US Electrification Potential Impact on Electric Load Composition

DRAFT

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DISCLAIMER

List of Acronyms

CLM	Composite Load Model
NERC	North American Electric Reliability Corporation
EIA	Energy Information Agency
RECS	Residential Energy Consumption Survey
CBECS	Commercial Buildings Energy Consumption Survey
MECS	Manufacturing Energy Consumption Survey
USDA	U.S. Department of Agriculture
NASS	National Agriculture Statistics Service
FHA	Federal Highway Administration

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Abstract

Electrification is a pathway to decarbonizing the energy sector because it allows for the use of low-carbon sources to generate electricity, such as wind, solar, and nuclear power. By shifting away from fossil fuels, which are a significant contributor to greenhouse gas emissions, electrification can help to reduce emissions, mitigate climate change, and achieve state and federal decarbonization goals. In addition, electrification can be used to power a wide range of end-use sectors, including transportation, buildings, and industry. However, this process would significantly impact load shapes and electricity demand. To quantify this impact, the maximum electrification potentials for the residential, commercial, industrial, transportation, and agriculture sectors were estimated by analyzing annual energy consumption by fuel type. Given the non-electric energy consumption, the new electric supply and load growth required to support electrification of fossil fuel energy sources are estimated for each sector based on different categories, such as region, climate zone, building size, and building type. Understanding the full potential of electrification is the first step towards predicting load shape changes and peak demand growth based on state policies or each sector's trajectory towards electrification goals. An analysis of the remaining electrification potential across the transportation, residential, commercial, industrial, and agriculture sectors indicates that full electrification would result in an additional 2.0, 1.4, 0.8, 3.6, and 0.42 trillion kWh of electric energy consumption, respectively. It follows that the maximum potential impact of electrification would be an increase of 8.22 trillion kWh of electricity consumption per year, or an approximate 210% increase in total electric energy consumption in the US.

1 Introduction

State and federal climate change goals include decarbonization of residential and commercial building, industrial, agricultural, and transportation energy consumption. Electrification of energy sources provides a relatively easy pathway to decarbonize many energy-intensive processes. Mounting research suggests that aggressive electrification of energy end uses is needed to achieve ambitious emission reduction goals for carbon dioxide [1].This process will result in potential significant changes to the composition of electric loads connected to the bulk power system, resulting in changes to its dynamic behavior and the reliability requirements the NERC reliability organization and member utility must meet to ensure resource adequacy[2].

This report is the first in a multi-phase load modeling study, and presents a preliminary assessment of the maximum potential impact of electrification on composite electric loads that impact the bulk power system. The analysis presented in this report provides an understanding of the total capacity and load growth increase that remains, and the subsequent report will cover the consequent changes in the load shapes.

The composite load model (CLM) was introduced to improve the accuracy of electric load models used by NERC reliability organizations and member utilities when performing planning studies. The composite load model augments the traditional so-called ZIP model, i.e., constant impedance, current, and power load components, with motor and power electronic components. In particular, the CLM adds four motor models with different inertial and phase characteristics, i.e., fan, compressor, process, and induction motors, as well as power electronic models for inverter-based loads and distributed energy resources. Underlying the CLM is an end-use load composition data set that is used to determine the fraction of each load component on a particular feeder, on any given day of the year at any given hour of the day. The end-use load shapes that support this end-use load composition data are determined in significant part by the amount of end-use electrification on the subject feeder. End-use electrification varies widely according to the region and to some degree according to the locality or utility.

End-uses which are not yet electrified are the principal source of the electrification potential examined in this report. The analysis is divided into four main load classes, commercial and residential buildings, industrial loads, transportation, and agricultural loads. The potential and fractional increase of total energy use for each load class is presented.

2 Methodology

The analysis method is based on the conversion of all direct-use fossil energy sources to electrification. This method does not consider whether the energy source for the electricity itself is fossil-based. Four principle load classes are considered: buildings (both commercial and residential), industrial loads, transportation, and agricultural loads. The electric power supply required to convert all direct-use fossil energy sources to electric is calculated simply by summing all fossil energy sources, while the fractional load growth is estimated by taking the ratio of the new electric supply requirement to the current electric load. Therefore, end-use energy consumption data by fuel type are essential to understand electrification effects on electric load components.

The principal source of data for building electrification is the CBECS and RECS data from EIA [3][4]. Although the data is somewhat older, with commercial building data from 2018 and residential building data from 2015, the lack of significant electrification in recent years suggests that these data sets will provide sufficient indication of the energy and fractional load growth potential, as well as provide reasonably good breakdown on the factors most directly influencing the load growth potential from building electrification.

The data source used for industrial electrification is the MECS survey data from EIA for 2018 [5]. The survey includes 15,000 establishments and represents 97-98% of manufacturing energy consumption. The data provides end use energy consumption by fuel type for the different regions and industries by NAICS code. Industrial loads are estimated using the current electricity consumption and load growth is calculated from the other energy sources consumption that are yet to be electrified.

The agricultural energy data was collected from the U.S. Department of Agriculture, Economic Research Service report for 2016 [6]. The energy consumption by fuel type for the agriculture sector was estimated using data on farm expenses for energy inputs as reported by the National Agricultural Statistics Service (USDA, NASS). For instance, natural gas consumption across the agricultural sector is estimated using the total amount of expenses reported to buy natural gas times the average natural gas price for that year.

