (Choi et al., 2021; State of California, 2018). San Francisco, the commercial, financial, and cultural center of Northern California, set more aggressive climate action targets of reducing emissions by at least 61% compared to 1990 levels by 2030, and achieving net-zero emissions by reducing emissions by 2040 (City & County of San Francisco, 2021). To achieve this goal, since 2021 San Francisco has required all new buildings to have zero onsite fossil fuel emissions and has set the goal of zero onsite fossil fuel emissions from all large existing commercial buildings by 2035 (American Legal Code Library, 2022). Building electrification accompanied by decommissioning of gas infrastructure are key strategies to meet the city's climate targets (City & County of San Francisco, 2021).

Rapid and widespread electrification would require revisions to numerous policies, including electricity rate design, building codes and appliance standards, incentives, outreach, education, and energy efficiency program targets that require reduction of total electricity usage. Mahone et al. assessed impacts on the electric grid from pathways of electrification, energy savings, and GHG reductions in the building sector across several regions of California (Mahone, Amber et al., 2018). Deason et al. describe benefits, barriers, and supporting policies to all-electric buildings from a national perspective. This study finds that electrification in buildings is cost-effective in new buildings where a heat pump can provide heating and cooling where winters are mild (Deason et al., 2018). Also, electric buildings are suggested for optimal standalone microgrid for sustainable electrification with renewable energy sources for rural communities (Kamal et al., 2023; Konneh et al., 2022). Peng et al. proposed a novel solar photovoltaic-driven heat pump (PVHP) system and conducted a comprehensive and in-depth study on the matching performance and zero-energy potential of PVHP for office buildings (H. Li et al., 2023; S. Li et al., 2021, 2022), which provides a brand new idea and scheme for building electrification. The results showed that 90% electricity usage of the PVHP can be self-satisfied by the PV power generation, which can provide important technical support for building electrification and decarbonization. Regnier et al. examined the energy efficiency measure packages that are recommended by utility incentive programs, which promote achieving energy cost effectiveness for large commercial buildings (Regnier et al., 2022). Duncan et al. evaluated the performance of energy systems and technologies for building electrification and provided approaches to improve the grid operations to meet dynamic electric loads by buildings (Elmallah et al., 2022).. Hopkins et al. estimated that if space and water heaters in one-third of California's buildings are shifted from natural gas to electricity by 2030, it will reduce GHG emissions by seven million metric tons annually, equivalent to eliminating GHG emissions from 1.5 million cars annually (Hopkins et al., 2018). Decarbonization pathways need energy savings by energy efficiency measures along with electrification, and this is essential to reduce the energy and power burdens in the grid and achieve net-zero buildings (RMI, 2022). Recent studies evaluated the GHG reduction potentials from energy efficiency and electrification packages for residential buildings under California climate conditions (Sun, Kusumah, et al., 2022; Walker et al., 2022; Wei et al., 2021), and they discussed challenges of decarbonization pathways for the residential buildings in cold climates (Berrill et al., 2022; Nadel & Fadali, 2022). Also, there was a study to explore community scale decarbonization pathways using building energy retrofit simulations (Valencia et al., 2022).

San Francisco has a "Mediterranean" climate with cool summers. Winter temperatures and rainfall patterns are similar to the Mediterranean climate, but summer is unusually cool because of the upwelling of cold deep ocean water from below the thermocline driven by onshore winds along California coast, causing fog which functions as a natural air conditioner for the city and the surrounding areas. In 2019, buildings in San Francisco were responsible for 41% of citywide emissions; evenly split between residential and commercial buildings (City & County of San Francisco, 2021). Of that total, the overwhelming majority (87%) was from natural gas burned to operate heating systems, boilers, water heaters, clothes dryers, and cooking appliances, while 13% was from electricity. While emissions from buildings have successfully been cut in half since 1990—thanks to aggressive energy efficiency investments, stringent green building codes, and a cleaner electricity supply—achieving net-zero emissions by 2040 will require a systematic shift of natural gas loads to 100% renewable electricity (City & County of San Francisco, 2021).

San Francisco's 2021 Climate Action Plan proposes existing building electrification as a key strategy for reducing carbon emissions (City & County of San Francisco, 2021). The plan's emphasis on electrification is similar to that of many other cities, in part because many subnational governments committed to carbon emissions reduction targets are consistent with the

Paris Agreement goal of limiting climate change to 1.5°C warming. In addition, California is transitioning electricity generation to renewable and very low-emission resources. Power generation serving San Francisco is cleaner still, with 83% of the electricity supply derived from renewable resources in 2019 (SF Environment, 2022). San Francisco's key strategy to "eliminate fossil fuel use in existing buildings by tailoring solutions to different building ownership, systems, and use types" raises the question: Is the electric distribution grid ready today to support widespread electrification? Public understanding of the infrastructure implications of achieving a city's targets for decarbonization via electrification faces three key constraints: (1) access to utility energy usage data for model calibration and validation, (2) access to utility infrastructure data to characterize capacity of the present-day electric grid to accommodate changes in load, and (3) the institutional capacity to quantify impacts through simulation and analysis. In California, obtaining utility infrastructure details and energy usage data to address such questions would require extensive engagement with multiple state regulators and the electric utility; a slow process with high transaction costs and no certainty of success.

This case study demonstrates a bottom-up approach to provide insights to decision-makers, using building performance simulations that build upon various data sources that are publicly available. By applying the Energy Data Vault (EDV) workflow (NREL, 2022c), a synthetic smart meter dataset was generated in lieu of access to high-resolution measured data. The synthetic load data was aggregated to district scale to analyze the implications of state and local government policy goals on peak and seasonal demand on electric distribution infrastructure serving those districts.

The contribution of the study to the state of the art is the development and application of a bottom-up simulation-based approach that uses public records of building parameters and energy use, quantifies impacts of electrification on electric demand of buildings at district scale and determines whether the existing power grid infrastructure can handle the increase in electric peak demand, as well as evaluates energy efficiency upgrades as a key strategy to help reduce energy demand and achieve energy savings. The outcomes can inform city and utility in planning building electrification and decarbonization at district scale.

The rest of the paper is organized as follows. Section 2 describes the Method; Section 3 presents the results and analysis; Section 4 discusses the results, implications, limitations of the study and potential future research; Section 5 draws the conclusions.

2. Method

To address the questions raised in the Introduction, building performance was simulated for two districts of San Francisco.

2.1 The overall approach

Three key considerations informed the selection of two study areas:

- Districts must be served by identifiable electric distribution infrastructure, and primarily comprised by the common commercial building uses supported by the EDV Workflow at the time of analysis: office, retail, restaurant, and hotel.

- Utility infrastructure data must be available to determine the present-day load and estimate available capacity of lines or a feeder serving a business district. For this project, grid capacity was extrapolated from data provided by Pacific Gas & Electric Company's Distribution Resource Planning Data Portal (PG&E, 2022a) and the Grid Needs Assessment (GNA) public datasets from the Distribution Investment Deferral Framework (DIDF) map (PG&E, 2021).
- A complete year of monthly energy use data must be available for a substantial fraction of buildings in the district.

We adopted the EDV workflow to generate the synthetic dataset of annual 10-minute energy use profiles of each building in the two districts. Major steps were: (1) the building stock characteristics were compiled into a GeoJSON file for visualization in CityBES and later converted into a CSV file; (2) the building stock characteristics CSV file was imported, and the baseline building energy models were generated using the EDV workflow (NREL, 2022c); (3) the baseline models were automatically calibrated using the OpenStudio Model Calibration gem (Sun et al., 2016; Sun, Hong, et al., 2022); (4) the calibrated baseline models were run with EnergyPlus version 9.4 to produce the annual 10-minute energy use profiles (NREL, 2020); (5) a set of electrification measures were selected and applied to the baseline models, and the electrified building models were run to produce the energy use profiles; and (6) a set of energy efficiency retrofits were selected and applied to the electrified buildings, and the retrofitted building models were run to produce the energy use profiles.

Utility data privacy rules limit access to utility usage data; the slow process of obtaining data for academic analysis is time consuming, uncertain of success, and often requires that researchers agree to avoid publishing data that can be associated with specific utility customers. Both aspects impede informed public policy decision-making. Slow, labor-intensive processes to apply for and acquire utility data inhibit or stymie timely analysis, while public policy goals are time-bound. When research is bound by non-disclosure stipulations, full transparency is not possible. The EDV project produced a method to avoid these constraints by implements a simulation workflow to generate synthetic energy data using energy models incorporating stochastic variation in building occupant behavior, and validated the synthetic data is similar to measured energy use. Thus, synthetic energy data is useful for algorithm verification and prototyping but not constrained by utility data rules and regulations.

EnergyPlus, the simulation engine of the EDV workflow, is the U.S. Department of Energy's flagship whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings.

CityBES is an open data and computing platform for modeling and analysis of building stock in cities for energy efficiency retrofits, electrification, decarbonization, and climate resilience (Hong et al., 2016, 2018; Sun et al., 2021). CityBES uses EnergyPlus as the underlying simulation engine to simulate building performance while considering urban context. In this study, CityBES was used to visualize the 3D building shape, while the model creation and simulations were done using the EDV workflow to provide a statistical representation of variation in building occupant behavior, in addition to building use and physical features. GeoJSON is an open standard format designed for representing simple geographical features, along with their non-spatial attributes.

The simulation results were compiled and analyzed to characterize the impacts of electrification and energy retrofits on building performance in terms of annual energy use, peak electric demand, and annual carbon emissions. All the load profiles (at the 10-minute interval for the whole building and major end uses) and the building models were compiled into a synthetic smart meter dataset for public release at the Energy Data eXchange (EDX) portal (Hong et al., 2022). Finally, the buildings' electric demands were aggregated for comparison with the capacity of the distribution line to evaluate whether the existing electrical power lines need to be upgraded due to the building electrification with and without an energy efficiency retrofit. Figure 1 shows the overall approach and workflow.

The electrification measures include using heat pump systems for space heating, water heating, cooking, and laundry equipment. The measures were developed with input from industry experts. The energy efficiency measures cover major building systems, including building envelope (wall, roof, window); lighting systems; service water heating; plug loads; and heating, ventilation, and air conditioning (HVAC) systems. They were refined with input from industry experts.

