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Carbon Free Colorado: An Integrated Resource Plan for the Public Service Company of Colorado 2020-2050

Vignesh Devaki Murugesan
University of San Francisco, vigneshdm1990@gmail.com

Adam Lokar
University of San Francisco, amlokar@dons.usfca.edu

Carbon Free Colorado

An Integrated Resource Plan for the Public Service Company of Colorado

2020-2050

Prepared by

CONSIDER A SPHERICAL SOLAR PANEL

ADAM LOKAR

VIGNESH DEVAKI MURUGESAN

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List of Abbreviations

CT – Combustion turbine

CCGT – Combined cycle gas turbine

CCS – Carbon capture and sequestration

DNI – Direct Normal Irradiation

EV – Electric vehicle

GH2 – Green Hydrogen

GHG – Greenhouse gas emissions

HP – Heat Pump

IRA – Inflation Reduction Act

IRP – Integrated Resource Plan

PSCo – Public Service Company of Colorado

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Executive Summary

The State of Colorado has aggressive goals to mitigate the impacts of climate change and reduce greenhouse gas emissions. This includes the target to reduce economy-wide emissions 90 percent by 2050 by decarbonizing the electricity sector and electrifying end uses of energy in buildings and transportation.

This Integrated Resource Plan (IRP) outlines the Public Service Company of Colorado's (PSCo) strategy to accommodate the growing energy demand of its customers while transitioning to renewable energy. The IRP attempts to quantify the impact of Colorado's clean energy and climate policy by comparing three different scenarios:

1. Reference Scenario. New capacity is met with the lowest cost of generation ignoring Colorado Renewable Energy Standard.
2. 100% Carbon Free by 2050. Additional capacity is met with lowest cost mix of renewables sufficient to meet Colorado's Renewable Energy Standard.
3. High Electrification. Adheres to Colorado's Renewable Energy Standard while also accommodating added demand from the electrification of buildings and transportation sectors.

The existing PSCo electricity system is predominantly based on fossil fuel based with a summertime peak demand of 6.9 GW. When accounting for the forecasted growth in demand and the scheduled retirement of existing resources, there is a shortfall in capacity beginning in 2026 and expected to grow to 8 GW by 2050. Therefore, all three scenarios require the addition of new generation capacity to meet growing demand. A much greater and more rapid buildout of renewable energy is required for the 100% Carbon Free and High Electrification scenarios with the overall nameplate capacity varying from 18 GW, 26 GW and 39 GW by 2050 across the three scenarios. In the lowest cost Reference Scenario natural gas generation makes up just over 50 percent of the total generation mix with a mixture of wind and solar meeting the other half of the generation. In the Carbon Free and High Electrification Scenarios wind and solar combine for 80 percent of the overall generation. The remaining 20 percent of the generation is a mixture of gas with carbon capture and sequestration and combustion turbines retrofitted to run on green hydrogen.

The electrification of buildings and transportation results in the load profile shifting from a summer peaking to winter peaking system and increases the peak demand by over 4.5 GW. However, in part by shifting electric vehicle charging loads, rates do not fluctuate significantly and actually decrease in the near term. Altogether, by 2050 the average rate of the Carbon Free and High Electrification Scenarios were 14 percent and 18 percent higher than the Reference Scenario in 2050. While not an insignificant amount, it shows that the decarbonization of the Colorado electricity system and broader economy is within reach and that cost should not be considered as the predominant barrier to climate action.

I. Introduction

Background

A key requirement of all Colorado electric utilities is to produce an Integrated Resource Plan (IRP) that outlines the utility's strategy to accommodate the growing energy demand of its customers over a specified planning timeframe. An IRP typically considers several factors including the growth in demand, the projected capacity of the existing energy system, the constraints of various energy resources, environmental regulations, and costs to ratepayers. This approach ensures there is a transparent planning process for how each utility will add new electricity resources to meet future demand while also remaining compliant with Colorado's clean energy regulations and minimizing costs. All electric utilities must have an IRP approved by the Colorado Public Utilities Commission in order to procure or develop additional generation resources.

A key consideration when planning for future generation, is integrating sufficient renewable energy to meet Colorado's clean energy regulations. At the same time, the electrification of major sectors of Colorado's economy is expected to increase demand. Therefore, planned actions by the State of Colorado to mitigate the impacts of climate change are likely to result in a significant transformation in the electricity sector. The purpose of this report is to study the Public Service Company of Colorado's (PSCo) electricity system and develop an IRP from 2020 to 2050 that illustrates the impact associated with the decarbonization of the electricity sector and the broader economy of Colorado. This IRP compares multiple scenarios to help quantify the potential impacts of Colorado's climate policies to answer three key questions:

1. What is the least cost pathway to a carbon neutral electricity sector in 2050?
2. How does a high rate of electrification impact the carbon neutral pathway?
3. How do these scenarios compare to a business-as-usual approach?

Regulatory Environment

Colorado Climate Policy

In 2019 the Colorado Assembly passed House Bill 19-1261 that sets the target to reduce economy-wide emissions 26 percent by 2025, 50 percent by 2030, and 90 percent by 2050 relative to 2005 levels. The 2021 Colorado Greenhouse Gas (GHG) Pollution Reduction Roadmap calls for rapidly transitioning to carbon free electricity generation sources while decarbonizing Colorado's economy through electrification, particularly the buildings and transportation sectors.

Colorado Renewable Energy Standard

Colorado's Renewable Energy Standard is established by Senate Bill 19-236 and requires large regulated utilities to provide 80 percent renewable energy by 2030 and 100 percent carbon free electricity by 2050 so long as doing so is technically and economically feasible, in the public interest, and consistent with Colorado law. This IRP includes a framework for how PSCo quantifies the need for future resources, plans for how those resources will be procured, and from the sources necessary to meet this rigorous Renewable Energy Standard.

Inflation Reduction Act

The preparation of this IRP follows the recently adopted Inflation Reduction Act (IRA) that makes historic investments in domestic energy production and clean energy. The IRA funds tax credits for activities such as renewable energy generation, electric vehicle (EV) adoption, and home energy upgrades. By proactively planning for and charting a pathway towards net zero energy PSCo ensures that its customers are well positioned to benefit from this historic federal investment.

Public Service Company of Colorado

PSCo is an investor-owned utility and subsidiary of Xcel Energy that serves gas and electricity to its customers. It is the largest electric utility in Colorado serving 1.3 million residential customers, 220,000 commercial, and 313 industrial customers. PSCo's service territory extends across the populated regions of the front range including Denver, Boulder, and Fort Collins shown below in Figure 1.

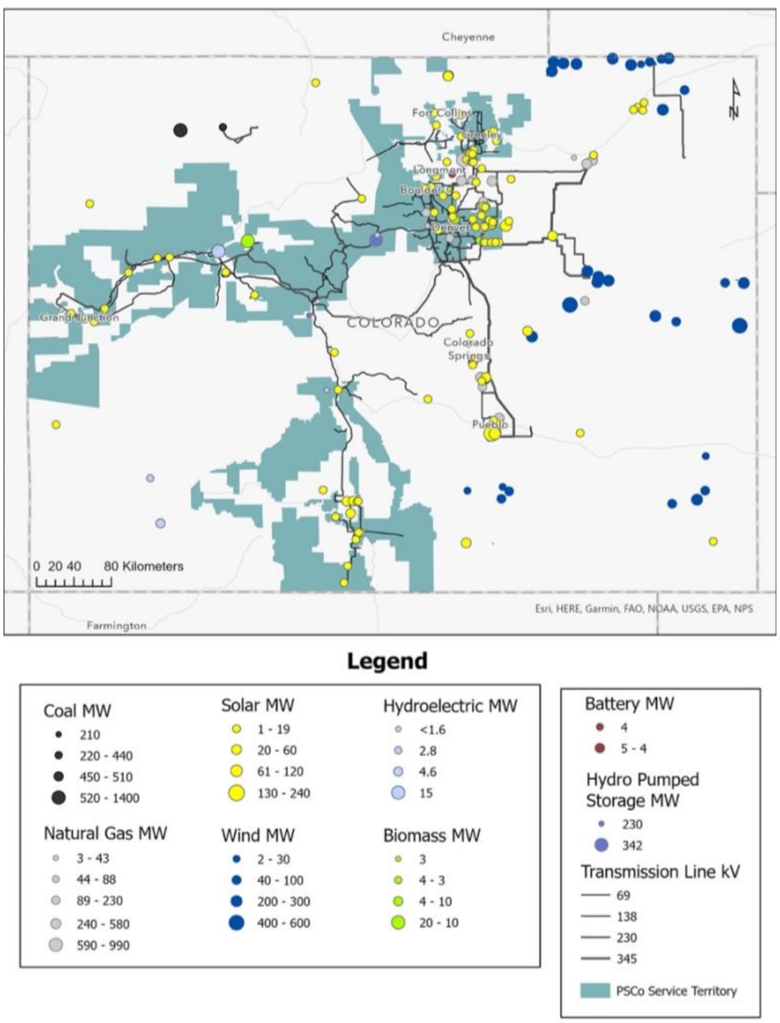

Figure 1. PSCo's service territory and existing resources

PSCo’s average retail rate for electricity is 13 cents per kWh. In 2021 PSCo’s energy mix was majority fossil fuel based with 32 percent from coal and 29 percent from natural gas. The remaining generation was a mixture of wind, solar, and hydroelectric.

