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Assessment of Natural Gas and Electric Decarbonization in State of Colorado Residential Sector

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Executive Summary

There is active dialogue on policy considerations pertaining to future pathways for reducing greenhouse gas (GHG) emissions. This report focuses on energy use and future GHG reduction pathways for the Colorado residential sector, with quantitative and qualitative information on consumer costs and environmental benefits as well as a review of real-world challenges and potential unintended or unanticipated consequences of residential electrification, particularly issues associated with space heating in a cold-climate region like Colorado.

Key findings:

- **Natural gas is a cost-effective energy choice for Colorado homeowners.** The residential cost of electricity relative to natural gas has grown in Colorado over the past 15 years. In 2022, Colorado homeowner electricity prices were 3.35 times higher than natural gas on an energy-equivalent basis.
- **Consumer surveys across the US provide evidence that most homeowners prefer natural gas** over electricity, particularly for space heating, water heating, and cooking.
- **Electrification of Colorado homes will more than double consumer annual energy costs.** Annual energy costs for Case 1 (natural gas including a 98% efficient gas furnace) are $1,525 million compared to Case 6 (electricity including an HSPF 9 electric heat pump) at $3,239 million. This represents an over $2 billion increase in annual energy bills for current homes using natural gas in the state (112% higher).
- **Electrification of Colorado homes will raise consumer annualized capital costs for energy equipment.** Annualized equipment costs for Case 1 are $942 million and for Case 6 $1,528 million. This represents a $586 million increase in annualized capital costs with electrification (62% higher).
- **Natural gas pathways for GHG reductions have lower societal costs when measured in $/metric ton of CO_2 reduced.** Using currently available high-efficiency gas equipment results in cost effective GHG reductions ("negative costs" of -$83/metric ton of CO_2). Renewable natural gas with existing high-efficiency equipment and next-generation natural gas heat pumps increase total GHG reduction potential, albeit at higher costs ($46 to $209/metric ton of CO_2).
- **Electric GHG abatement costs are higher than the natural gas cases; today's most popular electric heat pumps (HSPF 9.0) correspond to GHG abatement costs ranging between $405 to $552/metric ton of CO_2.** Higher efficiency electric heat pumps (e.g., HSPF 13.0) improve GHG abatement costs, dropping to $250 to $307/metric ton CO_2.
- Current all-electric Colorado homes using electric resistance heating or HSPF 9 heat pumps with today's power generation mix in the state result in higher CO_2 emission rates than a natural gas home.
- **A significant issue with residential electrification scenarios in cold-climate regions centers on the intense seasonal energy use required for space heating**. Report data highlights the large increase in peak winter electricity use that would occur in the Colorado residential sector with widespread electrification (see Figure 34). The potential power

generation and electric infrastructure cost and reliability implications for consumers and society are significant.

- **There is no evidence wind or solar resources can address prospective seasonal energy-intensive space heating electricity peaks during Colorado winters**. These systems have a meaningful drop in winter output (e.g., during January).
- Using the matching principle and reasonable options at this juncture, **most new winter seasonal peak electricity demand that arises from electric space heating will be met with dispatchable natural gas generation**. Without GHG mitigation for this scenario, potential electric space heating GHG reductions will be less than anticipated.
- There is no evidence battery energy storage can play a value-added role in meeting elevated winter long-duration electricity demands.
- Using hybrid space heating systems whereby electric heat pumps operate at milder temperatures and natural gas heating systems operate at cold temperatures avoids a host of issues associated with electric heat pumps
- Gas distribution systems have quantifiably higher service reliability and lower outage rates than electric distribution systems. An increasing number of homes in Colorado and nationally are installing natural gas generators to avoid the cost and issues associated with grid power interruptions.

The following is a suggested set of energy efficiency and GHG reduction measures that offer a cost-effective multi-faceted pathway – as well as high optionality value and flexibility to respond to future information and innovations:

1. A core focus emphasis on building envelope efficiency improvements that help consumers reduce their annual energy costs, improve indoor comfort, reduce natural gas and electric energy consumption (including peak energy demand), and reduce GHG emissions
2. Incentives for cost-effective GHG abatement options such as high-efficiency natural gas equipment (e.g., 95-98% efficient gas furnaces and water heaters) and gas heat pumps (130%+ efficiency) for space and water heating
3. Encouraging the expanded use of renewable natural gas (RNG) and related pathways for producing and using low-carbon sources of methane or hydrogen (including power-to-gas) that can lower the carbon intensity of gaseous energy delivered to homes
4. Expanded use of hybrid space conditioning systems based on the concept of a high-efficiency natural gas furnace and an electric heat pump system as an upgrade to a conventional whole house air conditioning system, working together with smart controls at the home and utility level to optimize cost, energy delivery system asset utilization, and GHG reductions.

Introduction

There is active international, national, state, and local dialogue on policy considerations pertaining to future pathways for reducing greenhouse gas (GHG) emissions. This report focuses on energy use and future GHG reduction pathways for the State of Colorado (CO) residential sector, with certain elements that apply to various regions in the United States (US). Natural gas and electricity, the two main residential energy choices in Colorado, are reviewed in terms of: (1) the current market situation and (2) potential future pathways for GHG reductions using natural gas or electricity or hybrid approaches employing both energy options.

This report, an update to an earlier 2021 publication, provides a quantitative assessment of Colorado residential consumer economic impacts (e.g., capital costs and annual energy costs) and societal benefits and costs (e.g., GHG reduction and $/metric CO_2 equivalent reduction) stemming from various future natural gas, electric, and hybrid natural gas/electric scenarios.

It also highlights other considerations for these energy supply systems, with an emphasis on system-wide challenges from broader electricity use for space heating in cold-weather regions like Colorado:

(1) high winter peak-day/peak-month energy demand,
(2) issues associated with the need for expanded electric generation, transmission, distribution, and energy storage assets on a limited seasonal basis, and
(3) the type of generation resources typically employed for longer-duration seasonal space heating.

These issues may result in higher than anticipated consumer and societal costs, lower than expected real-world GHG reduction benefits, and greater risks of electric grid instability and outages.

The report reviews trends in Colorado residential natural gas and electricity prices and discusses high-level potential future electric system asset investment issues that could arise from greater electricity use in homes. While highly relevant to policy discussions, the potential impact of future electric infrastructure on residential electricity prices in Colorado is outside the report scope and is not included in this economic assessment.

Recommendations are made for pursuing common sense and cost-effective measures for reducing GHG emissions from Colorado homes. Gaseous resources – conventional natural gas and renewable gases – and their resilient delivery infrastructure can play a positive long-term role in realizing GHG reductions. These recommendations emphasize consumer choice, making cost-effective investments (including leveraging existing infrastructure and improving building envelope thermal efficiency), the potential role for hybrid home natural gas and electric systems, an expanded role for low-carbon gaseous energy resources, and the value of future innovation and optionality. The report places an emphasis on quantified (i.e., $/metric ton of CO_2) GHG reduction pathways.

Colorado Home Energy Use, Prices, and Preferences

Natural gas and electricity are the main energy choices for Colorado homes. Figure 1 is a summary of Colorado homes based on space heating energy source. Natural gas has a dominant share (69%) of the CO residential space heating market, followed by electricity at 23%.

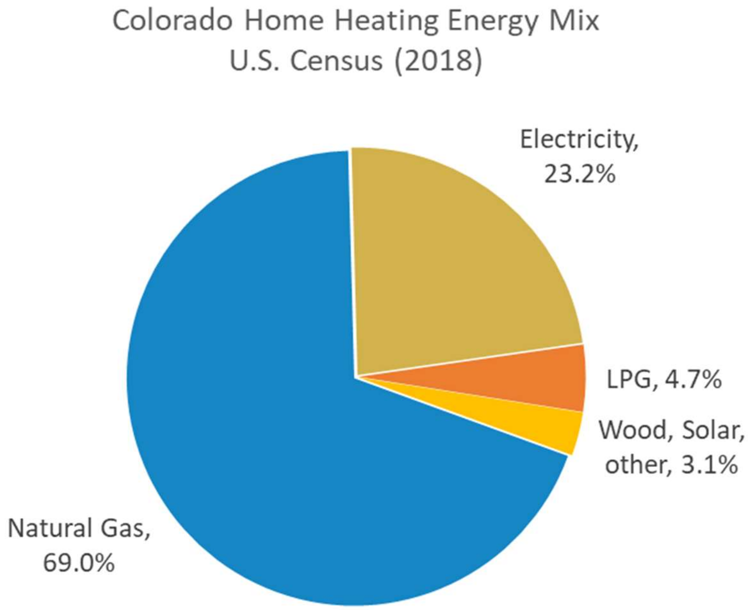


Figure 1: Colorado Residential Space Heating Home Share (US Census)

Figure 2 shows trends in growth in the number of Colorado homes using natural gas from 2000 to 2021. Over this period, the number of gas homes has grown by about 42% -- reflecting the continued popularity of natural gas as a home energy source. Coincidental with this growth is a downward trend in the annual gas use per home. This indicates ongoing trends toward more efficient energy use through measures such as higher-efficiency appliances (e.g., furnaces and water heaters) and improvements in residential home building insulation and windows. This Colorado trend mirrors data seen across the US over the past four decades.

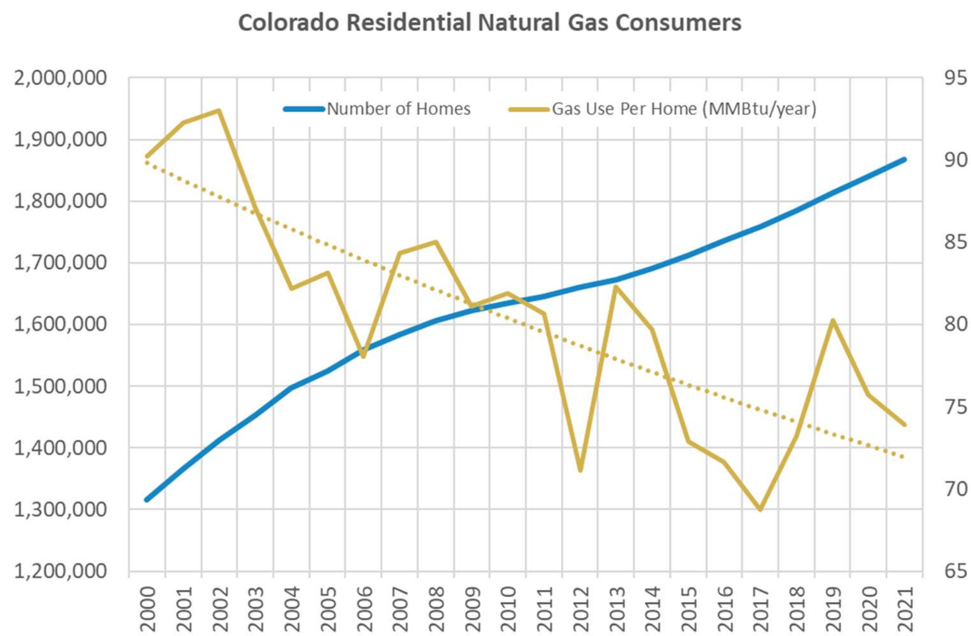


Figure 2: Trends – Number of Colorado Homes Using Natural Gas and Average Annual Gas Use Per Home (Department of Energy – Energy Information Administration; DOE-EIA)

Colorado residential energy preferences mirror national home energy surveys. Figure 3 shows national residential homeowner survey results, highlighting a strong consumer preference for natural gas over electricity in four primary thermal energy applications: space heating, water heating, cooking, and clothes drying. Homeowners prefer natural gas, with gas space heating, water heating, and cooking as highly preferred home energy choices.

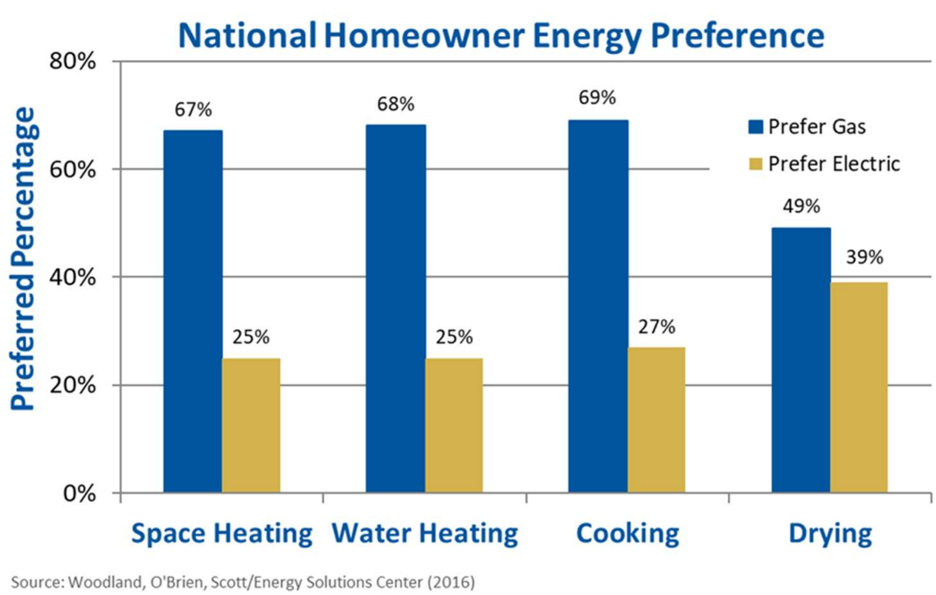


Figure 3: National Residential Homeowner Energy Preferences

Across the US residential sector, substantially more energy is used for space heating than cooling – especially in cold weather regions (Figure 4). As a first-order approximation, the energy required for home space conditioning depends on temperature differences inside and outside a dwelling. For example, cooling a home on a hot 90°F summer day to 74°F is a temperature difference of 16°F. In contrast, heating a home from 20°F to 70°F on a cold day is a temperature difference of 50°F (or nearly three times more energy); this effect is more pronounced during sub-zero temperature conditions. Across much of the US, heating season duration and the total runtime hours for space heating equipment is considerably higher than is needed during the cooling season. This is certainly true in cold-weather regions like Colorado.

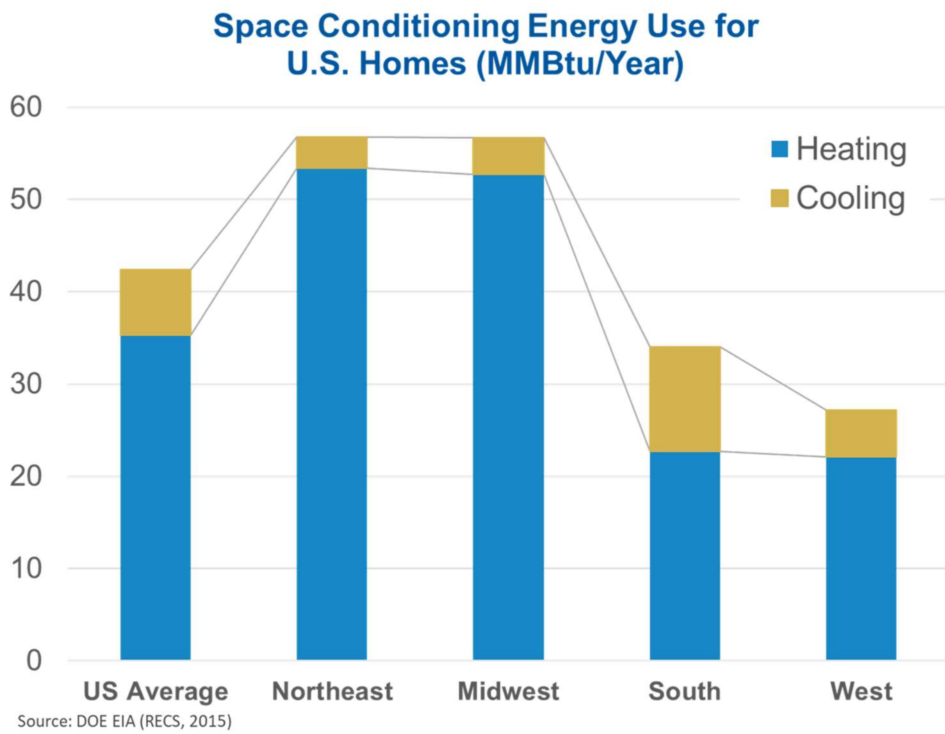


Figure 4: Annual Average Space Conditioning Energy Use for U.S. Homes

Heating and Cooling Degree Days (HDD and CDD, respectively) are metrics that account for: (1) space conditioning temperature differences (that is, between outdoor and indoor temperatures) and (2) the number of days needed for space heating and cooling. Figure 5 shows HDD and CDD values since 2000 for the U.S. and the Mountain Region (as a proxy for Colorado). CDD in the Mountain Region are like the U.S. average, while Mountain Region HDD are higher than the U.S. average. Annual Mountain Region HDD are 3.4 times greater than CDD requirements. This highlights a core theme in this report: the significant seasonal energy requirements for space heating in cold-weather regions like Colorado pose a serious challenge for energy delivery systems – particularly on peak cold days, weeks, and months.