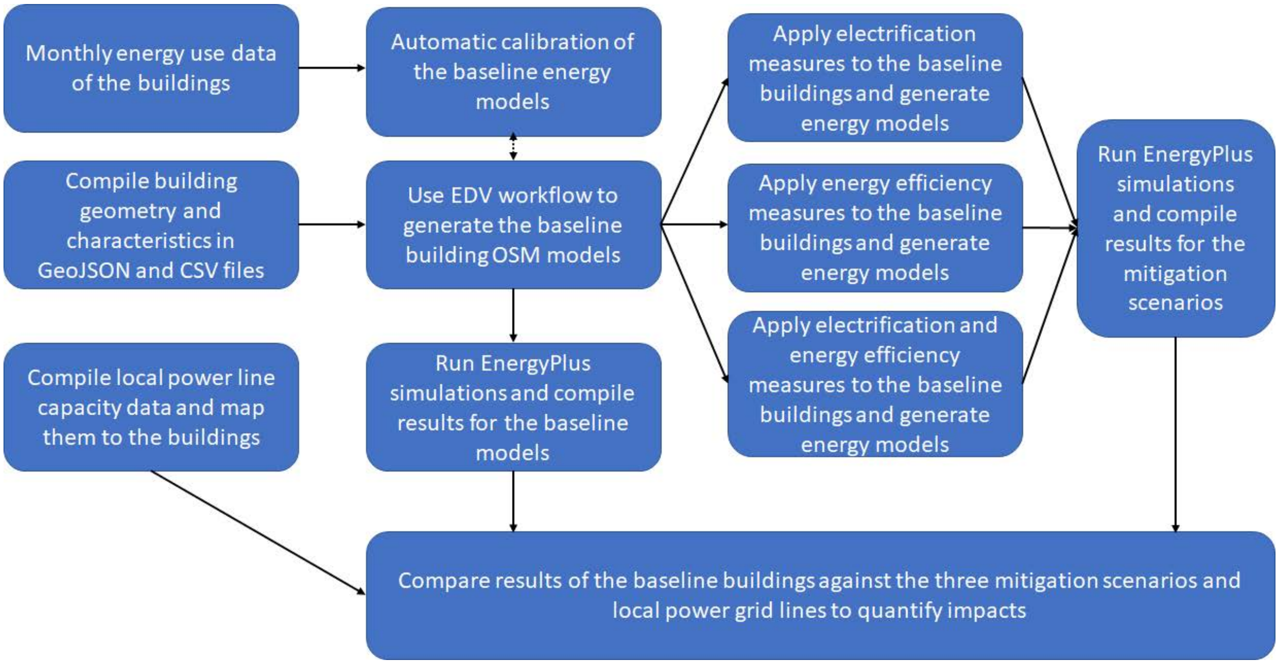


Figure 1. Workflow of the case study

2.2 Characterization of the two districts of buildings

The case study districts were selected based on the predominant building types and publicly available data characterizing the electric grid. Our primary interest was in the electrification of commercial buildings, which are colored in red tones on the map in Figure 2. The area covered by the gray "cloud" in the figure is served by secondary networks with a different grid configuration designed for higher reliability, which complicates understanding of available capacity and the ability to accommodate DERs (PG&E, 2022b); for simplification, the project avoided analysis in this area. Among the remaining commercial-dominant neighborhoods, we selected two districts in the red circles based on the data availability of PG&E feeders and lines, as well as recommendations from SF Environment.

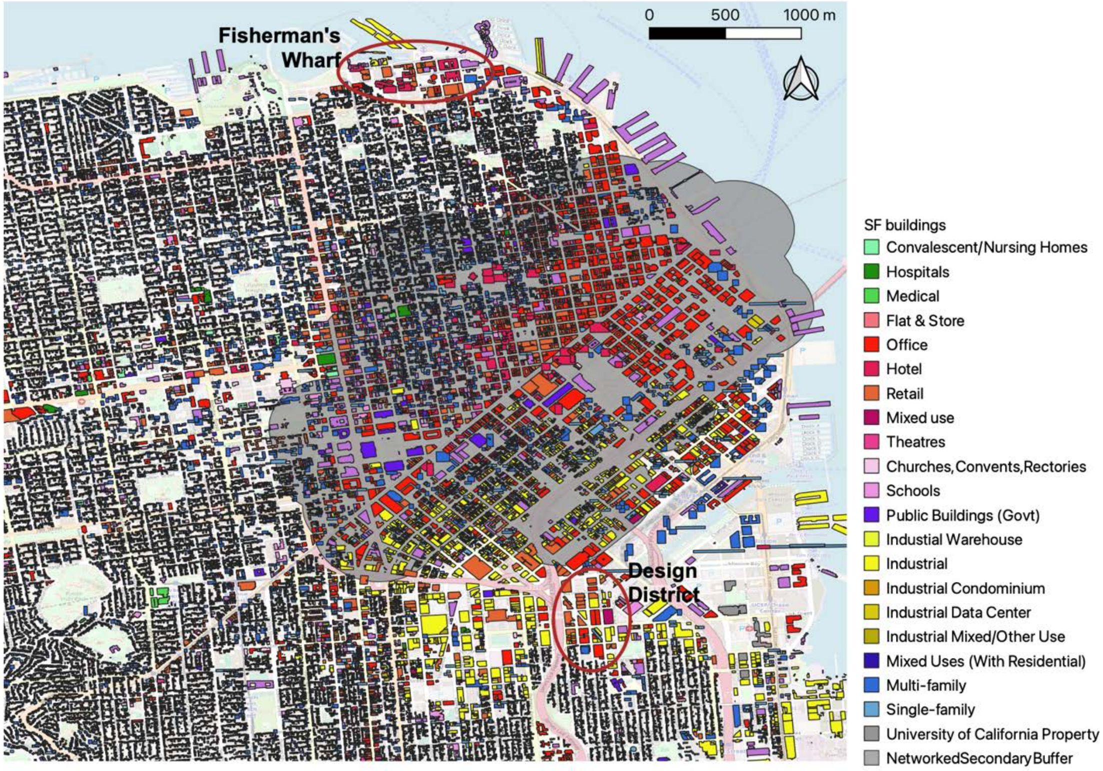
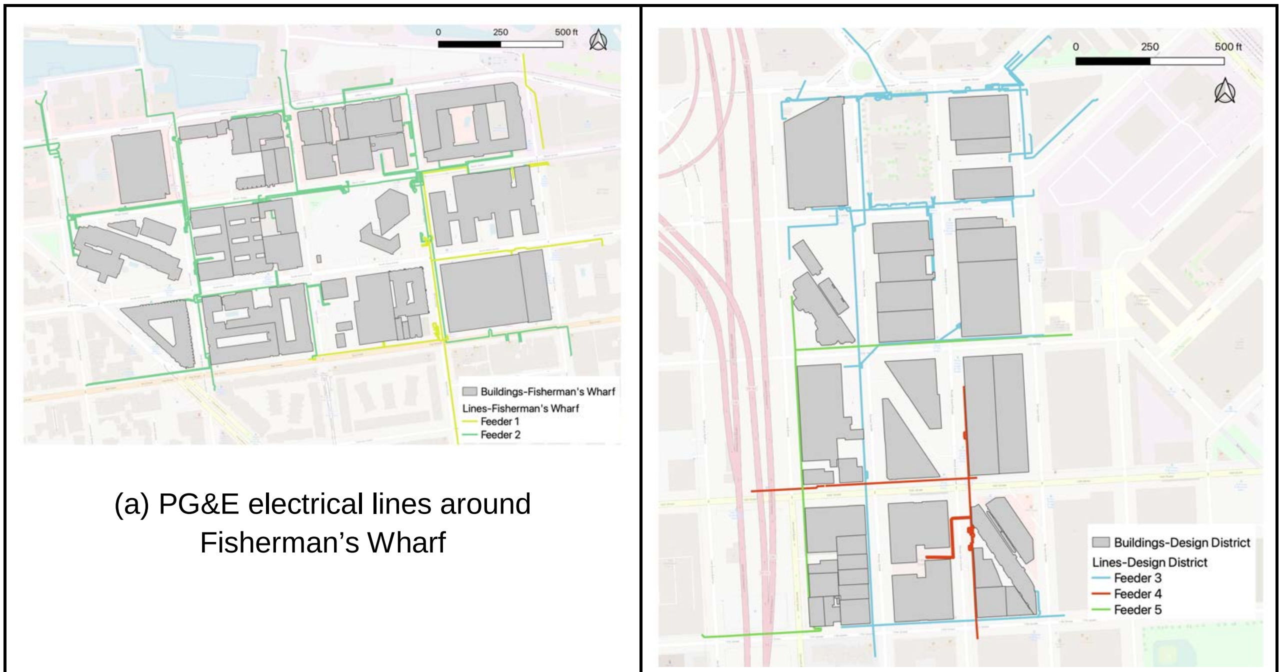


Figure 2. San Francisco commercial building types and locations

Colored lines in Figure 3 show the electrical lines and feeders provided by PG&E’s Integration Capacity Analysis (ICA) map (PG&E, 2022a). Each feeder contains multiple line segments. There are two feeders serving Fisherman’s Wharf and three feeders serving the Design District. The project team was unable to access data indicating the exact line serving each building due to privacy concerns, so the lines geographically closest to the site are assumed to serve the buildings in the selected district. For each line segment, PG&E provides load integration capacity, which is defined as the “amount of load that can be installed at that location without any thermal or voltage violations at the time the integration capacity analysis was performed.” Each feeder has an associated substation with zero or more capacitor banks, which are a source of reactive power and power factor correction. Data also were provided by PG&E’s GNA dataset to calculate the expected available load capacity of each feeder or bank for the future five years. These were used to evaluate the feasibility of the electrification project with simulated load changes from the mitigation scenarios and measures.



(a) PG&E electrical lines around Fisherman's Wharf

(b) PG&E electrical lines around the Design District

Figure 3. PG&E electrical lines around the two districts; grey blocks represent the building footprints, and different line colors differentiate the electrical lines belonging to different feeders

The first district is located in the Fisherman's Wharf district of San Francisco. It consists of 29 buildings, which are mostly hotels and retail stores. The second district is located in the Design District of San Francisco, which has 25 buildings, including office buildings, a few furniture showrooms, and stores. Table 1 shows the statistics of the building total floor area and building count by use type for the two districts. Figure 4 shows the 3D illustration of the buildings in each district in CityBES.

(a) Buildings in Fisherman’s Wharf

(b) Buildings in the Design District

Figure 4. Illustrations of 54 buildings in the two districts

Table 1. Summary of building types and gross floor area in the two districts

Building types	Design District		Fisherman’s Wharf	
	Total gross floor area [m²]	Building Count	Total gross floor area [m²]	Building Count
Small Hotel (≤ 30,000 m^2)	-	-	171,312	10
Small Office (≤ 2,500 m^2)	11,106	6	-	-
Medium Office (> 2,500 m^2 and ≤ 7,500 m^2)	21,121	5	9,317	3
Large Office (>7,500 m^2)	39,210	3	-	-
Retail	84,675	11	49,601	15
Restaurant	-	-	688	1
Total	156,111	25	230,918	29

2.3 Creation and calibration of the baseline building models

The EDV workflow was used to generate the baseline building OpenStudio models (OSM files) by reading the building characteristics in CSV format. OpenStudio is an open source cross-platform (Windows, Mac, and Linux) collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. The basic characteristics required are the building type, building height or number of floors, building total floor area, and year of construction, compiled from various public records including San Francisco's building footprint database, property tax records, and energy audit reports shared by SF Environment, as well as Google maps. HVAC system information available for some buildings through public energy audit reports was incorporated in baseline building energy models. The audit reports are made available through City of San Francisco's Existing Buildings Energy Ordinance which applies to non-residential buildings with gross floor area of 10,000 square feet or more. The ordinance requires commercial buildings to benchmark energy use and also requires an energy audit or a plan to reduce carbon emissions. (AMLegal, 2022)

The baseline models were then calibrated using the OpenStudio Model Calibration gem and public records of monthly energy usage in 2019 obtained via San Francisco's local energy ordinance. However, some buildings in the target area were exempt due to size or use, and some buildings had failed to report 2019 energy use. Of the 37 buildings where monthly energy use data were available, 25 building models consisted of the building uses and HVAC system types covered by the capabilities of the OpenStudio Model Calibration gem. The automatic model calibration process was applied, using monthly energy use data in 2019 and local weather data in 2019 as inputs (one building model was calibrated using energy and weather data from 2018, due to availability). The OpenStudio Model Calibration gem was developed based on the pattern-based calibration algorithm (Sun et al., 2016; Sun, Hong, et al., 2022). The pattern-based algorithm automates a process to calibrate individual energy models by identifying bias patterns of monthly simulated and measured energy use. Compared with purely mathematical optimization-based calibration method, the pattern-based method encompasses more engineering insights and experience by linking pattern recognition with the underlying building physics. Its calibration process includes four major steps: (1) running the original pre-calibrated energy model to obtain monthly simulated electricity and gas use; (2) establishing a pattern bias, either universal or seasonal, by comparing load shape patterns of simulated and actual monthly energy use; (3) using pre-programmed logic to select which parameter to tune first based on the combination of bias pattern type and weather type; and (4) automatically tuning the calibration parameters and checking the progress using pattern-fit criteria (Sun et al., 2016). The building model parameters that were calibrated included occupant density, lighting power density, equipment power density, window properties (U-factor and solar heat gain coefficient [SHGC]), indoor space cooling/heating temperature setpoints, cooling system efficiency coefficient of performance (COP), and space infiltration rate.