For transportation, only the electrification of internal combustion engines is considered and other combustion-based engines such as jet engines and combustion turbines are not included. Transportation data was collected from the Federal Highway Administration 2019 data which includes the number of miles driven by each vehicle type across the United States [7]. The transportation sector is considered as a separate load class for electrification analysis across the states but would eventually be considered according to where and how the load is connected to the bulk power system. In the case of personal transportation, electric vehicle chargers are connected to residential and commercial buildings, and in some cases to public services. Heavy duty transportation electrification is connected to industrial loads, e.g., heavy duty charging infrastructure for trucks, and electric rail systems. Agricultural transportation electrification, if any, is connected through agricultural loads. Given the unclear distribution of transportation loads, the analysis is limited to quantifying the total load growth due to transportation electrification.

3 Analysis

The analysis is developed by load class, with energy consumption as the primary input, and power demand developed using seasonal, weekly, and daily load shapes. The overall analysis structure is shown in Figure 1.

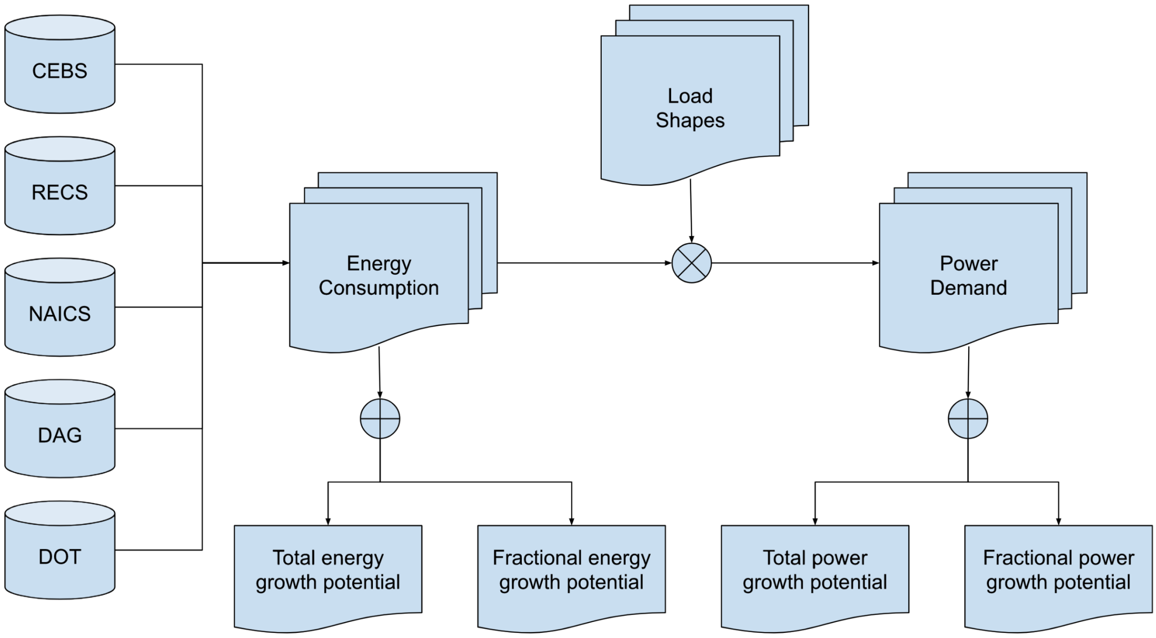


Figure 1: Analysis Structure

This report focuses on the energy consumption part of Figure 1, while the subsequent reports in this study will describe the predicted rate of electrification and the impact of the present results on load shapes dynamics. End-use energy consumption data from various sources, which are presented as inputs in Figure 1, are collected and analyzed to determine the energy consumption by fuel type across the load classes. By converting all direct-use fossil energy sources to electric, the total electric energy growth potential can be calculated. Fractional electric energy growth is the load growth due to electrification from the current electric load.

3.1 Transportation Electrification

The driving behavior across the United States is investigated for different vehicle types, including motorcycles, passenger cars, light trucks, buses, single-unit trucks, and combination trucks. The number of miles driven by each vehicle type for urban and rural highways and roads are estimated using Tables VM2 and VM4 from the Federal Highway Administration 2019 data. The data from 2019 represents driving behavior corresponding to the peak miles traveled before the pandemic hit. The total energy consumption in kWh is calculated using the average energy consumption of electric vehicles in kWh/mile for each vehicle type [9].

Full electrification of transportation would result in approximately 2.0 trillion kWh of additional electricity consumption per year. Current US annual electric energy consumption is 3.9 PWh, which implies that full transportation electrification would result in a 51% increase in total electric energy consumption in the US. The energy growth due to transportation electrification is shown in Figure 2. Energy growth potential is greatest in the states with the most number of miles traveled by vehicles, i.e. California, Texas, and Florida accounting for over 25% of the total new energy requirements for transportation electrification.