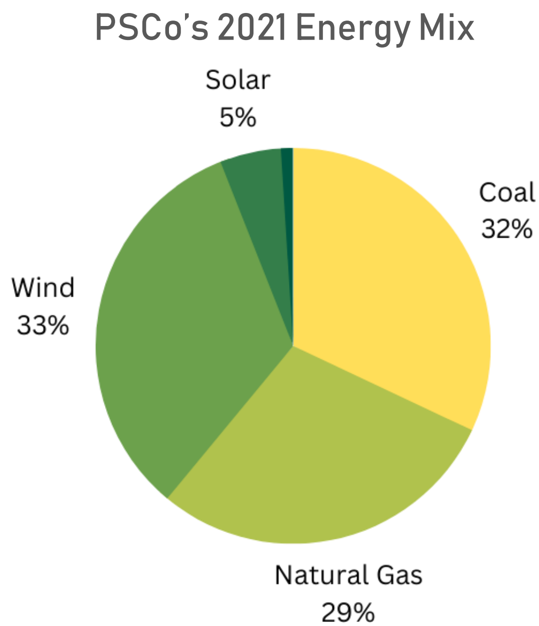

Figure 2. 2021 PSCo's Energy Mix

Load and Resource Needs Assessment

PSCo’s most recent IRP in 2021 shows that over a 30-year period from 2020 to 2050 electricity demand is expected to grow steadily with an increasing population and economic growth. PSCo’s peak demand plus an 18 percent reserve margin is expected to grow from 8.2 GW in 2020 to 10 GW in 2050 while annual energy consumption is expected to grow from 34,000 GWh in 2020 to 47,000 GWh in 2050.

PSCo owns or procures sufficient resources to maintain a healthy reserve margin until 2026 at which point a shortfall occurs with a number of large coal plants planned for retirement in the 2020s including the Comanche, Pawnee, and Hayden coal plants. Together these coal plants represent 1.4 GW of generation capacity. With other planned retirements and the growth in demand the shortfall in resource capacity is expected to reach over 8 GW by 2050 as shown below in Figure 3.

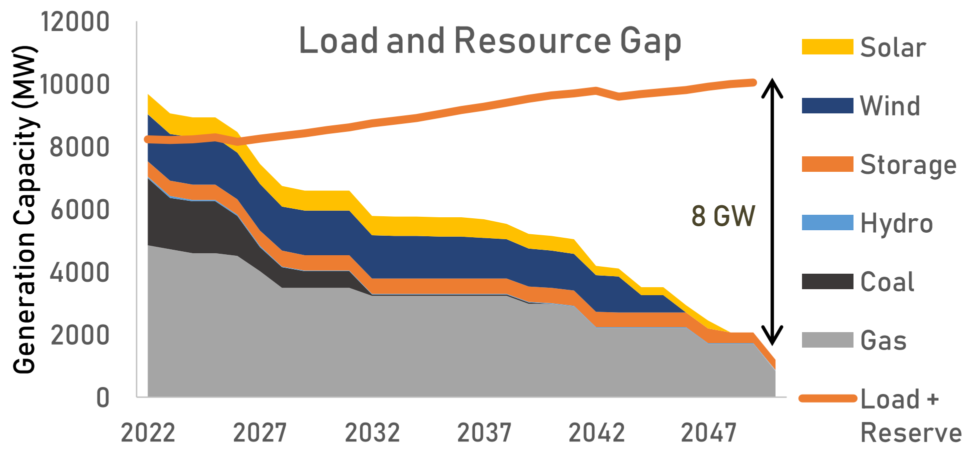

Figure 3. Load and resource needs over planning period

II. Scenarios

Scenarios Overview

Charting the pathway to meet PSCo's future resource shortfall with carbon free electricity pursuant to the requirements of Colorado's Renewable Energy Standard will require careful planning. At the same time, it is expected that more will be required of PSCo's electricity system in order to decarbonize the buildings and transportation sectors as required in Colorado House Bill 19-1261. The emissions associated with energy consumed in buildings represents 17 percent of Colorado's total GHG emissions while the transportation sector accounts for 22 percent. In order to reduce these emissions, the Colorado Pollution Reduction Roadmap calls for widespread electrification of these sectors by 2050 by promoting the use of heat pumps for space and water heating and transitioning from internal combustion engine vehicles to electric vehicles. To illustrate these potential impacts of these policies this IRP analyzes three different scenarios.

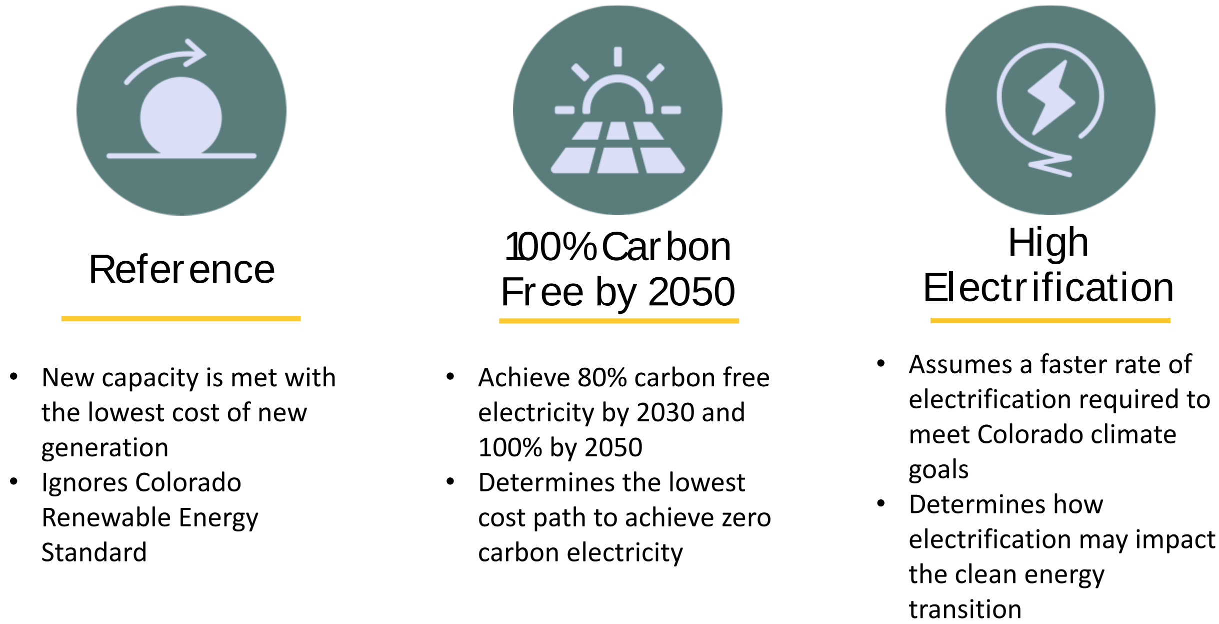

Figure 4. Scenario descriptions

Reference Scenario

The Reference scenario is meant to convey a business-as-usual approach to capacity expansion of the PSCo system independent of any environmental regulations. In this scenario PSCo's existing generation resources and purchased power are allowed to retire at their expected timelines, including the Comanche, Pawnee, and Hayden coal plants. Capacity is then added to the system to meet the nearly 8 GW shortfall with the lowest cost mix of solar, wind, storage, combined cycle gas turbines (CCGT), and gas combustion turbines (CT). Growth in electricity demand in this scenario increases as expected in PSCo's 2021 IRP as illustrated previously.

Scenario 2. 100% Carbon Free by 2050

The 100% Carbon Free by 2050 Scenario analyzes the impacts of Colorado's Renewable Energy Standard. In this scenario existing resources are again retired as expected. However, additional capacity is expanded with a mixture of solar, wind, and storage sufficient to achieve 80 percent carbon free energy sales by 2030. In order to achieve 100 percent carbon free electricity by 2050 while maintaining the balancing of supply and demand on the bulk grid, other forms of dispatchable thermal generation are incorporated including gas turbines with carbon capture and sequestration (CCS) and retrofitted gas turbines to run on green hydrogen (GH2). As with the Reference Scenario, load growth is again consistent with PSCo's 2021 IRP projections.

Scenario 3. High Electrification

The High Electrification Scenario builds on a carbon free system by incorporating a higher rate of electrification of residential energy use and electric light duty vehicles. The pace of electrification chosen for these sectors is consistent with the approach detailed in Colorado's Pollution Reduction Roadmap which charts a pathway to meeting Colorado's climate goals. The lowest cost mixture of carbon free resources was then chosen to meet this added demand while also meeting Colorado's Renewable Energy Standard.

For all scenarios geothermal, nuclear, and additional hydroelectricity, were not considered based on geographic or other regulatory restrictions that make a significant buildout of these resources unlikely.

III. Results

Capacity Mix

All scenarios require adding capacity in order to meet the growing shortfall in PSCo's system. The differences in capacity across each scenario, shown below in Figure 5, are a result of the constraint to meet Colorado's Renewable Energy Standard, accommodate new loads from electrification, or maintain the lowest cost system.