Two metrics—the Coefficient of Variation of Root-Mean Squared Error (CVRMSE) and the Normalized Mean Bias Error (NMBE)—were used to evaluate the calibration results based on ASHRAE Guideline 14 (ASHRAE, 2002). Among the 25 buildings, 17 buildings were calibrated successfully using the monthly source energy as the performance metric. The monthly source energy was calculated as the sum of the monthly electricity source energy with a source factor of 2.8 and the monthly natural gas source energy with a source factor of 1.05 (EnergyStar, 2020). Table 2 shows the summary of the calibration results of the buildings, and Figure 5 illustrates the calibration metrics results, i.e., NMBE and CVRMSE, of the total source energy use of the 25 buildings, including 17 buildings that were successfully calibrated and 8 buildings that failed to meet the criteria. For the building models that failed to the calibration criteria, the results of the last tuning step in the calibration process (Figure 5), usually have the lowest bias metrics, and are adopted for further simulation analysis. For the calibration-successful building models, the NMBE are all within ±5% and CVRMSE are all less than 15%. As their NMBE results are scattered evenly from −5% to 5%, the method doesn't lead to systematic errors.

Table 2. Summary of calibration status for buildings in the two districts

	Design District	Fisherman's Wharf
Total # of buildings	25	29
# of buildings with monthly energy data	17	20
# of buildings covered by the calibration algorithm	15	10
# of buildings calibrated successfully	10	7

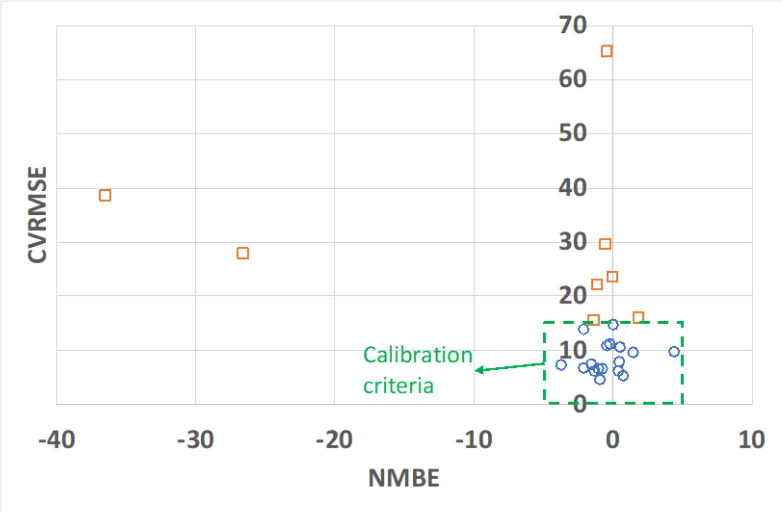


Figure 5. NMBE and CVRMSE results of the successfully calibrated 17 building models and the failed 8 building models.

It's worth noting that the monthly energy use data for several buildings exhibit abnormal patterns, which makes calibration challenging. For example, Figure 6 shows monthly electricity and natural gas consumption for two buildings. Building 1's energy use (both electricity and natural gas) increased throughout the year. Building 2’s electricity use dropped dramatically in May, and consumed no natural gas during the second half of the year. Either profile might reflect the occupancy change or errors in meter data reporting. Without additional details characterizing building operation changes, data with such irregular seasonality (or lack thereof) cannot be used for model calibration.

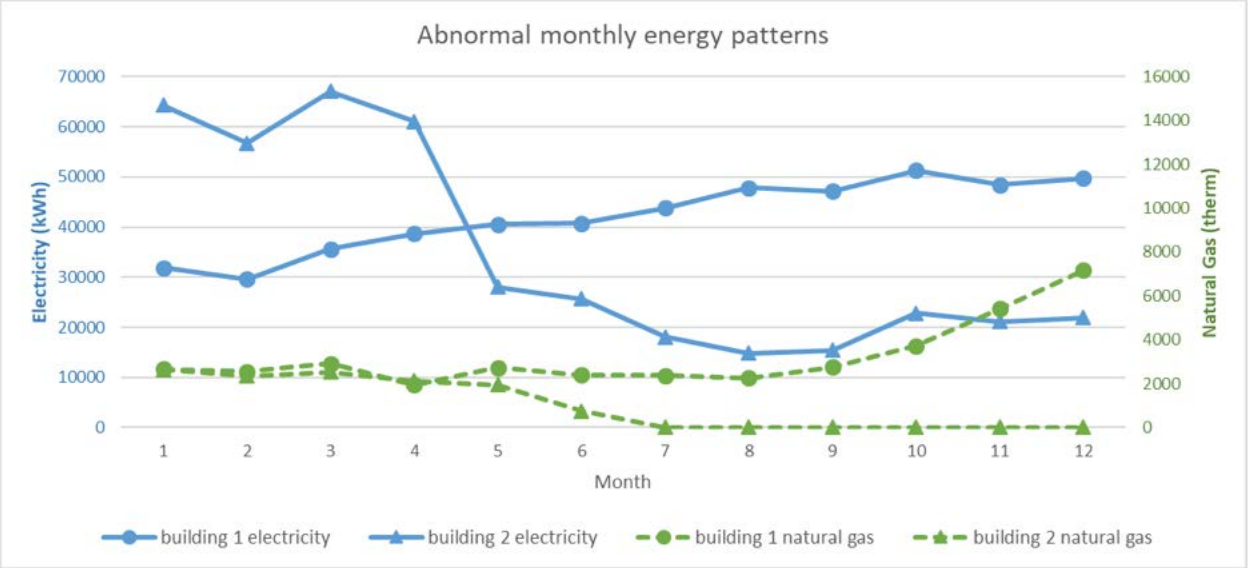


Figure 6. Example buildings with abnormal monthly energy use patterns

A limitation of the EDV workflow is that models cannot be accurately generated for mixed-use buildings. For mixed-use buildings with a dominant use type by building total floor area, it was assumed that the dominant type was used for the entire building. For mixed-use buildings without a primary use type (e.g., half restaurant and half retail), a baseline model of each type was generated. After simulation, the model that had energy consumption closer to the measured annual energy use was considered to be the best approximation for the given building.

2.4 Definition of mitigation scenarios and measures

Based on the baseline buildings and their energy systems, we defined three mitigation scenarios for modeling and analysis: (1) the electrification scenario, where all baseline building end uses using natural gas are converted to electric equipment, including heat pumps for space heating and water heating, induction cooking, and electric drying; (2) the energy efficiency scenario, where all baseline buildings are retrofitted for higher efficiency, covering building envelope, lighting, plug loads, HVAC systems, and service hot water systems; and (3) the combined electrification and energy efficiency scenario, where all baseline buildings are electrified and retrofitted for energy efficiency.

The electrification scenario included the following measures:

- Replace existing HVAC systems using natural gas with electric systems meeting the minimal efficiency requirements prescribed in the ASHRAE 90.1-2019 standards for:

    - small hotels: from a packaged terminal air conditioner (PTAC) with electric baseboard heat system to a packaged terminal heat pump (PTHP) system with a COP of 4.1.
    - small offices, retail, and restaurants: from a packaged single zone air conditioner (PSZ-AC) with gas coil heating to an air-source heat pump (ASHP) with a COP ranging from 3.3 to 4.1, depending on the capacity.
    - medium offices: from a packaged variable air volume (PVAV) with hot-water coil reheat to an ASHP with a COP ranging from 3.3 to 4.1, depending on the capacity.
    - large offices: from a central gas boiler (central VAV with hot-water coil reheat) to an air-to-water heat pump with a COP ranging from 2.7 to 3.6, depending on the outdoor air temperature (the central chiller for cooling remains the same).
    - According to the audit report, two offices already used heat pump HVAC systems, so this measure was not applied to them.
- Replace existing gas water heaters or boilers with heat pump water heaters (HPWH) for small hotels, offices, and restaurants. Note that we assume retail buildings do not have hot water systems.
- Replace gas cooking systems with electric induction cooking systems for restaurants. Note that other building types do not have cooking systems.
- Replace a gas laundry system with an electric resistance system for hotels. Note that other building types do not have laundry systems.

The energy efficiency (EE) scenario includes 10 EE measures incorporating recommendations from the domain experts. These measures are a subset of the energy efficiency technologies modeled in the BayREN Integrated Commercial Retrofits (BRICR) project (SF Environment, 2022). The EE measures cover major building energy systems including lighting, envelope, plug loads, service hot water, and HVAC systems:

- Retrofit lighting with light-emitting diode (LED): Lighting power density (LPD) declines to 6.46 W/m^2 (0.6 W/ft^2).
- Add daylight controls: Daylight control sensors are installed to zones with exterior windows.
- Add occupancy sensors for lighting control: Reduce LPD by 5%.
- Add roof insulation: Add a layer of insulation with R10 (R-value of 10.0 hour-ft^2-°F/Btu or 1.76 m^2-K/W), to the existing roofs.
- Install low-flow faucets and showerheads: Reduce water use by 10%.
- Install plug-load controls: Reduce plug load electric power density by 20%.
- Enable demand controlled ventilation that reduces outdoor air intake when the actual occupancy is less than the design occupancy.
- Add or repair economizers: Enable economizer control with a high limit dry-bulb temperature of 20.5°C (69°F).
- Add air sealing to reduce infiltration through the envelope: Reduce the infiltration rate by 30%.
- Add an energy recovery ventilation (ERV) unit with 80% efficiency.

Table 3 shows the mapping of the electrification and EE measures with the building types in the two districts. EnergyPlus simulations were conducted for individual buildings in the two districts considering the baseline and three scenarios: The Electrification package, the EE package, and the combined Electrification + EE package. The 2019 actual weather data from a nearby station of the two districts were used in the simulations (source data from The POWER Project of NASA).