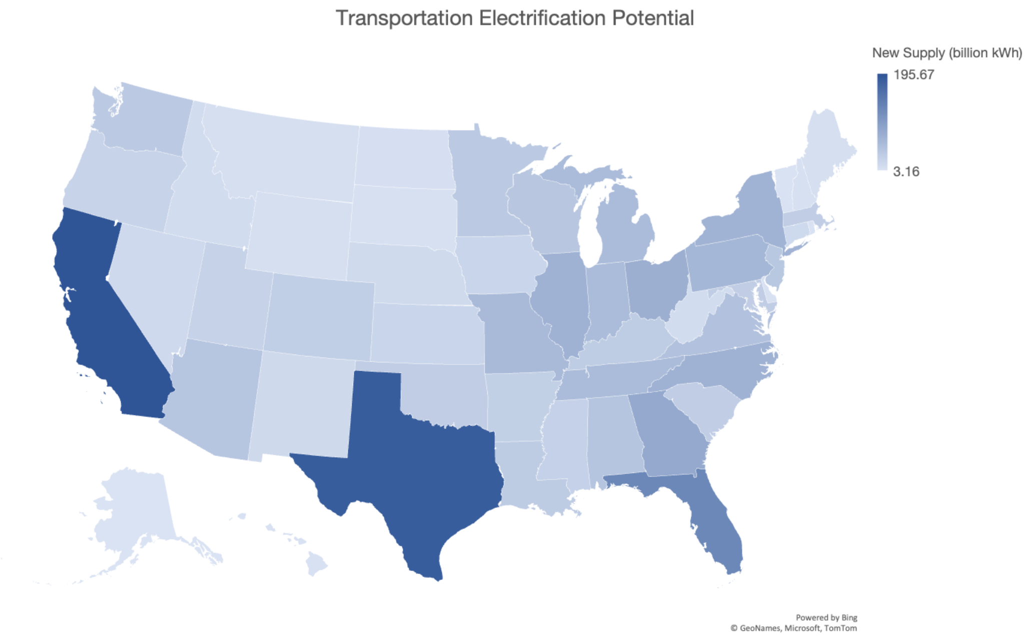


Figure 2: Transportation electrification energy growth by state

3.2 Building Electrification

In buildings, direct-use fossil energy sources considered include natural gas, propane, and fuel oil. Prime motives such as internal combustion engines used for backup power generation are assumed to be replaced with battery storage and not included in the energy consumption or power demand estimates.

3.2.1 Commercial Building Electrification

Commercial building energy data is collected from EIA CBECS 2018 data Table C1, which provides total energy consumption by fuel type for commercial buildings. The consumption data is segregated by building size, building type, vintage, census region, and climate zone.

Full commercial building electrification would result in approximately 0.80 trillion kWh of additional electric energy consumption. This suggests that full commercial building electrification would result in 66% increase in commercial sector electric energy consumption and 20% increase in total electric energy consumption in the US.

The commercial building electrification energy growth is shown in Figure 3. Energy growth potential is greatest in the most populous states, i.e. New York, Illinois, California, Ohio, Michigan, Texas, Pennsylvania, and Florida accounting for 50% of the total new energy requirements for electrification.

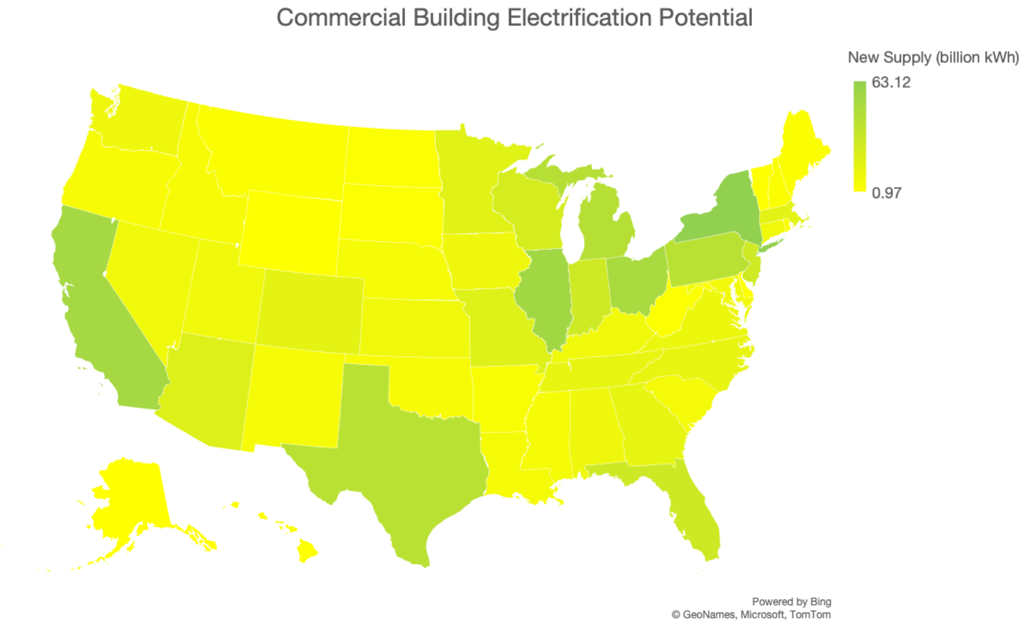


Figure 3: Commercial building electrification energy growth by state

The fractional increase in electric energy use is shown in Figure 4. This greatest fractional increase is in the mixed mild climate regions with New York, Illinois, Ohio, Michigan, Pennsylvania, Massachusetts, Colorado, Iowa, Utah, Connecticut, Nebraska, and Rhode Island having the largest fractional increase in electric energy consumption at about 50% .