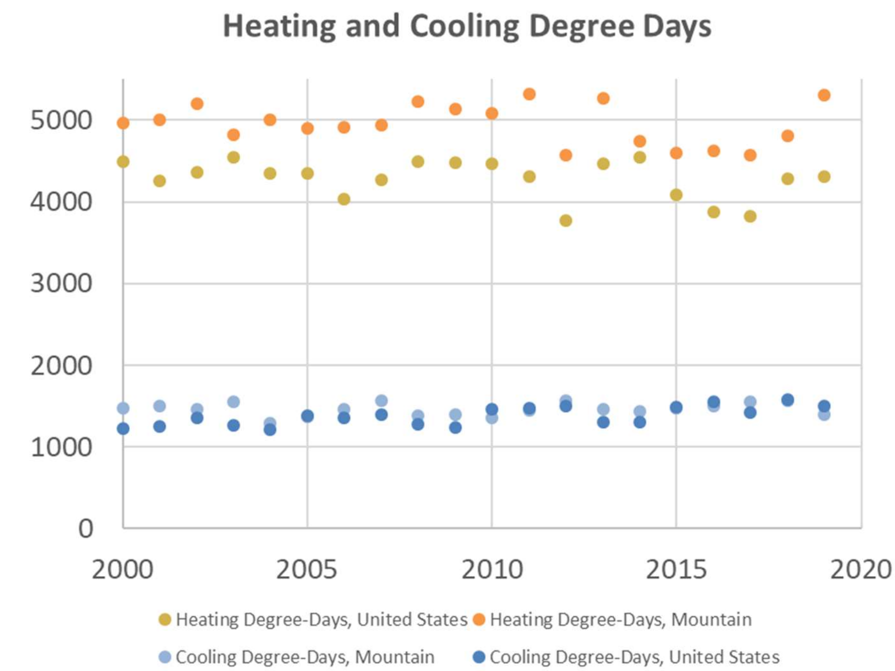


Figure 5: U.S. and Colorado Heating and Cooling Degree Days (DOE-EIA)

HDD and CDD data also serve as a proxy for space conditioning energy use. Figure 6 shows monthly electricity and natural gas energy use in Colorado homes over a seven-year period (2015 to 2022). Year-to-year variations are due to HDD and CDD needs in a year (i.e., extended cold or hot weather during a season). Each line is on the same energy use scale, enabling direct comparisons. This highlights the large seasonal natural gas energy required to heat Colorado homes compared to the electricity needed for cooling. This pattern of high natural gas winter peaks is commonly seen across much of the U.S. – especially in colder climate regions.

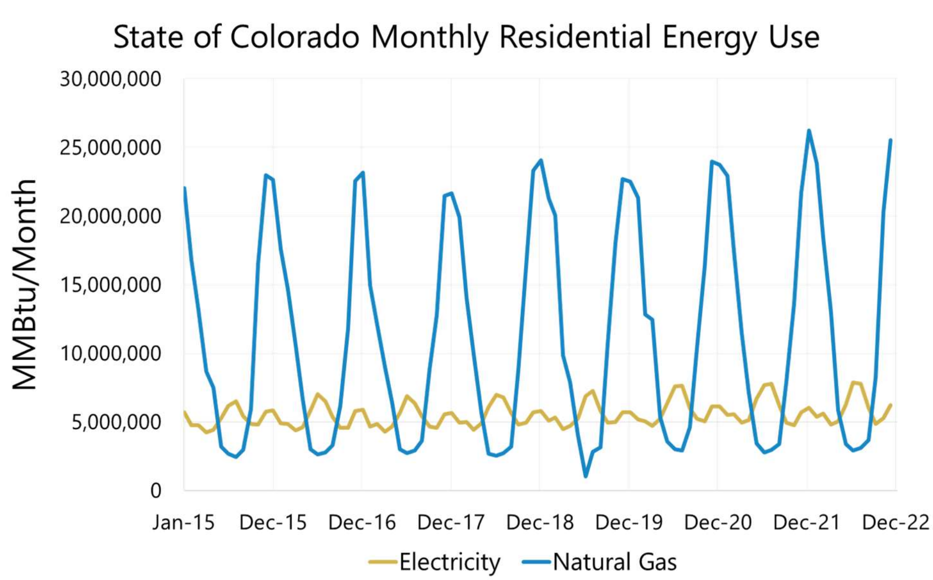


Figure 6: Monthly Residential Energy Use in Colorado Over Eight Years (DOE-EIA)

A primary reason people prefer natural gas is its cost-effectiveness. Figure 7 shows trends for average annual Colorado residential electricity and natural gas prices since 2005. During this period, residential electricity prices grew 58% while natural gas prices grew 24% (mainly due to inflation during 2021-2022 that impacted electricity and natural gas prices). Colorado homeowner electricity prices are 3.35 times greater than natural gas on an energy equivalent basis. According to DOE-EIA, the average CO residential electric price was 14.29 cents/kWh in 2022. In similar energy units, average CO residential natural gas prices were about 4.26 cents/kWh in 2022. Natural gas is a cost-effective energy option for Colorado consumers.

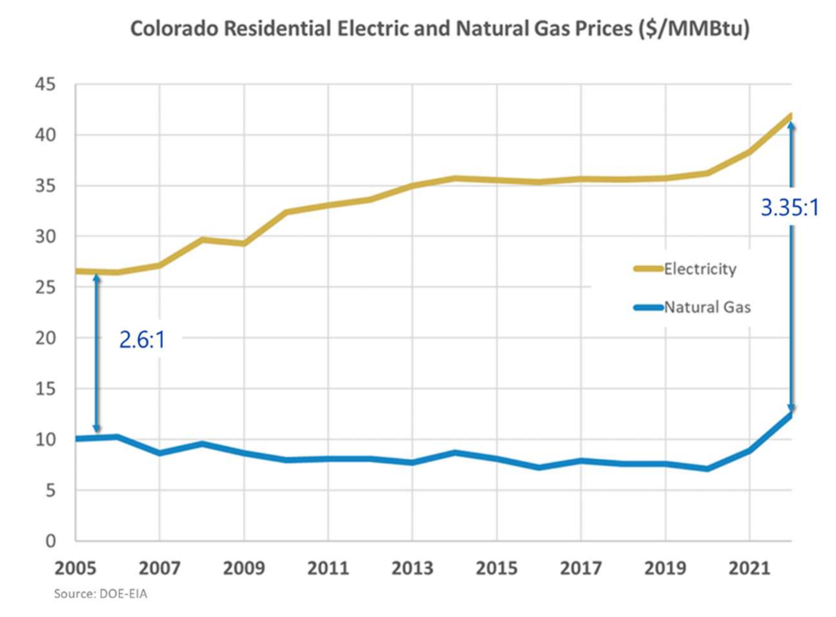


Figure 7: Colorado Residential Electric and Natural Gas Price Trends (DOE-EIA)

Beyond the economic value natural gas provides, consumers also prefer natural gas because of its performance advantages over equivalent electric options:

- Homes heated with natural gas offer greater indoor comfort due to higher delivered air temperature compared to electric heat pumps
- Natural gas furnaces and boilers provide 2-3 times greater energy delivery rates than electric heat pumps, allowing (for example) rapid heat up when using overnight energy saving setback thermostats
- Natural gas water heaters provide rapid water heating and faster recovery times when using conventional storage water heaters or continuous hot water with newer tankless water heaters
- Natural gas cooking equipment provides more rapid stovetop heating of water or food products, along with greater control, than conventional electric resistance stoves

An increasing number of homeowners are using natural gas for other uses such fireplaces, outdoor grills, and home emergency generators. Natural gas fireplaces are a clean-burning alternative to wood fireplaces, providing seasonal indoor comfort while reducing the carbon monoxide and particulate emissions associated with wood-burning.

Residential generators are becoming increasingly popular as a means of improving home energy security, reliability, and resilience. According to the US Census American Housing Survey, over 23% of single-family homes (nearly 15 million in total) in the US had some form of home power generation – a stationary or portable generator typically fueled by natural gas, propane, or gasoline. Over the past 15 years, natural gas home generators have grown in popularity (Figure 8), due to growing criticality of electricity to provide space conditioning, refrigerated food storage, sump pump operation, as well as home internet and other important services.

Figure 8: Typical Natural Gas Home Emergency Generator (Spectrum Electric Ltd; Conifer, CO)

In regions with intermittent electric service or potential for extended weather-driven power outages, natural gas home generators provide an important level of homeowner security and value, reducing concerns over potential property losses or impacts to personal safety. The important topic of energy delivery systems and home energy reliability will be discussed in a later section. The uniquely high reliability of natural gas distribution energy service (and convenience of avoiding periodically refilling propane or gasoline tanks) is an important driver for consumers choosing natural gas emergency generators for their homes and businesses.

Colorado Home Greenhouse Gas Reduction Pathways

This section highlights various natural gas, electric, and hybrid natural gas/electric GHG reduction pathways for Colorado homes. This provides context for the following section on GHG reduction pathways benefit/cost information. In crafting GHG reduction scenarios, it is essential to review and understand the complex dynamics that exist in the design and operation of natural gas and electric energy delivery systems along with factors such as real-world end-use equipment performance. This facilitates an informed framework for differentiating between reasonable future pathways versus idealized or potentially risky future scenarios that may have unintended or unanticipated impacts.

Residential Greenhouse Gas Emission Reduction Pathways

Experts recognize there is not a single solution to reducing GHG emissions, instead it will require a combination of available and emerging technology pathways that can result in cost-effective approaches to lowering climate change threats. There are a variety of potential measures and pathways for reducing residential-sector GHG emissions, including: (1) natural gas appliance improvements, (2) electric appliance improvements, (3) building envelope enhancements, (4) hybrid natural gas and electric appliance improvements, and (5) use of renewable energy (e.g., renewable natural gas, renewable hydrogen, rooftop solar PV, and rooftop solar thermal).

Figure 9 provides a natural gas consumer-oriented depiction of near-term (commercially available) and mid-term emerging home appliances, efficiency measures, and renewable energy options for reducing GHG emissions. As discussed in the following benefit/cost analyses, these represent practical near-term and mid-term options that can be less costly, more feasible, or less risky than wholesale residential electrification changes.

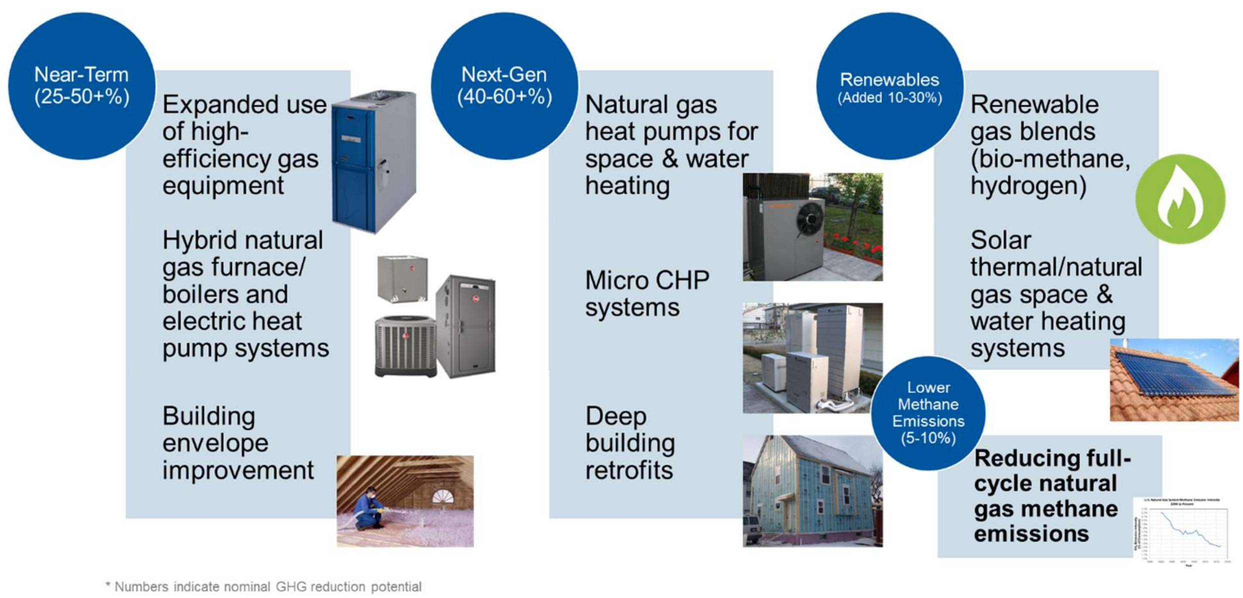


Figure 9: Natural Gas Home Greenhouse Gas Emission Reduction Pathways

Regarding near-term options, a practical consideration is the potential for hybrid high-efficiency natural gas furnaces or boilers coupled with electric heat pumps (e.g., as an upgrade to a traditional home air conditioning system). In this hybrid space conditioning approach, electric heat pumps can be used during milder outdoor temperatures (e.g., 40°F and above) while natural gas space heating is used at colder temperatures when electric heat pump heating output and efficiency decline. This combination of currently available technologies can be used to optimize energy use, comfort, and life cycle costs for cold-climate homes.

For next-generation solutions, mew technology developments indicate a potential role for: (1) natural gas heat pumps and (2) renewable gas. The following sections will touch on these topics as well as a discussion on electric heat pumps and electric power generation in Colorado.

Space Heating and Heat Pumps

This section reviews space heating, the largest residential energy use in Colorado homes and the most challenging and costliest to electrify.

Table 1, based on DOE-EIA Residential Energy Consumption Survey (RECS) data, shows multi-year trends for US residential natural gas and electric heating systems. The number of electrically heated homes has grown over the last 25 years (along with the total building stock), but most homes today with electric heat rely on low-cost. inefficient electric resistance heating. Fortunately, the percentage of electrically heated homes using electric heat pumps has increased in recent years but remains below 50% share of all electrically heated homes. From an energy efficiency program and GHG reduction perspective, public policies should prioritize upgrading inefficient electric resistance home heating systems to electric heat pumps.

Table 1: Trends for U.S. Electric Residential Heating Systems (DOE-EIA RECS)

DOE-EIA RECS Main Heat Source (millions of homes)	1993	2005	2015	2020
All Homes	96.6	111.1	118.2	123.5
Natural Gas Homes – All Types (% of homes)	50.8 (52.6%)	58.2 (52.4%)	57.7 (48.8%)	62.7 (50.8%)
Electric Heating – All Types (% of homes)	25.3 (26.2%)	33.7 (30.3%)	40.9 (34.6%)	42.6 (34.5%)
Electric Heat Pumps (% of Electric Homes)	7.5 (29.6%)	9.2 (27.3%)	11.8 (28.9%)	17.2 (40.4%)

Electric air-source heat pumps (EHP or ASHP) have higher first costs than conventional gas heating systems as well as performance and efficiency issues at cold temperatures. Below about 40°F, most electric heat pumps exhibit system tradeoffs that may include: (1) reduced heating capacity and lower supply air temperatures, (2) lower system efficiency (or Coefficient of Performance, COP), (3) higher energy use for defrosting outside coils, and (4) increasing need for supplemental heating energy. In some instances, electric heat pumps will use electric resistance heating to provide supplemental thermal energy – resulting in an increase in electricity consumption and peak power kW demand and a precipitous drop in total electric heating system efficiency. In other instances, homes switch to another form of supplemental heating such as a natural gas furnace during cold periods to avoid costly supplemental electric resistance heating.

