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Translating Climate Change and Heating System Electrification Impacts on Building Energy Use to Future Greenhouse Gas Emissions and Electric Grid Capacity Requirements in California

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Abstract

The effects of disruptions to residential and commercial building load characteristics due to climate change and increased electrification of space and water heating systems on the greenhouse gas emissions and resource capacity requirements of the future electric grid in California during the year 2050 compared to present day are investigated. We used a physically-based representative building model in EnergyPlus to quantify changes in energy use due to climate change and heating system electrification. To evaluate the impacts of these changes, we imposed these energy use characteristics on a future electric grid configuration in California using the Holistic Grid Resource Integration and Deployment model. With regards to greenhouse gas emissions, we did not observe a significant effect from climate change since the increase in load was met by using available excess renewable generation. The electrification of heating systems almost doubles electric grid greenhouse gas emissions, but reduces total emissions by 30-40% due to the near elimination of on-site natural gas usage. Climate change only prompted modest increases in grid resource capacity since the additional electric load generally occurred during times with available renewable generation. Electrification required greater capacity increases, due to the higher magnitude of load increases and lack of readily available renewable generation. This study 1) translates climate change and electrification impacts to system-wide endpoint impacts on future electric grid configurations and 2) highlights the complexities associated with the translation of building load impacts to system-wide endpoints of emissions and grid capacity requirements.

Keywords: Building Energy Demand, Electric Grid, Climate Change Impacts, Heating Electrification Effects

1. Introduction and Background

California, a series of executive orders and laws starting in the year 2002 have formalized renewable energy portfolio goals which specify the percentage of electric load that must be met with renewable energy by certain years [1, 2]. Many studies have studied how to meet these energy goals, focusing on determining the optimal mixture of low-carbon and renewable energy resources based on criteria such as cost, grid reliability, and environmental impact. The E3 PATHWAYS study [3] examined economy-wide technology transformation scenarios to meet the 80% reduction in greenhouse gases target by 2050. Studies conducted by LBNL and UC Berkeley utilized the SWITCH model to determine the most cost-effective energy technology investments in the electricity sector under different policy and technical constraints [4, 5]. The studies to date have considered changes in the energy demand based on factors such as policy objectives, improvements in equipment efficiency, and population growth.

However, in the context of electric grid resource planning, disruptive changes in the characteristics of building energy demands due to climate change and/or increased electrification have not been previously considered in the literature. These disruptions may affect the ability of the system to meet decarbonization targets. For example, increased loads due to climate change can affect the scale of grid resources required to achieve a given greenhouse gas reduction target. In contrast, the electrification of space and water heating systems has the potential to reduce the reliance of residential and commercial heating needs on fossil fuel resources (natural gas, kerosene, etc…). Electrified heating devices are also more energy efficient compared to fuel-based boilers. However, installing these systems introduces new loads to the electric grid, which may call for adjustments in the capacity of grid resource installations.

The impact of climate change on building energy demand has been extensively studied in recent years. In California, Sathaye et al. [6] found that peak loads increased by up to 22% comparing year 2100 levels with year 2003-2009 levels due to warming temperatures. Xu [7] found that total building energy consumption in California is expected to increase by up to 8% in the year 2100 due to increases in space cooling loads in response to climate change. Huang [8] applied Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) climate data to analyze the impact of climate change on the characteristics of building energy demands, finding that individual climate zones experience between -17% and 21% changes in their annual energy consumption. Wan [9] investigated climate change impacts in Chinese cities, finding that overall greenhouse gas emissions increased by between 0.5% to 4.3% by 2100 using a present-day electricity mix. Zhou [10] modeled climate change impacts on buildings across the United States, finding that depending on location total energy use can vary from -10% to +10% by 2095. Spandagos [11] also assessed climate change impacts on Asian cities, finding that total energy consumption increased by between 9.5% in Hong Kong to 23.3% in Tokyo due to climate change.

Many studies have also been conducted for other regions of the world, and range from individual buildings to regions. Dirks et al [12] demonstrated a novel, detailed method for characterizing building peak demands called the Building ENergy Demand (BEND) model. Shaik et al [13] examined how climate change can impact different energy sectors in different U.S. regions from a price perspective. Pilli-Sihvola [14] also investigated the impacts of climate change on electricity consumption in Europe from a cost of electricity perspective. Petri and Caldiera [15] investigated impacts of climate change on residential heating and cooling in the U.S. from the perspective of heating and cooling degree days. Shibuya and Croxford [16] analyzed climate impacts on an office building in Japan, finding that total loads increase by up to 27.2% in the year 2090 in Tokyo. Shen [17] focused on 4 climactically different cities across the U.S.

using IPCC AR4 data and found that different regions will respond differently to climate change. Mathew et al. [18] evaluated the impact of weather variance on annual total source EUI finding the annual source EUI has an overall variation range of about 2.5%. Additional work in these and related areas have been carried out for China [11, 19], Turin, Italy [20], and Portugal [21]. Many studies have also focused on other aspects such as differences by building type and building design optimization [22-24].

Efforts to increase the electrification of end uses are increasing in California in order to better synchronize these loads with renewable electricity generation and the effects of building system electrification have also been studied from different perspectives. Roux [25] conducted a life cycle analysis of climate change and electric heating effects on greenhouse gas emissions from buildings and found that the total carbon footprint increased by between 14% and 43% depending on the life cycle analysis method. Protopapadaki [26] investigated the impact of heat pump deployment on residential distributions in Belgium, concluding that rural feeders could overload at 20-30% heat pump penetration. Raghavan et al. [27] studied scenarios for decarbonizing residential water heating in California, concluding that the carbon intensity of the electric grid must decline alongside increases in heating electrification to facilitate greenhouse gas reductions. Teng et al. [28] investigated the flexibility benefits of electrified heating in the UK, concluding that dispatching these loads can reduce electricity system costs. Eyre and Baruah [29] also investigated heating system electrification in the UK but found that peak winter electricity demand increased up to 30% from increases in electrification.

Most analyses of climate change and electrification impacts on building loads focus on impacts on the building itself (e.g. building energy consumption or peak load) without explicitly identifying the system-wide impacts on energy infrastructure or environmental outcomes. At best, these system-wide impacts are discussed or calculated indirectly. In addition, the perturbations of climate change and heating system electrification are often studied using a present-day or near-term electricity resource mix. However, in many areas, the electricity resource mix will be different once climate change and large-scale electrification effects become significant. In this context, the novelty of this work is twofold:

- This study imposes the impacts of climate change and building electrification on simulations of the electric grid in order to characterize future environmental impacts and electricity system needs. This translation to explicit system-wide impacts is important in decarbonization and resource adequacy planning, and may not be accounted for when system dynamics are ignored.
- This study characterizes climate change and heating electrification impacts for a future electric grid configuration as opposed to a current or near-term configuration. It is important to use a grid configuration which is representative of the system during the years when climate change and electrification impacts are expected to take place (year 2050), as this can exhibit very different results than many analyses which focus on impacts to a current or near-term grid configuration.

The results from the study provide quantitative assessment of impact of electrification and climate change on building electric demand, electric grid capacity, and GHG emissions, which can inform California state policy and pathway to meet the state’s GHG reduction goal. Detailed policy implications are discussed at the end of the paper.