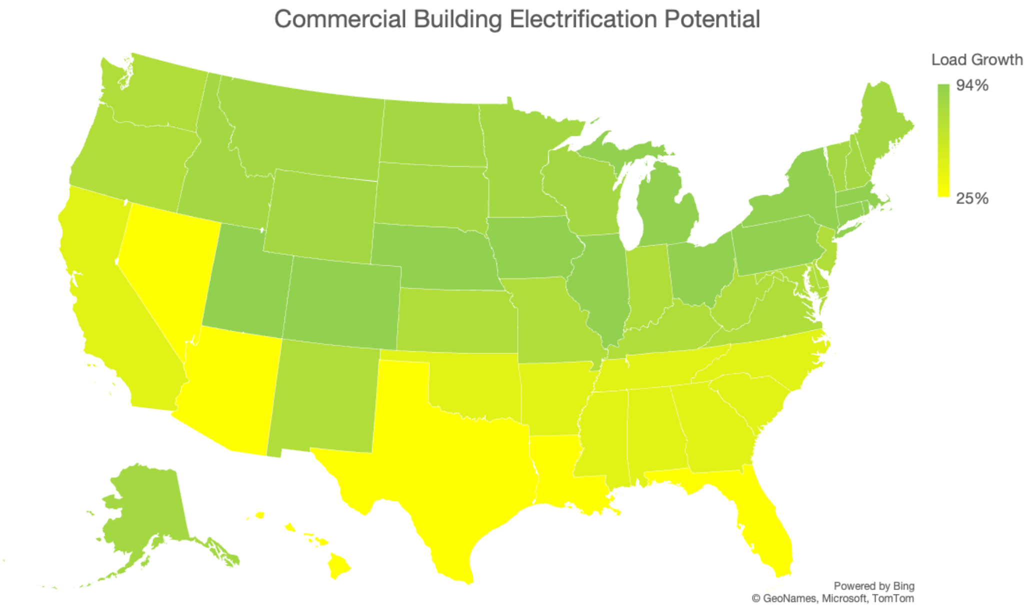
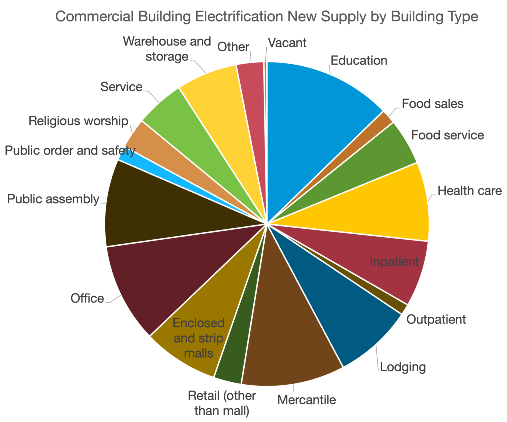


Figure 4: Commercial building electrification fractional load growth by state



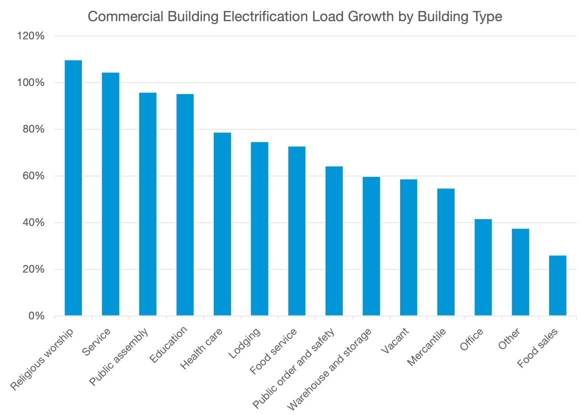


Figure 5: Commercial building electrification new supply requirement by building type

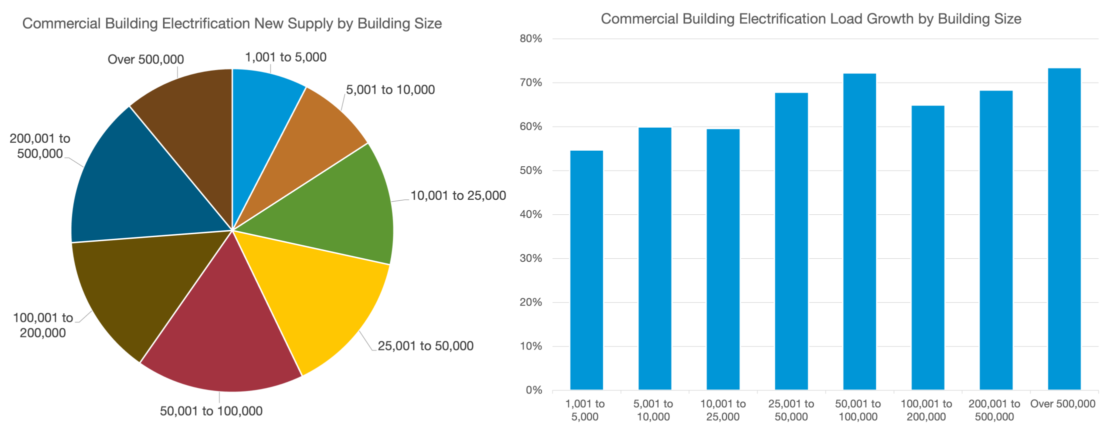


Figure 6: Commercial building electrification new supply requirement by building size