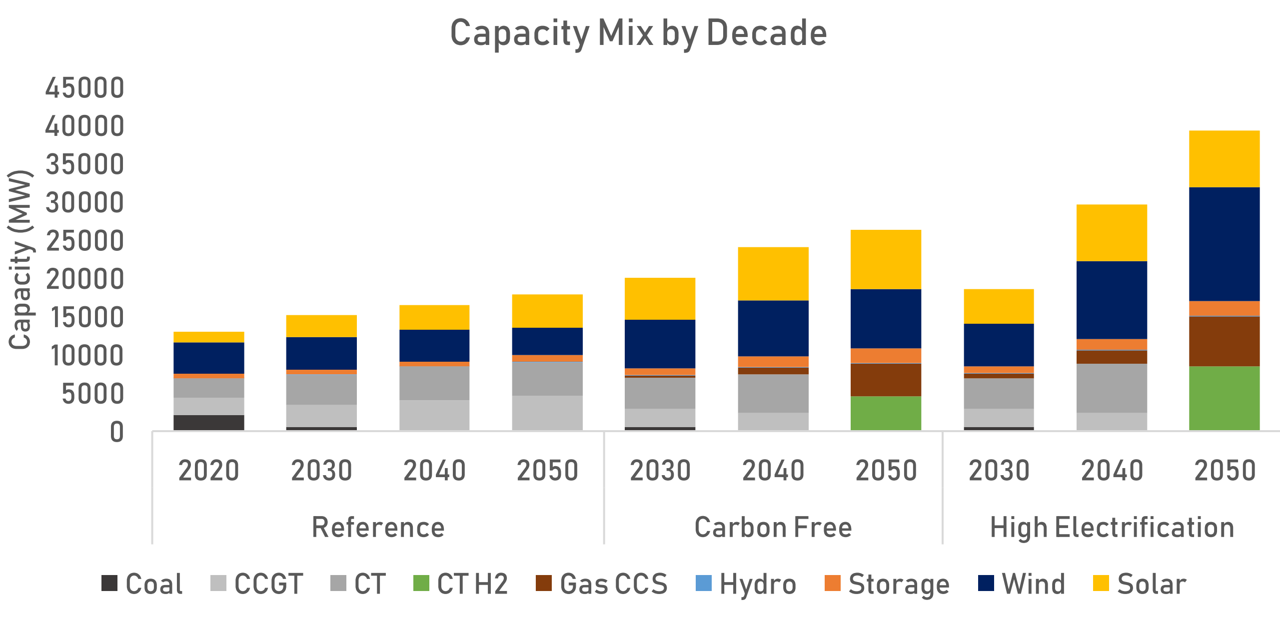

Figure 5. Capacity mix by decade

Reference Scenario

In the Reference Scenario it is assumed that PSCo will retain its existing renewable resources already in their portfolio and either renew purchasing agreements or rebuild the same capacity going forward once a renewable resource has reached its end of life. Any additional capacity needs are met with the lowest cost of generation which results in largely a combination of gas CCGT and CT. It is still cost effective to maintain existing and add additional wind, solar, and storage particularly when accounting for incentives through the IRA. Retiring older coal plants that are then replaced with higher efficiency natural gas CCGT is also found to be cost effective. The nameplate capacity mix of the Reference Scenario maintains a roughly 50 percent gas generation with a combination of CCGT with CT and 50 percent mixture of wind, solar, and storage. The total nameplate capacity of the electricity system grows from 13 GW in 2020 to 18 GW in 2050.

Carbon Free Scenario

The Carbon Free Scenario considers how to expand capacity to meet Colorado's Renewable Energy Standard of 80 percent carbon free electricity sales by 2030 and 100 percent by 2050. The aggressive requirement of 80 percent renewable electricity sales by 2030 requires that a large amount of renewable energy generation capacity is built out before 2030. This addition of new renewables then continues through 2050. Even with the high levels of renewables a certain amount of dispatchable generation capacity is needed to meet reliability standards. These dispatchable resources are operated with lower capacity factors compared to the Reference Scenario. To meet the seasonal imbalances in energy demand a mix of more novel zero carbon dispatchable resources are considered. First, gas generation utilizing an Allam Cycle that allows for 100 percent carbon capture and sequestration is built out in each decade. Given the high capital costs associated with this type of generation a capacity factor greater than 20 percent is needed to make economic sense. Before 2040 additional dispatchable generation capacity is added using traditional gas CT. However, after 2040 any CT that was added in earlier decades is retrofitted to run on GH2 to achieve 100 percent zero carbon system by 2050. Utilizing GH2 is under the assumption that an industry producing GH2 will exist that consumes electricity during off peak hours and sells GH2 back to PSCo during peak hours to maintain reliability. The low round-trip efficiency and high fuel cost associated with GH2 results in this generation used infrequently with capacity factors around 1 percent. Overall, the nameplate capacity of the 100% Zero Carbon system increases to 26 GW by 2050.

High Electrification Scenario

The High Electrification Scenario builds on the carbon free electricity system by also considering how the resource mix may change with the electrification of vehicles and residential buildings. In the High Electrification Scenario again there is a rapid increase in renewable generation capacity between 2020-2030 to achieve Colorado's Renewable Energy Standard. There is a higher increase in wind capacity as compared to the Carbon Free Scenario due to higher loads during morning and evening hours for space heating during winter months when there is low solar output. By 2050 the High Electrification Scenario increases peak demand by 4.5 GW as compared to the other two scenarios resulting in a total nameplate capacity of 39 GW, which is 50 percent higher than the total Carbon Free capacity.

Generation Mix and Curtailment

The mix of energy generation in each scenario varies due to the resource mix required to achieve GHG reduction goals or changes in the load shape due to the demand from electrification. The complete breakdown of generation mix by decade for each scenario is shown below in Figure 6.

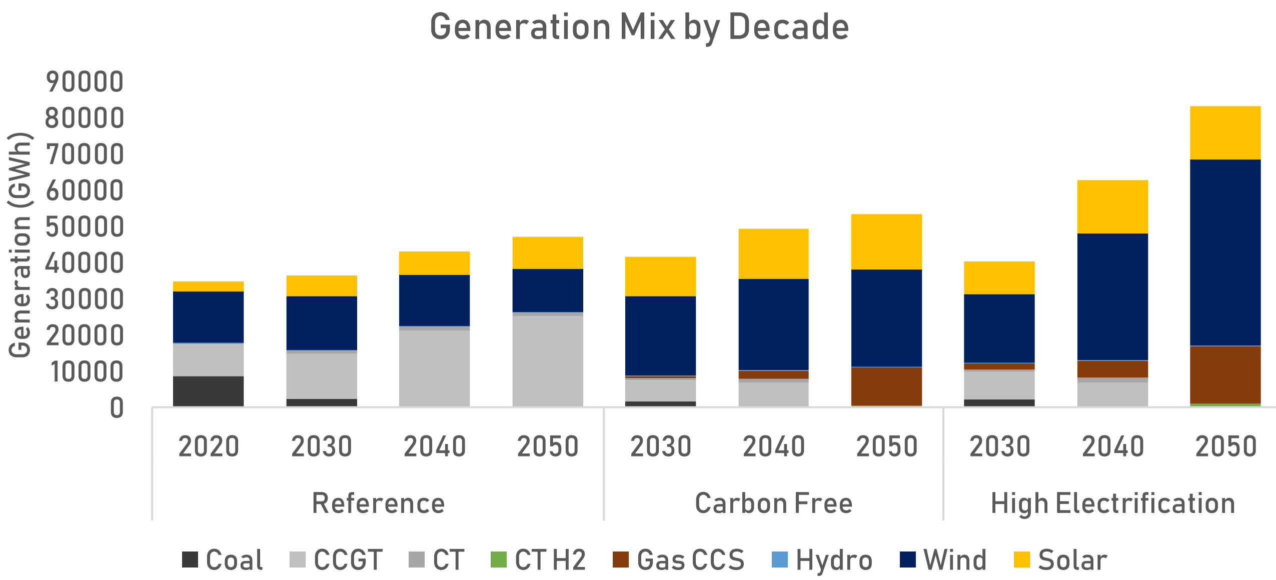

Figure 6. Generation mix by decade

In the Reference Scenario, CCGT constitutes the majority of generation in each decade with roughly 50 percent of electricity demand served by CCGT in 2050. The remaining generation is predominantly a mixture of wind and solar. Expanding renewables and a certain amount of storage are still cost competitive solutions to meet demand even under the lowest cost scenario. As the Reference Scenario does not overbuild renewable resources in order to reach emissions reduction goals, it is able to retain low levels of curtailment of less than 1 percent. Low curtailment is also enabled through the buildout of storage after 2040.

In both the Carbon Free and High Electrification Scenarios wind is largest source of generation with 50 percent of load served by wind in the Carbon Free Scenario and 60 percent in the High Electrification Scenario by 2050. As is reflected in the capacity mix, there is a greater reliance on wind to meet winter heating demands in the High Electrification Scenario. The net load after renewables is almost entirely met by gas with CCS with a very small amount of load met by GH2. Curtailment of renewables in the Carbon Free and High Electrification Scenarios varies from 11 percent to 15 percent respectively. Curtailment levels were partially reduced through the addition of 4-hour duration lithium-ion battery storage but also through the production of GH2 that made use of excess renewable production that otherwise would have been curtailed. Figures 7 and 8 below illustrate the dispatch of resources and magnitude of curtailment on a month hour basis for the Carbon Free and High Electrification Scenarios.