Manufacturer electric heat pump ratings do not satisfactorily account for real-world energy use, including factors such as: efficiency and capacity reduction from frost or dust accumulation on outdoor coils, energy used to defrost outdoor coils, standby parasitic power and cycling losses, efficiency and performance degradation due to improper refrigerant charge, and energy required for supplemental heating at cold temperatures. These factors result in overall real-world electric heat pump system efficiencies below rated values.

Figure 10 shows results from an independent large-scale cold-weather field test of residential electric heat pumps. System performance notably declined as outdoor temperatures dropped; impacts of snow and ice accumulation on outdoor electric heat pumps were also documented.

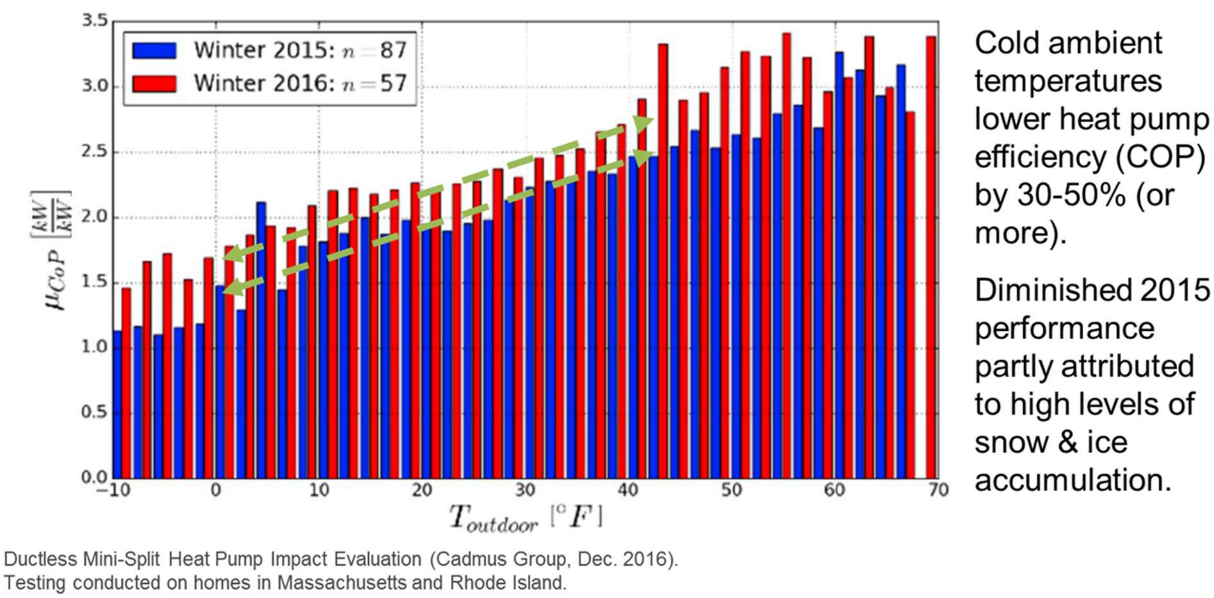


Figure 10: Cadmus Group Field Testing of Electric Heat Pumps in Northeastern U.S.

GTI Energy has also conducted extensive lab and field testing along with computer modeling of electric heat pump performance and efficiency, including conventional units as well as newer options characterized as cold climate (ccEHP) systems. Figure 11 shows representative performance data on electric heat pumps at colder temperatures (below 40°F). This accounts for real-world operating conditions like defrosting outside air coils and standby mode power consumption. Conventional electric heat pumps with nominal HSPF values around 9 (over 90% of current sales) show decreasing COP values at colder temperatures, with COP values falling below 1.5 around 10°F. Higher-efficiency (HSPF 10 and above) cold-climate electric heat pumps have improved efficiency but show a decline in efficiency from 40°F down to 10°F and lower.

Cold-climate heat pumps are an improvement, yet these higher efficiency electric heat pumps have greater first costs and are not currently representative of most electric heat pumps sold.

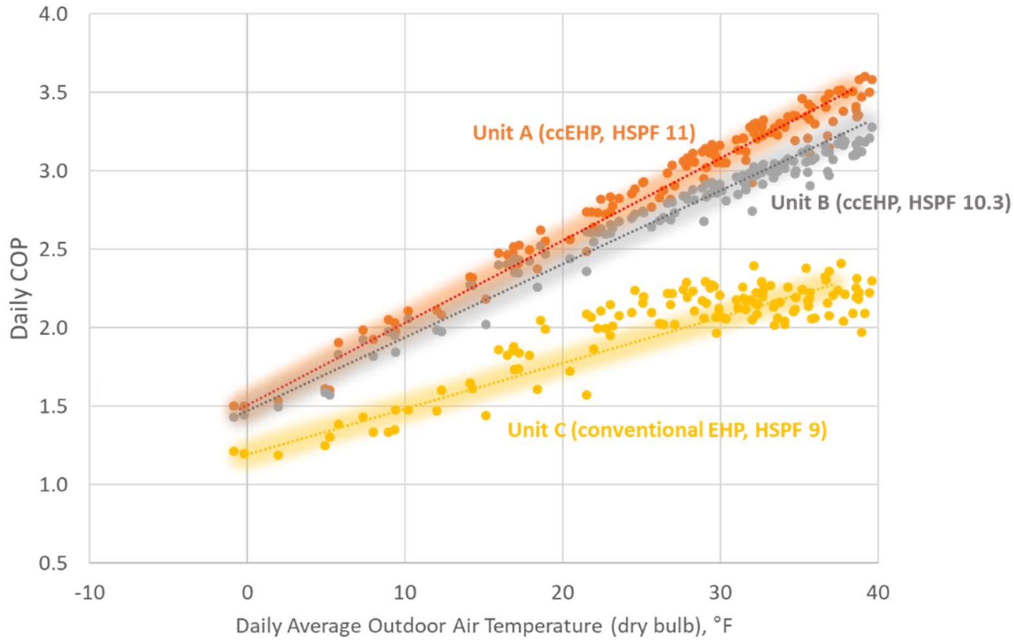


Figure 11: Electric Heat Pump Performance Below 40°F (Source: GTI Energy)

Figure 12 highlights the critical issue of non-linear increase in electricity use for space heating as outdoor temperatures drop. In this example, the building space heating load (shown in dark blue in left graph) increases by a factor of 2.7 at 20°F and by a factor of 3.9 at 0°F. Since electric heat pump efficiency (or COP) goes down with temperature, there is a compounded non-linear growth in average hourly electricity consumption at colder temperatures. For example, a conventional electric heat pump (HSPF 9, shown in light blue) will use 7.8 times more electricity at 0°F than it would at the baseline conditions of 40°F. The right figure shows an example of the absolute electricity consumed in an average hour as ambient temperatures change – with the more efficient heat pump using 9.3 times more electricity than its reference baseline at 40°F. On an absolute basis, the more efficient cold-climate electric heat pumps, shown in gold, uses about 20% less electricity than a conventional electric heat pump at 0°F. These graphs would continue a non-linear increase at sub-zero temperatures. Note that these data are based on a nominal, well-insulated 1,660 ft^2 home built to 2010 International Energy Conservation Code (IECC) building standards. Older homes and/or larger homes will have proportionately larger hourly electricity demands.

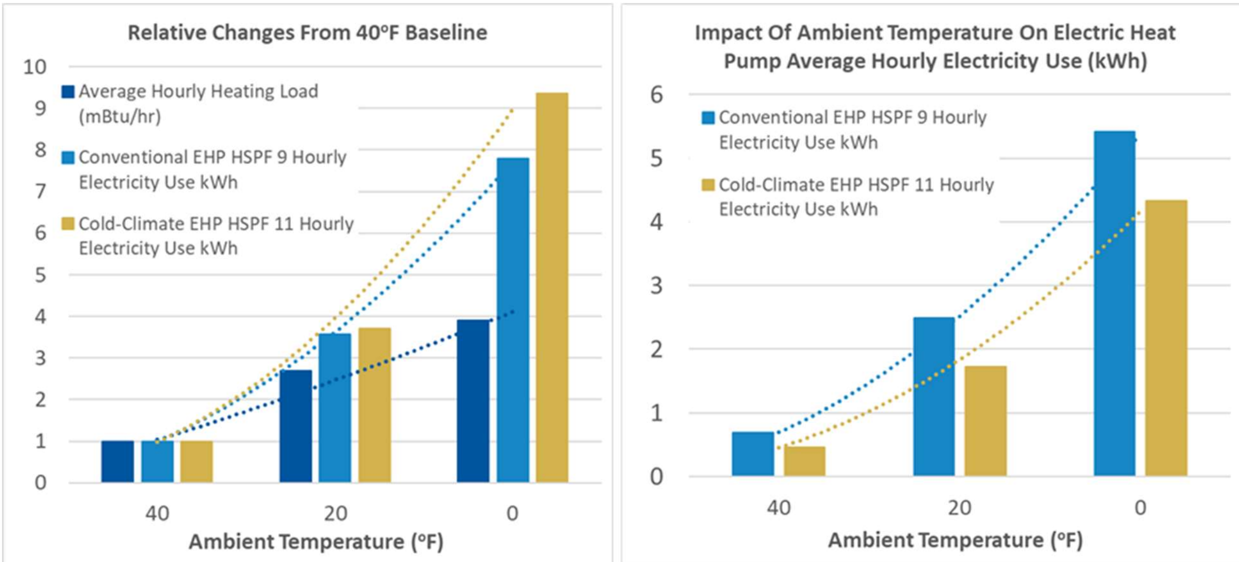


Figure 12: Impact of Ambient Temperature on Electric Heat Pump Electricity Use

Cold-climate electric heat pumps have improved cold weather output and efficiency compared to conventional EHP units. This system performance is generally accomplished by raising refrigeration compressor speeds at colder temperatures and by including more heat exchanger surface area (resulting in higher capital costs).

Figure 13 shows GTI Energy modeling data on annual operating hours using conventional and cold-climate electric heat pumps in different regions. Cold-climate areas such as Denver and other northern-tier regions have annual electric heat pump heating-mode runtime values that are 2-3 times greater than heat pumps operated in milder climates. Cold-climate heat pumps carry more load at lower temperatures and more runtime than conventional electric heat pumps which rely on supplemental heating at colder temperatures, thereby reducing annual run time. At this juncture, there is uncertainty whether greater annual runtime hours and a higher compressor operating speed strategy will impact cold-climate electric heat pump equipment life.

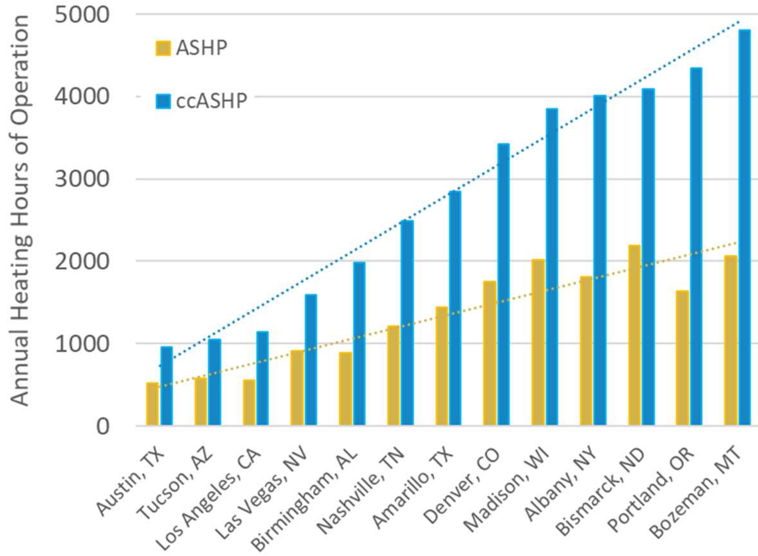


Figure 13: Electric Heat Pump Annual Heating Operating Hours in Different Climates (Source: GTI Energy)

In nearly all cases, operating electric heat pumps at very cold temperatures (e.g., below 10°F) leads to a drop in heating capacity and efficiency. This has implications for consumer energy costs and for electric infrastructure sizing, including:

- Is a back-up home heating source available to ensure consumer comfort and safety?
- Will supplemental electric resistance heating substantially raise consumer heating bills?
- Will widespread simultaneous use of electric resistance heating at cold temperatures result in significantly higher peak-day electric power (generation, transmission, and distribution) asset requirements?

From a consumer perspective there are three primary considerations: (1) equipment installed cost, (2) annual operating cost, and (3) equipment lifetime. Table 2 shows DOE data on space heating equipment cost and lifetime. The capital and installed cost of a conventional electric heat pump is estimated at 85% or greater than a natural gas furnace; higher-efficiency cold-climate heat pumps would be even greater. While not directly addressed in this report, the retrofit installed cost for replacing gas heating with an electric heat pump(s) may be higher – especially for homes using hydronic heating. In addition, the expected life of an electric heat pump is around 15.5 years – which is about 28% shorter than a natural gas furnace equipment lifetime of around 21.5 years.

Table 2: Space Heating System Installed Cost and Lifetime (Source: DOE/NREL)

Space Heating Systems	Installed Cost	Equipment Lifetime Range, (Midpoint)
Natural Gas Furnace	$2,760 - 3,040	16 – 27 Years (21.5 Years; ~40% longer)
Electric Heat Pump	$5,100 – 6,100 (~85+% higher)	9 – 22 Years (15.5 Years)

Consumers will pay more in capital costs for electric heat pumps compared to gas furnaces. This is due to the higher first cost of electric heat pumps as well as shorter equipment lifetime. The full life-cycle cost impact is lessened when factoring in consumers using air conditioning (AC) systems (since an electric heat pump provides heating and cooling in one unit).

Figure 14 illustrates the full-fuel-cycle energy and CO_2 emissions rates of various natural gas and electric space heating pathways (e.g., gas furnace, gas heat pump, conventional electric heat pump, and electric resistance heating). The gas and electric heat pumps show operation at two ambient temperature conditions (10°F and 40°F) due to their sensitivity to ambient temperatures. The electric scenarios tie back to using gas combined-cycle power plants (typical marginal power generation resources used for winter peak electricity loads in most parts of the US; use of marginal coal generation would result in considerably higher CO_2 emission levels). At 40°F, the electric heat pump offers about a 15% reduction in source energy and CO_2 emissions compared to a gas furnace; a cold-climate electric heat pump at 40°F would provide a 39.7% reduction. At 10°F, conventional electric heat pumps use more total energy use and emit 37% more CO_2 emissions; cold-climate electric heat pumps at 10°F would result in a 2.5% increase in CO_2 emissions. As illustrated, electric resistance space heating is the most inefficient and highest CO_2 emissions pathway for heating a home – over twice that of a gas furnace when operating at 10°F (underscoring the need to avoid using electric resistance heating at cold temperatures, including as a supplemental heating source for electric heat pumps).