2. Methodology

2.1. Methodology Outline

We obtained representative building prototypes for residential and commercial buildings from the U.S. Department of Energy Building Energy Codes Program, developed by Pacific Northwest National Laboratory (PNNL) and the National Renewable Energy Laboratory (NREL) for the EnergyPlus simulation program. We obtained EnergyPlus weather perturbations from downscaled climate data representing each of the California's sixteen Building Climate Zones [30]. With EnergyPlus, we simulated building prototypes under both historical and future (year 2050) climate conditions in each climate zone. Additionally, scenarios with space and water heating systems representing present-day systems and fully-electrified systems are examined. From the simulations, we obtained the electric load profiles and energy demands under present-day, climate change, and heating system electrification scenarios. Finally, we imposed these responses as load changes on the electric grid, and captured the response of the electric grid using the Holistic Grid Resource Integration and Deployment (HiGRID) model, which is detailed in Section 2.5. These steps are presented in detail in this section below. The methodology is visualized in Figure 1:

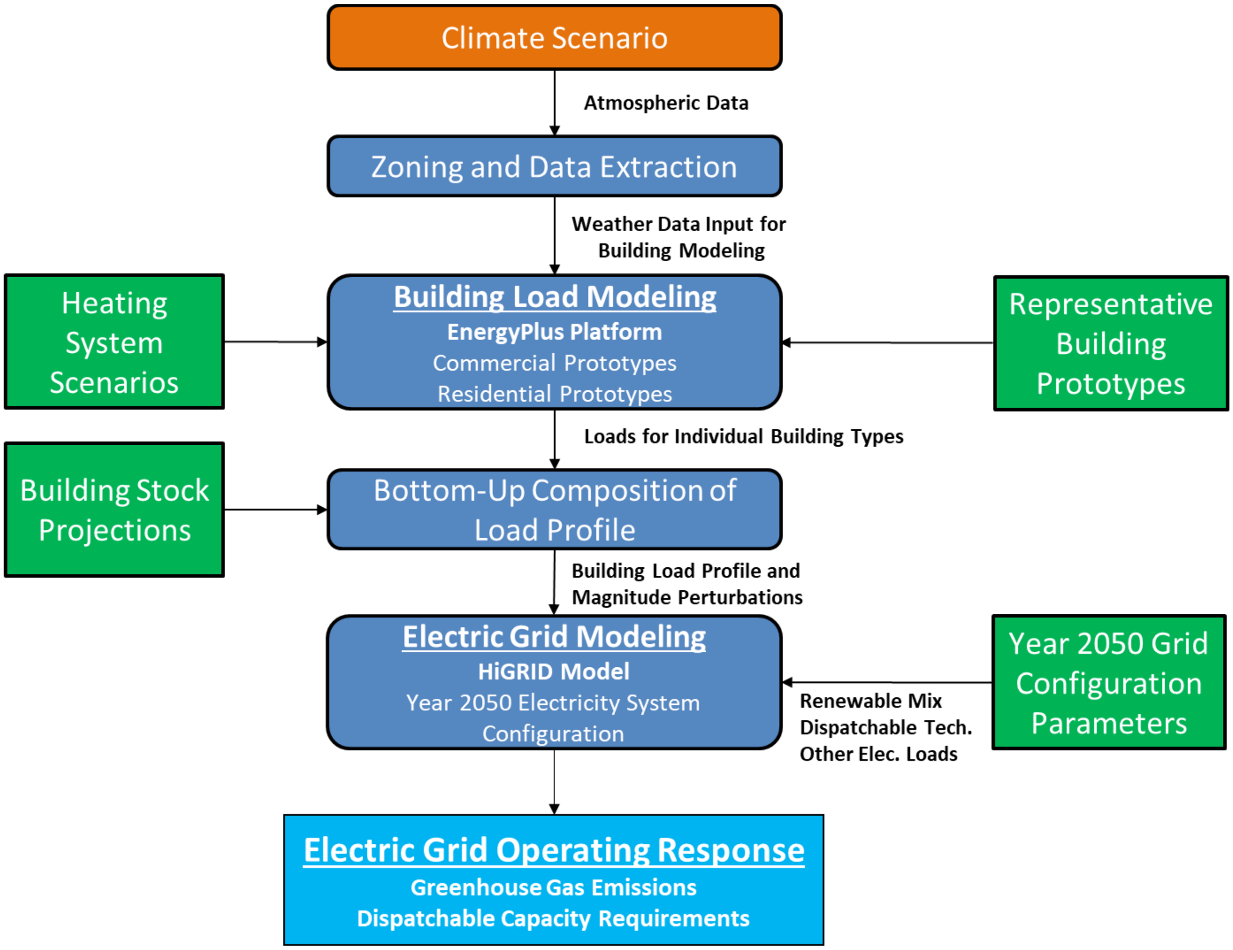

Figure 1 – Overview of the Study Methodology

It is very important to note that this study focuses on how the effects of climate change and heating system electrification on building energy use characteristics manifest as **system-wide** endpoint impacts. The analysis presented here isolates the effect of changes in building energy use characteristics.

We used the EnergyPlus platform for building load modeling. EnergyPlus is an open-source program that models heating, ventilation, cooling, lighting, water use, renewable energy generation, and other building energy flows. The EnergyPlus platform requires two primary input files to simulate the hourly-resolved, year-long energy use profiles of an individual building:

- A **building prototype model** representing the physical dimensions and characteristics of the building to be analyzed.
- A **weather data input file** representing the hourly profile of weather parameters in the location surrounding the building.

This study draws on a number of available prototype building models and weather data files to carry out the present analysis. These are summarized in Table 1:

Table 1 - Datasets Used in EnergyPlus

Dataset	Information	Purpose	Source
Building Energy Codes Program Residential Building Prototypes	Set of 32 Residential Building Prototype Models	Simulated to provide hourly energy use profiles of residential buildings	U.S. Department of Energy Building Energy Codes Program [31]
Building Energy Codes Program Commercial Building Prototypes	Set of 16 Commercial Building Prototype Models	Simulated to provide hourly energy use profiles of commercial buildings	U.S. Department of Energy Building Energy Codes Program [32]
Title 24 Representative Weather Files	Representative historical weather data in EnergyPlus format for each of California's Title 24 climate zones	Represents weather conditions under which the building prototypes operate without climate change	EnergyPlus Weather Database, California Energy Commission [33]
Downscaled Localized Construction Analogs (LOCA) and Variable Infiltration Capacity (VIC) Climate Outputs	Temporally and spatially resolved climate parameter data for California for different climate models	Used to perturb the Title 24 Representative Weather Files to create EnergyPlus weather inputs representing climate change	LOCA [34], VIC [35]

We provide a description of the building prototypes is provided in the Supplementary Information (Tables S1-3).

A key assumption in utilizing the listed building prototypes is that the average representative building in year 2050 is represented by a building which complies with current state-of-the-art codes. In the real building stock, buildings are distributed across different vintages, and the turnover of the building stock is relatively slow. Buildings that were constructed up to 100 years ago are still in operation along with buildings which were recently constructed. In addition, any older buildings have had retrofits which might have resulted in reduced energy consumption. Given this variability, to represent the energy consumption of an average currently-operating building, it would have energy consumption profiles which are larger than those of recently constructed buildings and smaller than those of older legacy buildings. In this context, the key assumption used in this study is reasonable given the age of the existing building stock and current levels of efficiency. Additionally, there is no reliable way of predicting what the building codes will be in future years, especially over the long-term timeframe considered in this study, much less to develop building prototype models that are representative of the energy use characteristics of those future buildings. Therefore, this is the most reasonable representation of the future building stock that can be obtained for the scope of this analysis. Overall, however, this assumption is not expected to affect the overall trends and takeaways of the results, but only their specific numerical extent.

The analytical procedure is outlined into the following steps:

1. For each Title 24 Building Climate Zone:
    a. Create EnergyPlus weather files representing climate change effects by perturbing historical EnergyPlus with LOCA-downscaled climate change projections.
    b. Simulate each residential and commercial building prototype in EnergyPlus to obtain hourly-resolved electric load and fuel use with weather files representing weather under historical and future climate change conditions
2. Determine the proportion of each residential and commercial building type in the total building stock using literature data, and determine the contribution to the total statewide load in each Title 24 Building Climate Zone based on population.
3. Compose the statewide residential and commercial sector load profile by combining the load profiles of individual buildings in the determined proportions of the previous two steps under historical and climate change weather conditions.
4. Simulate the behavior of the electric grid under the resource mix projected for year 2050 in response to the changes in residential and commercial load profiles due to climate change and/or electrification
5. Characterize the response of total system greenhouse gas emissions and dispatchable capacity requirements from grid simulations due to climate change and/or electrification impacts on residential and commercial buildings.