Table 3. Measures applied to the electrification and energy efficiency retrofit scenarios

Scenario	Measure	Small hotel	Small office	Medium office	Large office	Retail	Restaurant
Electrification package	Replace existing HVAC with PTHP	X					
	Replace existing HVAC with ASHP		X	X		X	X
	Replace existing central gas boiler for space heating with an air-to-water heat pump				X		
	Replace gas water boiler with HPWH	X	X	X	X		X
	Replace gas cooking system with induction cooking system						X
	Replace gas laundry system with electric system	X					
Energy efficiency package	Retrofit lighting with LED	X	X	X	X	X	X
	Add daylight controls	X	X	X	X	X	X
	Add occupancy sensors for lighting control	X	X	X	X	X	X
	Add roof insulation	X	X	X	X	X	X
	Install low-flow faucets and showerheads	X	X	X	X		
	Install plug-load controls		X	X	X		

	Enable demand controlled ventilation		X	X	X	X	X
	Add or repair economizer	X	X	X	X	X	X
	Add air sealing to reduce infiltration through envelope	X	X	X	X	X	X
	Add energy recovery ventilation unit		X	X	X	X	X

2.5 Carbon emissions factors

Carbon dioxide emissions outputs are reported from the EnergyPlus simulations using the 8,760 hourly CO_2 emissions factors for electricity and an annual average value for natural gas. We started with the 2019 electricity CO_2 equivalent (CO_2e) emissions factors (8,760 hourly values) for California from the Cambium database (NREL, 2022a) and scaled them down proportionately to ensure the annual average emissions factor of electricity matched that of the local utility (PG&E) serving San Francisco. Cambium datasets contain modeled hourly emission, cost, and operational data for a range of possible futures of the U.S. electricity sector through 2050, with metrics designed to be useful for forward-looking analysis and decision support. Table 4 shows that according to the Cambium database, California statewide electricity emissions factors are significantly greater than the annual average emissions factors reported by PG&E using the specific sources of generation that they purchase power from. Cambium data were used here to incorporate the variation in carbon emitted based on time of the day and day of the year, ranging from 211 to 686 kilograms of CO_2e per megawatt-hour (kgCO_2e/MWh). Hourly data allows better characterization of behavioral variation and temporal variation from building to building within uses and between uses. To reflect the attributional mix of generation sources specific to the utility, we applied a local emission scale-down factor of 0.19 (93/482) to all hourly Cambium CO_2 emissions intensity data.

Figure 7 shows the derived scaled-down hourly CO_2e emissions factors heatmap reflecting the local utility electricity emissions rate in 2019. The heatmap illustrates the 8,760 hourly emission factors representing 365 days in X axis and 24 hours in Y axis. The darker blue colors indicate hours with higher CO_2e emission intensity of the electricity from the grid. The heatmap shows the electricity has higher emissions during the summer afternoon and evening hours as well as spring morning hours for the California power grid. We used the natural gas CO_2 emissions factor of 277 kgCO_2e/MWh from the U.S. Environmental Protection Agency's (EPA) Emissions & Generation Resource Integrated Database (eGrid) (NREL, 2022b; US EPA, 2020).

Table 4. Range of CO_2 Emission Factors (unit: $kgCO_2e/MWh$)

Data Source	**Minimum**	**Average**	**Maximum**	**Fuel**
Cambium - California 2019 (NREL, 2022a)	211	482	686	Electricity
Pacific Gas & Electric - 2018 (PGE&E, 2021)	-	93	-	Electricity
EPA eGrid (NREL, 2022b; US EPA, 2020)	-	277	-	Gas

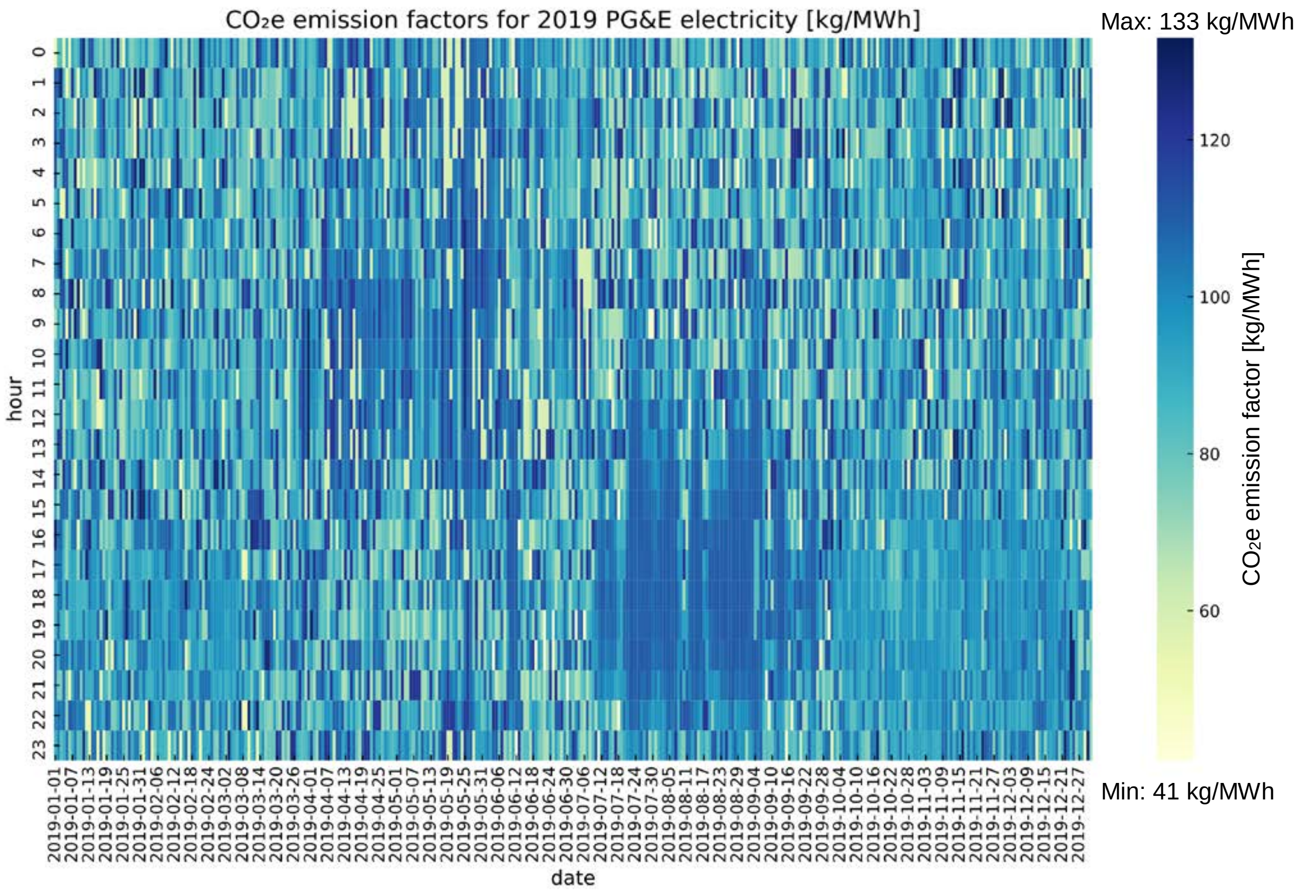


Figure 7. Heatmap of the derived hourly electricity CO_2e emissions factors for PG&E in 2019

3. Results and Analysis

EnergyPlus simulation results are reported for monthly electricity use, monthly natural gas use, annual peak electricity demand, annual electricity use, annual natural gas use, annual site energy use intensity (EUI), annual CO_2 emissions, and major end uses by each building in the two districts for both the baseline and three mitigation scenarios. Energy consumption of individual buildings were summed to determine the district energy use, while the coincident peak electric demand of the district was calculated, through post processing, from the aggregated time interval electric demand of all buildings in the district.

The simulation results and the building models were compiled into a synthetic smart meter dataset and shared with the public through the National Energy Technology Laboratory's Energy Data eXchange (EDX) portal (Hong et al., 2022). The dataset includes the simulated annual 10-minute energy use profiles of the two districts of buildings for the baseline, the electrification scenario, the energy retrofit scenario, and the combined electrification and energy upgrades scenario.

3.1 Baseline simulation results

Table 5 shows the annual electricity and natural gas usage by building type in the two districts. The Design District consumed an annual 16,269 MWh of electricity and 3,500 MWh of natural gas and had a peak electric demand of 906 kW that occurred on September 25. Fisherman's Wharf consumed an annual 39,721 MWh of electricity and 15,214 MWh of natural gas and had a peak electric demand of 1,472 kW that occurred on September 25. Fisherman's Wharf consumes more energy and has a higher peak electric demand than the Design District because it contains more buildings, and the hotels, restaurants, and retail buildings have larger EUIs than office buildings.

The 11 retail buildings are dominant in the Design District, followed by the three large office buildings in terms of annual energy use. In Fisherman's Wharf, 10 hotels comprise the majority of floor area and consume over 75% of the total electricity and natural gas in the district.

Table 5. Baseline annual electricity and natural gas consumption by building type for each district

District	Energy	Restaurant	Large Office	Medium Office	Retail	Small Hotel	Small Office	Total
Design District	Electricity [MWh]	-	5,932	3,124	6,232	-	980	16,269
	Natural Gas [MWh]	-	604	658	2,112	-	126	3,500
Fisherman's Wharf	Electricity [MWh]	415	-	1,347	8,853	29,105	-	39,721
	Natural Gas [MWh]	618	-	525	2,932	11,139	-	15,214

Figure 8 shows ranges of the two districts' baseline simulated site EUI by building type, and compares the simulated results with measured data of real buildings from the U.S. Department of Energy's Building Performance Database (BPD). The BPD buildings were sorted by building type and filtered for ASHRAE climate zone 3C, the same as San Francisco. BPD contains measured data on energy consumption, characteristics, and equipment for more than one million buildings across the U.S (U.S. Department of Energy, 2022; Walter & Sohn, 2016). The simulated site EUI of baseline buildings of three building types (office, hotel, and retail) are within the BPD ranges, indicating the rationality of simulation results. The simulated retail buildings are relatively on the higher ends of BPD range, possibly caused by different use and operation patterns.

Restaurants are excluded from Figure 8 because there is only one restaurant in Fisherman's Wharf and it exhibited the highest site EUI (1503 kWh/m^2) among other building types due to heavy energy use for cooking. Cooking-related natural gas consumption is estimated to comprise about 30% of energy use, and this restaurant-related electric equipment comprises about 20% of the site energy consumption.