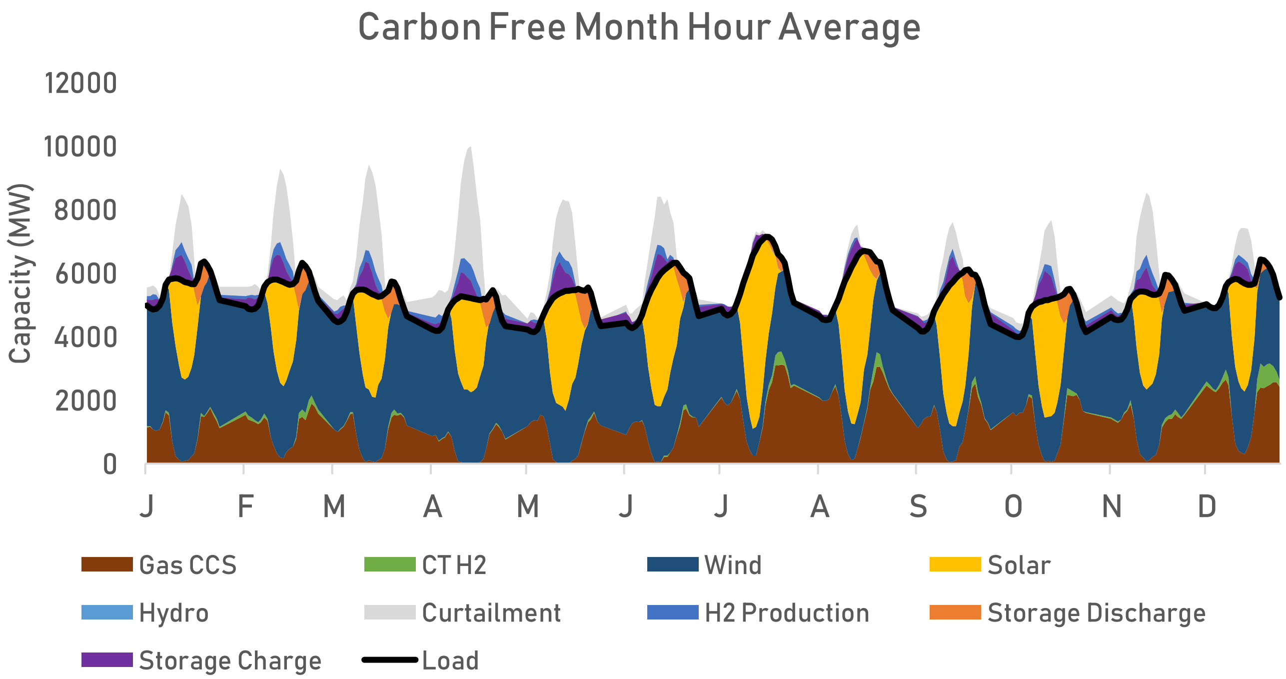

Figure 7. Carbon free scenario in 2050 month-hour average

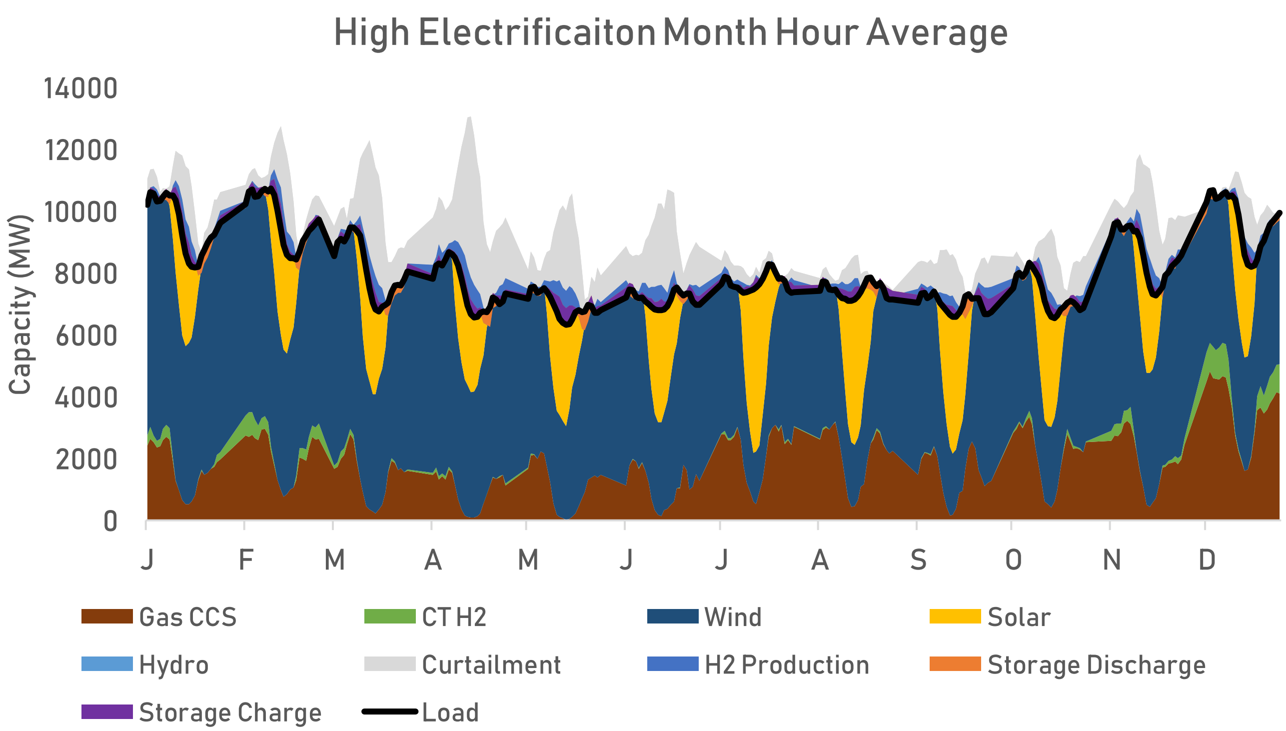

Figure 8. High electrification scenario in 2050 month hour average

It should be noted that GH2 generation accounts for nearly 20 percent of total capacity in both the Carbon Free and High Electrification scenarios, it accounts for only 1 to 3 percent of total generation. This is due to the high marginal cost of GH2 making it uneconomic to run outside of peak hours to accommodate the seasonal variations in demand. However, on days when there is high demand and low renewable generation, such as on a cold winter morning, the GH2 capacity can become crucial to maintain reliability as shown in Figure 9.

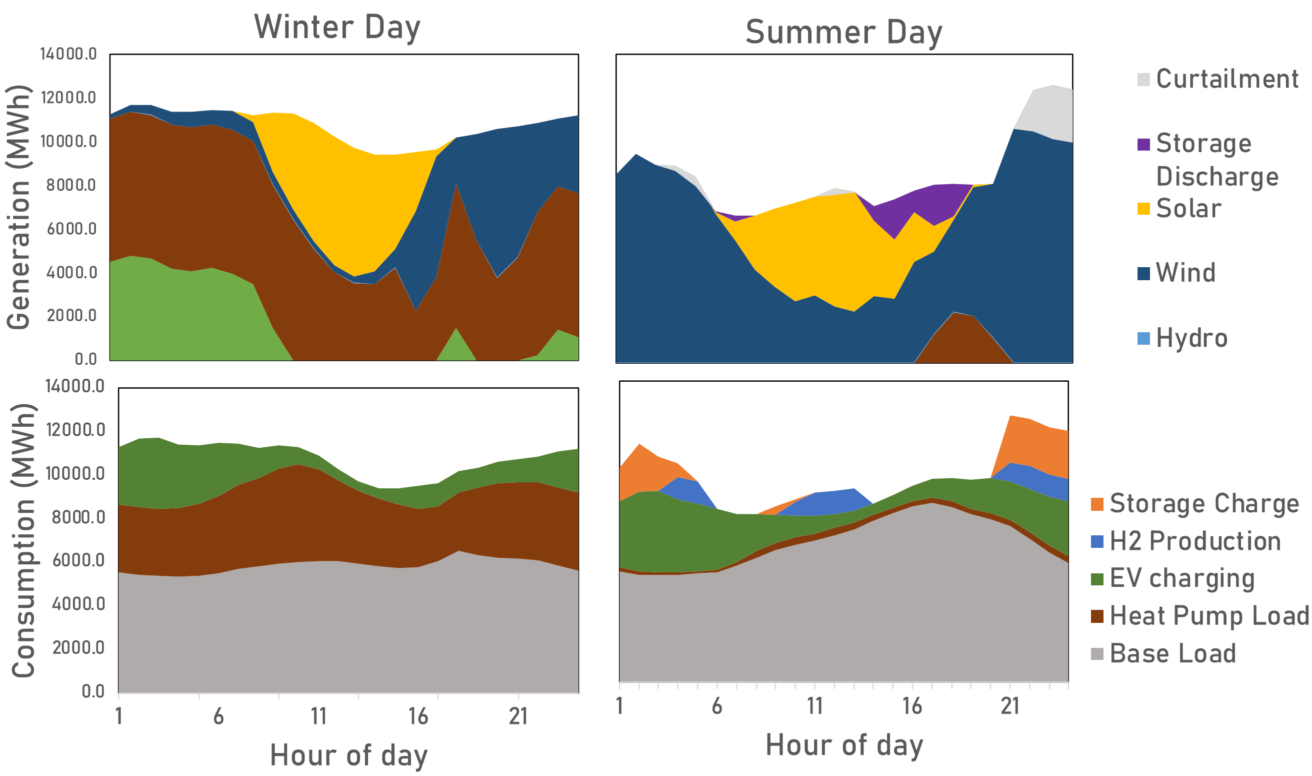

Figure 9. Comparison of high and low renewable energy capacity days

Revenue Requirement and Rates

One of the key components this IRP seeks to determine is the cost to decarbonize Colorado's electricity system. In the Reference Scenario older, less efficient forms of generation are replaced with a mixture of more efficient gas generation and an optimized capacity of renewables. At the same time loads are assumed to grow as expected in PSCo's most recent IRP. Over the planning period the total cost of the electricity system remains relatively steady and electricity rates drop by 3 cents per kWh with fixed costs spread out over growing demand.