2.2. Calculation of Weather Conditions under Climate Change for EnergyPlus Simulations

An overview of the approach to translating changes due to climate change into EnergyPlus is presented schematically in Figure 2:

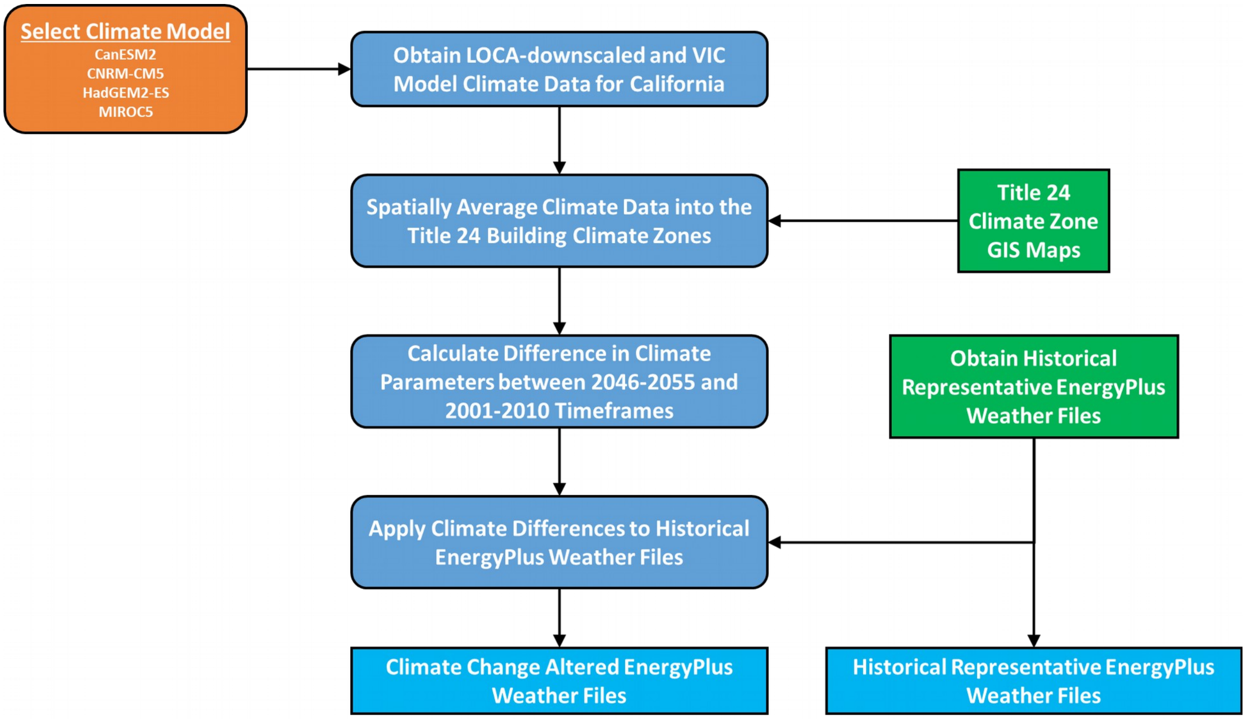

Figure 2 - Schematic of Approach to Calculate Weather Conditions under Climate Change for EnergyPlus

For this study, we followed the California Energy Commission's recommendation for using four climate models, CanESM2, CNRM-CM5, HadGEM2-ES, and MIROC5, under IPCC's Representative Concentration Pathway (RCP) 8.5 forcing scenario. These four climate models were chosen by the California 4th Climate Assessment to represent the spectrum of climate change behaviors projected to occur in the state [36]. The HadGEM2-ES model represents warm/dry climate behavior, CNRM-CM5 represents cool/wet climate behavior, CanESM2 represents a balance between the HadGEM2-ES and CNRM-CM5, and the MIROC5 model represents a more variable behavior spanning the range covered by the other three models. For each of the climate models, we obtained precipitation depth, dry bulb temperature data from the Localized Constructed Analogs (LOCA) downscaled climate model simulations [34] and corresponding relative humidity and wind speed output from the VIC hydrological model [35]. We averaged each climate parameter from the original 1/8th degree resolution over each of the California Title 24 Building Climate Zones, as presented in Figure S1 of the Supplementary Material.

We obtained representative historical weather files for EnergyPlus from the EnergyPlus database for each Title 24 Building Climate Zone [37]. The weather parameters obtained are listed in Table S4 of the Supplementary Material. We used key parameters driving building energy use overlapping between EnergyPlus and the climate models. These are presented in Table S5 of the Supplementary Material.

The climate change scenario is represented by the years of 2046-2055 and compared to a historical baseline of 2001-2010. For each Title 24 Building Climate Zone, the difference between the climate change scenario and the historical baseline is applied to perturb each of the parameters from the observational data. From the results, we created weather files representing climate change conditions for use in EnergyPlus:

$$\Delta x_{cc} = x_{mavg,2046-2055} - x_{mavg,2001-2010} \quad (1)$$

$$x_{cc} = x_{aavg,2001-2010} + \Delta x_{cc} \quad (2)$$

Where the “x” variable represents the following parameters:

- T = Dry Bulb Temperature
- RH = Relative Humidity
- Td = Dew Point Temperature
- P = Precipitation Depth

The subscripts assigned to each variable represent:

- Δx_{cc} = The modeled difference in parameter x between the future period affected by climate change and the historical baseline period
- $x_{mavg,2046-2055}$ = Modeled average parameter x value for the period spanning 2046-2055 for each model.
- $x_{mavg,2001-2010}$ = Modeled average parameter x value for the period spanning 2001-2010 for each model.
- $x_{aavg,2001-2010}$ = Observed parameter x value for the period spanning 2001-2010.

This process yields EnergyPlus weather files representing local weather under climate change for each Title 24 Building Climate Zone, climate model.

2.3. Simulation of Building Prototypes in EnergyPlus under Historical and Climate Change Conditions

With the weather files from Section 2.2, we simulated each of the 54 residential and commercial building prototypes in EnergyPlus. For each combination of climate model, climate zone, and building type, we obtained:

- The hourly-resolved annual electric load profile
- Annual fuel usage by building type
- Annual energy demand by end-use

We used these results to build up the aggregate residential and commercial load and demand profiles for each region, as described in the next section.

2.4. Bottom-Up Composition of Residential and Commercial Building Electric Load and Energy Demands

We used the distribution of buildings by type in California to compile the individual profiles from section 2.3 to compose the electric load and energy demand in each climate zone and subsequently for the entire state. This process is described schematically for a single climate zone in Figure 3.