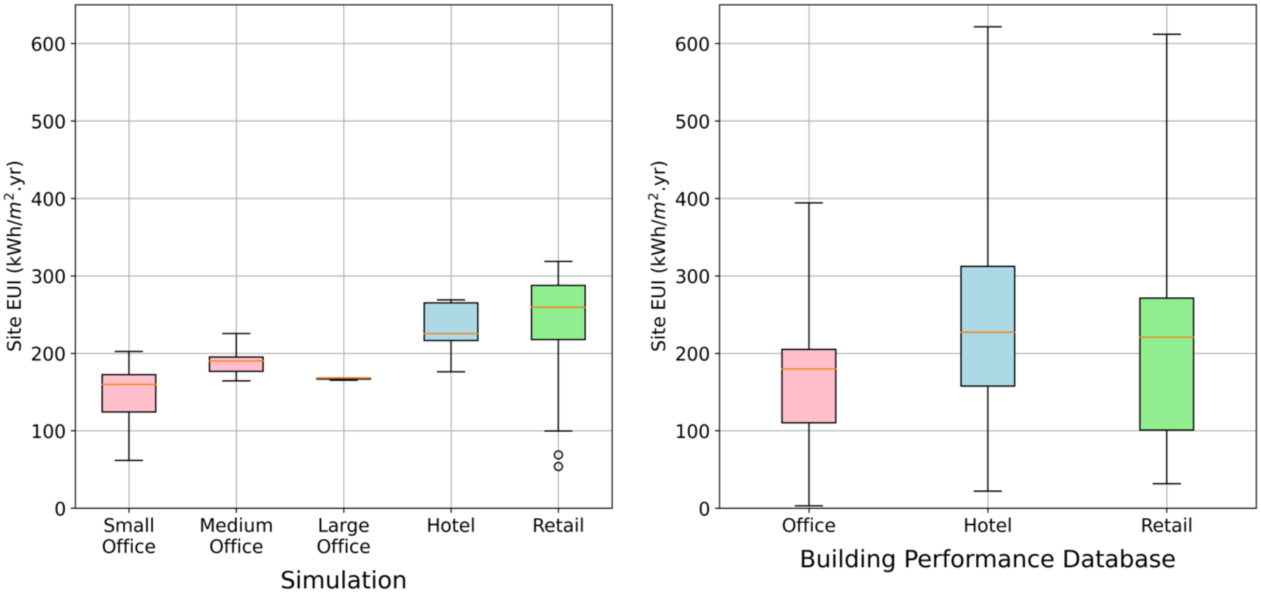


Figure 8. Left: box plot of the simulated annual site energy use intensity (EUI) for the baseline buildings in the two districts by building types; Right: box plot of the measured annual site EUI by building types from the Building Performance Database.

Figure 9 shows the monthly electricity, natural gas usage, and peak electricity demand by districts. Both districts had the highest electricity usage in August, narrowly followed by July and September. San Francisco is located in climate zone 3C, a mild marine climate, where a marginal (up to 10%) increase in the cooling energy use during the summer season is typical. Both districts have many buildings with natural gas-based space heating and service hot water systems, and this results in much higher natural gas consumption in the winter season.

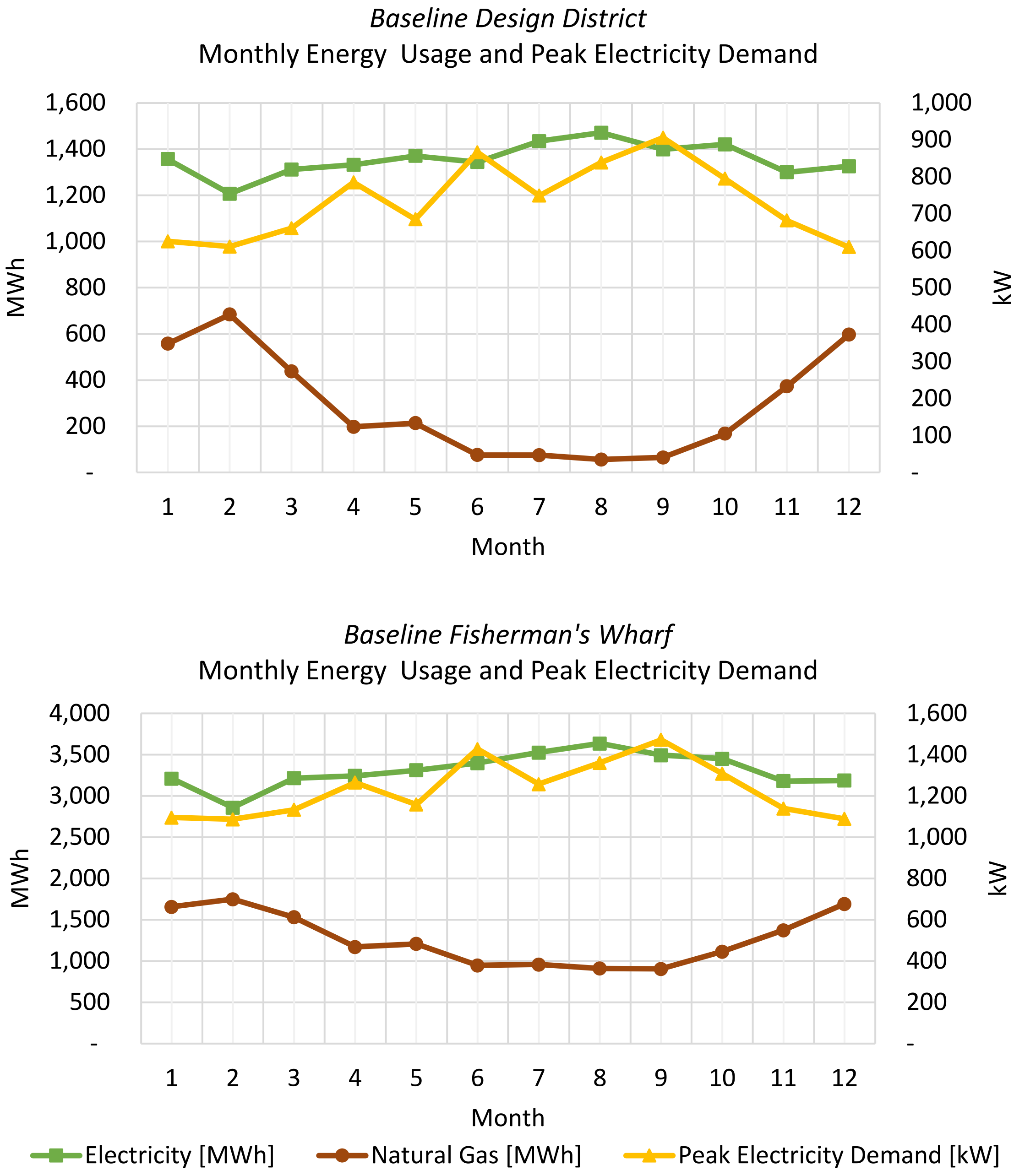


Figure 9. The simulated baseline monthly electricity and natural gas use and peak electricity demand by each district (top: Design District; bottom: Fisherman’s Wharf)

3.2 Mitigation scenario simulation results

The simulation results of the three mitigation scenarios were compiled and compared with the baseline results in figures 10 to 13 and tables 6 to 9. Figure 10 shows the annual total electricity and natural gas usage by scenario for each district, while Figure 11 shows details of the electric and gas end uses. Figure 12 shows the annual peak electricity demand for the baseline and three mitigation scenarios of the two districts. Figure 14 shows the annual CO_2 emissions from the two districts' electricity and natural gas consumption. Figure 13 provides a detailed electric load profile on the peak demand day for each scenario by district. Table 6 summarizes the annual energy usage, peak electric demand, and CO_2 emissions and their percentage changes from the baseline for each scenario in the two districts. Tables 7 to 9 show more detailed annual site energy, electricity, natural gas, peak demand, CO_2 emissions, and their reductions compared to the baseline for each scenario by building type in each district.

3.2.1 Electrification scenario results

The electrification scenario shows increases of 0.5 gigawatt-hours (GWh) (3.3%) and 5.8 GWh (14.5%) in annual electricity consumption for the Design District and Fisherman's Wharf, respectively (Table 6). However, there were reductions of annual site energy usage by 3 GWh (15%) in the Design District and 9.4 GWh (17%) in Fisherman's Wharf (Figure 10). This is mainly from replacing the inefficient natural gas based furnaces and boilers with basic modern heat pump-based space heating and service water heating systems, which are inherently more efficient than existing conditions. Electric resistance space heating and water heating were excluded from the basic electrification scenario to reflect California's building energy standards. Also, natural gas-based cooking systems were replaced with higher efficiency electricity-based induction cooking systems in the restaurant in the Fisherman's Wharf study area, and natural gas burning laundry drying systems were replaced with similar efficiency electric resistance drying systems in hotels. Given California's relatively high retail electricity costs, more efficient heat pump drying systems may be used in practice.

Table 6. Annual site energy, electricity, natural gas, CO_2 emissions, peak electricity demand, and occurrence time for the baseline and three mitigation scenarios of the two districts

District	Package	Site Energy [GWh]	Site Energy Saving [%]	Electricity [GWh]	Electricity Saving [%]	Natural Gas [GWh]	Natural Gas saving [%]	CO_2 emission [ton]	CO_2 emission saving [%]	Electricity Peak [kW]	Electricity Peak saving [%]	Electricity Peak [Timestamp]
Design District	Baseline	19.8	-	16.3	-	3.5	-	2,506	-	906	-	9/25/2019 15:20
	Electrification Package	16.8	14.9%	16.8	-3.3%	-	100%	1,586	36.7%	895	1.2%	9/25/2019 15:20
	EE Package	11.8	40.6%	9.5	41.9%	2.3	34.3%	1,530	38.9%	542	40.2%	9/25/2019 15:00
	Electrification + EE Package	9.6	51.4%	9.6	40.9%	-	100%	907	63.8%	540	40.4%	9/25/2019 14:50
Fisherman's Wharf	Baseline	54.9	-	39.7	-	15.2	-	7,962	-	1,472	-	9/25/2019 16:10
	Electrification Package	45.5	17.2%	45.5	-14.5%	-	100%	4,282	46.2%	1,581	-7.4%	9/25/2019 16:10
	EE Package	39.6	27.9%	26.1	34.3%	13.5	11.1%	6,209	22.0%	970	34.1%	9/25/2019 16:10
	Electrification + EE Package	31.4	42.8%	31.4	20.9%	-	100%	2,956	62.9%	1,086	26.3%	9/25/2019 16:10

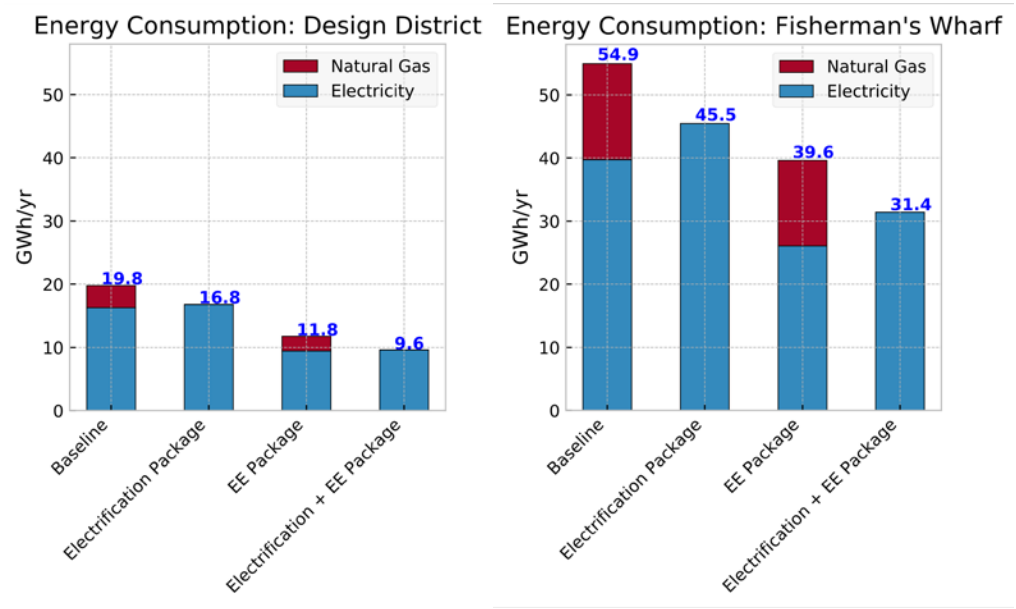


Figure 10. Annual energy usage of electricity and natural gas for each package by each district (left: Design District; right: Fisherman's Wharf)

Table 7 shows all building types reduced site energy consumption from the electrification package. The replacement of natural gas heating systems with electric equipment contributed to a large portion of the increased electricity consumption in both districts (Table 7). The restaurant in Fisherman's Wharf almost doubled its electricity consumption; the result of fuel switching from high use of natural gas cooking and hot water systems to all-electric equipment. The Fisherman's Wharf district has hotel buildings that consume significant amounts of natural gas for service water heating and laundry. Therefore, the increase of electricity consumption in the basic electrification scenario is much larger than that of the Design District. As part of the HVAC system upgrade in the electrification package, Figure 11 shows that cooling, fan, and pump energy consumption was slightly reduced due to the smaller fans and higher-efficiency equipment required by the current building energy codes.