In the Carbon Free Scenario the total cost of the electricity system increases steadily each decade with the largest increase coming before 2030. Rates initially increase to meet the 2030 Renewable Energy Standard but then decrease back to 2020 levels as demand grows and older generation is retired and replaced with more cost-effective renewables.

In the High Electrification scenario, rates initially remain flat due to new demand that can be easily incorporated into a renewable portfolio and the retirement of older generation. In the final decade rates increase with the development of more expensive zero carbon capacity including the conversion of existing CT to run on GH2 to meet growing peak demands predominantly due to winter demand for space heating.

By 2050 the Carbon Free and High Electrification Scenario rates are 14 to 18 percent higher than the Reference Scenario. It should be noted that this analysis does not take into account any potential savings for ratepayers associated with decreased gas bills or gasoline for vehicles that could potentially offset all or a portion of these increases in electricity charges.

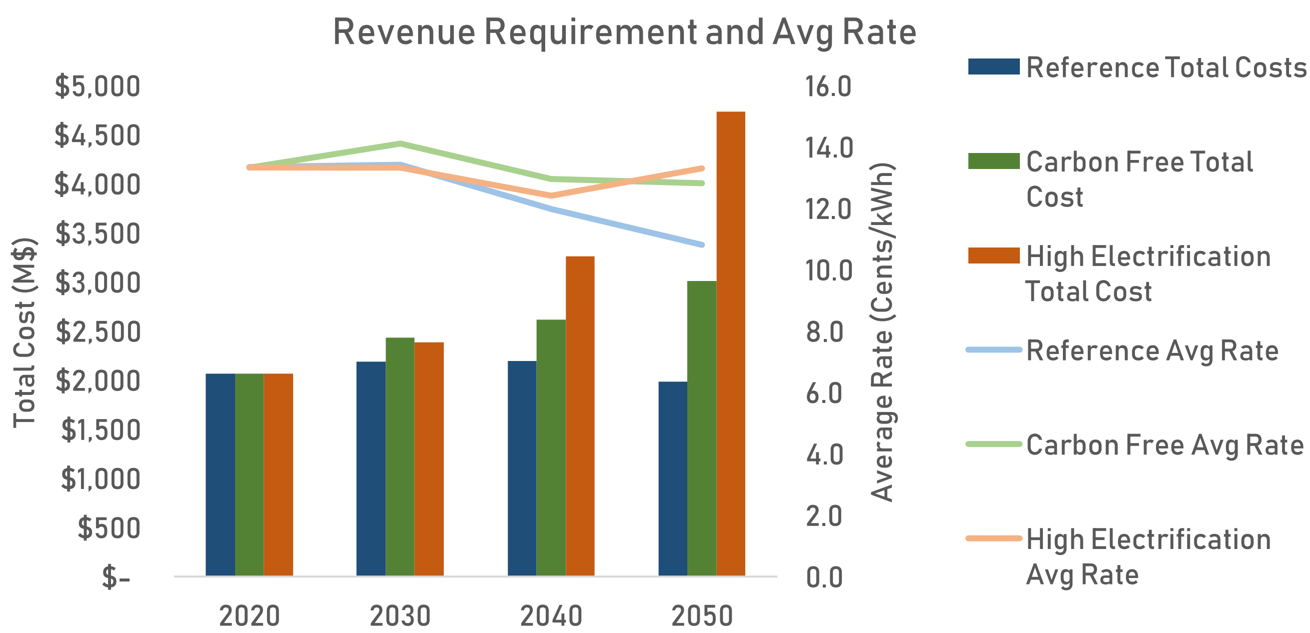

Figure 10. Revenue requirement and average rate

Emissions and Emission Intensity

The emissions across each scenario vary based on whether they adhere to Colorado's Renewable Energy Standard and the lowest cost generation mix to be compliant. The Reference Scenario emissions intensity drops initially with more efficient generation but then remains flat as total generation increases after 2030 with increased load. In the Carbon Free and High Electrification Scenarios emissions trend steadily towards zero with the largest drop-off between 2020 and 2030. It should be noted that this quantifies emissions only from the electricity sector as there are emissions reductions associated with electrification that are not quantified here.

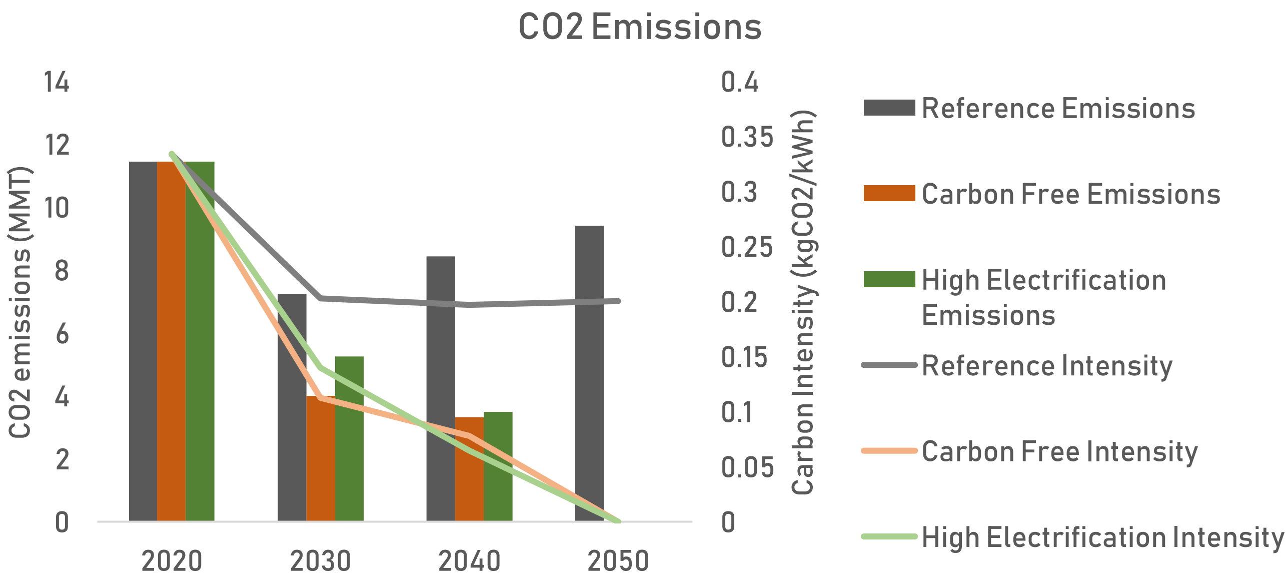

Figure 11. Emissions and emissions intensity for the electricity sector

Impacts of Electrification

Since electrification is one of the major pillars of decarbonization, it is important to study its impact on the base load. The methodology behind obtaining and processing of the electrification load is discussed in the Electrification Load Scaling subsection of Methodology section. First, the impact of only electrifying heating loads due to heat pumps (HP) is studied and then the effect of EV charging is added on top.

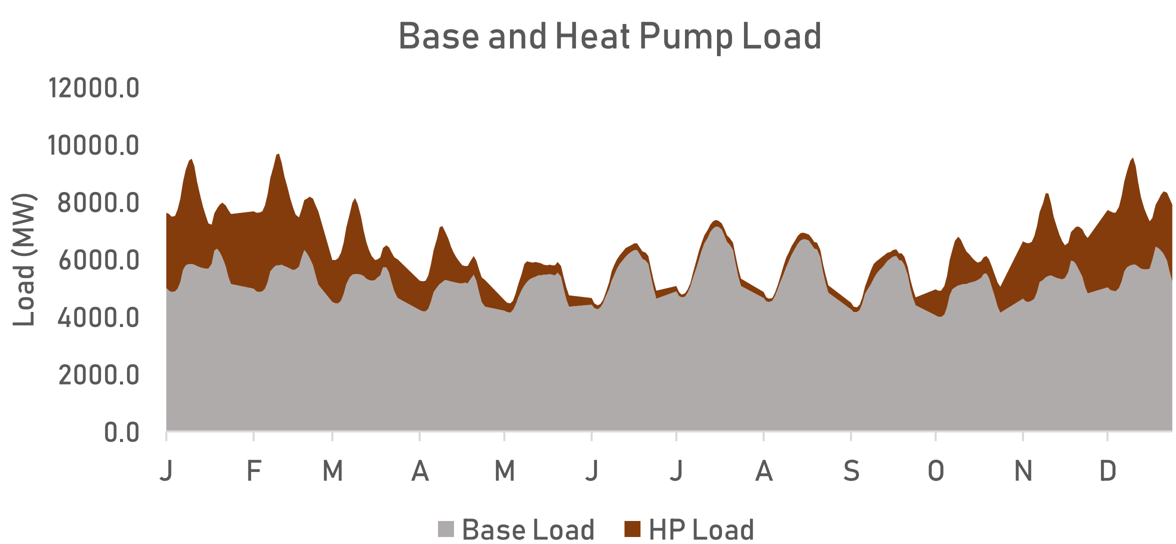

Figure 12. Adding heat pump load to the base load

It is clear from figure 12 that adding only heating load to the base load changes the summer peaking system to a winter peaking system. Also, it decreases the overall load factor from 62 percent to 53 percent. Therefore, it is important to increase the load factor through methods like shifting EV charging as discussed in the next section to decrease the overall system cost.