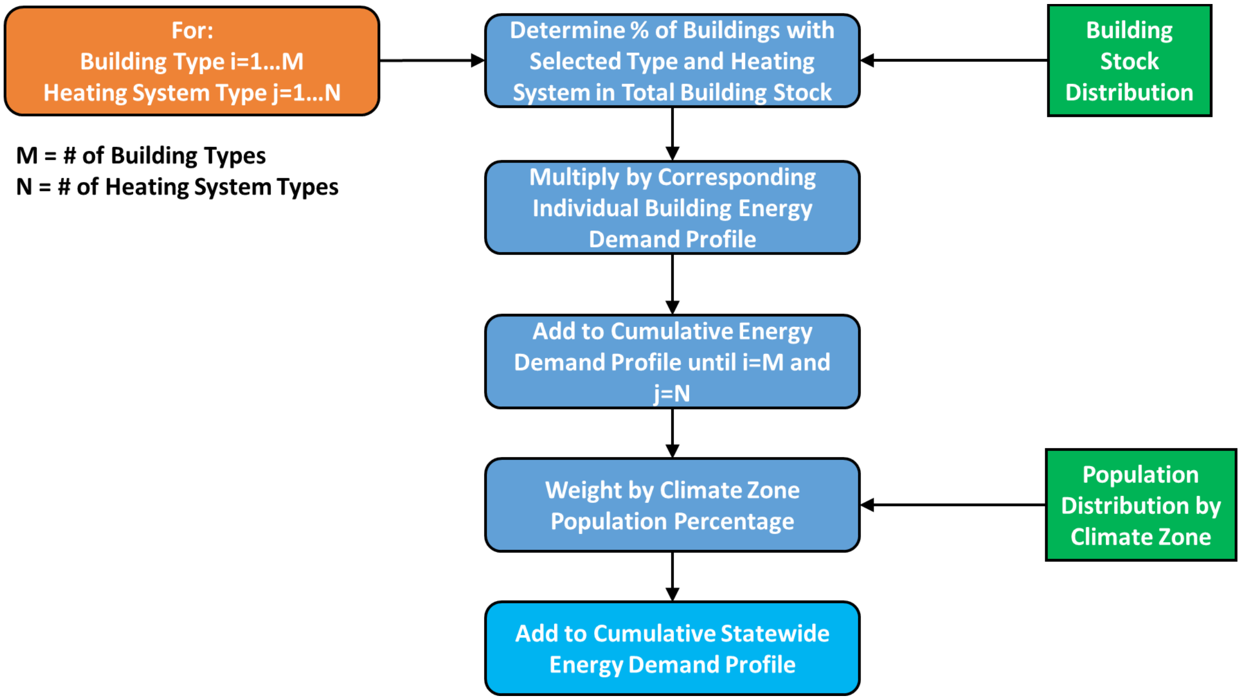

Figure 3 - Process for Bottom-Up Composition of Building Energy Demand Profile in a Single Climate Zone

This process was repeated for each climate zone until all of the 16 climate zones were accounted for, producing the statewide energy demand profile. We generated the statewide energy demand profiles for each climate model and for the historical observations.

2.4.1. Residential Buildings

In this study, we examined two scenarios for the heating system distribution. The first uses distributions obtained from the 2014 PNNL survey and the 2009 California Residential Appliance Saturation Survey (CRASS), as described by “Base” in Table 2. For each U.S. Census Division, we used the heating system type and foundation system type distributions provided by PNNL for new single-family and multi-family homes [38]. This is consistent with the key assumption of this study that the building codes representing the average 2050 building fleet will be equivalent to the characteristics of current-day new construction. For single family homes, we also obtained California-specific distributions from for CRASS heating system type [39].

The second simulates a fully electrified residential sector where all heating systems are converted to high efficiency electric heat pumps, as described by "Electrified” in Table 2. Additionally, the distribution of residential buildings by heating type are presented by foundation type in

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Table 2 - Heating system distribution for residential buildings

Heating System Scenario	**Heating System Type** [%]	**Single Family**	**Multi Family**
Base	Electric Heat Pump	1.04	14.9
	Gas Heating	89.5	84.2

	Oil Heating	8.3	0.2
	Electric Resistance Furnace	1.04	0.8
Electrified	Electric Heat Pump	100	100

Table 3 - Foundation type distribution for residential buildings

Foundation Type [%]	**Single Family**	**Multi Family**
Slab	37	37
Heated Basement	8.9	8.9
Unheated Basement	3.1	3.1
Crawlspace	51	51

Since distributions are unavailable for each climate zone, we assumed all Title 24 Building Climate Zones would have the same distributions. We weighted the contribution of each climate zone to the statewide distribution by population, which we calculated by combining ZIP code data from each climate zone [33] with population size in each ZIP code from the U.S. Census American Fact Finder [40] (see Table S6 of the SI).

We used data from the 2009 U.S. Energy Information Administration Residential Energy Consumption Survey (RECS) [41] to obtain the distribution of housing units in the California by single-family and multi-family categories. Maintaining the distributions by heating system type, foundation system type, and population, we aggregated and scaled the load profiles for the single-family and multi-family building prototype are using the number of housing units to obtain statewide profiles for electric loads and energy demands:

$$l_{CZ,SF} = \left[\sum_j \sum_i L_{ij} \cdot w_i \cdot w_j \right]_{SF} \cdot Pop_{dist,CZ} \tag{3}$$

$$l_{CZ,MF} = \left[\sum_j \sum_i L_{ij} \cdot w_i \cdot w_j \right]_{MF} \cdot Pop_{dist,CZ} \tag{4}$$

$$L_{SF} = \sum_{CZ} l_{CZ,SF} \cdot N_{SF} \tag{5}$$

$$L_{MF} = \sum_{CZ} l_{CZ,MF} \cdot N_{MF} \tag{6}$$

$$L_{CA,res} = L_{SF} + L_{MF} \tag{7}$$

Where:

- $l_{CZ,SF}$ = the electric load of a representative single-family building from climate zone CZ to the total residential electric load. This accounts for heating type and foundation type distributions and creates a single representative building for the zone.
- $l_{CZ,MF}$ = the electric load of a representative multi-family building from climate zone CZ to the total residential electric load. This takes into account the distributions by heating type and foundation type and creates a single representative building for the zone.

- L_{ij} = The electric load profile for the residential prototype building with heating system i and foundation type j
- w_i = The fraction of residential buildings with heating type i
- w_j = the fraction of residential buildings with foundation type j
- $Pop_{dist,CZ}$ = the fraction of total population in each climate zone
- N_{SF} = the number of single-family housing units
- N_{MF} = the number of multi-family housing units
- L_{SF} = The total statewide electric load profile for single-family residences
- L_{MF} = The total statewide electric load profile for multi-family residences
- $L_{CA,res}$ = Total statewide electric load profile for the residential sector

We also used this process to obtain the fuel usage and total site-level energy demands, under historical and climate-change affected conditions. For this analysis, we scaled the outputs of the historical conditions case to match the year 2010 residential electricity consumption and obtain a scaling factor, which was then applied to the climate change condition outputs. This was done to ensure that both current and future conditions had a consistent scale and changes between them were due to climate change and/or electrification only. This is necessary because building prototypes used in this study are larger than the average size of the actual buildings of the same type in California.

2.4.2. Commercial Buildings

For commercial buildings, we obtained data on the building stock by type from two sources: 1) the California Commercial End-Use Survey (CEUS) [42] and 2) the U.S. Energy Information Administration Commercial Buildings Energy Consumption Survey (CBECS) [43]. The CEUS database provided information for floorspace of different commercial building types in the state. The categories provided in the CEUS database, however, are slightly different than the types of prototype buildings used in this study. We used data from CBECS for the West census region to supplement the CEUS data regarding the distribution between building types that the CEUS database aggregates. A listing of the CEUS categories used in this study, their correspondence with the ASHRAE commercial building prototypes, and the ratios of the ASHRAE commercial building types in the CEUS categories are presented in Table 4:

Table 4 - Distribution of commercial building types for California used in this analysis

CEUS Category	Floorspace (kSq. m)	ASHRAE Building Prototype	Ratio in Category by floorspace	Source
Health	21609.80	Hospital	0.57	EIA CBECS West
		Out-Patient Care	0.43	EIA CBECS West
Large Office	61355.84	Office Large	1.00	N/A
Lodging	25087.90	Apartment High Rise	0.25	Assumed
		Apartment Mid Rise	0.25	Assumed
		Hotel Large	0.25	Assumed
		Hotel Small	0.25	Assumed
Refrigerated Warehouse	8875.95	Warehouse	1.00	N/A
Restaurant	13832.51	Restaurant Fast Food	0.50	EIA CBECS West
		Restaurant Sit Down	0.50	EIA CBECS West
Retail	65222.83	Retail Stand Alone	0.47	EIA CBECS West

		Retail Strip Mall	0.53	EIA CBECS West
School	41351.68	School Primary	0.50	Assumed
		School Secondary	0.50	Assumed
Small Office	33592.24	Office Medium	0.50	Assumed
		Office Small	0.50	Assumed
Warehouse	51483.68	Warehouse	1.00	N/A