Table 7. Annual site energy (top), electricity (middle), and natural gas (bottom) consumption and reduction percentages compared to the baseline for each scenario/package by building type in each district

Site Energy

District	Building Type	Baseline	Electrification Package [MWh]	Reduction [%]	EE Package [MWh]	Reduction [%]	Electrification + EE Package [MWh]	Reduction [%]
Design District	Large Office	6,537	6,071	7.1%	3,687	43.6%	3,339	48.9%
	Medium Office	3,782	3,112	17.7%	2,419	36.0%	1,793	52.6%
	Retail	8,344	6,569	21.3%	4,988	40.2%	3,879	53.5%
	Small Office	1,106	1,060	4.1%	658	40.5%	602	45.5%

Fisherman's Wharf	Restaurant	1,033	819	20.7%	850	17.8%	698	32.4%
	Medium Office	1,872	1,327	29.1%	1,226	34.5%	745	60.2%
	Retail	11,785	9,446	19.8%	5,302	55.0%	3,639	69.1%
	Small Hotel	40,245	33,882	15.8%	32,228	19.9%	26,319	34.6%

Electricity

District	Building Type	Baseline	Electrification Package [MWh]	Reduction [%]	EE Package [MWh]	Reduction [%]	Electrification + EE Package [MWh]	Reduction [%]
Design District	Large Office	5,932	6,071	-2.3%	3,239	45.4%	3,339	43.7%
	Medium Office	3,124	3,112	0.4%	1,869	40.2%	1,793	42.6%
	Retail	6,232	6,569	-5.4%	3,800	39.0%	3,879	37.8%
	Small Office	980	1,060	-8.1%	546	44.3%	602	38.6%
Fisherman's Wharf	Restaurant	415	819	-97.3%	323	22.1%	698	-68.2%
	Medium Office	1,347	1,327	1.5%	796	40.9%	745	44.7%
	Retail	8,853	9,446	-6.7%	3,230	63.5%	3,639	58.9%
	Small Hotel	29,105	33,882	-16.4%	21,729	25.3%	26,319	9.6%

Natural Gas

District	Building Type	Baseline	Electrification Package [MWh]	Reduction [%]	EE Package [MWh]	Reduction [%]	Electrification + EE Package [MWh]	Reduction [%]
Design District	Large Office	604	-	100.0%	448	25.9%	-	100.0%
	Medium Office	658	-	100.0%	550	16.4%	-	100.0%
	Retail	2,112	-	100.0%	1,188	43.7%	-	100.0%
	Small Office	126	-	100.0%	112	11.2%	-	100.0%
Fisherman's Wharf	Restaurant	618	-	100.0%	526	14.9%	-	100.0%
	Medium Office	525	-	100.0%	430	18.0%	-	100.0%
	Retail	2,932	-	100.0%	2,072	29.3%	-	100.0%
	Small Hotel	11,139	-	100.0%	10,499	5.7%	-	100.0%

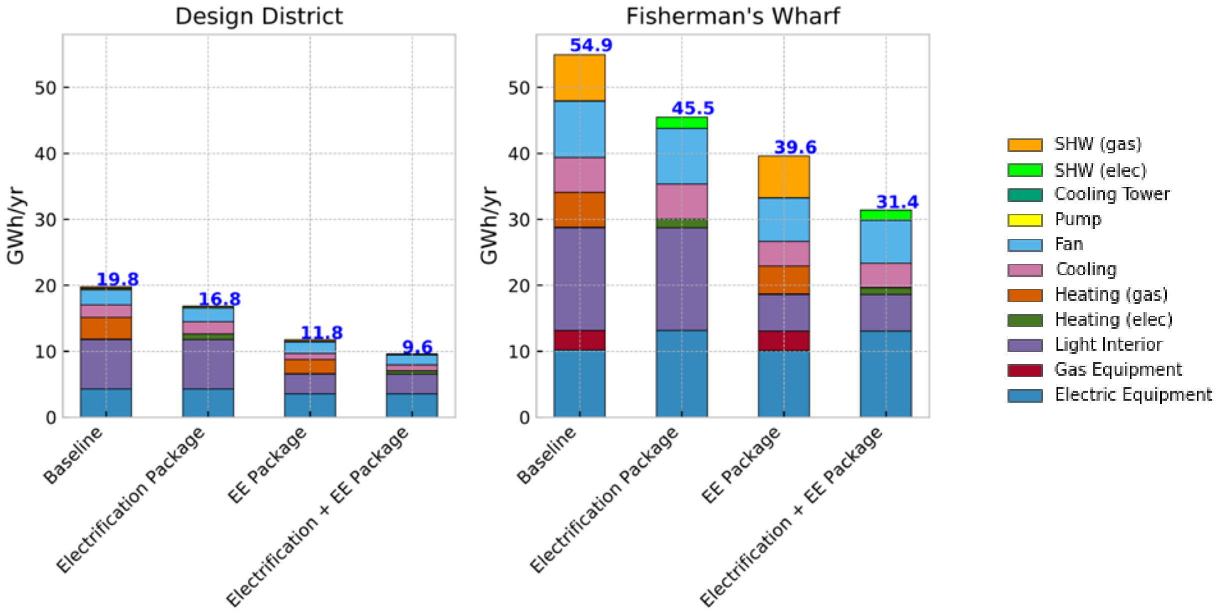


Figure 11. Annual energy usage by end-use type for each scenario of the two districts (left: Design District; right: Fisherman's Wharf)

For the annual peak electric demand, Fisherman's Wharf showed a 7.4% increase in the basic electrification scenario, while the Design District showed a marginal 1.2% decrease (Figure 12, Figure 13, and Table 6). The coincident peak electric demand for both districts occurred on the afternoon of September 25 when the dry-bulb temperature reached 94.4°F (34.7°C) at 3 pm, which was the warmest day in 2019. Although electricity demand increased some from switching from natural gas to electricity for the service hot water systems, the office and retail buildings in the Design District have low hot water demand, thus peak electricity demand was reduced slightly in the basic electrification scenario. Fisherman's Wharf showed a higher increase in peak electricity demand due to the fuel switching from natural gas to electricity for the cooking and laundry systems for the restaurant and hotels, and Figure 13 reflects increased electric demand from these systems during the daytime hotel and restaurant operation hours.

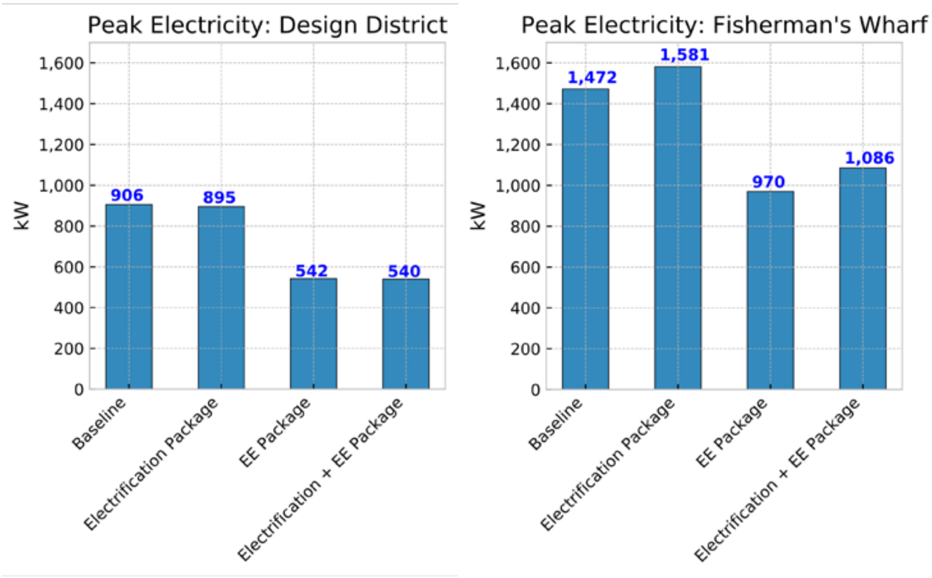


Figure 12. Electricity peak demand for each package of the two districts (left: Design District; right: Fisherman's Wharf)

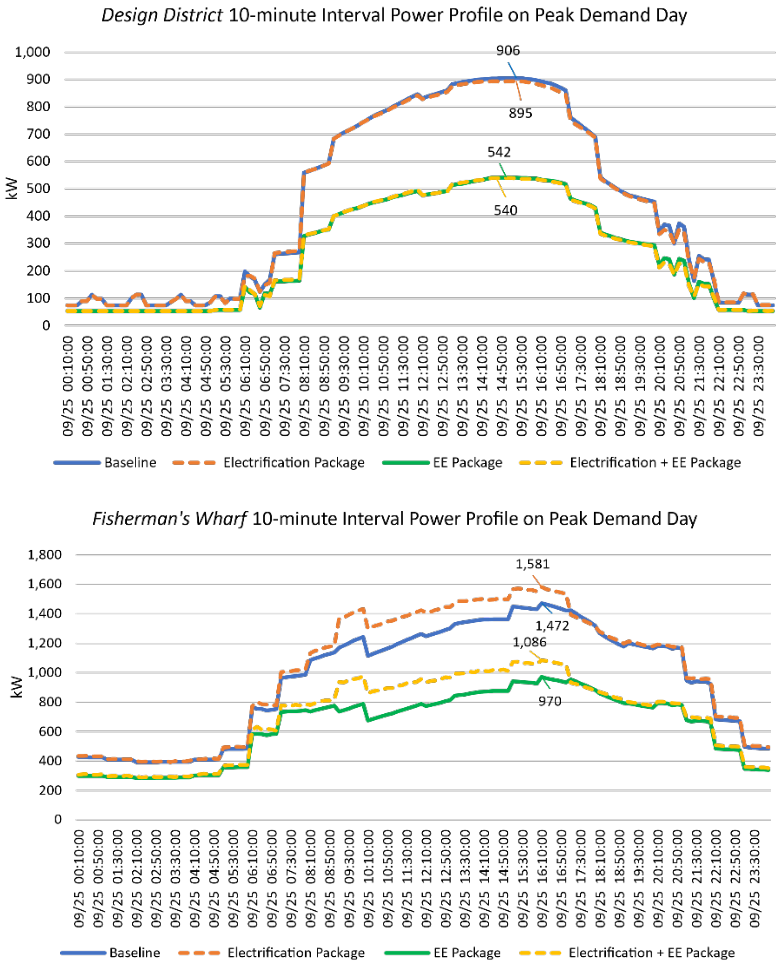


Figure 13. 10-minute interval load profiles on the peak electricity demand day for each scenario by each district (top: Design District; bottom: Fisherman's Wharf)