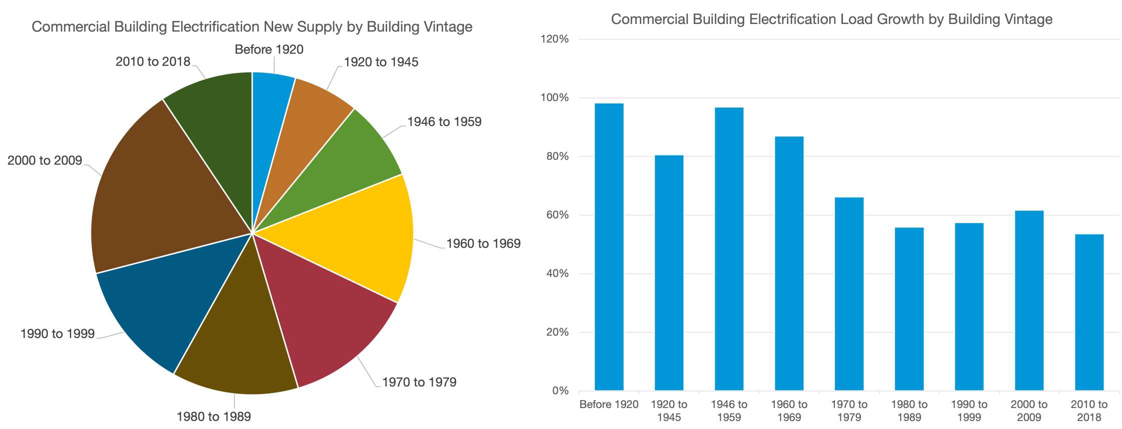


Figure 7: Commercial building electrification new supply requirement by vintage

Commercial new electric supply and load growth by building type, building size, and vintage are shown in Figure 5,6, and 7, respectively. The pie chart to the left shows the new electric supply share among the categories, while the right bar chart shows the load growth for each category due to electrification. Although older buildings have a higher load growth from their base load, commercial buildings constructed between 2000-2009 have the highest share of new electric supply as they hold the highest number of buildings in the data.

3.2.2 Residential Building Electrification

Residential building energy data was collected from EIA RECS 2015 data Tables CE4.2 through CE4.5, which provide end-use consumption by fuel type for the Northeast, Midwest, South, and West, respectively. The end-use data is segregated by climate zone, housing unit type, vintage, size, household size, household income, and primary heating fuel type for space heating, water heating, air-conditioning, refrigeration, and all other loads.

Full residential building electrification would result in approximately 1.4 trillion kWh of additional electricity consumption per year. This corresponds to a 111% increase in residential sector electric energy consumption and a 36% increase in total electric energy consumption in the US.

The residential building electrification energy growth is shown in Figure 8. Similar to commercial building energy growth, residential energy growth potential is greatest in the most populous states, i.e. New York, Illinois, California, Pennsylvania, Ohio, Michigan, Texas, and Massachusetts accounting for 50% of the total new energy requirements for electrification.

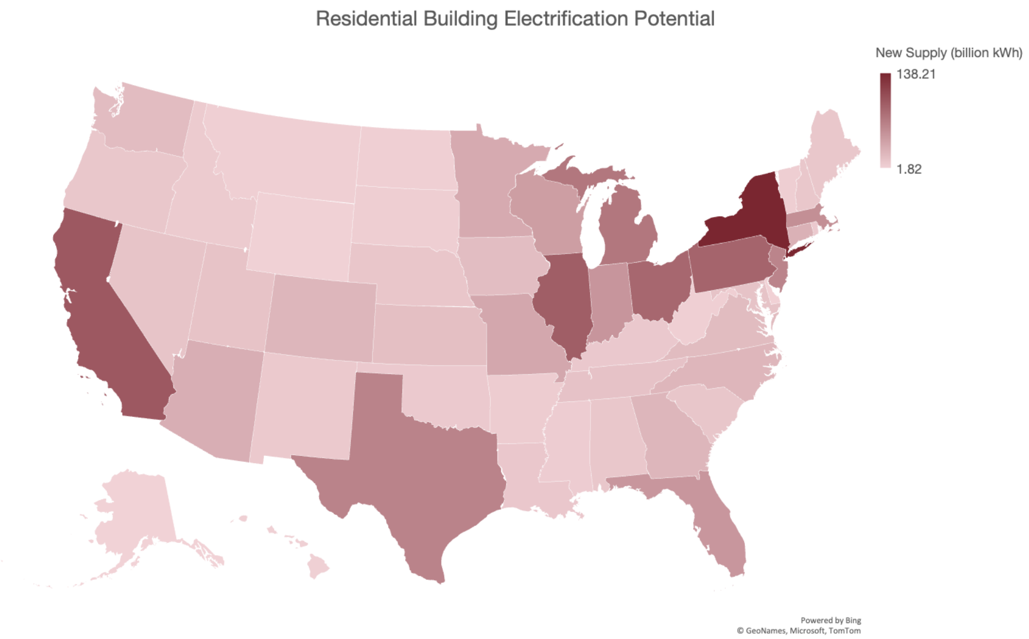


Figure 8: Residential building electrification energy growth by state

The fractional increase in electric energy for residential buildings is shown in Figure 9. The greatest fractional increase is in the Northeast and Midwest regions, where a significant amount of fossil energy sources are used for winter heating.