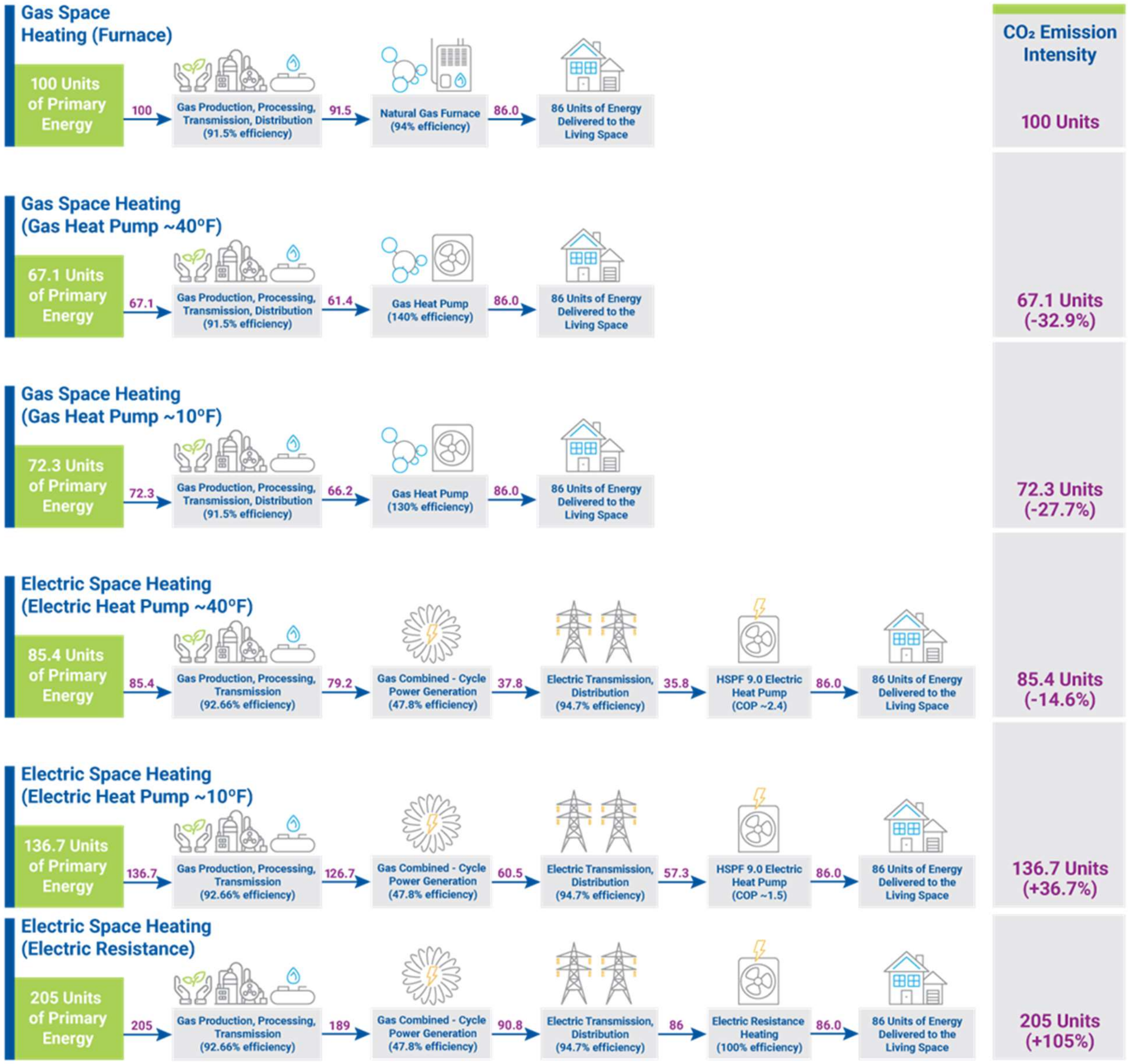


Figure 14: Full-Fuel-Cycle Comparisons of Gas and Electric Heating Pathways

Complementing electric heat pumps with natural gas furnaces and boilers (i.e., hybrid gas/electric systems) and using natural gas to satisfy heating loads during colder temperatures helps ameliorate consumer and societal cost impacts (Figure 15 and Figure 16). Natural gas supplemental heating is a cost-effective peakshaving approach that avoids electric grid sizing impacts during very cold periods (when electric heat pump efficiency declines and electricity use goes up). A hybrid heating strategy also avoids operating electric heating equipment mainly on dispatchable power generating systems (e.g., natural gas plants) that have higher GHG emission rates resulting in minimal or negative full-fuel-cycle CO_2 emission benefits.

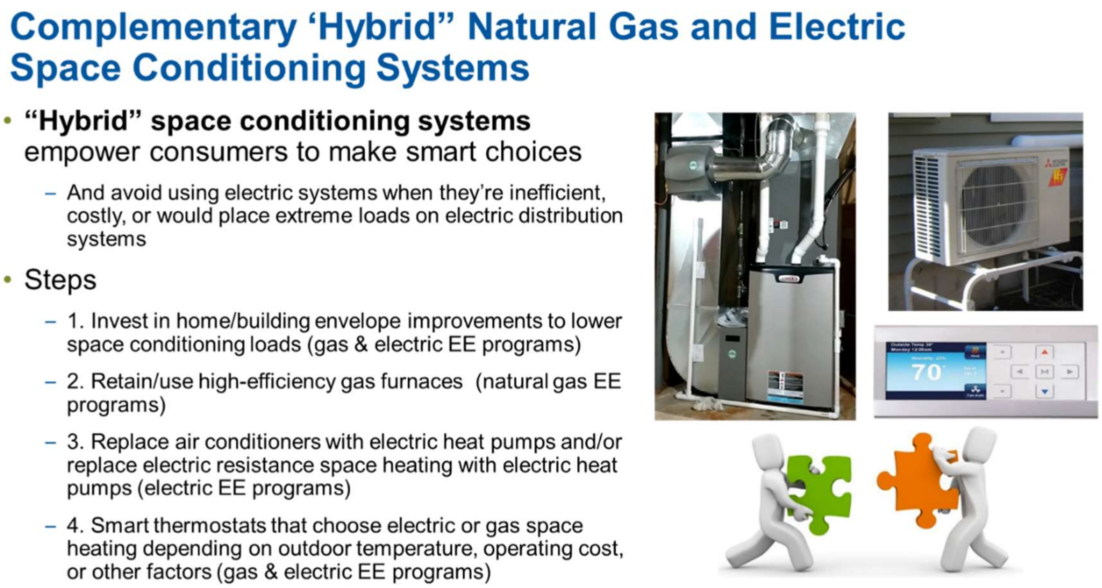
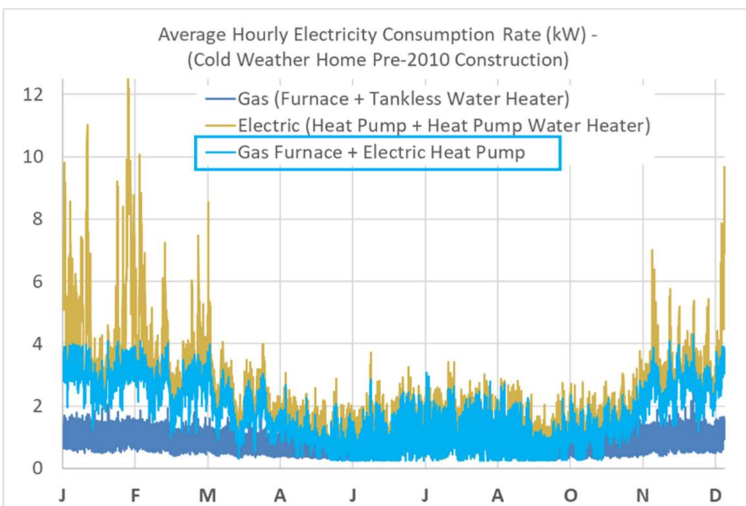


Figure 15: Natural Gas and Electric Hybrid Heating Systems



Detailed 8,760 hour residential home energy model.

All-electric home space heating results in massive increases in peak winter demand.

Hybrid heating approach with natural gas furnace and electric heat pump (run on mild winter days) dramatically lowers peak electric demand impacts and related negative issues.

Figure 16: Hybrid Natural Gas and Electric Space Heating System (GTI Energy)

Events in 2021 illustrate the impact cold temperatures have on electricity demand in regions where over 50% of homes use electric space heating as their primary energy choice. Figure 17 shows DOE-EIA electricity usage in Texas in February 2021 as a function of outdoor temperature (based on the average daily temperature in Dallas, TX). During this period, a cold-weather front moved into Texas (and much of the US) over a multi-day period that led to a nearly 40% increase in total electricity demand; this increase was driven by electric space heating loads in the residential, commercial, and industrial sectors. This substantial increase in electricity demand due to cold temperatures could not be adequately met by all generation resources, leading to widespread outages over an extended period. While much discussion has centered on electricity supply, it is important to highlight this outage event was precipitated by severe increases in electric space heating loads. Over 60% of Texas homes use electric space heating as their primary heating source.

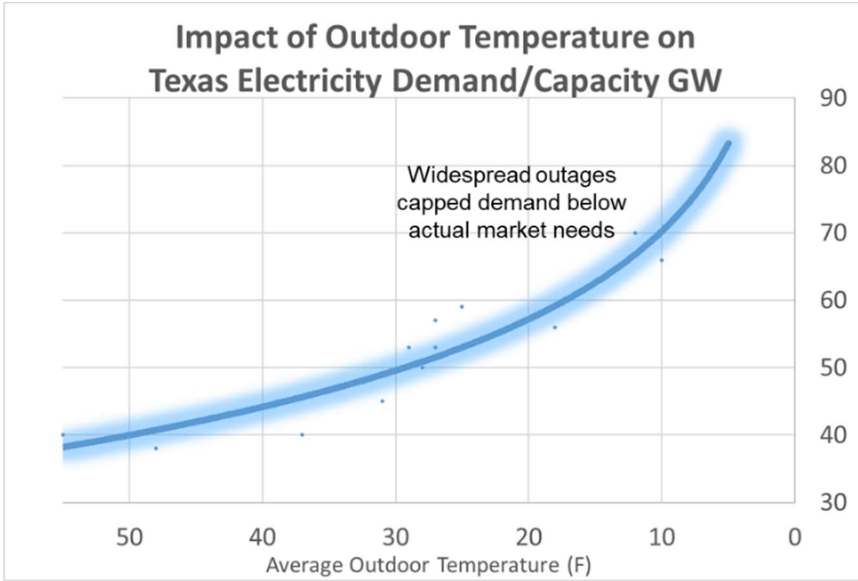


Figure 17: Impact of Cold Temperatures on February 2021 Texas Electricity Demand

The February 2021 cold-weather event was a very expensive incident that exposed consumers in multiple states to high personal safety risks and unexpectedly large energy cost impacts. This empirical data reinforces the non-linear impact of cold temperatures on space heating electricity demand. Adding more electric space heating loads places an enormous peak electricity burden on electric generation, transmission, and distribution systems – considerably more so than space cooling. The much colder temperatures in Colorado would further add to the challenges displayed by this example.

Figure 18 and Figure 19 show results of GTI Energy modeling of a 1,660 ft^2 Colorado home built to the 2010 International Energy Conservation Code (IECC) standard. These graphs show electricity use and space heating energy costs for five different space heating scenarios: baseline natural gas, two hybrid gas/electric systems, and two electric heat pump-only systems. Hybrid gas and electric systems provide a potential middle-ground solution that avoids many of the deleterious effects with dedicated electric heating systems in cold-weather regions – including scenarios such as what occurred in Texas in February 2021.

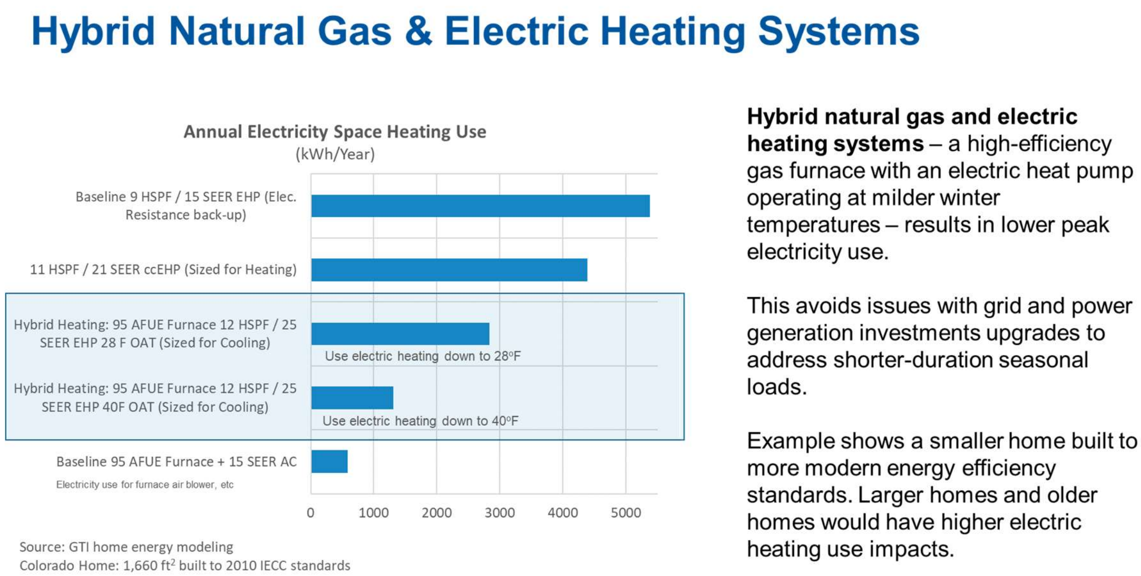


Figure 18: Hybrid Natural Gas and Electric Heating System Comparisons (Electricity Use; GTI Energy)

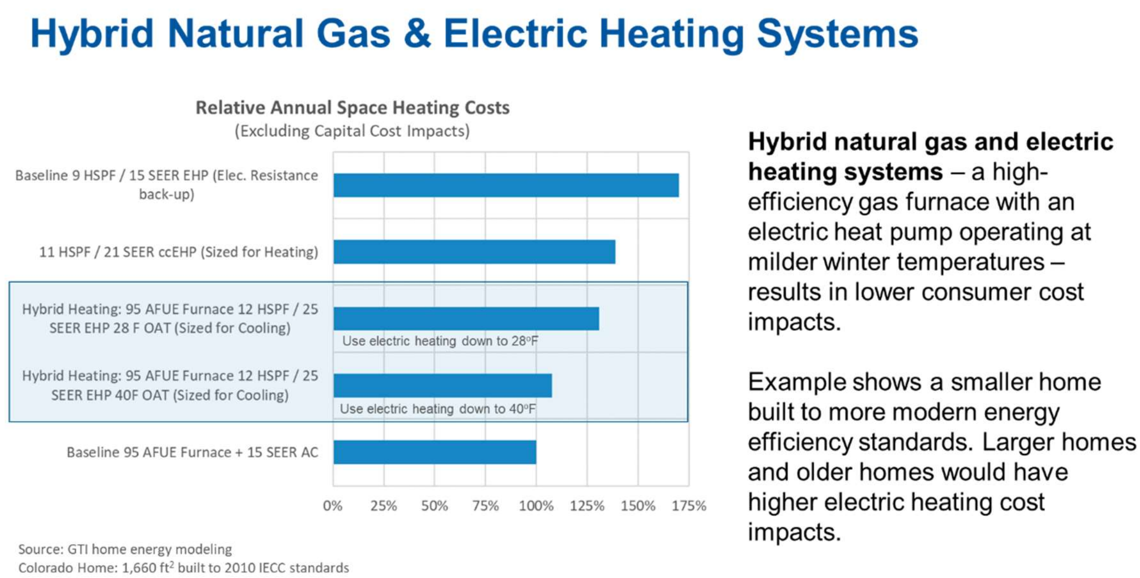


Figure 19: Hybrid Natural Gas and Electric Heating System Comparisons (Space Heating Energy Cost; GTI Energy)

Homes with natural gas heating typically use a forced-air furnace or a boiler that circulates hot water in a hydronic loop. These can be either mid-efficiency (e.g., 80% efficient) or high efficiency condensing systems (e.g., efficiencies of 92-98%). In addition, gas-fired tankless water heaters and boilers can be used as combination devices (also called combi systems) that provide hot water and space heating service, with rated efficiencies of 80% to around 98%.

Natural gas heat pumps are like electric heat pumps but use natural gas as the primary energy input. There are several gas heat pump designs with varying levels of efficiency (Figure 20) – all improvements over conventional furnaces. Like electric heat pumps, gas heat pump performance and efficiency vary with outdoor temperatures, though the adverse impact of cold outdoor temperatures on efficiency is much smaller with gas heat pumps than with electric heat pumps. There are several gas heat pump technology and product development efforts underway – documented in a GTI Energy report*: The Gas Heat Pump Technology and Market Roadmap (2019)*.