We assumed the share of floorspace between the ASHRAE commercial building prototypes in the categories of Lodging, School, and Small Office since data for this breakdown are unavailable for California. For this analysis, this set of commercial buildings is taken to represent the entire commercial sector. We also assumed the distribution of commercial buildings by type is assumed to be the same in each Title 24 Building Climate Zone and the contribution of each climate zone to the total is weighted by population. Scaling up of the commercial building loads to represent statewide levels was done to match total commercial floorspace instead of number of buildings. The process of calculating the statewide commercial electric loads and energy demands are described as follows:

$$l_{CZ,Com} = \sum L_k \cdot w_k \cdot Pop_{dist,CZ} \tag{8}$$

$$A_{CZ,Com} = \sum A_k \cdot w_k \tag{9}$$

$$L_{CA,com} = \sum l_{CZ,Com} \cdot \frac{A_{CZ,Com}}{A_{total}} \tag{10}$$

Where:

- $l_{CZ,Com}$ = the electric load of a representative commercial building from climate zone CZ to the total residential electric load. This takes into account the distributions by commercial building type used in each zone.
- L_k = The electric load profile of commercial building type k
- w_k = The fraction of commercial building type k in the total by floorspace.
- $Pop_{dist,CZ}$ = the fraction of total population in each climate zone
- $A_{CZ,Com}$ = the area of the representative commercial building from climate zone CZ to the total commercial electric load. This takes into account the distributions by commercial building type used in each zone. Since we were considering the distributions by building type in each zone as consistent between zones, this term is the same in all climate zones.
- A_k = The area of commercial building type k in the total by floorspace (sq.m)
- A_{total} = The total floorspace of commercial buildings in California (sq.m)
- $L_{CA,Com}$ = Total statewide electric load profile for the commercial sector

This process was also carried out to obtain the fuel usage and total site-level energy demands, under historical and climate-change affected conditions.

Similar to the residential sector, a scenario is also included where six of the commercial building prototypes are fully electrified, representing 70.5% of the commercial floorspace. The details of the systems which were electrified are available in Table S7 of the Supplementary Material.

2.5. Electric Grid Modeling and Future Grid Configuration

We imposed the statewide hourly electricity demand profiles for each of the climate cases: historical and climate change represented by four climate models as electric loads on the electric grid in the year 2050. Greenhouse gas emissions and dispatchable resource capacity requirements are calculated as outputs of an electric grid simulation. We also repeated this process for the cases where the residential and commercial buildings are electrified. Schematically, this is presented in Figure 4:

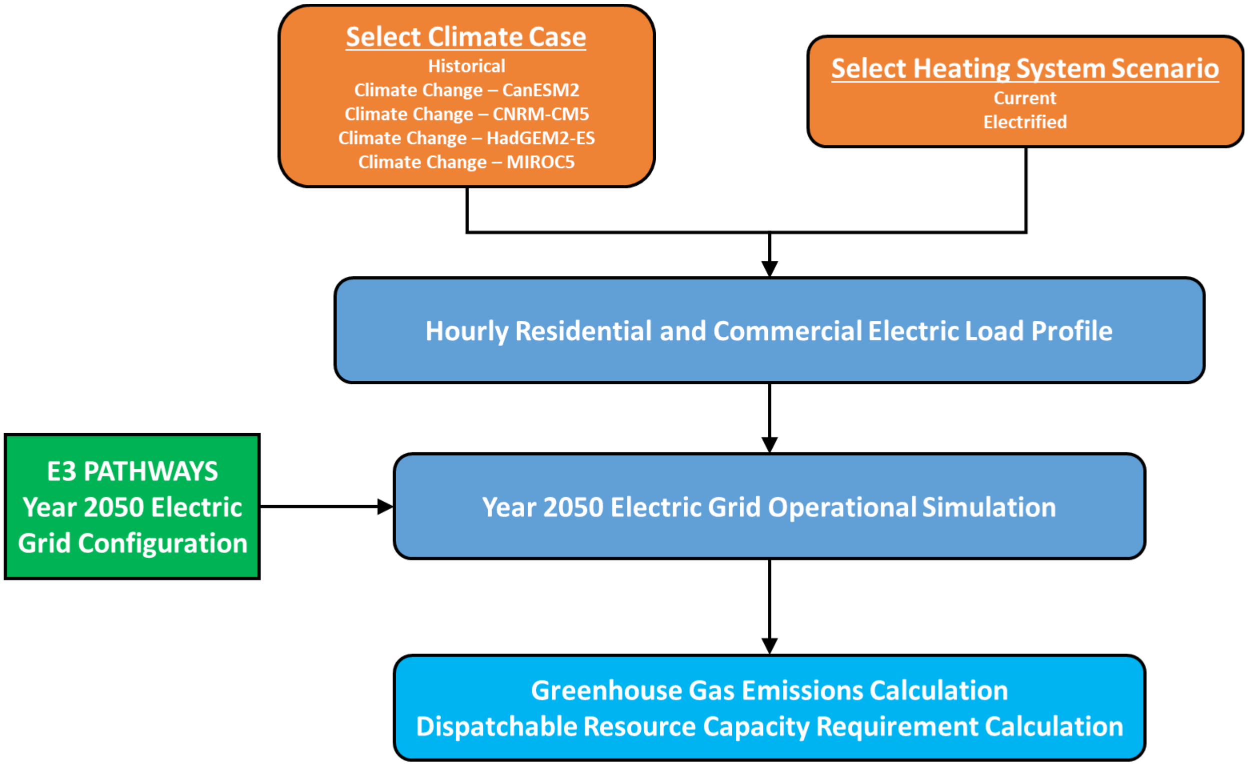

Figure 4 - Schematic Representation of Imposing Climate Change and Electrification Affected Load Profiles on the Year 2050 Electric Grid

Simulation of the electricity system is accomplished using the Holistic Grid Resource Integration and Deployment (HiGRID) model. The HiGRID model captures the hourly dispatch of electric grid resources in response to perturbations in operating environments or grid resource configuration, while meeting constraints for resource dynamic capabilities, load balancing, and ancillary service requirements. For more detail, the reader is referred to published literature on the HiGRID model from Eichman et al [44], Samuelsen et al. [45], and various applications of the HiGRID model in analyzing electric vehicle and energy storage integration [46-48], water-energy system analyses [49, 50], and climate impacts on the electricity system [51].

The future electric grid resource mix used in this study is represented by the year 2050 in the Energy Environmental Economics (E3) PATHWAYS study [52]. The E3 PATHWAYS study was an effort carried out starting in 2015 to determine different pathways for reaching an 80% reduction in economy-wide greenhouse gas emissions by the year 2050. This study determined changes in the energy resource mix that are required to meet the required greenhouse gas emission reductions determined based on resource availability and cost. The inputs used for the grid mix and electric loads for non-commercial and non-residential sectors are specified in Table 5 and Table 6. Note that only the magnitudes are used as inputs: the profiles for sector load demands and renewable generation are modeled directly within HiGRID, and therefore may be different than the reference scenario. Additionally, since the residential and commercial sectors are modeled directly in this study, the value from the E3 PATHWAYS study was not used. For this study, electric vehicle charging is assumed to be grid-responsive within the constraints of vehicle travel patterns [48, 53, 54], and hydrogen production is modeled as fully dispatchable subject to constraints of meeting the hydrogen demand [48].

Table 5 - Annual Electric Load Demand Magnitudes for Non-Residential, Non-Commercial Sectors

Sector	**Annual Electric Load Magnitude [PJ]**
Industrial / Other	258.94
Transportation – Light Duty Electric Vehicles	176.95
Transportation – Other Electric	156.45
Transportation – Hydrogen Production	151.70

Table 6 - Year 2050 Renewable Capacity Levels

Grid Resource	**Installed Capacity [MW]**
Centralized Solar PV	83,919
Rooftop Solar PV	29,000
Centralized Wind	64,085
Geothermal	4,460
Hydropower	15,620
Energy Storage	29,750

As outputs from the HiGRID model, two metrics are investigated to characterize the impacts of climate change and heating system electrification:

- **Greenhouse Gas Emissions:** This refers to both greenhouse gas emissions from the electric grid and on-site building fuel usage.

- **Electric Grid Dispatchable Resource Capacity Requirement:** This refers to the installed capacity of dispatchable (non-baseload, non-fixed) electricity generation resources required to maintain the reliability of the electricity system. Note that this refers to the capacity needed not only to balance electric loads, but also for ancillary services and reserves.