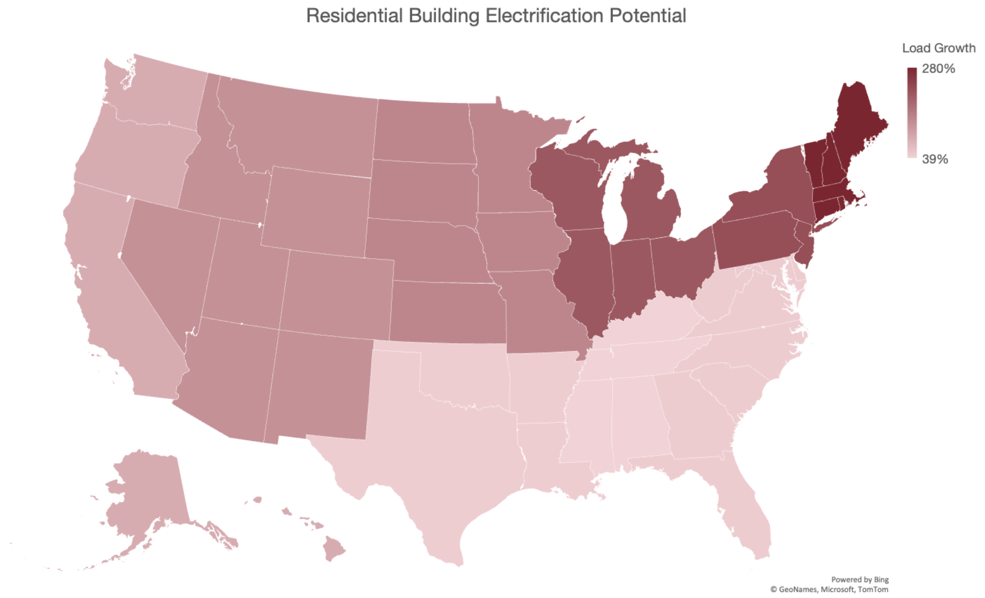


Figure 9: Residential building electrification fractional load growth by state

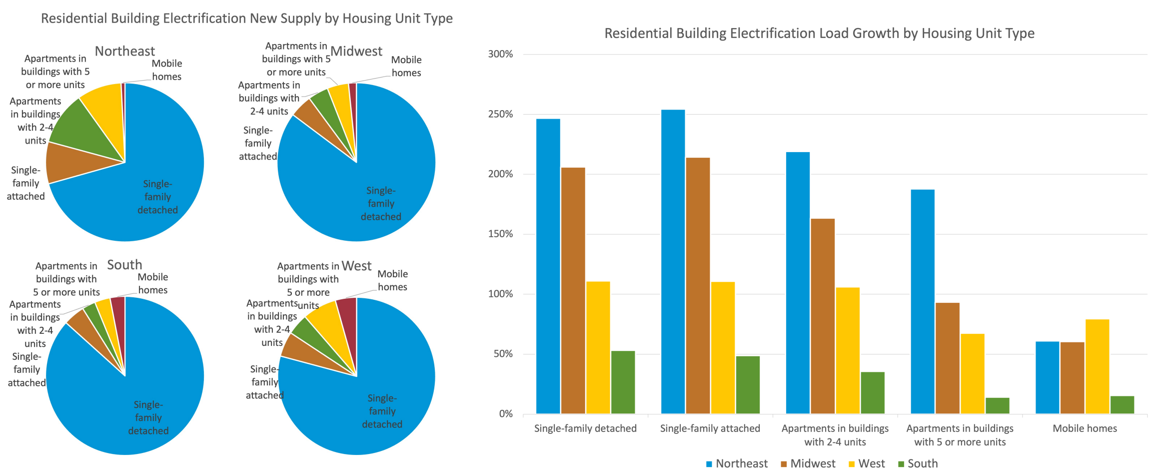


Figure 10: Residential building electrification new supply requirement by housing type