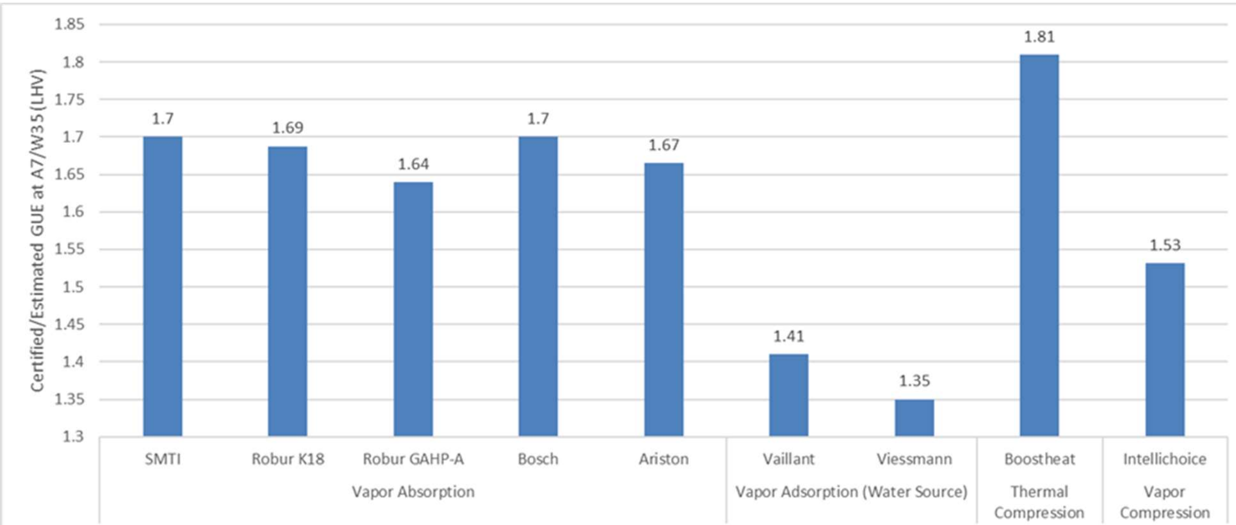


Figure 20: Example Natural Gas Heat Pumps and Efficiency

Figure 21 shows an example of a natural gas heat pump. Units are now commercially available for use in single and multi-family residential applications as well as for commercial buildings; additional equipment is anticipated to be introduced into the US market in coming years. Gas heat pumps can increase efficiencies by 45% or more compared to traditional high-efficiency gas furnaces and boilers.

Figure 21: Example Natural Gas Heat Pump

Electricity Generation in the US and Colorado

This section reviews the current and potential future Colorado power generation situation. The role of power generation is intimately connected to understanding residential electrification GHG reduction pathways and potential implications. This enables a comprehensive full-fuel-cycle review of primary energy and GHG emissions.

The US electric power generation sector has seen significant change over the past two decades, driven by the growth of natural gas, wind, and solar power generation sources and a precipitous decline in coal generation made possible by a large fleet of aging coal power plants. Figure 22 shows US power generation sector changes since 2015, facilitated by natural gas, wind, and solar. Across the country, this has led to large declines in coal power generation output.

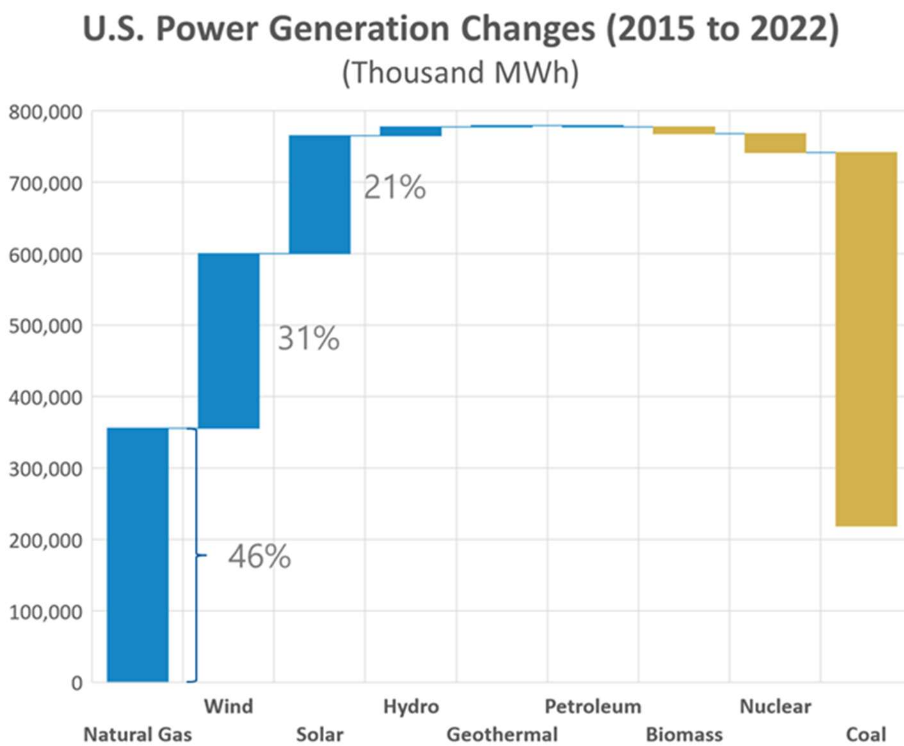


Figure 22: Changes in US Power Generation Output (2015–2022, DOE-EIA)

Figure 23 shows comparable Colorado power generation changes since 2015, with wind, natural gas, and solar as leading new generation sources. These mainly displaced coal but also were needed to handle overall growth in electricity consumption in the state and/or reduced need for imported power from other states.

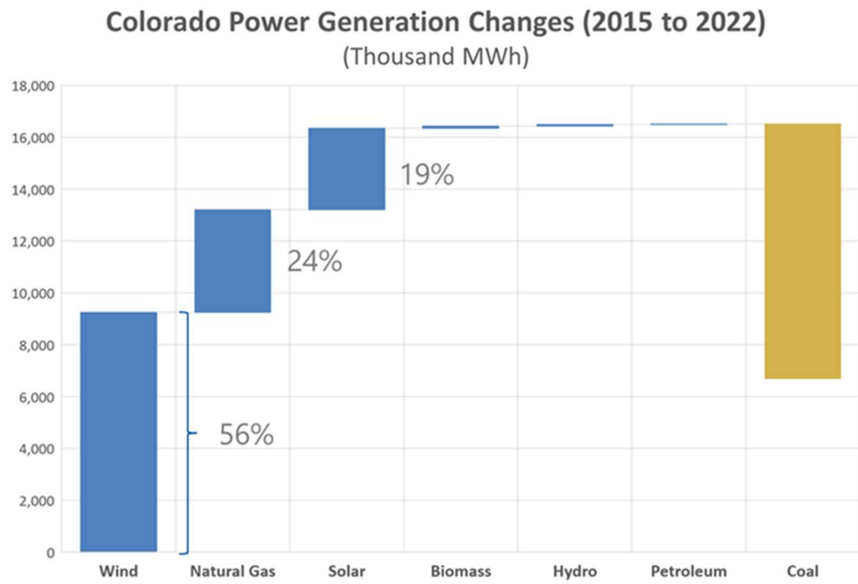


Figure 23: Colorado Power Generation Changes (2014–2019, DOE-EIA)

Figure 24 shows trends in the US and Colorado average power generation CO_2 emission rate since 2005 (includes estimated Colorado values for 2021 and 2022). The US averaged about 360-365 grams of CO_2 emitted per kWh of electricity generated in recent years, a nearly 39% reduction compared to 2005. Colorado has also made notable progress, with an average CO_2 emission rate around 486 g CO_2/kWh in 2022; this is about 33% higher than the US average, with the gap narrowing in recent years.

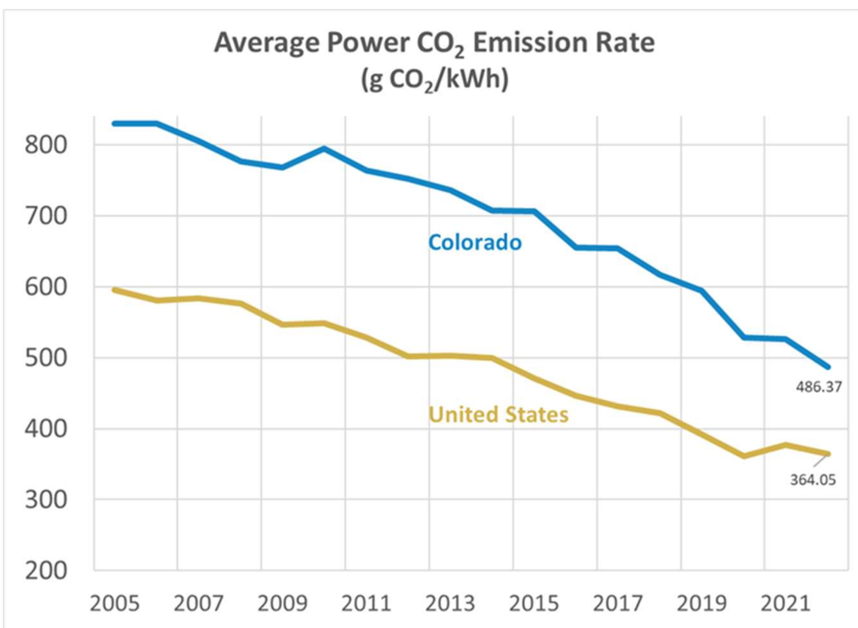


Figure 24: US Power Generation Average CO2 Emission Rate (DOE-EIA)

Table 3 compares the 2022 US and Colorado power generation mix. Areas of differentiation include: (1) coal – higher use in Colorado, (2) nuclear – not present in Colorado, (3) wind –

higher use in Colorado, and (4) natural gas – higher national use. Of these, the primary factor contributing to Colorado's higher power sector CO_2 emissions rate (compared to the US average) is greater reliance on coal generation. Continued displacement of coal with wind, solar, and natural gas should sustain future Colorado CO_2 emission rate reductions.

Table 3: US and Colorado 2022 Power Generation Mix (DOE-EIA)

2022 Power Generation Mix	United States	Colorado
Natural Gas	39.8%	26.7%
Coal	19.5%	37.2%
Oil	0.6%	0.0%
Nuclear	18.2%	0.0%
Hydro	6.2%	2.9%
Wind	10.2%	28.6%
Solar	4.8%	6.5%
Biomass	1.3%	0.3%
CO_2 Emission Rate (g/kWh)	364	486 (est.)

From a planning perspective, one can formulate scenarios for Colorado's potential longer-term power generation mix. It is pertinent though to consider the following factors pertaining to residential electrification in cold-weather regions that may influence potential future scenarios:

- High winter seasonality of space heating energy use
- Nature of seasonal/non-baseload power generation resources and their emission rates compared to baseload or average power generation resource mixes
- Incongruity of solar PV generation output (and to a lesser extent wind) with winter peak electric heating loads
- Electrical energy storage limitations and energy losses

Each of these issues will be more fully reviewed in the following sections. It remains unclear whether analyses by Black Hills Energy and Xcel Energy on Colorado residential electrification have fully accounted for these considerations. If these factors are not fully accounted for, there is a potential for electric power generation and grid under sizing (with grid cost and reliability implications) as well as shortfalls in expected GHG emissions.

Seasonal and Non-Baseload Power Generation

Seasonality is a fundamentally important consideration for generating power for building space conditioning. The implications of seasonality are often not fully addressed in building electrification GHG reduction policy discussions. Yet, it is extremely significant and must be prudently addressed to ensure winter electric grid reliability.

As shown previously in Figure 6, seasonal natural gas space heating loads are vastly larger than seasonal electricity use for summer cooling. The importance of seasonality, however, is more than just the challenge of delivering intense amounts of energy for short periods (e.g., multiple days or even 2-4 months for space heating loads in cold climates). This alone is quite problematic and will be explored in detail. What is also relevant is the type of power generation plants used to meet seasonal electricity use and, by inference, those power generation resources that are unable to provide seasonal dispatchability.

Seasonal or dispatchable, (i.e., non-baseload) power plants are different than the average or baseload power generation mix such as nuclear power plants or intermittent wind and solar generation. From a GHG reduction policy perspective, seasonal power generation resources can have appreciably different CO_2 emission rates than baseload plants. Given the substantial energy used for space heating, not properly accounting for seasonal power generation emission rates will likely result in a significant over-estimation of electrification GHG benefits.

Table 4 shows Colorado state-level power generation resources: (1) as an annual average and (2) marginal seasonal power generation resources. While Colorado's power generation averages around 486 g CO_2/kWh over the year and around 437 g CO_2/kWh nominal baseload (using a spring month as an example), the marginal or seasonal values during peak winter and summer use (mainly from space conditioning loads) differs substantially due to a high reliance on dispatchable coal and natural gas generation. In 2022, the Colorado summer marginal emission rate is 1,238 g CO_2/kWh and the winter marginal generation rate is 1,747 g CO_2/kWh. (The methodology for calculating seasonal marginal generation rates is described in Appendix B of GTI Energy report titled "Seasonal Residential Space Heating Opportunities and Challenges"). The high winter marginal emission rates reflect the large increase in coal (mainly) and natural gas power generation to meet incremental peak winter demand for electricity while also offsetting or compensating for declines in winter wind and solar generation.

Table 4: Colorado 2022 Power Generation Mix (DOE-EIA)

Colorado Power Generation Mix	DOE-EIA Colorado Annual Average	DOE-EIA 2022 Colorado Nominal Baseload (April)	DOE-EIA 2022 Colorado Winter Marginal Seasonal (January)	DOE-EIA 2022 Colorado Summer Marginal Seasonal (August)
Natural Gas	26.2%	19.6%	23.3%	31.0%
Coal	36.4%	28.8%	40.1%	40.5%
Oil	0.0%	0.0%	0.1%	0.0%
Nuclear	0.0%	0.0%	0.0%	0.0%
Hydro	2.8%	2.3%	3.5%	2.5%
Wind	28.0%	40.7%	28.5%	19.0%
Solar	6.3%	8.2%	4.3%	6.6%
Biomass	0.3%	0.3%	0.3%	0.2%
Seasonal Monthly Generation (million kWh)	--	4,406	4,969	5,841
Average CO_2 Emission Rate (g/kWh)	486.4	437.0	585.5	633.8
Seasonal Marginal CO_2 Emission Rate (g/kWh)	**--**	**--**	**1747.7**	**1238.1**

Figure 25 shows the seasonal winter (i.e., January) and summer (i.e., August) outputs for coal, natural gas, wind, and solar along with nominal baseload generation during a typical spring month (e.g., April). The figure highlights the ramp up of coal and natural gas generation that takes place to meet winter (e.g., January) and summer (e.g., August) incremental demand for space conditioning (i.e., heating and cooling, respectively). Along with meeting the added seasonal electricity demand, these generation resources need to offset losses from wind or solar when they occur in winter (both wind and solar) and summer (wind). Wind and solar show a large decline in generation output during the peak space heating month of January. Additional space heating loads through electrification will exacerbate this issue.