When all the buildings' peak electricity demands were aggregated by building type (Table 8), all building types except the medium office showed a higher peak electricity demand than the baseline when electrified. For retail and small office buildings, the peak demand time shifted from summer to winter, due to the increased electricity use for heating. Hotels and the restaurant had more electricity demand from the fuel switching for service hot water, cooking, and laundry. For large office buildings, the electrification does not change the peak demand time. As the central chillers for cooling remain the same in the large office buildings, there is no cooling system-related electricity usage change. There is a slight electricity increase from the service hot water from the HPWH system. For most medium office buildings, the electrification scenario did not change the peak electricity demand date, which occurred on September 25. The baseline of medium office buildings uses PVAV with DX coil for space cooling and hot-water coil for space heating; when it was electrified to ASHP systems with a higher COP, the cooling and fan energy were reduced. As the peak demand for medium office buildings happens during summer, the increase in electricity load from winter heating does not affect annual peak demand. The gas-powered service hot water loads in the medium offices are low compared with other building types, thus its electrification with high efficient HPWH results in minimal extra electric demand. These factors contributed to the medium offices' mild decrease (about 5%) in peak electric demand due to electrification.

Table 8. Peak electricity demand and reduction percentages compared to the baseline for each package by building type in each district

District	Building Type	Baseline	Electrification Package [MWh]	Reduction [%]	EE Package [MWh]	Reduction [%]	Electrification + EE Package [MWh]
Design District	Large Office	289	290	-0.2%	166	42.6%	178
	Medium Office	195	186	4.8%	134	31.6%	131
	Retail	368	464	-26.0%	235	36.1%	339
	Small Office	60	72	-20.2%	33	44.7%	52
Fisherman's Wharf	Restaurant	15	28	-86.7%	12	21.8%	25
	Medium Office	84	80	5.2%	51	39.5%	57
	Retail	489	529	-8.3%	201	58.8%	376
	Small Hotel	969	1,086	-12.1%	742	23.4%	888

Fuel switching from natural gas to all-electric systems significantly reduced CO_2 emissions for the buildings in each district. The electrification scenario shows CO_2 emissions were reduced by 37% in the Design District and by 46% in Fisherman's Wharf (Figure 14 and Table 6). As Table 4 depicts, the CO_2 emission factor from electricity (93 $kgCO_2e/MWh$) is about one-third of that from natural gas (277 $kgCO_2e/MWh$). As Table 9 shows, there were more fuel switching buildings (hotels and restaurants) in Fisherman's Wharf, which resulted in more CO_2 emissions reductions in Fisherman's Wharf than in the Design District.

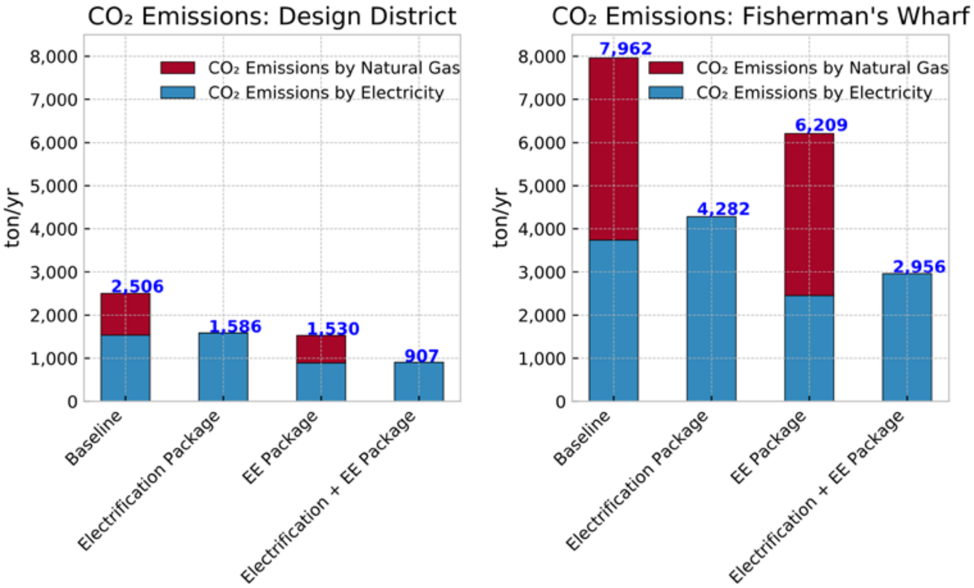


Figure 14. Annual CO_2 emissions for each scenario by each district (left: Design District; right: Fisherman's Wharf).

Table 9. Annual CO_2 emissions and reduction percentages compared to the baseline for each package by building type in each district

District	Building Type	Baseline	Electrification Package [MWh]	Reduction [%]	EE Package [MWh]	Reduction [%]	Electrification + EE Package [MWh]	Reduction [%]
Design District	Large Office	726	572	21.3%	429	40.9%	315	56.7%
	Medium Office	477	293	38.5%	329	31.1%	169	64.6%
	Retail	1,176	621	47.2%	689	41.4%	367	68.8%
	Small Office	127	100	21.5%	82	35.2%	57	55.4%
Fisherman's Wharf	Restaurant	211	77	63.3%	176	16.2%	66	68.7%
	Medium Office	272	125	54.1%	194	28.7%	70	74.2%
	Retail	1,651	893	45.9%	880	46.7%	344	79.2%
	Small Hotel	5,828	3,187	45.3%	4,957	14.9%	2,476	57.5%

At the district level, the timing of coincident peak electric demand remained in September (Figure 13 and Table 6) for the baseline and electrification scenarios. For some individual buildings the peak demand may shift from September to winter or early summer. For example, in the Design District, most (nine) retail buildings and half (three) of the small offices changed the timing of peak demand from September (baseline) to February (electrification). For Fisherman's Wharf, most retail buildings changed peak demand to February; most hotels changed peak to June, July, or early September; and the restaurant peak changed to June. This is one of the main reasons the district-level peak demand does not increase dramatically with electrification.

3.2.2 EE retrofit scenario results

The EE retrofit scenario shows reductions in annual electricity consumption and natural gas from the baseline conditions. The annual site energy consumption was reduced by 41% for the Design District and by 28% for Fisherman's Wharf (Figure 10, Table 6). The Design District had electricity savings of 42% and natural gas savings of 34%. Fisherman's Wharf had electricity savings of 34% and natural gas savings of 11%.

The lighting measure package with the LED retrofit and daylight and occupancy-based lighting control contributed to about 60% of the energy savings from the baseline. The smart electric plug load control saved 16% of the electric equipment energy use in the Design District office buildings. Demand controlled ventilation, economizer retune, infiltration reduction, and ERV system contributed to about 30% HVAC system energy savings. Low-flow water faucets and showerheads can save about 10% of the service hot water energy usage for hotel and office buildings.

The peak electricity demand decreased by 40% (from 906 kW to 542 kW) in the Design District and by 34% (from 1,472 kW to 970 kW) in Fisherman's Wharf (Figure 12, Figure 13, and Table 6). Fisherman's Wharf had a lower peak electricity reduction compared to the Design District because Fisherman's Wharf has a restaurant with heavy gas use for cooking and water heating.

The annual CO_2 emissions were reduced by 39% in the Design District and by 22% in Fisherman's Wharf, due to the energy efficiency retrofits (Figure 14 and Table 6).

3.2.3 The combined Electrification + EE retrofit scenario results

The combined electrification and EE retrofit scenario led to reductions of 51% of annual site energy use for the Design District and 43% for Fisherman's Wharf (Figure 10 and Table 6). Although the electrified end uses consume electricity, the net impact was electricity savings of 41% for the Design District and 21% for Fisherman's Wharf, due to the efficiency measures.

The peak electricity demand (Figure 12, Figure 13, and Table 6) in the Design District declined from a 906 kW baseline to 540 kW (by 40%), similar to the 542 kW peak demand for the EE retrofit-only scenario. Efficient electrification of Fisherman's Wharf reduced the peak electricity demand there from a 1,472 kW baseline to 1,086 kW (by 26%).

The combined scenario shows annual CO_2 emissions were reduced significantly, by 64% for the Design District and by 63% for Fisherman's Wharf (Figure 14 and Table 6).

Table 7 shows that retail and medium office buildings had the largest site energy reductions from the combined Electrification + EE retrofit scenario. The largest peak electricity demand reduction (39%) was observed for the large office buildings in the Design District (Table 8). All buildings can achieve greater than 50% reduction of CO_2 emissions from the combined package (Table 9).

3.3 Comparison of simulated peak electric demand with PG&E's grid capacity data

According to PG&E Distribution Resource Planning Data Portal user guide, when adding new load to a location it is necessary to evaluate three considerations: existing line capacity, future feeder capacity, and future capacitor bank capacity at the substation. Since peak demand decreased after electrification in the Design District, we concluded that existing infrastructure can accommodate the load. This analysis is limited to the feasibility of electrification of Fisherman's Wharf within the line capacity available at the time the map data were published. Due to the unknown connectivity between the grid and the buildings as mentioned above, all the feeders intersecting the district were assumed to serve the district and used to analyze the potential impact of the electrification. It is worth noting that PG&E constantly updates the ICA data. The data used for analysis was acquired in December 2021.

First, the "Load Hosting Capacity" from the ICA results for each line segment was evaluated. Since each feeder connected to the selected district served multiple lines, the minimum load capacity of lines within each feeder was used for conservative evaluation. As shown in Table 10, one of the feeders in the Fisherman's Wharf district was reported by PG&E as having zero capacity for all line segments, which might be an error or omission, or may suggest that there was no capacity for any new load to be added. The minimum line capacity within the other feeder is 840 kW, which is sufficient to cover the 109 kW increase of peak load after the electrification.

Table 10. Line capacity evaluation for Fisherman's Wharf

Feeder ID	District	Min. Line Capacity (kW)	Max. Line Capacity (kW)
022011111	Fisherman's Wharf	0	0
022801136	Fisherman's Wharf	840	2,650

The second step was to check if the feeders of interest had adequate capacity. PG&E's Grid Needs Assessment dataset provided predictive Facility Rating and Facility Loading for the future five years for each feeder. The difference between the two values is the available load capacity of the feeder, as shown in Table 11. The feeder with enough line capacity (022801136) is forecast to have enough capacity for the future five years. Within the period of available data, the additional load from electrification can be accommodated.