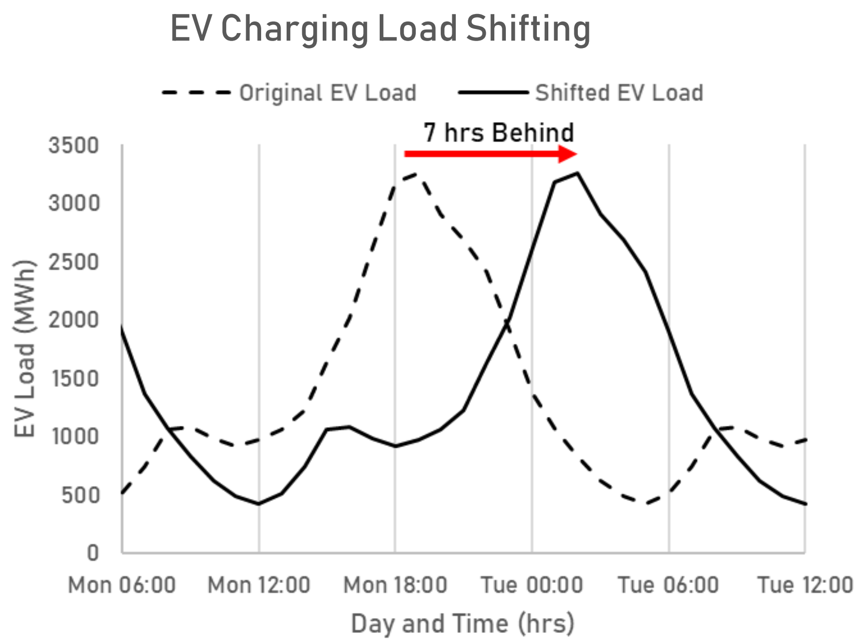

Figure 13. Shifting of EV charging profile 7 hrs behind from Evening peaking to Midnight peaking

The EV charging profile of the electrification load is shifted to reduce the additional capacity requirement. It is found that shifting the peak charging load from evening hours to midnight reduces the peak gross load from 15.5 GW to 13.4 GW and reduces the average rate from 14 to 13 cents per kWh.

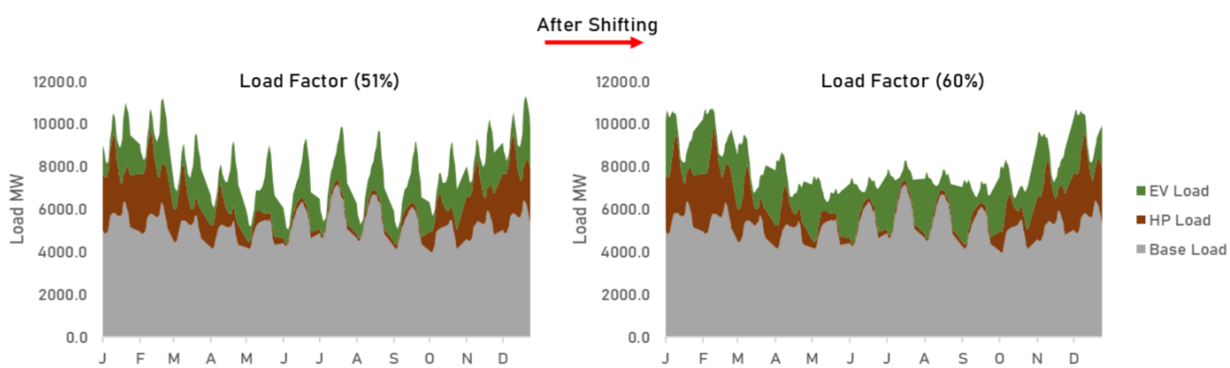

Figure 14. Month Hour average after EV load shifting

As shown in figure 14 when shifting the EV load by 7 hours the peak of EV charging falls into the valley of the base load around midnight. This shifting increases the load factor from 51 percent to 60 percent.

Since it is difficult for PSCo to predict the exact sales of the HPs or EVs it is useful to forecast average rates for different sales percentages. Also, it is important to know the impact of HP or EV sales target on the average rate.

Table 1. Impact of different 2050 sales targets of EV and HP on 2050 average rates (cents/kWh).

HP/EV (2050)	0%	50%	100%
0%	12.3	11.8	11.5
50%	12.4	11.9	11.6
100%	13.7	13.1	12.8

As shown in the previous section, shifting the EV load increases the load factor of the total load, this positive effect can be seen as decreasing the average rate from 13.7 to 12.8 cents per kWh for the 100 percent HP sales target scenario as EV sales percent increases. Also worth noticing is that for 0 percent EV sales the average rate increases almost exponentially as the HP sales target increases from 0 percent to 100 percent, this comes from the capacity needed to serve a few peak hours in the winter mornings.

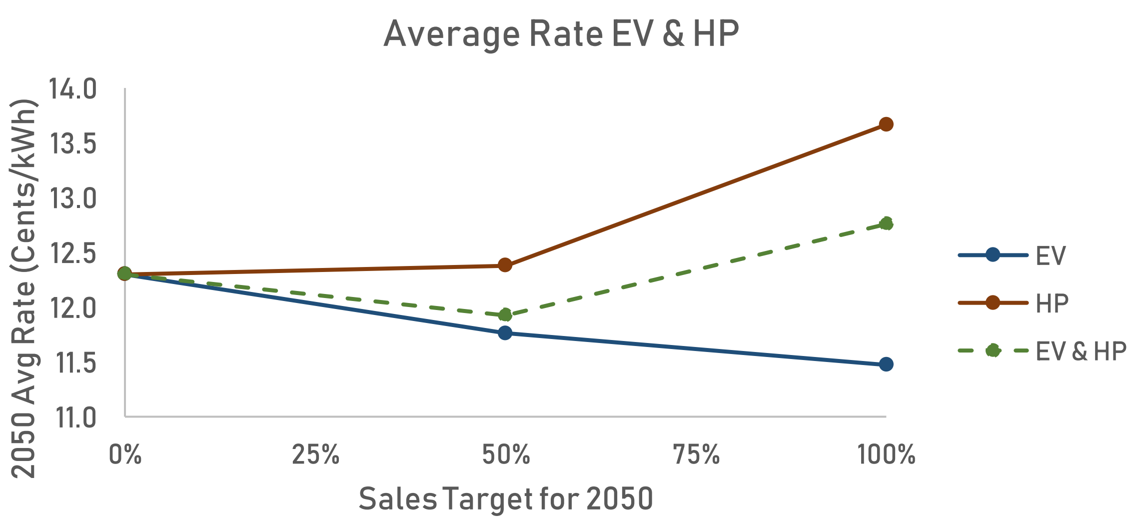

Figure 15. EV's positive effect of decreasing the rates when combined with the sales of HP.

The above figure shows the effect of EV only, HP only, and EV and HP combined sales target (diagonal values in the Table 1). Higher EV sales decreases the average rate as there is more energy sold for a given amount of capacity, thereby spreading fixed costs over more kWh's sold and decreasing the cost per kWh. As seen in the dotted green curve, EV charging loads can help offset the costs associated with meeting the electricity demand for heating.

IV. Methodology

Siting Renewables

When determining the renewable generation shapes it is important to consider the renewable resource potential specifically available in Colorado. The National Renewables Energy Lab's (NREL) System Advisory Model (SAM) is used to gather accurate renewable shape profiles and capacity factors in Colorado. Renewables are sited in regions with high output potential, that can take advantage of existing transmission capacity, and that are reasonable locations where future development of renewables are likely to take place. For example, many areas in Colorado that have high wind potential are also located in mountainous regions that are either unlikely to accommodate future development or are public lands protected by conservation regulations. In locations where no transmission capacity exists an additional transmission adder of $100 per kW is included. Figure 12 below shows the exact locations where renewable shapes were chosen using the NREL SAM tool. Most of the solar resources are chosen in the San Luis Valley where there is high solar potential and access to existing transmission. Wind resources are located in eastern Colorado, mostly near transmission though some away from existing transmission.