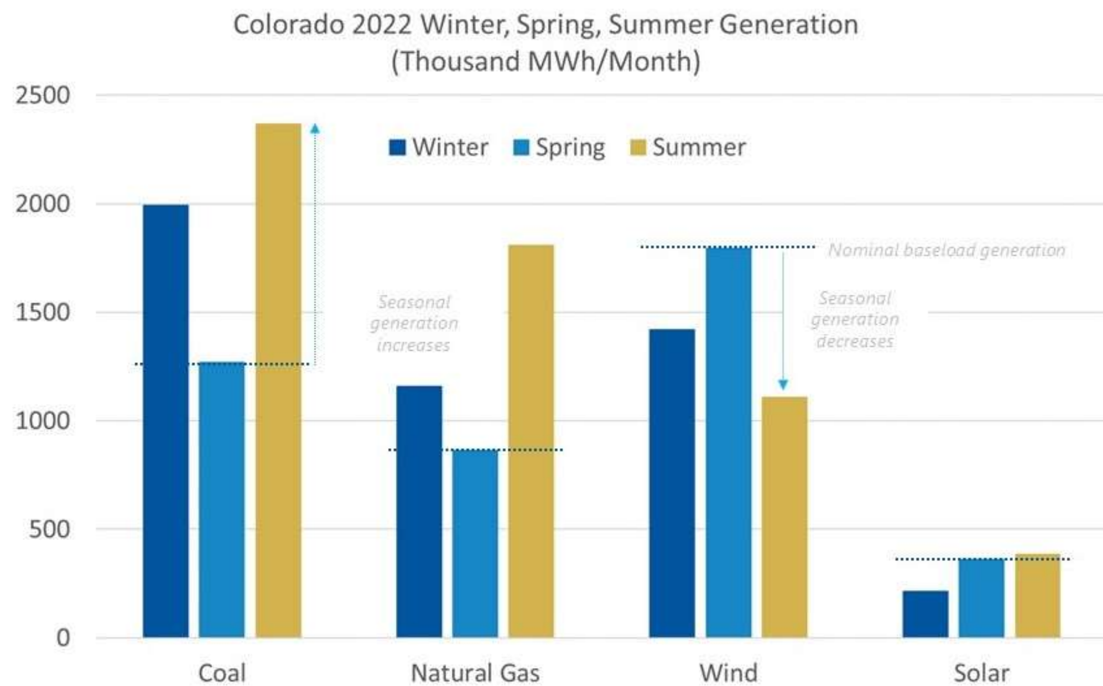


Figure 25: Colorado 2022 Baseload, Winter, and Summer Generation Mix (DOE-EIA)

Monthly solar and wind generation levels vary throughout the year. As shown in Figure 26, solar is an incremental summer resource helping offset summer peak cooling loads, but during the Colorado winter, solar PV systems show an approximate 45-50% output decline. This is due to the fewer winter sunlight hours and reduced sun angle; increased cloud cover or snow and ice accumulation on solar PV panels can further reduce winter solar PV output.

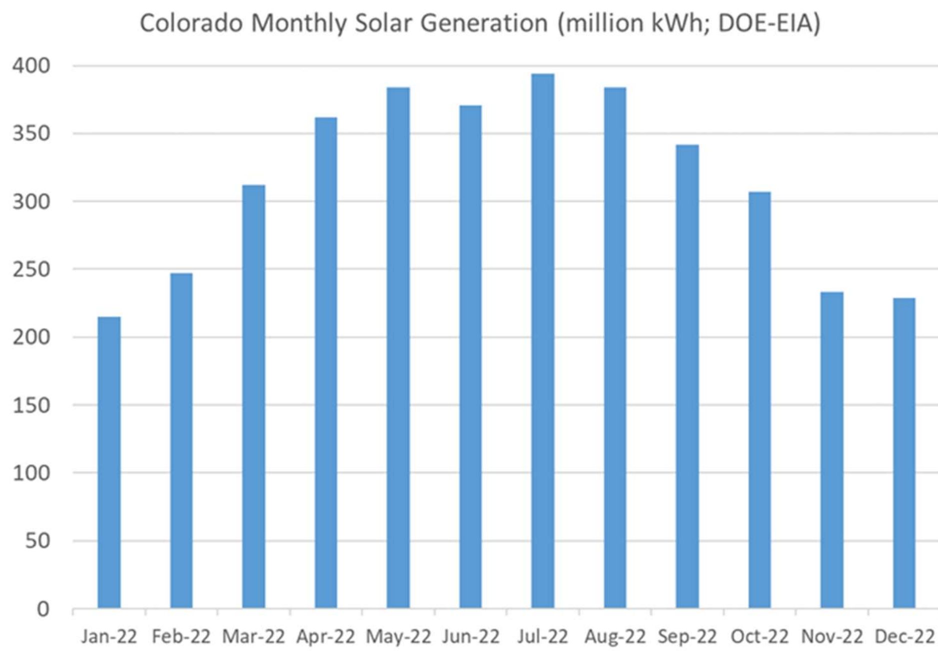


Figure 26: Monthly Colorado Solar PV Generation (DOE-EIA; 2022)

Figure 27 shows monthly Colorado wind generation output during 2022, with a decline in January generation compared to peak levels in April.

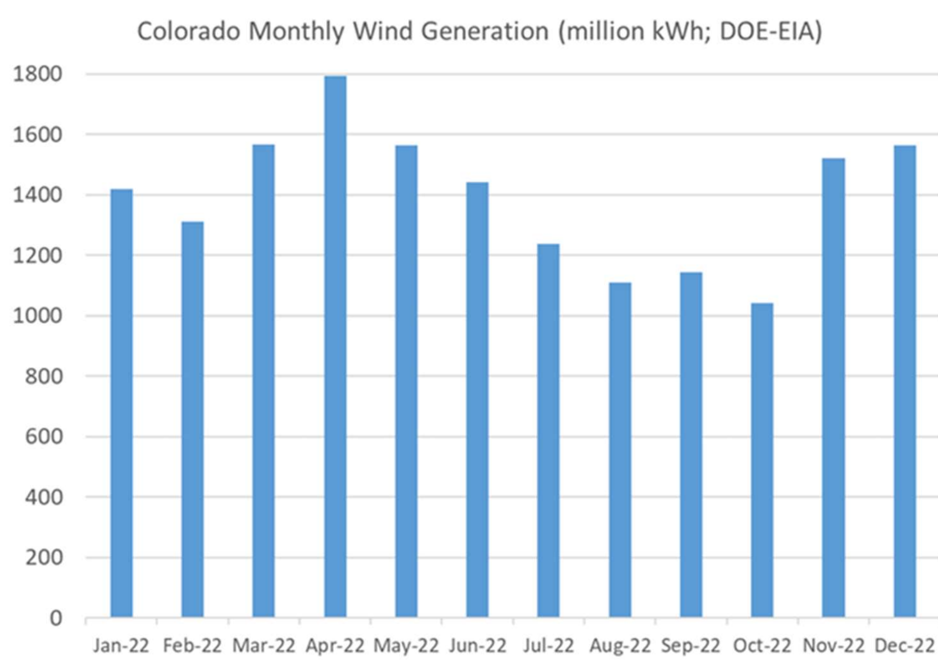


Figure 27: Monthly Colorado Wind Generation (DOE-EIA; 2022)

One key issue with wind and solar generation resources is their known intermittent output due to variability in weather conditions (e.g., wind speed, cloud cover) and other factors. In the Xcel filing to the Colorado Public Utilities Commission, they prudently highlight an example of a multi-day drop in wind generation (Figure 28). While drop-off of wind generation for this duration may be somewhat unusual, empirical evidence clearly shows many days during the winter when wind and solar generation in Colorado declines substantially (Figure 29). From the perspective of reliable electric grid operation, it is essential to plan for these scenarios.

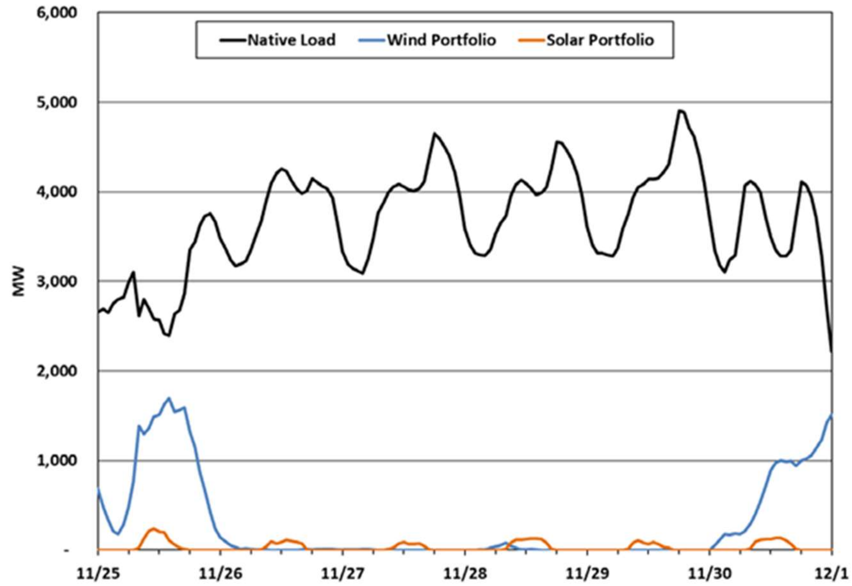


Figure 28: Example Winter Decline In Wind Generation (Nov. 2015; from Xcel CO PUC filing)

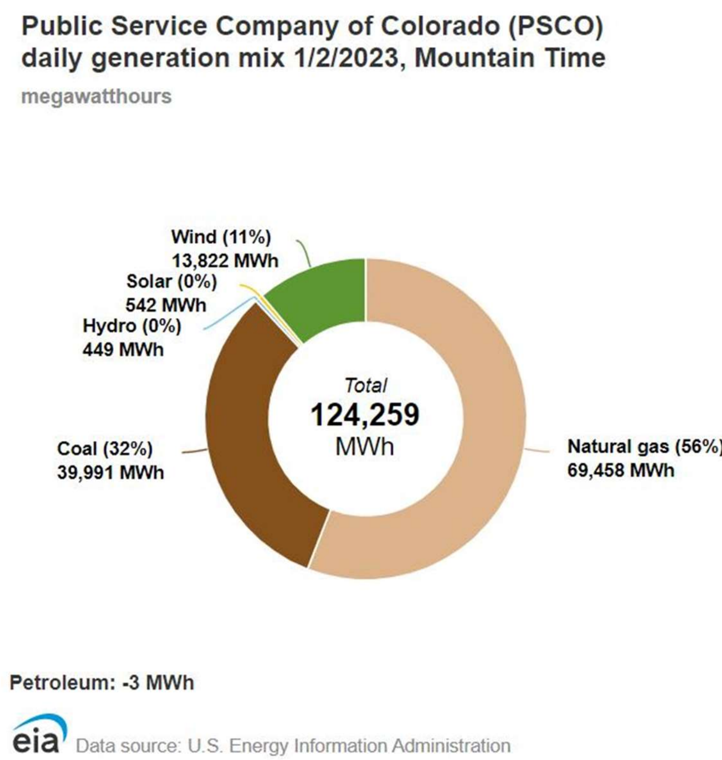


Figure 29: Example Single-Day Winter Generation Public Service Company of Colorado (DOE-EIA)

Subsequent report sections will discuss the potential future Colorado power generation mix and provide details on full-fuel-cycle emissions from using natural gas and electricity in the Colorado residential sector. In advance, there are several key interim considerations and conclusions based on this section:

- The current average Colorado power generation CO_2 emission rate (486 g/kWh) is 33.5% greater than the US average (364 g/kWh).
- Emission rates for marginal winter seasonal power generation in Colorado (exceeding 1000 g/kWh) are vastly higher than the annual average. Currently, this makes it particularly unattractive in Colorado to replace natural gas space heating with electricity as a GHG reduction strategy.
- There is no current evidence wind or solar resources can address prospective seasonal energy-intensive space heating electricity peaks during Colorado winters (e.g., in January). Both resources show a significant decline in winter generation that is offset by ramping up coal and natural gas generation.
- Extended periods of low winter wind and solar generation would necessitate an extremely large reserve capacity for dispatchable generation (e.g., gas power generation) to ensure grid reliability.

Future Power Generation Scenarios in Colorado

The future Colorado power generation outlook can be gauged based on the current generation mix, coupled with recent market experience and future assumptions based on state policy goals for phasing-out coal use and increasing wind and solar generation (while noting the misalignment of wind and solar generation with seasonal winter space heating loads).

Assuming an 80% reduction in CO_2 emissions rate from a 2005 baseline as the Colorado policy goal, Table 5 provides a potential future generation mix for the 2030-2040 timeframe (assuming no overall change in demand). This scenario assumes a full shutdown of coal generation. Colorado power generation emitted about 830 g CO_2/kWh in 2005 and 486 g CO_2/kWh in 2022 (a 41% reduction). An 80% emission rate reduction in the 2030-2040 timeframe is equal to about 166 g CO_2/kWh. The amount of natural gas generation in this table was adjusted to equal this CO_2 emissions rate. Carbon capture or use of renewable gas could result in higher levels of gas generation being used (depending on economic competitiveness).

Table 5: Projected 2030-2040 Colorado Power Generation Mix

Colorado Power Generation (Thousand MWh)	Colorado 2022 Power Generation	Colorado Generation Mix Circa 2030-2040	Change From 2022 to Circa 2030-2040	% of Circa 2030–2040 Generation Mix
Coal	21,723	0	-21,723	0.0%
Natural Gas	15,612	18,190	2,578	30.5%
Wind	16,706	26,245	9,539	44%
Solar (all solar)	3,780	13,362	9,582	22.4%
Hydro/Pumped Hydro	1,664	1,664	0	2.8%
Biomass	166	166	0	0.3%

There are potential limitations to this 2030-2040 scenario, including two key considerations:

1. The viability of a predominantly wind and solar generation mix at this level of market share (around 66%) reliably providing 8,760-hour power generation has, to date, not been empirically demonstrated anywhere in the US.
2. Hefty increases in electricity demand (e.g., from vehicles or more acutely from a large-scale residential electrification scenario) would greatly add to requirements for new wind and solar capacity;
    a. If the future includes large levels of electric space heating, this will raise the extremely challenging issue of winter peak electricity use when solar and wind output drop off, leading to the necessity even for more seasonal dispatchable generation (e.g., gas combined-cycle plants).

Figure 30 shows trends in power generation CO_2-specific emission levels (g CO_2/kWh), including leading states such as California and New York and the projected trend for Colorado CO_2 emission rates in 2030-2040 based on Colorado public policy. The ability of Colorado to sustain the levels of reduction seen since 2010 using only wind and solar has not been empirically demonstrated in any region in the US. States with the lowest CO_2 power generation emission rates typically rely on appreciable levels of nuclear or hydro power resources for achieving low carbon intensity. Further, even leading states like California and New York have seen slower levels of reductions during the past decade. This is not entirely surprising due to the greater challenges (i.e., diminishing marginal returns principle) with each additional increment of decarbonization. Achieving the Colorado 2030 target is not a foregone conclusion.

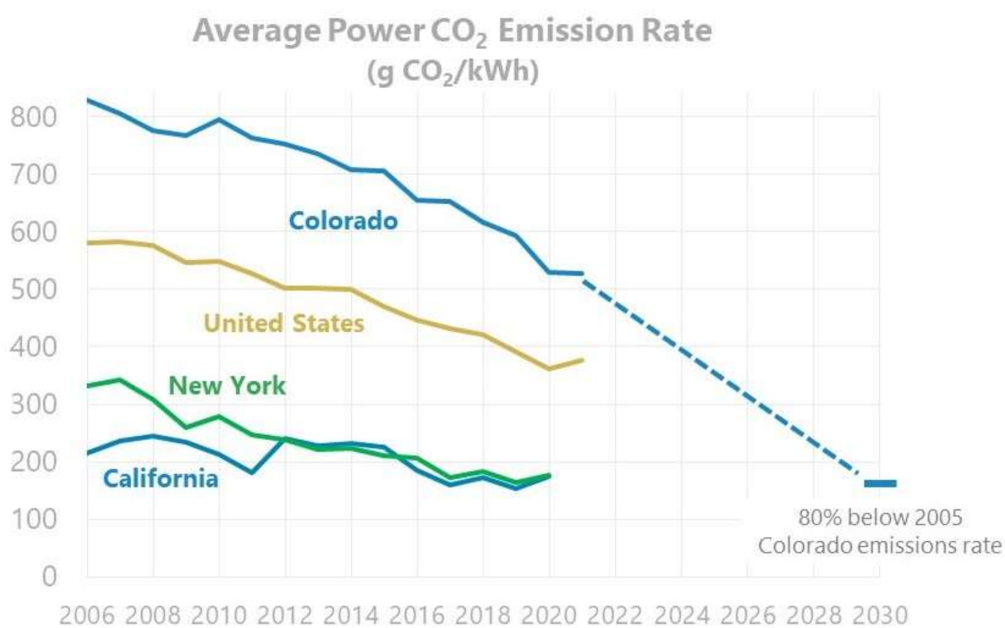


Figure 30: Power Generation CO2 Emission Rate Trends

This does not imply the Colorado 2030 clean power generation goals cannot be obtained, but does provide a cautionary note regarding challenges that may lie ahead, including:

- Electric transmission constraints limiting the ability to move power from remote wind and solar supply resources to major demand centers
- Lower marginal value of new wind and solar resources and potential for greater curtailment during portions of the year due to mismatch between supply and demand (which may undermine the economic investment case for new supplies)
- Concerns over grid stability due to higher levels of reliance on intermittent wind and solar generation resources
- Potential issues with community acceptance of new large-scale wind and solar PV generation resources or high-voltage electric transmission lines

Figure 31, from a DOE 2021 report on the US wind market, empirically illustrates the diminishing marginal value principle, a well-known economic concept. That is, increasing wind market penetration makes that resource less valuable to the grid; this should be reflected in lower prices paid to compensate wind resources. These reductions in value may due to transmission capacity constraints, excess production during periods such as spring and fall months, or other factors. The same principle also applies to solar generation, as highlighted in Figure 32 where the California Independent System Operator has invoked increasing levels of solar PV curtailment with greater PV market penetration. These figures reinforce the cautionary note regarding the viability of a grid scenario that is highly dependent on wind and solar generation.