Table 11. Load capacity forecast for the Fisherman's Wharf feeder from 2021 to 2025

Feeder ID	District	Capacity 2021 (kW)	Capacity 2022 (kW)	Capacity 2023 (kW)	Capacity 2024 (kW)	Capacity 2025 (kW)
022801136	Fisherman's Wharf	2,470	1,450	430	460	500

Apart from the line segments and the feeders, banks associated with the substation also need to have adequate capacity over the future five years. However, no published records were found characterizing banks associated with the substation for feeder 022801136 for Fisherman's Wharf, so we are unable to evaluate whether electrification may cause any issue with the banks. Overall, within the limits of available data, if buildings in Fisherman's Wharf were served by feeder 022801136, existing grid capacity is adequate to cover the increase in peak electric load due to the electrification of buildings.

4. Discussion

4.1 Summary of results and findings

When the baseline buildings were fully electrified, increases of 0.5 GWh and 5.8 GWh in annual electricity consumption were projected for the Design District and Fisherman's Wharf district, respectively. However, elimination of gas loads resulted in a net reduction in annual site energy use of 3 GWh (15%) in the Design District and 9.4 GWh (17%) in Fisherman's Wharf. Most important to this study, Fisherman's Wharf showed a 109 kW (7.4%) increase in peak electric demand when electrified without other efficiency measures, while a marginal 1.2% decrease was projected for the Design District. Based on distribution grid capacity metrics published by PG&E, existing power infrastructure serving Fisherman's Wharf can accommodate the 109 kW increase in electric demand in the electrification-only scenario. The electrification scenario shows annual CO_2 emissions are reduced by 37% in the Design District and by 46% in Fisherman's Wharf. Based on the method applied here, CO_2 emissions per unit of electricity are about 34% lower than those of natural gas, so fuel switching from natural gas end uses to electric systems significantly reduces the CO_2 emissions for the San Francisco buildings.

Looking at buildings by use type, the electrification scenario increased peak electric demand from the baseline buildings by 86.7% (restaurant), 8.3% to 26% (retail), 20.2% (small office), and 12.1% (hotel buildings). The medium-sized offices showed a 5.2% reduction in peak demand, while the large office buildings showed almost no changes (0.2%) in peak demand.

When the baseline buildings were retrofitted with energy efficiency measures, the annual site energy consumption was reduced by 41% for the Design District and by 28% for Fisherman's Wharf. The Design District had 42% electricity savings and 34% of natural gas savings. Fisherman's Wharf had electricity and natural gas savings of 34% and 11%, respectively. The peak electricity demand significantly decreased by 40% (from 906 kW to 542 kW) in the Design District and by 34% (from 1,472 kW to 970 kW) in Fisherman's Wharf. The annual CO_2 emissions were reduced by 39% in the Design District and by 22% in Fisherman's Wharf, due to the energy efficiency retrofits.

When the combined electrification and EE retrofit scenario was applied to the baseline buildings, there were reductions of annual site energy use by 51% for the Design District and 43% for Fisherman's Wharf. Although fuel switching causes increased electricity usage, the EE package contributed to electricity savings of 41% for the Design District and 21% for Fisherman's Wharf. The peak electricity demand in the Design District declined from 906 kW to 540 kW (by 40%). Fisherman's Wharf reduced peak electricity demand from 1,472 kW to 1,086 kW (by 26%). The combined scenario shows annual CO_2 emissions are reduced significantly, by 64% for the Design District and by 63% for Fisherman's Wharf.

In summary, electrification of small and medium commercial buildings at district scale tends to increase electricity use and has varying effects on peak electric demand; in some cases the capacity of the local power grid (line segments, feeders, or banks) may need to be expanded if no significant efficiency improvements are implemented. However, the effect on peak demand depends on the composition of building types in the district, and may be offset by higher efficiency equipment for cooking, space conditioning, and commercial laundry, as well as building efficiency measures to reduce heating and cooling load and hot water use. While existing electric distribution equipment may be sufficient, electric infrastructure serving individual buildings with heavy gas end uses, such as restaurants, have more potential for challenges due to increases in electricity usage and peak electric demand if electrified. Further study of combinations of high-efficiency equipment and ventilation would offer helpful guidance for retrofits, as well as provide insight into the practicality of mitigating electric distribution upgrades via demand-side management. San Francisco buildings have greater benefits in CO_2 emissions reductions from electrification measures than some other areas do because of the relatively clean electricity supply. Electrification may shift the time (e.g., from summer to winter) when the peak electric demand occurs for individual buildings or entire districts, especially for baseline buildings with heavy gas use for space heating during winter.

A district's energy demand profiles of electricity and natural gas are determined by the composition of the buildings, their existing systems and equipment, and their efficiency levels. Results from this case study can inform strategy of decarbonization for similar commercial districts in similar climates. However, subject to the data availability, the bottom-up building energy modeling approach can be applied to all types of districts (e.g., residential, and mixed-use) in a city.

4.2 Policy implications

Energy efficiency retrofits can significantly reduce carbon emissions, energy use and peak electric demand. When efficiency is coupled with electrification, the combined mitigation strategy can reduce energy use and limit CO_2 emissions to emissions from electric generation, and even reduce peak demand of districts of buildings. Reducing peak demand helps to delay or prevent the need to upgrade existing grid infrastructure, which can be costly and slow. As an example, San Francisco's goal of net zero emissions by 2040 (starting from 2022 when its climate action plan was published) will require reducing emissions from buildings by an average of 5.6% annually.

Much can change in a decade and the authors defer to utilities regarding what urban infrastructure improvements are possible in coming years. Nonetheless, widespread electrification is a complex undertaking with many stakeholders and influences, and a fundamental risk management strategy is reducing or eliminating dependencies. Building owners, business districts, and policymakers can have greater confidence in the maintenance of existing infrastructure capacity. Rapid and widespread electrification goals are more likely to be met if they are not dependent on substantial investment in the grid. Understanding practical paths to achieving the City's emission reduction goals should contribute to San Francisco stakeholders' confidence the goals can be met with today's grid assets and established building technologies.

The current appliance-by-appliance or building-by-building approach to building decarbonization likely will not allow local governments to meet their climate and emissions goals in time and rely upon a low-wage industry that largely eschews permitting. Zonal decarbonization at the district or neighborhood level presents the opportunity to work with utilities to bring large capital investment, deployed by skilled labor capable of making high quality installations, and to leverage economy at scale to improve cost effectiveness of decarbonization. This aligns with the recommendations made by the industry (BDC, 2023). Camarasa et al. (2022) also pointed out, to achieve the 1.5°C global warming target, the building sector will need to employ a suite of strategies including new construction of net-zero carbon buildings, high rates of energy renovation in existing buildings, low-energy-consumption behavioral practices, development of new low-energy building technologies and appliances, deployment of centralized and decentralized renewable energy sources (RESs), and widespread electrification of building technologies. In the Existing Building Decarbonization Code, New Building Institute (NBI, 2022) estimated by requiring existing buildings to be more energy efficient, cities could cut about 30% of all urban emissions by 2050, which is an essential strategy to building decarbonization.

Integrating electrification into a suite of energy efficiency upgrades will save energy, utility cost, and carbon, and mitigating peak electrical loads can improve utilities' ability to predict and respond to demand. Predictability and moderation aid resilience for building systems and simplify planning to improve utility power grid reliability.

This example of district-scale modeling and analysis will help building portfolio owners understand the technical options for pursuing efficient electrification retrofits in their existing assets. It will also provide valuable insights to state and local policy makers who seek to decarbonize the existing building stock.

4.3 Limitations and future work

There are limitations in this simulation-based study. First, more than half the buildings do not have valid monthly energy use data, so their baseline models were not calibrated. Second, a limited number of multifamily buildings in or adjacent to the two districts (and likely connected to the lines and feeders serving the study areas) were excluded from the analysis. Third, published data characterizing power grid distribution line capacity data does not provide about individual building level equipment; assumptions that rely on aggregated grid metrics available from utility companies can provide directional indications informing policy analysis that would not otherwise be available to local officials, but assessments of this sort are conceptual, and cannot substitute for detailed engineering analysis necessary to maintain and operate grid infrastructure. Last, the individual buildings' electric service capacity is not available, so we cannot determine whether modifications to electric service lines, switchgear, or associated building-specific components may be necessary.

These limitations, especially the availability of the building energy use data and the power grid distribution and capacity data, unfortunately can apply to most buildings in a city. With the value of data being recognized by governments and policy makers, data sharing and transparency regulations can enable public access to such data to support policy related modeling and analysis. The modeling approach adopted in this case study is recommended for districts with adequate public data of buildings and local grid infrastructure. Collaborating with local utility provider and city government can address some of the data gaps.

Future work is to expand the modeling and analysis to other types of districts, including residential districts and mixed-use districts. The cost-effectiveness analysis of the efficiency upgrades and electrification also can be included in future. As the HVAC energy use of buildings highly depend on the local climate conditions, future studies can expand to other hot, cold, or mixed climate zones where cooling and/or heating energy demand can be significantly larger than that of buildings in a moderate climate such as San Francisco, leading to potentially quite different results from the three mitigation scenarios.

5. Conclusions

Two districts dominated by commercial buildings in San Francisco were selected to study how building electrification at the district scale influences annual building energy use and peak electric demand, as well as how energy efficiency retrofits can complement electrification to mitigate changes to peak electric demand, meeting the building decarbonization policy objectives within the capacity of the existing power grid infrastructure serving the districts. A simulation workflow was used to create EnergyPlus-based energy models for these buildings. The baseline models were automatically calibrated with available monthly utility bill data. Then three mitigation scenarios were evaluated: (1) the electrification scenario; (2) the energy efficiency scenario; and (3) the combined electrification and energy efficiency scenario.

Major findings from the study include:

- **The electrification scenario** increased annual electricity consumption but reduced the annual site energy usage, mainly due to replacing the inefficient natural gas furnaces and boilers with more energy efficient heat pumps for space heating and service water heating. Fisherman’s Wharf showed a 7.4% increase in peak electric demand due to electrification, which can be accommodated by the existing power grid, while the Design District showed a marginal decrease. The electrification scenario resulted in significant CO_2 emissions reductions mainly due to the clean electricity supply.
- **The combined electrification and energy retrofit scenario** led to significant reductions in the annual site energy use and peak electric demand and carbon emissions for both districts. The combined scenario resulted in annual CO_2 emissions reductions—by 64% for the Design District and by 63% for Fisherman’s Wharf.
- These results indicate that impacts of electrification depend on local building stock, and that **combining electrification and energy retrofits is an effective strategy to decarbonize buildings and decrease or avoid delays for modification of electric utility infrastructure**. This approach can not only reduce carbon emissions, but also

reduce or limit an increase in peak electric demand, which can help to avoid or delay local power grid capacity upgrades and significantly accelerate building electrification in cities. Outcomes from the study can inform city and utility in their planning of building decarbonization at district scale which is essential to meeting their carbon and climate goals.

The simulation-based bottom-up approach adopted in this study creates and calibrates detailed energy models for each of the buildings and their mitigation measures, which is powerful to consider context of each building and its energy systems, and is able to provide specific decarbonization recommendations of either individual measures or their packages to each building. However, the detailed building energy models need good characteristics and operational data as well as monthly energy consumption data of each building which may not be available for a large number of buildings. So this approach complements other approaches such as data-driven analytics or top-down building stock modeling and offer stakeholders choices considering their use cases, data availability, and experience with building energy modeling.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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