2.5. Cases Investigated in this Study

The results are presented for the following cases (Table 7). The base case represents present-day conditions in terms of climate and heating system types for reference. The CanESM2, CNRM-CM5, HadGEM2-ES, and MIROC5 cases represent the range of projected climate change impacts on the system. The Base+Elec case isolates the impact of heating system electrification without considering climate change. Finally, the remaining cases represent the combined impacts of climate change and heating system electrification.

Table 7 - Cases Examined in this Study

Case Name	**Climate Change**	**Heating System Electrification**
Base	None	None
CanESM2	CanESM2 climate model, RCP 8.5	None
CNRM-CM5	CNRM-CM5 climate model, RCP 8.5	None
HadGEM2-ES	HadGEM2-ES climate model, RCP 8.5	None
MIROC5	MIROC5 climate model, RCP 8.5	None
Base + Elec		100% Residential and 80% Commercial heating electrification
CanESM2 + Elec	CanESM2 climate model, RCP 8.5	100% Residential and 80% Commercial heating electrification
CNRM-CM5 + Elec	CNRM-CM5 climate model, RCP 8.5	100% Residential and 80% Commercial heating electrification
HadGEM2-ES + Elec	HadGEM2-ES climate model, RCP 8.5	100% Residential and 80% Commercial heating electrification
MIROC5 + Elec	MIROC5 climate model, RCP 8.5	100% Residential and 80% Commercial heating electrification

3. Results and Analysis

3.1. Effects on Greenhouse Gas Emissions

The effects of climate change and building heating system electrification on electric grid and on-site building greenhouse gas emissions are presented in Figure 5:

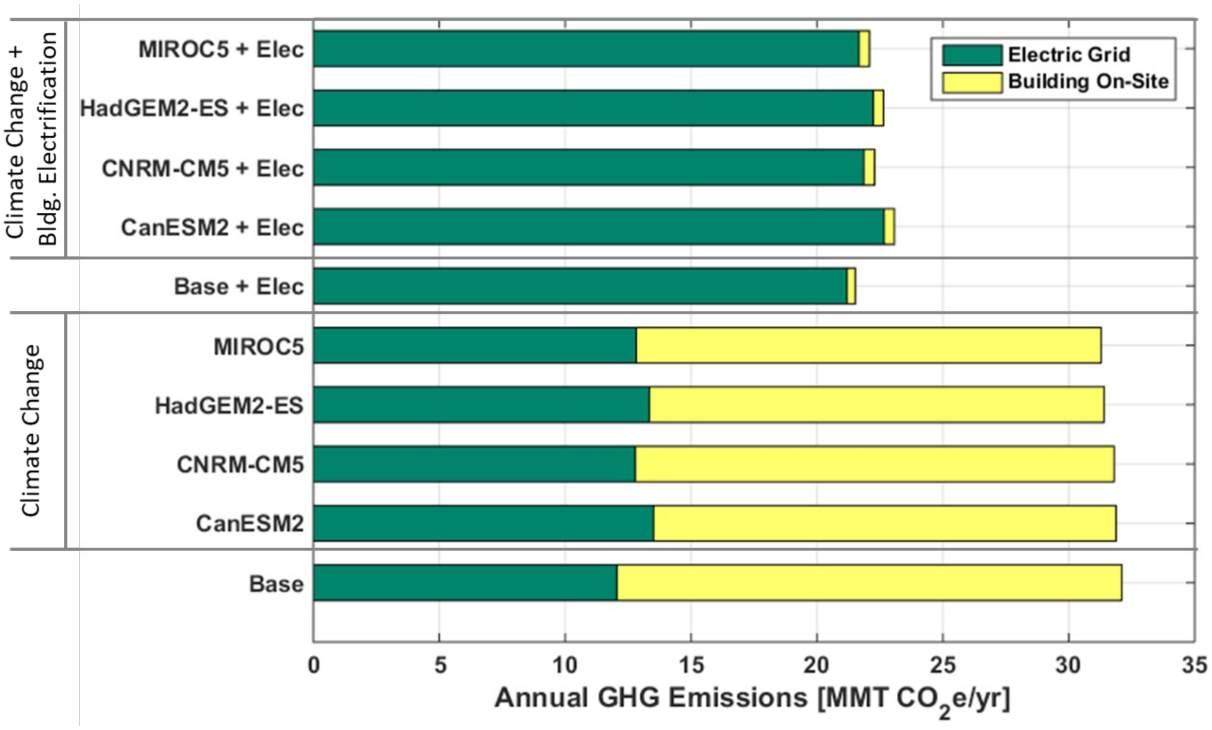

Figure 5 - Climate Change and Heating Electrification Impacts on Greenhouse Gas Emissions

We split the greenhouse gas emissions into two components: emissions from the electric grid, and emissions from fuel used on-site in residential and commercial buildings. The base case exhibits 32.1 MMT CO_2e/yr of greenhouse gas emissions, with 20.0 MMT CO_2e/yr from on-site natural gas usage and 12.1 MMT CO_2e/yr from the electric grid. Climate change increases electric grid emissions due to increased cooling loads, however this is offset by decreases in on-site natural gas usage for heating, since the increased temperatures cause reductions in heating demand in residential and commercial buildings. The net climate change effect is a very slight reduction in total greenhouse gas emissions for the individual climate change model projections, up to a maximum reduction of 0.9 MMT CO_2e/yr. Electrification of building space heating and water heating systems significantly increases greenhouse gas emissions from the electric grid by 9.13 MMT CO_2e/yr. Total greenhouse gas emissions, however, are reduced due to increases in efficiency associated with heat pump vs. natural-gas heating and the near elimination of on-site natural-gas usage. This effect could be strengthened with improvements in heat pump efficiency. With electrification and climate change combined, greenhouse gas emissions are slightly higher compared to the electrification-only case.

From Figure 5, we observe that climate change only has a very slight effect on total greenhouse gas emissions. This occurs because the increased electric loads due to temperatures affected by climate change tend to occur during the times of day and seasons of the year where excess renewable generation is highly available. Peak temperatures and therefore increased cooling loads occur during mid-day when significant solar generation is available, and during the spring and summer seasons when both solar and wind generation are at or near seasonal peaks in California. Therefore, much of the additional electric loads are satisfied by otherwise excess renewable generation, and do not contribute to increased greenhouse gas emissions. A sample time series of the additional uptake of otherwise excess renewable generation in the climate change case is presented in Figure 6. Note the reduction in the red area of the profiles representing curtailed renewable generation.

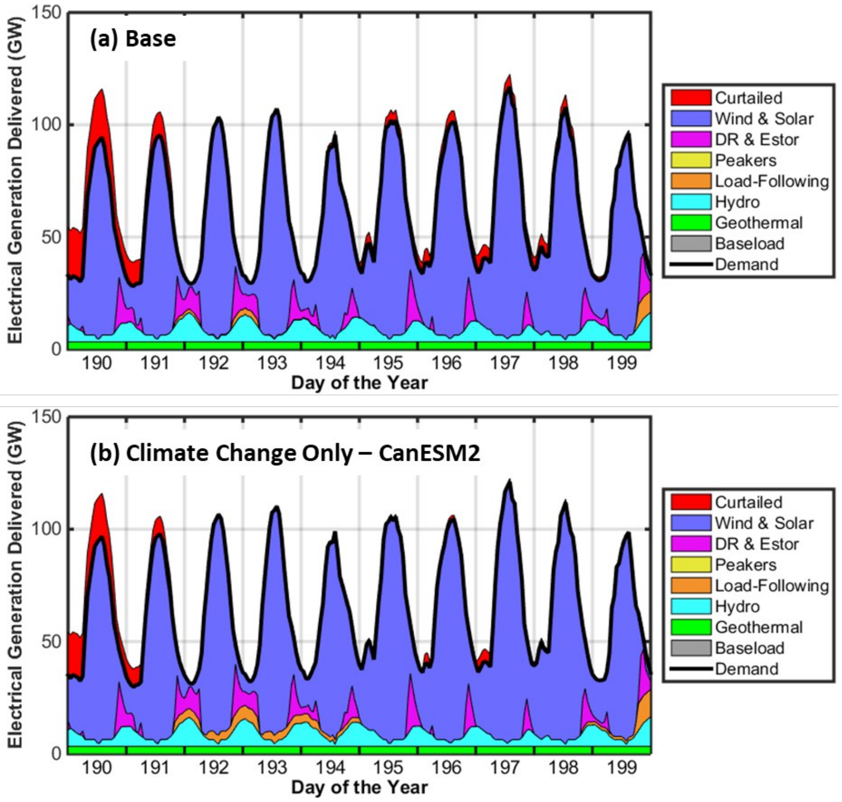

Figure 6 - Timeseries Snapshot of Grid Resource Dispatch - (a) Base Case, (b) Climate Change Only (CanESM2)