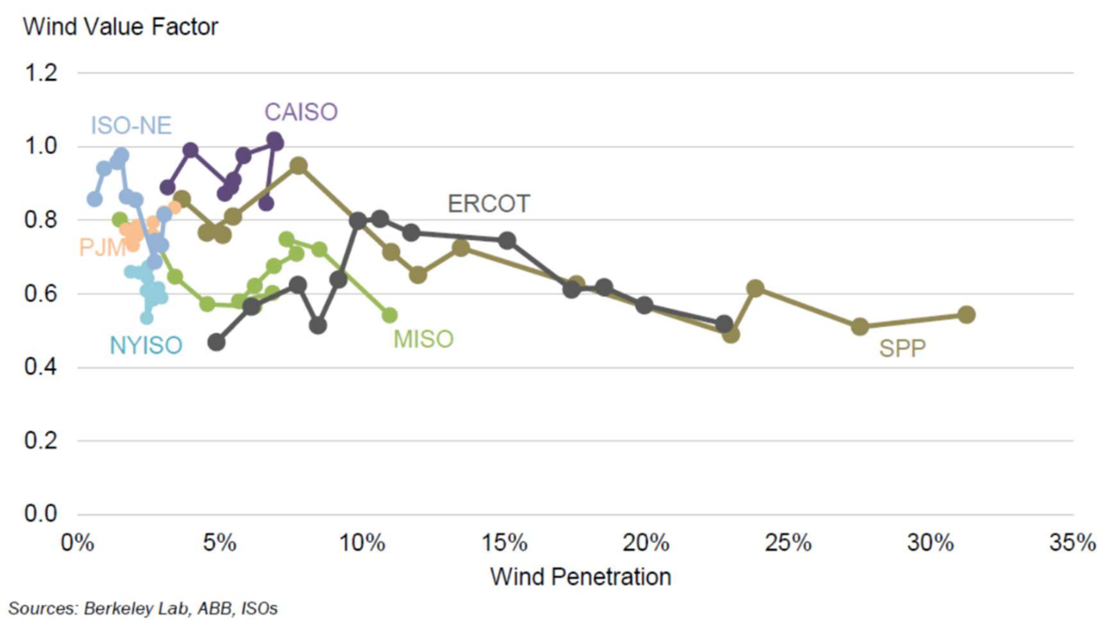


Figure 31: Impact of Wind Market Penetration on Wind Market Value (DOE-EERE)

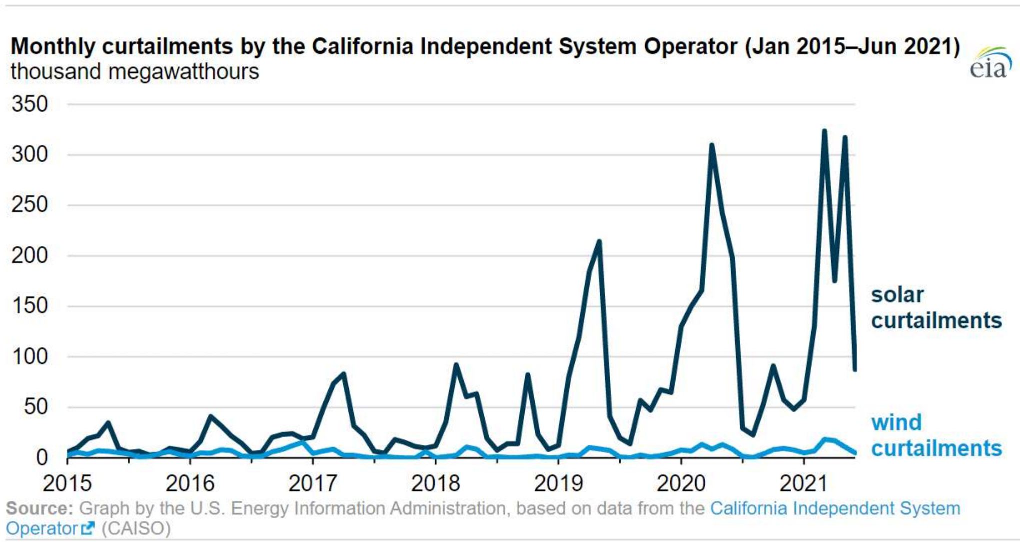


Figure 32: California ISO Solar and Wind Curtailments (DOE-EIA)

Residential electrification would necessitate even greater wind, solar, and gas generation additions. Figure 33 provides an approximation of the future Colorado power generation outlook in the 2030-2040 timeframe using the projected growth in wind and solar generation from Table 5. The added demand from full electrification of existing natural gas homes in Colorado is shown by the gold bars, assuming a nominal 50% reduction in site energy use with electricity appliances compared to natural gas equipment. Solar and wind are shown as additive stacked lines.

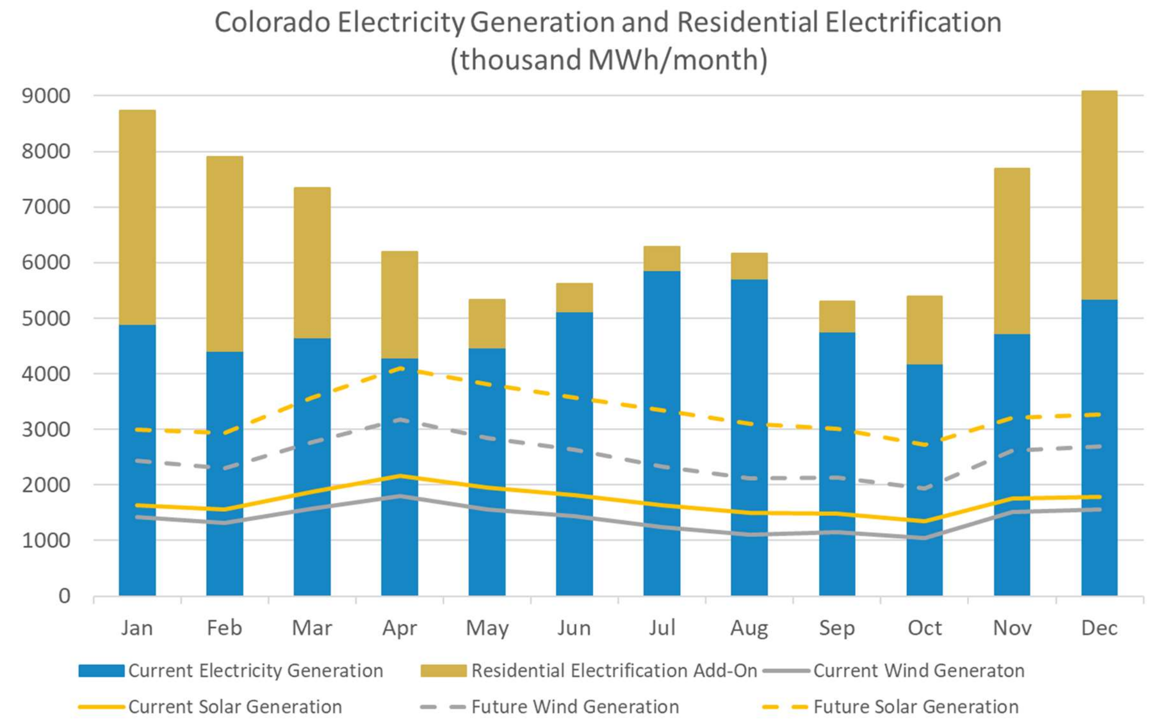


Figure 33: Current Monthly Electricity Colorado Electricity Generation and Projected Impact of Full Residential Electrification (DOE-EIA, GTI Energy)

Taking the current generation values (blue bars), one can see the higher penetration of wind and solar begins creating potential curtailment issues in off-peak months such April. Other instances of wind or solar curtailment could also arise throughout the year depending on local (e.g., transmission congestion) or temporal demand and supply mismatches (e.g., excess wind generation at night).

As shown in Figure 34, the combined impact of added January space heating electricity demand and the empirically confirmed renewable generation shortfall in that month would result in a substantial shortfall of renewable energy supply. The net effect is the added electric space heating demand in January would likely be met with dispatchable gas generation. In a cold month like January, this will likely result minimal benefit or possibly a net increase in CO_2 emissions compared to high-efficiency natural gas heating (as illustrated previously in Figure 14).

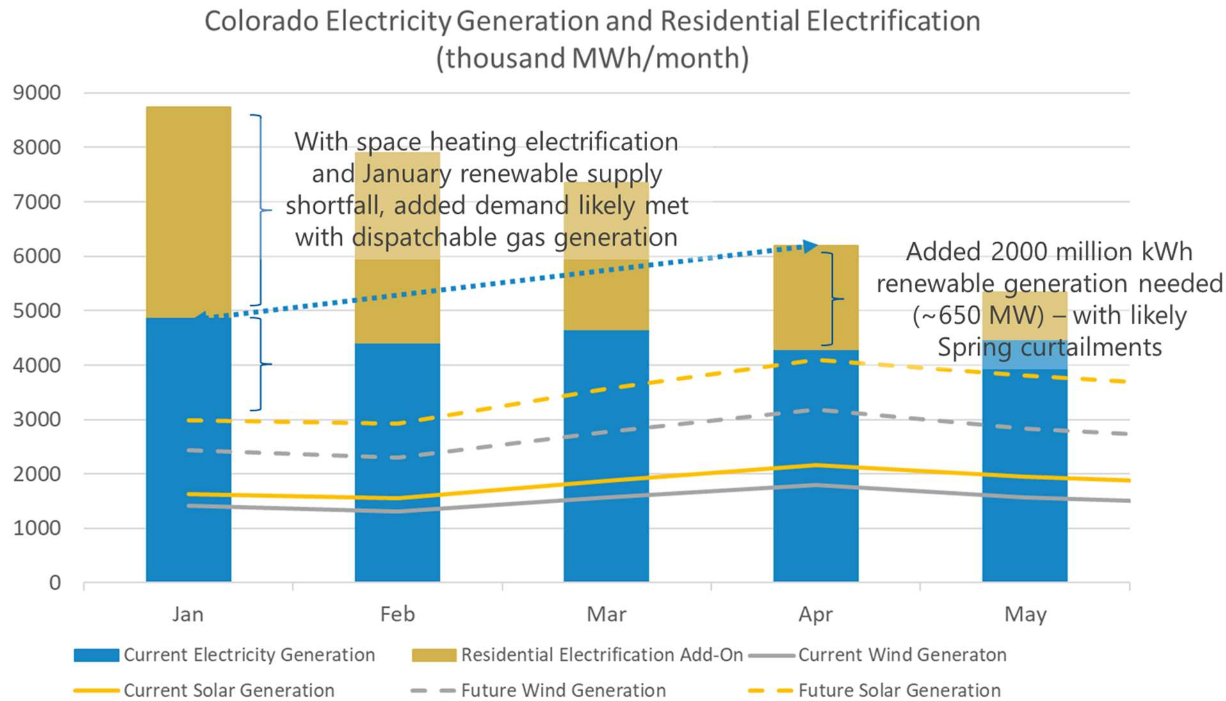


Figure 34: Combined Challenges of Electric Space Heating and the Shortfall of January Renewable Generation Supply (DOE-EIA, GTI Energy)

To address this type of seasonal issue, it is imperative to focus on the decarbonization of gas power generation using either renewable gases (e.g., renewable methane or hydrogen) or carbon capture and storage from dispatchable gas generation. The following sections discuss these options. Note that using renewable gas in appliances or distributed carbon capture from gas equipment are also potential scenarios for decarbonization of conventional direct gas use pathways.

Renewable Gas

The following is a brief overview of renewable gas potential in the US. There are several pathways to generate methane (CH_4) and other gases (e.g., hydrogen or H_2) from renewable resources, including:

- Conventional anaerobic digestion pathways that can produce bio-methane from landfills, wastewater treatment plants, farm digesters, and other sources (these are mature pathways with established and growing commercial use today)
- Thermochemical conversion (e.g., gasification) pathways that produce renewable methane or hydrogen from biomass materials (e.g., wood waste and agricultural waste)
- Power-to-gas concepts using renewable or zero-carbon power generation sources (e.g., wind, solar, nuclear) to produce hydrogen via water electrolysis (which can subsequently be combined with recycled CO_2 to produce methane – a process called methanation – if desired)

Figure 35, from the American Gas Foundation (AGF), provides a visual description of these renewable gas pathways and the energy sources that can be used to produce renewable gases.

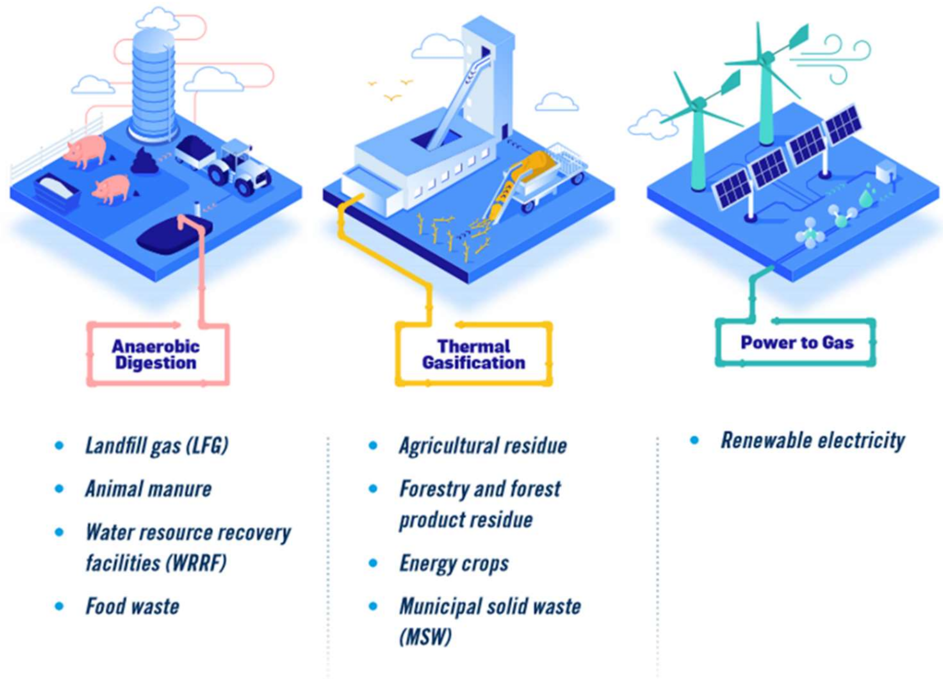


Figure 35: Renewable Gas Generation Pathways (Source: American Gas Foundation)

Renewable gas is an energy form – that is, chemical energy – which is important for several reasons: (1) it has intrinsically high energy density, (2) can be readily and efficiently stored as a compressed gas, (3) is potentially compatible with existing gas pipeline infrastructure and end-use equipment, and (4) can be efficiently delivered to customers with minimal energy losses. Renewable gases can be injected into gas pipelines and used onsite to generate power, heat homes and businesses, fuel vehicles, or fuel industrial process needs. The carbon intensity (CI) of renewable gas will vary depending on full-fuel-cycle GHG analysis, with potential very favorable negative CI scores from sources such as dairy processing facilities.