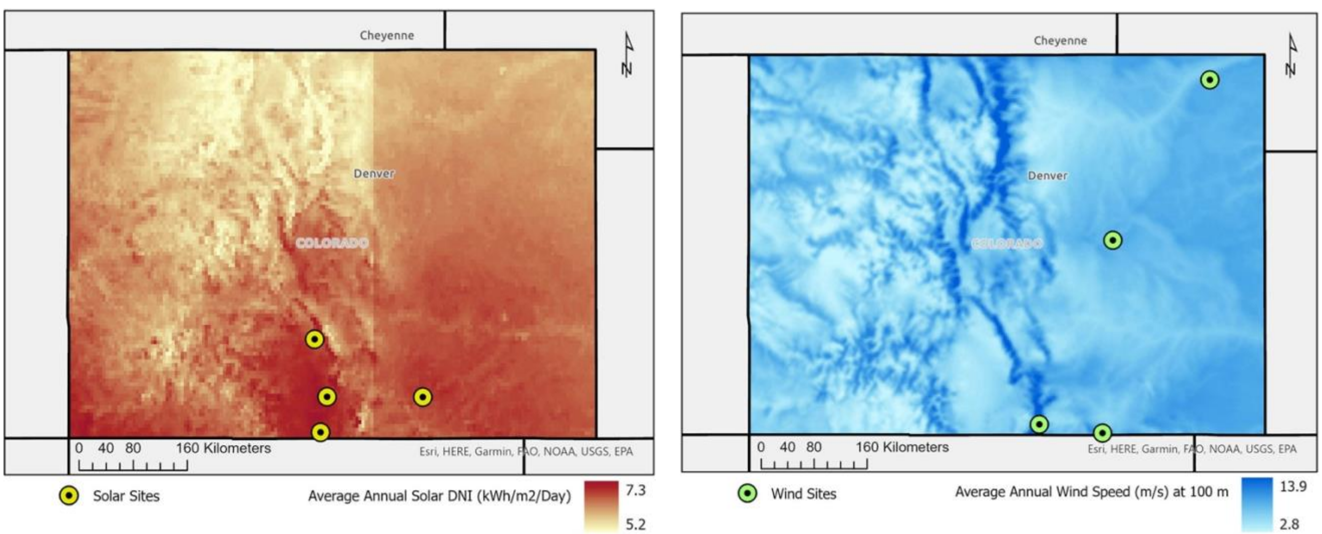

Figure 16. Solar and wind locations chosen for IRP

Load Forecasting

Reference Load Forecasting

The load forecast used in both the Reference Scenario and Carbon Free Scenario are forecasts from PSCo's 2021 IRP. PSCo typically forecasts demand under a variety of scenarios including a low growth, high growth, and a base scenario. The peak demand and load growth forecast under PSCo's base case was used for the Reference and Carbon Free Scenarios.

High Electrification Load Forecasting

To study the effect of high electrification on the grid, the load profiles of the EV load and heating load are added to the base load. The EV charging load profiles are obtained from Alternative Fuels Data Centre's Electric Vehicle Infrastructure Projection Tool (EVI-Pro). Profiles are gathered for Denver and the state of Colorado over a 24-hour period and are then appended manually to obtain a profile for all 8,760 hours in a year. Care is taken to differentiate a weekday and weekend profile. The profile is then normalized such that the sum of all values equals one.

In a separate spreadsheet an EV stock rollover model is used to calculate the energy supply needed to satisfy EV growth. The EV stock rollover model uses user demands including the service area population and future changes in EV and ICE performance data to estimated various stocks of EV and ICE for each year and from that the energy needs are calculated. In the stock rollover model only EV and ICE are considered. Then, the normalized EV charging profile is multiplied by the total energy to get the profile for that particular year. The EV load profile is also shifted to reduce the peak of the sum load profile. It is shifted such that the actual reserve margin increases to a maximum value if shifted. Through a systematic study it is found that shifting the maximum loading point 7 hours behind increases the actual reserve margin to the maximum as discussed in the Results section.

For the electrification of heating demand, the load profiles are obtained from NREL End-Use Load Profiles for the U.S. Building Stock. Separate load profiles are obtained for various home types and heating demand (space and water) for the state of Colorado and then summed to obtain the total load. As was done for the EV load profile, it is also normalized to a total energy of one. A heat pump stock rollover model is used to calculate heating demand growth within PSCo service area. The normalized heating profile is multiplied with the total heating energy demand to get a profile for that particular year. Finally, both EV and heating load profiles are summed to obtain the High Electrification Scenario load profile.

Capacity Expansion

Expanding capacity to meet the resource requirements for each scenario is done using an Excel based stack model. The stack model accounts for the fixed costs, variable costs, and performance characteristics of each resource type to dispatch the lowest cost available resource to meet demand under the constraints of each scenario. The optimum mix of resources is manually determined by using a screening curve and the Excel solver tool in the stack model.

Reference Scenario Capacity Expansion

In the Reference Scenario, it is assumed that PSCo retains its existing renewable resources and adds additional renewables only when cost effective to do so. The remaining capacity needs are met with the lowest cost new resources which are a mixture of CCGT and CT that are optimized using Excel Solver and a screening curve sufficient to achieve an 18% capacity reserve margin.

Carbon Free and High Electrification Capacity Expansion
In the Carbon Free and High Electrification Scenarios, the expansion of resources is constrained to meet Colorado's Renewable Energy Standard requirement of 80% renewable energy by 2030 and 100% carbon free electricity sales by 2050. To achieve the 2030 requirement a mixture of wind, solar, and storage are built out with the exact mixture determined using Excel Solver in the stack model. The additional capacity mix of firm dispatchable resources is determined using reasonable assumptions about the pace to build novel generation types such as Allam cycle gas turbines and by using Excel solver to meet reliability requirements.

Calculating Costs and Rates

Total costs are calculated by determining the overall cost of generation added to the cost of transmission and distribution. Average rates are then calculated by spreading out the total system cost over the served load, including electricity use for hydrogen production. The cost of generation considers both the fixed costs, including capital expenditures and fixed operations & maintenance, and variable costs including variable operations & maintenance and fuel costs. Additional variables including the PSCo's cost of capital, IRA tax credits, and the need for new transmission upgrades are factored into the cost of each new generator. Transmission and distribution costs are scaled directly proportional to the peak demand for the year in question. For certain new generation build out where it is expected new transmission is be needed an additional adder of $100 per kW is included.

V. Conclusions

This study seeks to quantify the impacts of Colorado's clean energy policies and chart a pathway forward for PSCo's electricity system. In doing so it seeks to answer these research questions:

1. What is the least cost pathway to a carbon neutral electricity sector in 2050?
2. How does a high rate of electrification impact the carbon neutral pathway?
3. How do these scenarios compare to a business-as-usual approach?

Least Cost Pathway to Decarbonization
This study found that the least cost approach towards decarbonizing the electricity system is one based predominantly on renewables with wind generation serving the majority of the load in all decades. Balancing the variable supply from renewables with daily and seasonal fluctuations in demand is done using a combination of storage, curtailment, and a diverse mix of dispatchable zero carbon technologies including gas with CCS and CT retrofitted to run on GH2. It should be noted that in the scenarios with carbon free electricity, additional fossil fuel thermal generation is still added in the coming decades to maintain a reliable system. These generators are either equipped with CCS or retrofitted later to run on GH2. The higher cost GH2 is run infrequently due to its high marginal cost while gas with CCS has higher fixed costs and therefore is operated more frequently.

Impacts of Electrification

Accommodating the additional loads associated with the electrification of vehicles and buildings requires a faster buildout of more generation capacity but has limited impacts on rates. In the near-term, rates for the High Electrification Scenario are lower than that of the Carbon Free Scenario and by 2050 there is only a 4% cost difference with High Electrification being slightly higher. Meeting the winter heating demands during low renewable output hours tends to have the highest impact on rates. However, any increase in rates can be offset by shifting EV charging loads from the net peak. Electrification also converts the overall electricity system to winter peaking with a higher reliance on wind energy to meet demand.

Comparison to the Reference Scenario

This study finds that a carbon free electricity system results in 14 to 18% higher electricity rates depending on the rate of electrification. This amounts to roughly an additional $20 per month on a typical PSCo utility bill. It should be noted that there are savings not factored into this study such as reduced spending on fossil fuel infrastructure, benefits to public health, and savings with more efficient appliances and vehicles. While not an insignificant amount for many households, it shows that there is an economically feasible approach towards decarbonizing the electricity sector and that cost is likely not the main challenge for the clean energy transition.

Appendix

Nameplate Capacity (MW) - Reference								
Resources	2020		2030		2040		2050	
	MW	Share	MW	Share	MW	Share	MW	Share
Coal	2130	16%	540	4%	0	0%	0	0%
CCGT	2267	17%	2888	19%	4014	24%	4611	26%
CT	2467	19%	3935	26%	4429	27%	4374	24%
Gas CCS	0	0%	0	0%	0	0%	0	0%
CT H2	0	0%	0	0%	0	0%	0	0%
Hydro	59	0%	58	0%	56	0%	56	0%
Storage	599	5%	599	4%	599	4%	946	5%
Wind	4124	32%	4325	28%	4125	25%	3525	20%
Solar	1358	10%	2874	19%	3284	20%	4393	25%
Total	13005	100%	15219	100%	16506	100%	17905	100%

Nameplate Capacity (MW) - Carbon Free								
Resources	2020		2030		2040		2050	
	MW	Share	MW	Share	MW	Share	MW	Share
Coal	2130	16%	540	3%	0	0%	0	0%
CCGT	2267	17%	2341	12%	2341	10%	0	0%
CT	2467	19%	4107	20%	5085	21%	0	0%
Gas CCS	0	0%	300	1%	900	4%	4242	16%
CT H2	0	0%	0	0%	0	0%	4582	17%
Hydro	59	0%	58	0%	56	0%	56	0%
Storage	599	5%	899	4%	1399	6%	1899	7%
Wind	4124	32%	6353	32%	7297	30%	7828	30%
Solar	1358	10%	5485	27%	6987	29%	7678	29%
Total	13005	100%	20083	100%	24065	100%	26286	100%