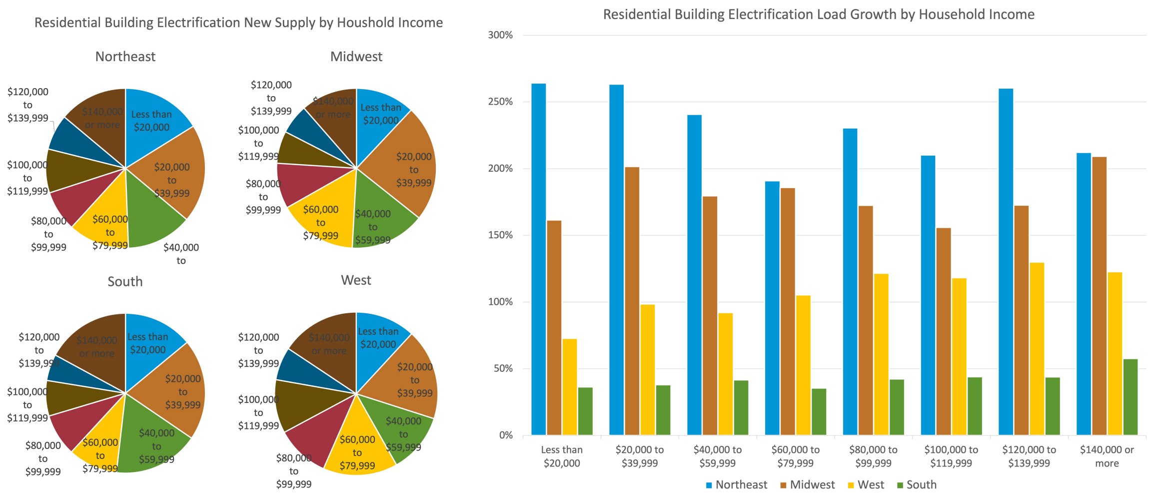


Figure 11: Residential building electrification new supply requirement by income

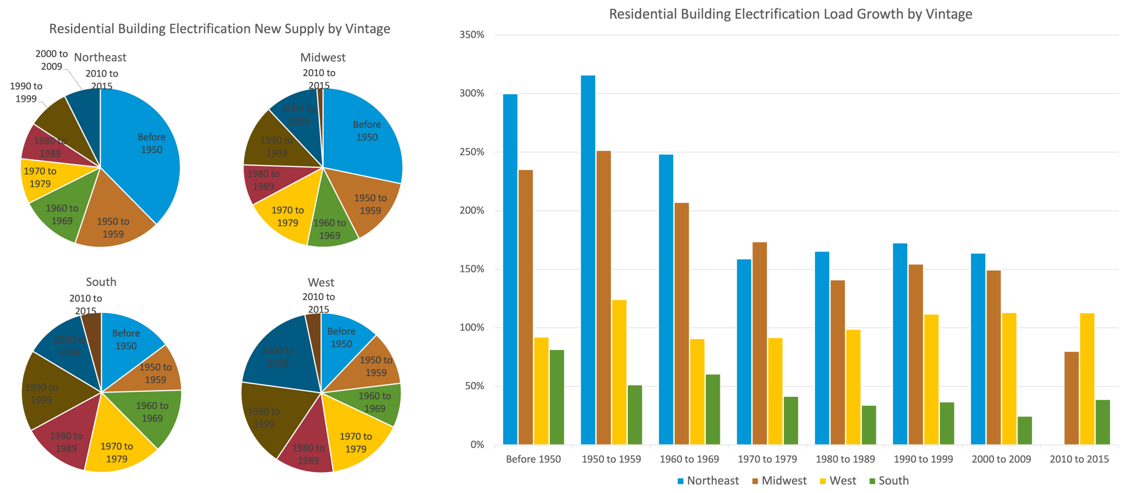


Figure 12: Residential building electrification new supply requirement by vintage

Residential new electric supply and load growth by vintage, house type, and household income for the different regions are shown in Figure 10, 11, and 12, respectively. The pie charts to the left show the new electric supply share among the categories for each region, while the right bar chart shows the load growth for each category and region due to electrification. According to Figure 10, single-family detached houses correspond to the majority of new electric supply for all the regions. Apartments in buildings with 2-4 units and 5 or more units had more than double the share of new electric supply for the Northeast region compared to the other regions.

3.3 Industrial Electrification

Within industry, manufacturing accounts for over 81% of annual energy consumption [8]. Industrial energy data was collected from EIA MECS 2018 data Tables 3.2 and 5.6. Table 3.2 includes end-use energy consumption by fuel, categorized by US manufacturing establishment using NAICS code, while Table 5.6 includes the total end-use energy consumption by fuel for most of the manufacturing establishments for the Northeast, Midwest, South, and West region. Mining, construction, and agriculture industries, which are not represented in MECS data, are excluded from this section due to the lack of detailed energy consumption data on these industries.

The industrial electrification new electric supply by industry is shown in Figure 13. The highest electrification energy growth is in the Petroleum and Coal Products and Chemicals industries. Other industries that still have a relatively high energy growth from electrifying all energy sources are Paper, Metals, Food, and other Mineral Products. The cumulative energy growth ratio to the total new electric supply potential is plotted on top of the bar chart and shows that electrifying Petroleum and Coal Products and Chemicals industries yields 60% of all industrial electrification. Similarly, electrifying the highest five industries, Petroleum and Coal Products, Chemicals, Paper, Primary Metals, and Food industry, achieves around 90% of all industrial electrification.