The increases in electric loads due to electrification of heating systems, however, do not follow the same temporal characteristics as the changes due to climate change. While water heating loads are relatively steady throughout the year, space heating demands peak during the winter months on a seasonal basis and the morning or nighttime hours on a daily basis, when the amount of excess renewable generation is relatively low. Additionally, increases in annual electric loads due to heating system electrification is much larger than increases due to cooling demand.

The normalized daily average profiles of excess renewable generation, added load due to climate change (average of the four climate models), and added load due to heating system electrification are presented in Figure 7:

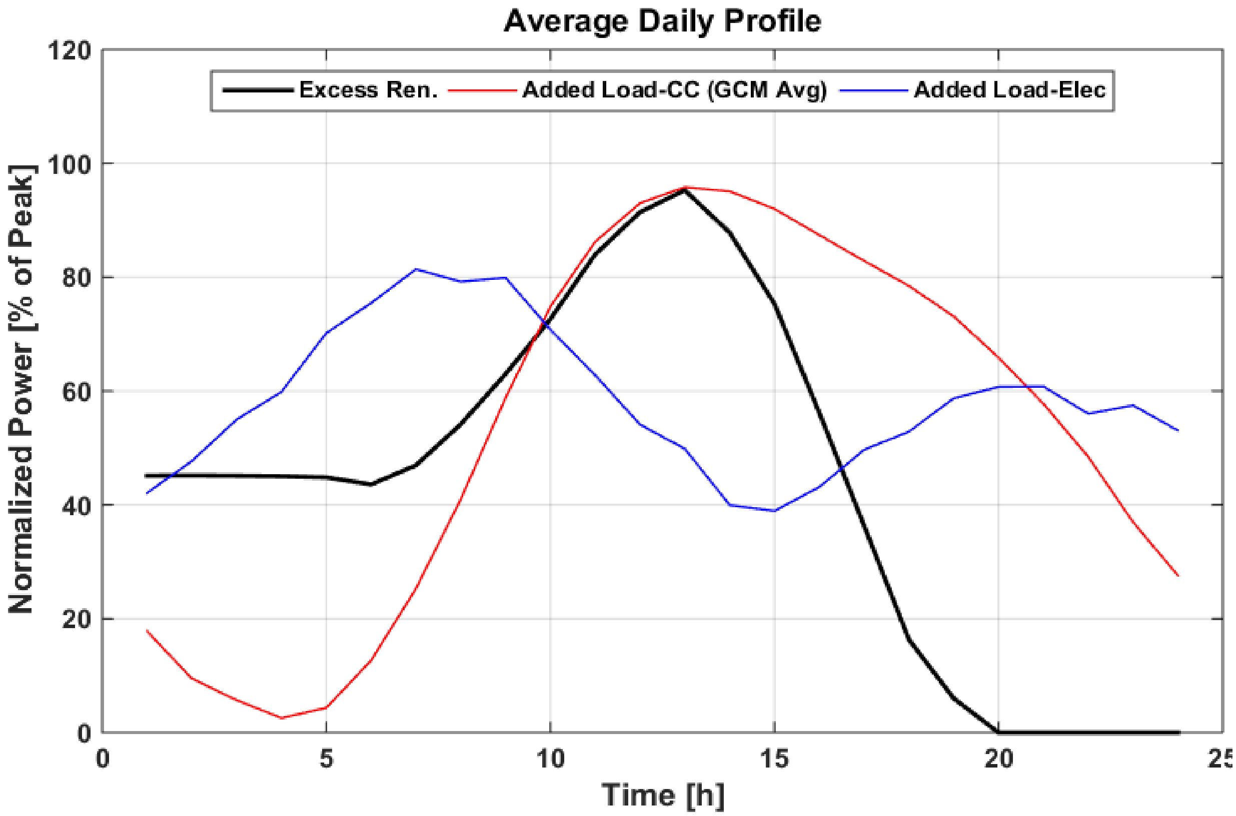

Figure 7 - Normalized Average Daily Profile - Excess Renewable Generation, Added Load due to Climate Change, Added Load due to Heating Electrification

Note that since these are normalized profiles, the profile types cannot be directly compared. A large fraction of the additional loads due to climate change occur approximately at midday, when excess renewable generation is relatively high, whereas the added loads due to heating system electrification tend to peak during the early morning and evening hours, outside of times when excess renewable generation is relatively available.

We explicitly examined the effects of the timing of electric load increases due to climate change and electrification and excess renewable generation can be examined explicitly. For each case, a breakdown of the raw load added, the additional uptake of excess renewable generation, and the net electric load added to the grid – which is the difference between the raw load and the uptake of renewable generation - is presented in Figure 8:

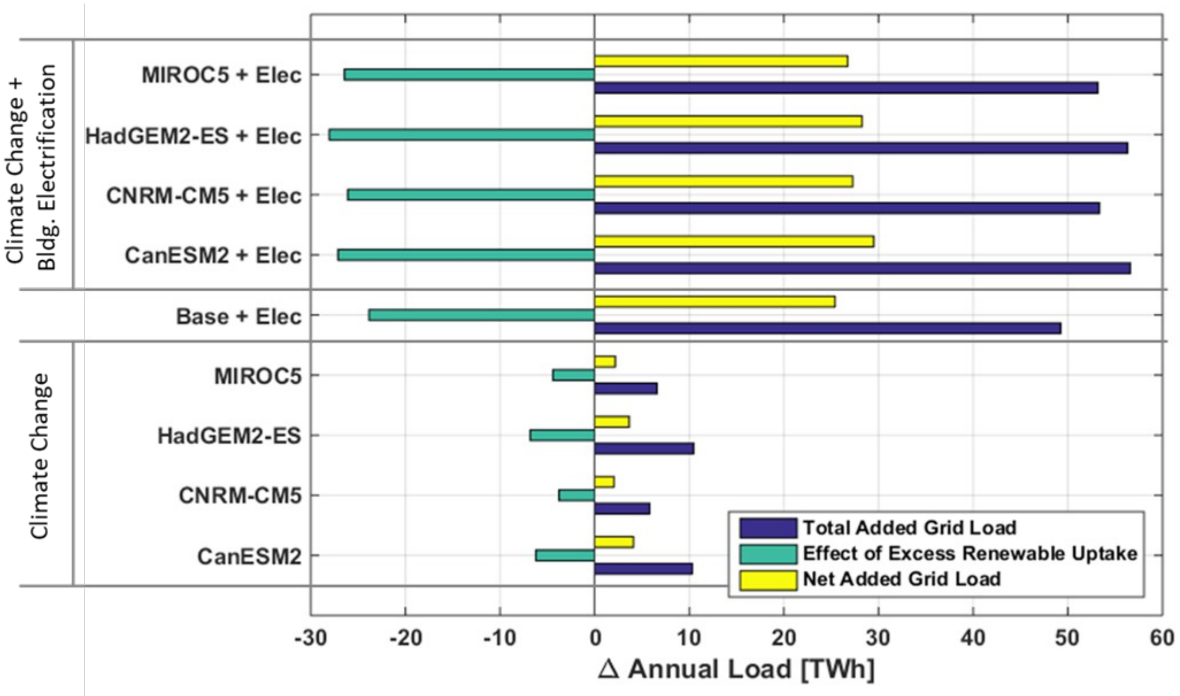

Figure 8 - Total and Net Added Electric Load and Increased Renewable Uptake from Base for each case.