Nameplate Capacity (MW) - High Electrification								
Resources	2020		2030		2040		2050	
	MW	Share	MW	Share	MW	Share	MW	Share
Coal	2130	16%	540	3%	0	0%	0	0%
CCGT	2267	17%	2341	13%	2341	8%	0	0%
CT	2467	19%	4035	22%	6456	22%	0	0%
Gas CCS	0	0%	600	3%	1800	6%	6579	17%
CT H2	0	0%	0	0%	0	0%	8432	21%
Hydro	59	0%	58	0%	56	0%	56	0%
Storage	599	5%	899	5%	1399	5%	1899	5%

Wind	4124	32%	5553	30%	10180	34%	14917	38%
Solar	1358	10%	4507	24%	7415	25%	7415	19%
Total	13005	100%	18533	100%	29647	100%	39298	100%

Net Generation (GWh) - Reference								
Resources	**2020**		**2030**		**2040**		**2050**	
	GWh	Share	GWh	Share	GWh	Share	GWh	Share
Coal	8659	25%	2314	6%	0	0%	0	0%
CCGT	8763	25%	12568	35%	21082	49%	25111	53%
CT	124	0%	696	2%	1026	2%	865	2%
Gas CCS	0	0%	0	0%	0	0%	0	0%
CT H2	0	0%	0	0%	0	0%	0	0%
Hydro	206	1%	202	1%	195	0%	195	0%
Wind	14169	41%	14858	41%	14169	33%	12108	26%
Solar	2706	8%	5726	16%	6542	15%	8753	19%
Total	34626	100%	36364	100%	43015	100%	47033	100%

Net Generation (GWh) - Carbon Free								
Resources	**2020**		**2030**		**2040**		**2050**	
	GWh	Share	GWh	Share	GWh	Share	GWh	Share
Coal	8659	25%	1570	4%	0	0%	0	0%
CCGT	8763	25%	5884	14%	6691	14%	0	0%
CT	124	0%	507	1%	1087	2%	0	0%
Gas CCS	0	0%	601	1%	2328	5%	10478	20%
CT H2	0	0%	0	0%	0	0%	517	1%
Hydro	206	1%	202	0%	195	0%	195	0%
Wind	14169	41%	21825	53%	25068	51%	26892	50%
Solar	2706	8%	10928	26%	13921	28%	15298	29%
Total	34626	100%	41517	100%	49291	100%	53381	100%

Net Generation (GWh) - High Electrification								
Resources	**2020**		**2030**		**2040**		**2050**	
	GWh	Share	GWh	Share	GWh	Share	GWh	Share
Coal	9046	26%	2137	5%	0	0%	0	0%
CCGT	9055	26%	7730	19%	6716	11%	0	0%
CT	141	0%	590	1%	1407	2%	0	0%
Gas CCS	0	0%	1553	4%	4669	7%	15899	19%
CT H2	0	0%	0	0%	0	0%	1018	1%
Hydro	206	1%	202	1%	195	0%	195	0%
Wind	14169	40%	19076	47%	34969	56%	51244	62%

Solar	2706	8%	8980	22%	14773	24%	14773	18%
Total	35322	100%	40268	100%	62730	100%	83130	100%

Generation Resource and Fuel Costs

CAPEX ($/kW)									
Year	**CT**	**CCGT**	**Coal**	**Solar**	**Wind**	**Hydro**	**Storage**	**Gas CCS**	**CT H2**
2020	$928	$1,049	$5,618	$1,377	$1,392	$2,528	$1,363	$2,770	$1,113
2030	$846	$999	$5,192	$776	$950	$2,528	$784	$2,334	$1,016
2040	$800	$955	$4,972	$708	$855	$2,427	$686	$2,025	$961
2050	$752	$907	$4,757	$638	$760	$2,427	$588	$1,831	$903

Fixed Operations and Maintenance Costs ($/kW-yr)									
Year	**CT**	**CCGT**	**Coal**	**Solar**	**Wind**	**Hydro**	**Storage**	**Gas CCS**	**CT H2**
2020	$20.90	$27.30	$142.90	$23.40	$42.63	$63.26	$34.08	$65.10	$20.90
2030	$20.90	$27.30	$142.90	$16.64	$38.95	$63.26	$19.60	$63.30	$20.90
2040	$20.90	$27.30	$142.90	$15.80	$36.03	$60.73	$17.15	$60.40	$20.90
2050	$20.90	$27.30	$142.90	$14.99	$33.11	$60.73	$14.70	$60.40	$20.90

Variable Operations & Maintenance ($/kW-yr)								
CT	**CCGT**	**Coal**	**Solar**	**Wind**	**Hydro**	**Storage**	**Gas CCS***	**CT H2**
$4.9	$2.2	$4.7	$0	$0	$0	$0	$12	$4.9

**Includes the cost of sequestering carbon $20/ton*

Heat Rate (MMBtu/MWh)				
CT	**CCGT**	**Coal***	**Gas CCS**	**CT H2**
9.9	6.4	9.7	5.6	9.9

Fuel Costs ($/MMBtu)			
Year	**Coal**	**Gas**	**Green H2**
2020	$2.00	$3.35	$22.3
2030	$1.95	$3.00	$14.9

2040	$1.91	$3.84	$7.4
2050	$1.89	$3.64	$7.4

Data Sources

Colorado Energy Office. “GHG Pollution Reduction Roadmap 2.0” (2021). https://energyoffice.colorado.gov/climate-energy/ghg-pollution-reduction-roadmap

Colorado 74th General Assembly, “Colorado SB 19-236” (2019). https://leg.colorado.gov/bills/sb19-236

U.S. Department of Energy, Office of policy, “Inflation Reduction Act Factsheet” (2022). https://www.energy.gov/sites/default/files/2022-08/8.18%20InflationReductionAct_Factsheet_Final.pdf

EIA Annual Energy Outlook. “Electricity Market Module” Table 3. Cost and performance (2022). https://www.eia.gov/outlooks/aeo/assumptions/pdf/electricity.pdf

IEA, “The Future of Hydrogen” (2019). https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

The U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office, “Hydrogen Shot” (2021). https://www.energy.gov/eere/fuelcells/hydrogen-shot

Office of Energy Efficiency & Renewable Energy, Solar Energy Technologies Office, “Solar Investment Tax Credit: What Changed?” (2022). www.energy.gov/eere/solar/articles/solar-investment-tax-credit-what-changed

Öberg, S., Odenberger, M., & Johnsson, F. (2022). Exploring the competitiveness of hydrogen-fueled gas turbines in future energy systems. International Journal of Hydrogen Energy, 47(1), 624-644. (CT Hydrogen Retrofit Costs). https://www.sciencedirect.com/science/article/pii/S0360319921039768

Glenk, G., & Reichelstein, S. (2022). Reversible Power-to-Gas systems for energy conversion and storage. Nature Communications, 13(1), 2010. https://www.nature.com/articles/s41467-022-29520-0

Chaturvedi, R., Kennedy, E., & Metew, S. (2021). CO2 sequestration by Allam Cycle. (Allam Cycle). https://repository.upenn.edu/cgi/viewcontent.cgi?article=1135&context=cbe_sdr

U.S. Environmental Protection Agency, Sector Policies and Programs Division Office of Air Quality Planning and Standards, “Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Combustion Turbine Electric Generating Units” (2022) (Allam Cycle Heat Rate). https://www.epa.gov/system/files/documents/2022-04/epa_ghg-controls-for-combustion-turbine-egus_draft-april-2022.pdf

NREL, Wind Resource Maps and Data "U.S. Multiyear Average Wind Speeds at All Heights Raster" (2017), https://www.nrel.gov/gis/wind-resource-maps.html

Draxl, C., Hodge, B. M., Clifton, A., & McCaa, J. (2015). Overview and meteorological validation of the wind integration national dataset toolkit (No. NREL/TP-5000-61740). National Renewable Energy Lab. (NREL), Golden, CO (United States).

NREL, Solar Resource Maps and Data, "The Americas Direct Normal Irradiance Multiyear annual and monthly averages Raster" (2018), https://www.nrel.gov/gis/solar-resource-maps.html

Sengupta, M., Xie, Y., Lopez, A., Habte, A., Maclaurin, G., & Shelby, J. (2018). The national solar radiation data base (NSRDB). Renewable and sustainable energy reviews, 89, 51-60.

NREL, The System Advisor Model (SAM 2022.11.21) (2022), https://sam.nrel.gov/download.html

Freeman, J. M., DiOrio, N. A., Blair, N. J., Neises, T. W., Wagner, M. J., Gilman, P., & Janzou, S. (2018). System Advisor Model (SAM) general description (version 2017.9. 5) (No. NREL/TP-6A20-70414). National Renewable Energy Lab. (NREL), Golden, CO (United States).

RE Explorer, "Solar and Wind potential map" (2023), https://www.re-explorer.org/

The U.S. Department of Energy, Alternative Fuels Data Center, "Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite", https://afdc.energy.gov/evi-pro-lite

NREL, "End-Use Load Profiles for the U.S. Building Stock" (2021), https://www.nrel.gov/buildings/end-use-load-profiles.html

Wilson et al. 2021. End-Use Load Profiles for the U.S. Building Stock: Methodology and Results of Model Calibration, Validation, and Uncertainty Quantification. NREL/TP-5500-80889. https://www.nrel.gov/docs/fy22osti/80889.pdf.