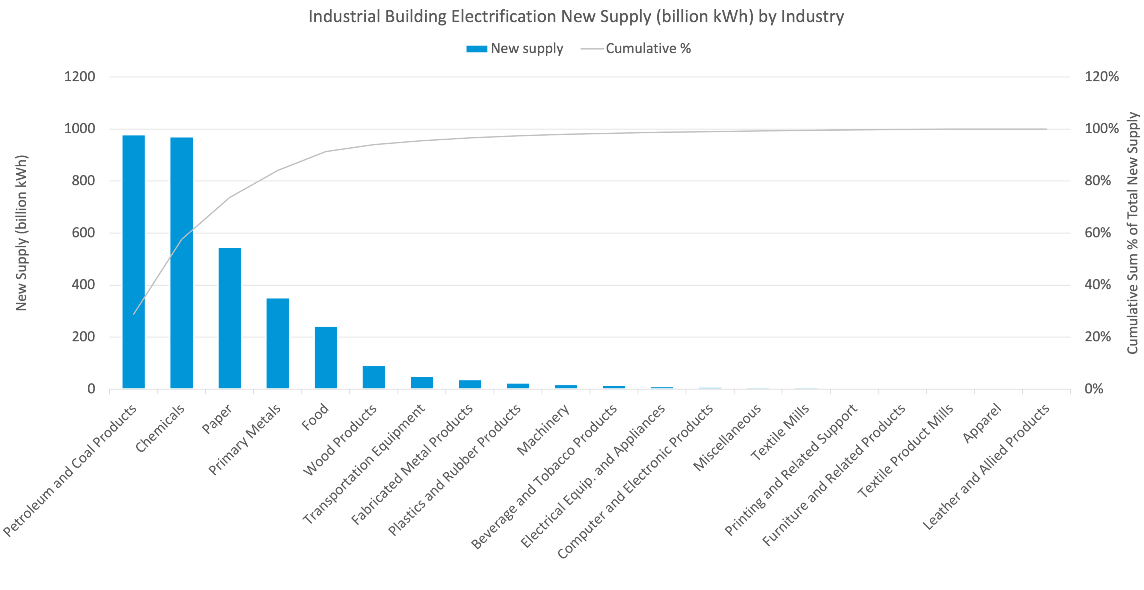


Figure 13: Industrial electrification new supply by industry

The full electrification of the industrial sector would result in approximately 3.6 trillion kWh of additional electricity consumption per year, which would represent a 92% increase in total electric energy consumption in the US. The Industrial sector is considered a “hard-to-abate” sector, as some non-electric industrial energy consumption cannot be directly electrified as they rely on fossil fuels for high-temperature processes or for chemical feedstock. However, some of the industrial processes can be indirectly electrified by using green hydrogen produced through electrolysis using electricity.

3.4 Agricultural Electrification

Agricultural energy consumption was collected from USDA, Economic Research Service report for 2016, which estimates the energy consumption using energy prices and farm expenses for energy inputs as reported by NASS. The report calculates the energy consumption using the total amount paid by farms for each fuel type multiplied by the average energy prices for that given year.

The agricultural energy consumption for 2016 was estimated to be 1872 TBtu, accounting for 44% diesel, 24% electricity, 13% natural gas, 11% gasoline, and 7% liquefied petroleum gas. Full electrification of the agricultural sector would result in approximately 0.42 trillion kWh of additional electricity consumption based on 2016 data, which would represent a 10% increase in total electricity consumption in the US.

4 Conclusion

Electrification is important for decarbonizing energy systems because it provides a relatively easy pathway to decarbonize many energy-intensive processes, given that the electricity source will be generated from clean sources. State and federal laws are already incentivizing switching to electric sources, such as electric vehicle and heat pumps tax incentives. However, electrification will result in significant increase in electricity demand, resulting in overloading the electric grid and affecting the dynamic behavior and reliability requirement. Therefore, it's crucial to understand the effect on load shapes to ensure a reliable and resilient electric grid that adapts with the changing behavior of the grid. The results of this report assess the maximum potential impact of electrification on the four load classes: building, industrial, public services and agriculture.

Full electrification of transportation, residential, commercial, industrial, and agricultural sectors would result in an additional 2.0, 1.4, 0.80, 3.6, and 0.42 trillion kWh of electric energy consumption, respectively. This means that maximum electrification potential would result in 8.22 trillion kWh of additional electricity consumption per year. Current US annual electric energy consumption is 3.9 trillion kWh, which implies that maximum electrification would result in a 210% increase in total electric energy consumption in the US.

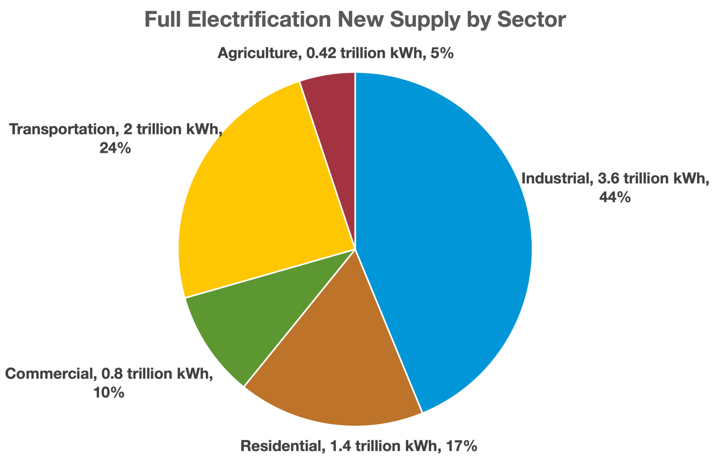


Figure 14: Full electrification potential by sector

4.1 Future Work

The quantification of the total remaining load to be electrified presented in this report serves as a starting point for obtaining annual projections of electrification rates regionally and by sector in the next phase of this study. Additionally, the load growth due to electrification will be used to scale existing load shapes to understand the effect on long term load forecasting. Load shapes show the power demand, which includes seasonal, weekly, and daily load profiles. This will be implemented based on sector trajectory or state policies; i.e. if a state passes a law to electrify a specific sector by a certain year, the load shape across that sector can be scaled according to the electrification penetration goal. Future reports will also estimate peak load increases based on electrification rates and load growth during peak load hours.

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