For the climate change cases, increases in annual electric load range between 5.82 and 10.47 TWh/yr. Due to the timing of these load increases, between 3.77 and 6.82 TWh/yr of otherwise excess renewable generation are utilized by these loads. Therefore, the net load added to the system that must be met by non-renewable resources is between 2.0 and 4.1 TWh/yr. The uptake of excess renewable generation is also present in cases with heating system electrification. Due to the larger magnitude of the increased electric load in these cases and the steadiness of water heating loads, there is still a significant amount of excess renewable generation. However, the percentage of the added load met by excess renewable generation is lower for the electrified cases compared to the climate change cases. This is presented explicitly in Table 8:

Table 8 - Percentage of Added Electric Load met by Excess Renewable Generation [%]

Heating System Scenario	**Climate Case or Model**	**Percentage of Added Electric Load met by Excess Renewable Generation [%]**
Base	CanESM2	60.21
	CNRM-CM5	64.82
	HadGEM2-ES	65.13
	MIROC5	66.89
Electrified	Historical (Base + Elec)	48.42
	CanESM2	47.90
	CNRM-CM5	48.90
	HadGEM2-ES	49.80
	MIROC5	49.72

For the climate change only cases, 60.2 to 66.9% of the raw added load is met by using otherwise excess renewable generation, whereas for the electrified cases this metric ranges between 46.0% and 49.6%.

These results indicate that while heating system electrification can reduce greenhouse gas emissions through efficiency improvements, increasing the temporal flexibility of heating loads to better align with renewables are needed to maximize the benefit of implementing heating electrification. We highlight that without any method for dispatching the loads associated with electrified space and water heating, these appliances will not fully utilize renewable electricity generation. In designing buildings with electrified heating systems, installation of thermal energy storage systems and intelligent use of building thermal mass should be given special consideration to maximize the environmental benefit of heating electrification.

3.2. Effects on Electric Grid Dispatchable Resource Capacity Requirements

The change in requirements for dispatchable resource capacity on the electric grid due to climate change and heating system electrification from the base case (in gigawatts) and the change in the peak residential and commercial electric load for each case over the base case is presented in Table 9:

Table 9 - Change in Residential & Commercial Sector Peak Load and Dispatchable Resource Capacity Requirement from Base

Heating System Scenario	Climate Case or Model	Change in Peak Load [GW]	Change in Grid Dispatchable Capacity Requirement [GW]
Base	CanESM2	3.70	0.57
	CNRM-CM5	2.68	0.13
	HadGEM2-ES	2.84	0.80
	MIROC5	3.44	0.02
Electrified	Historical (Base + Elec)	5.12	8.19
	CanESM2	8.38	6.94
	CNRM-CM5	7.52	8.75
	HadGEM2-ES	7.78	7.03
	MIROC5	8.27	6.75

The impacts of climate change alone do not significantly increase the requirements for dispatchable resource capacity on the electric grid. From the four climate models, increases in dispatchable capacity requirements range from negligible to 0.8 GW, over the base case amount of 27.7 GW. This is in comparison to the raw change in the combined residential and commercial building sector load peak due to climate change, which ranges between 2.6 and 3.7 GW or 9.4% to 13.3% in percentage terms, respectively.

The percentage increases in peak load reported here are in line with the trends reported in the literature. For reference, Franco [55] also reported increases in peak demand of 5.2% to 11.2% in California for a comparable timeframe (2035-2064) using climate models from the older IPCC 4th Assessment Report. Using the RCP 8.5 scenario, Sathaye [6] reported increases of up to 22% in California, for a later timeframe (2070-2099) than the current study (2046-2055). Sathaye also reports an increase in electric grid peak capacity of up to 38% by 2070-2099, which is greater than the peak load increase, due to compounding impacts on natural gas power plants and transmission systems. This differs from our results, as we assessed climate change impacts on a future grid configuration, while the aforementioned studies focused on impacts on a present-day electric grid configuration. Both studies provide key insights: the study by Sathaye indicates that if the current electric grid configuration is maintained, significant impacts may occur, while our study indicates that if the energy system achieves its targets for renewable integration and resource transformation, those impacts can be mitigated.

This highlights a complexity associated with translating climate change impacts on building loads to system-wide electric grid impacts. Increased temperatures and heat events occur under climate change, especially under the RCP 8.5 climate scenario utilized in this study, happen during the daytime and summer months when electric loads are already high. Due to the configuration of the electric grid in the year 2050 in California, however, these increases in raw peak load do not translate to increased grid resource capacity requirements because of their temporal alignment with renewable generation – particularly solar generation in this case study.

These results indicate that while heating system electrification can reduce greenhouse gas emissions through efficiency improvements, increasing the temporal flexibility of heating loads to better align with renewables are needed to maximize the benefit of implementing heating electrification. Without any method for dispatching the loads associated with electrified space and water heating, these appliances will not fully utilize renewable electricity generation. In designing buildings with electrified heating systems, installation of thermal energy storage systems and intelligent use of building thermal mass should be given special consideration to maximize the environmental benefit of heating electrification.

4. Conclusions

In this paper, we examined the impacts of climate change and heating system electrification on residential and commercial buildings from the perspective of how these impacts affect electric grid greenhouse gas emissions and resource capacity needs. This was accomplished by using physical-based representative building modeling in EnergyPlus to obtain changes in energy use profiles due to climate change and heating system electrification and imposing these characteristics on a future electric grid configuration in California using the Holistic Grid Resource Integration and Deployment (HiGRID) model. The primary conclusions of the study are as follows:

1. **Annual and peak load increases in building energy demand due to climate change do not necessarily translate to increased greenhouse gas emissions or electric grid capacity requirements in a future grid configuration.** The increases in annual and peak building loads due to climate change temporally aligned (daily and seasonally) with periods of high or excess renewable generation in California, causing much of the load increase to be met by carbon-free generation.

2. **Electrification of building heating systems provides a significant reduction in greenhouse gas emissions but requires significant increases in electric grid capacity.** Due to both the significant efficiency improvements over conventional natural-gas based heating systems used in California and the presence of a highly decarbonized grid in the year 2050, we predict reductions in greenhouse gas emissions. However, these large loads do not temporally align with daily renewable generation and therefore require increases in dispatchable electric grid capacity to support the electric grid configuration.

3. **The translation of building energy use impacts to system-wide endpoint impacts is important for assessing the implications of forcing due to climate change and electrification.** Most papers focus on building-level changes in energy use and indirectly project what those changes imply for endpoints such as greenhouse gas emissions. In contrast, the results of this study highlight cases where assessments of change in residential and commercial building energy use characteristics did not translate to endpoint impacts of system-wide emissions or capacity requirements.

5. Implications

These results can inform the development of state policy goals regarding renewable deployment and zero net energy (ZNE) building targets. With the increased role of electricity in meeting increased cooling needs, the electrification of heating systems imposes larger electric loads on the grid. These larger loads can impose additional difficulty in meeting a given renewable portfolio standard (RPS), which is based on percentage of the total electric load met by renewables. Overcoming this impact to meet RPS goals can be accomplished by further increasing the deployed capacity of renewable resources, but also by accelerating the deployment of advanced building codes and ZNE buildings. Advancements in policies and technologies that reduce building energy use for cooling and heating and encompass distributed generation such as solar PV can minimize additional stress on the larger electric grid and reduce the translation of these additional loads into greenhouse gas emissions.

Explicit examination of how these different options or combinations of them can help the energy system adapt to the effects presented in this study is a topic for future work. Investigating this topic would benefit from simulating ZNE building prototypes under different conditions, explicitly representing the building stock and future changes in distribution, and better coupling between climate data and weather inputs to assess building energy use.

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We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available the CMIP5 models CanESM2, CNRM-CM5, HadGEM2-ES, and MIROC5, listed in Table S8 of the SI. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

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