The AGF report, produced by ICF, highlights three renewable gas pathways (Figure 36) with a combined technical potential of about 4,512 Trillion Btu/year in 2040. This is comparable to the total amount of natural gas consumed in the US residential sector – indicating the possibility for a total renewable gas displacement of conventional gas sources for this segment. The AGF reports a technical potential for conventional biogas plus thermochemical-produced gases of about 145 Trillion Btu/year in Colorado. This is very close to amount of natural gas consumed in the Colorado residential sector – also indicating a long-term potential for renewable gas to meet the current in-state residential gas demand (which averaged about 130 Trillion Btu/year over the last decade).

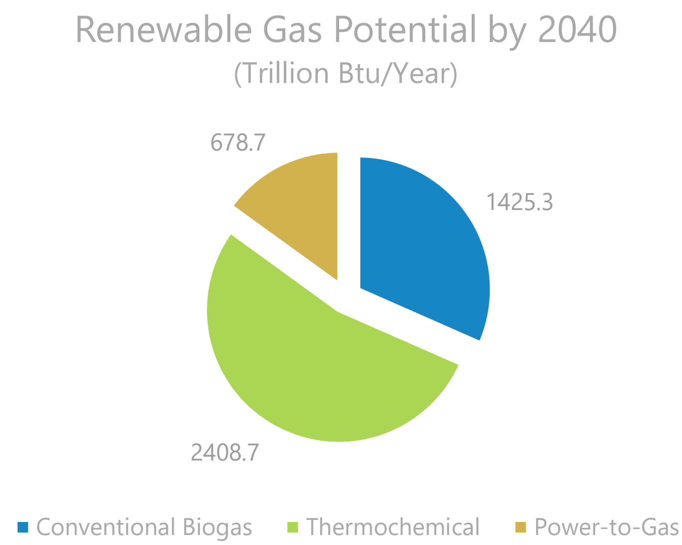
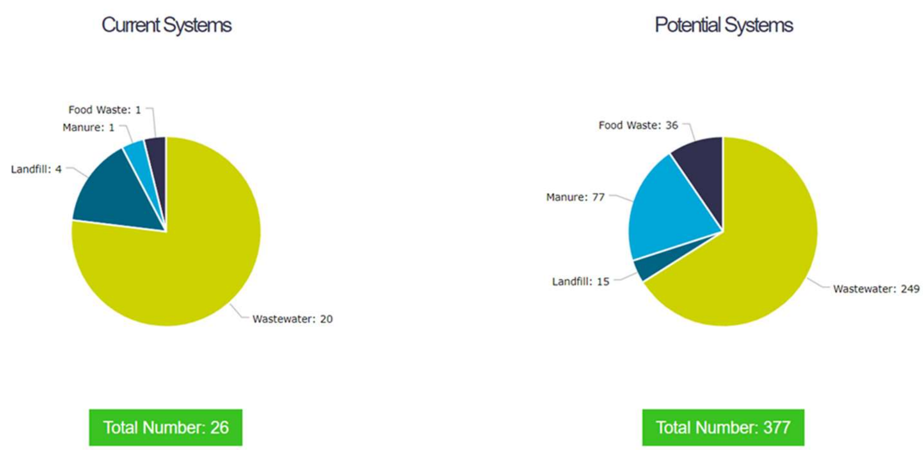


Figure 36: American Gas Foundation/ICF Renewable Gas Potential

Figure 37 is a snapshot of the operational and estimated conventional biogas/bio-methane potential in the State of Colorado. Presently, there are about 26 bio-methane systems operating in Colorado and a potential for 377 additional facilities. From a GHG policy perspective, these systems provide a highly effective means of (1) displacing the use of conventional natural gas and (2) reducing methane emissions to the ambient environment.



BIOGAS SYSTEMS CAN RECYCLE:

Type	Production	Biogas
Manure (total)	5.8 million tons/yr	11.6 billion cuft/yr
Broiler	-	
Dairy	*4.5 million tons/yr*	
Swine	*1.3 million tons/yr*	
Turkey	-	
Food Waste	1.79 million tons/yr	9.76 billion cuft/yr
Landfill	-	-
Wastewater Facility*	291 gallons/day	1.68 billion cuft/yr
Total Biogas	-	23.01 billion cuft/yr

*Wastewater facility greater than 1 MGD

Figure 37: American Biogas Council Colorado State Profile

Figure 38 shows an example Colorado-based biogas generation and clean-up facility – in this case, producing bio-methane that fuels compressed gas vehicles. Other bio-methane plants have onsite generators that convert bio-methane into renewable power or inject renewable gas into gas pipelines. These systems are widespread across the US and have seen substantial growth in recent years.

Figure 38: City of Longmont Biogas to CNG Facility

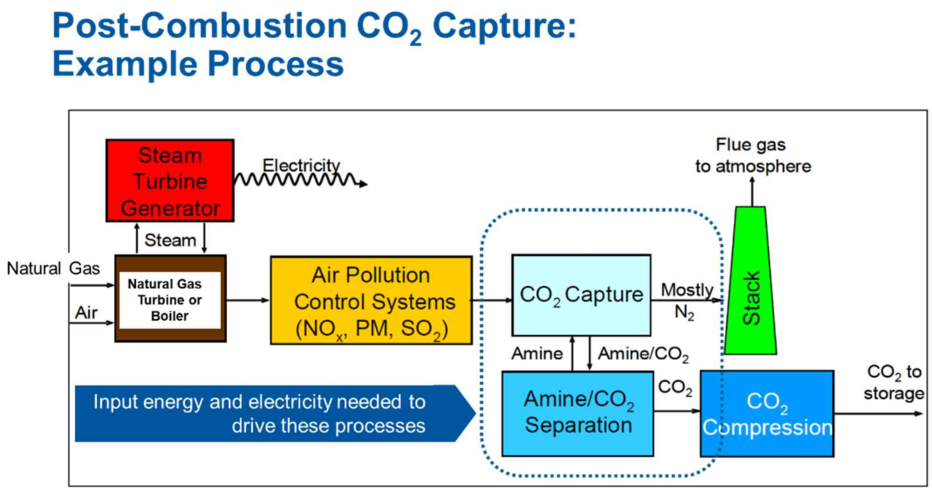
Next-generation renewable gas options are possible through (1) thermochemical conversion of biomass and (2) power-to-gas systems. These are not yet widely reduced to commercial practice but have long-term potential to expand the portfolio of options for producing renewable and sustainable forms of methane or hydrogen.

Thermochemical conversion of biomass to methane or hydrogen has several favorable attributes, including feedstock flexibility and greater capability to produce large volumes of renewable gas. These processes can convert agricultural wastes, forestry wastes, organic municipal wastes, and byproducts from a variety of industries. These facilities are typically 2-10 times larger than conventional biogas facilities. The sustainable availability of wood and other biomass materials in Colorado opens the potential for these processes to be a significant long-term source of renewable gas.

Power-to-gas is a pathway that produces hydrogen through the electrolysis of water. The power supply can come from any electrical source but is often viewed in the context of low-carbon power resources such as wind and solar power or from nuclear power plants. This hydrogen can be used directly, stored as a compressed gas, or injected into a pipeline. Through a process called methanation, it can also be combined with captured and recycled CO_2 to produce methane, which can be used directly with existing natural gas infrastructure. This pathway offers feasible large-scale storage of renewable energy with the capability to meet long-duration seasonal demand (e.g., space heating) which cannot be met by other electrical energy storage systems such as batteries.

Carbon Capture and Storage

Carbon capture and storage is a secondary pathway for decarbonizing gas combined-cycle power plants. Figure 39 shows an example CO_2 exhaust capture process. The CO_2 produced from this process can be sent via pipeline to an underground storage facility or employed in a CO_2-reuse approach.



Adapted from: **Source:** E. S. Rubin, "CO_2 Capture and Transport," *Elements*, vol. 4 (2008), pp. 311-317.

Figure 39: Example CO_2 Capture Process

There is a growing attention to CO_2 pipeline and storage systems, driven in part by Federal 45Q tax credits and market efforts to reduce the carbon intensity of various segments (e.g., major industrial and power generation facilities). There are potential subsurface CO_2 storage locations throughout the US (Figure 40).

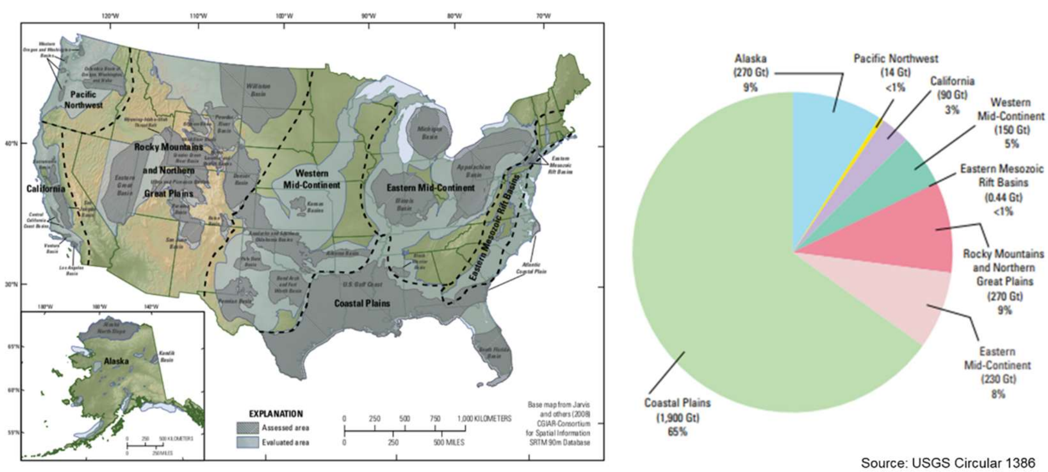


Figure 40: US CO_2 Storage Potential

Colorado Home Greenhouse Gas (GHG) Reduction Analysis

This section highlights information on the benefits and costs of various natural gas, electric, and hybrid natural gas/electric GHG reduction pathways for Colorado homes. This analysis is based on a free, publicly accessible online tool developed by GTI Energy: Energy Planning Analysis Tool (EPAT; http://epat.gastechnology.org/).

Energy Planning Analysis Tool (EPAT) & Benefit/Cost Scenario Analysis

Developed by GTI Energy, EPAT is a free publicly accessible analytical tool that allows users to compare a baseline and alternative scenario analysis of home energy use. EPAT relies on government published and published data sources to estimate source energy (i.e., full-fuel-cycle) and emissions for energy sources like natural gas and electric. EPAT accounts for upstream energy use and emissions in the production and delivery of energy, including features such as methane emissions from the full natural gas production and delivery chain as well as full-fuel-cycle energy losses and emissions from electric power generation, transmission, and distribution. The EPAT electric generation component relies on the US Environmental Protection Agency (EPA) Emissions & Generation Resource Integrated Database (eGRID) information, with granular information on power generation plant efficiency and emissions on a city, state, or regional level.

In this analysis, we use an estimated population of Colorado natural gas homes with a common baseline being homes using an 80% efficient natural gas furnace, 62% efficient water heater, and conventional natural gas cooking and dryer equipment. From this, a series of pair-wise comparisons are made using the same baseline and alternative scenarios or cases. Table 6 shows a summary matrix of scenarios in this analysis. These will be referred to as Case 1, Case 2, etc, in the analysis discussion. Detailed reports of each case are in an appendix.

Table 6: Colorado Residential GHG Reduction Scenario Cases

Natural Gas	No RNG	50% RNG
Baseline (80% efficient furnace, 62% efficient water heater, standard cooking and dryer appliances)	Baseline	--
Existing High-Efficiency (98% efficient furnace, 95% efficient water heater, high-efficiency dryer)	1	2
Emerging High-Efficiency (140% efficient natural gas heat pump, 130% efficient gas heat pump water heater, high-efficiency dryer)	3	4
Electricity	**Current Power Mix**	**Future 2030-2040 Power Mix**
Baseline Electric (all electric-resistance heating equipment)	5	8
Typical High-Efficiency Electric (HSPF 9.0 electric heat pump, water heater/EF = 0.95, standard cooking/dryer)	6	9
Emerging High-Efficiency Electric (HSPF 13.0 electric heat pump, efficient natural gas heat pump, electric heat pump water heater EF 2.0, induction cooking, high-efficiency dryer)	7	10

Building envelope improvements are not part of the quantitative analysis. However, improved home weatherization is a critically important component of a resident building GHG reduction program. These measures provide value to consumers in the form of lower annual energy bills and improved indoor comfort while also reducing natural gas and electricity use for home space conditioning.

The analysis focuses on energy used for space heating, water heating, cooking, and clothes drying. To properly account for capital costs, the natural gas cases include the cost of central air conditioning systems in 80% of the homes, using the DOE-EIA RECS 2015 data showing 77.6% of Mountain Region homes use air conditioning. This allows for equitable capital cost treatment of electric heat pumps which are more expensive than gas furnaces but also provide cooling. The cases with 50% renewable natural gas (RNG) assume an RNG price of $18/MMBtu. The RNG is assumed to be carbon neutral in this analysis. Depending on the resource, the CI Score for RNG can be positive or negative.

The current Colorado power generation mix and future 2030-2040 power generation mix were shown previously in Table 5. Note that the advanced natural gas cases also use the future 2030-2040 power generation mix, reflecting likely future GHG emission reductions for electricity used in gas equipment (e.g., furnace blower fans).

The EPAT analytical tool captures consumer costs in two main categories: annual energy costs (natural gas and electric) and capital costs. In this analysis, equipment capital costs are annualized by a simple amortization achieved by dividing the capital cost by the expected equipment life of the space heating systems. As noted, for gas furnaces this is 21.5 years and for heat pumps (electric or gas) this is 15.5 years. The annual energy costs and annualized capital costs are added together to provide a nominal annualized cost for each scenario – and used to calculate the GHG abatement costs in $/metric ton of GHG emissions reduced. A brief comment is warranted about capital costs. The EPAT tool relies on the NREL National Residential Efficiency Measures (NREM) Database for equipment costs; this information resource may underestimate installed equipment costs.

Consumers looking to fully electrify their homes will face additional upfront costs for upgrading the electric service feed and electrical panel (to 200 amps or greater) and for additional home circuits. According to a NAHB-Home Innovation Research Lab report, this can be an added upfront consumer cost of about $2600 or more. For this analysis, a nominal $2000 one-time cost per home is included for electric service upgrades. In some cases, consumers may face additional retrofit costs for upgrading space-conditioned air distribution systems; this is particularly true for homes currently using hydronic heat distribution (e.g., adding something like a SpacePak or similar small duct high-velocity system). There is no attempt to include these latter costs in this analysis.

EPAT results also include information on the annual site and source (or full-fuel-cycle) energy use as well as a suite of annual conventional emissions (e.g., NO_x, SO_x) and GHG emissions (e.g., CO_2, methane, CO_2e).

The annualized costs are divided by the annualized emission reductions between the baseline natural gas baseline scenario and each individual case. This results in a GHG cost/benefit ratio – also referred to as a carbon, CO_2, or GHG abatement cost – reported as $/metric ton reduction in CO_2 or CO_2e emissions. In most cases, this GHG abatement cost results in a positive number that have consumers (and society) paying a premium in their overall energy budget to lower GHG emissions. In some instances, the GHG abatement cost is negative; in these highly favorable instances, consumers are saving money and reducing GHG emissions. GHG abatement costs values can be considered in the context of a carbon tax or the notion of the social cost of carbon.

In some instances – e.g., electric systems using the current Colorado power generation mix – the level of GHG emissions increase over the natural gas baseline. These instances will be labeled "GHG Increase" without any GHG abatement value (i.e., it is not a viable GHG reduction measure).

Colorado Home GHG Reduction Pathways Cost and Benefit Results

Table 7 (at the end of this report section) provides summary data on Cases 1 through 10.

Figure 41 provides a breakdown of the annual changes in total energy cost and annualized capital cost for each of these scenarios. The most cost-effective options are using high-efficiency natural gas equipment (Case 1 & 2, without and with 50% RNG blends). Gas heat pumps provide significant consumer energy cost savings, but with a high first cost hurdle. For the electric scenarios, using electric resistance equipment (Cases 5 or 8) has the highest energy and total costs. Electric heat pumps (Case 6 or 9 and 7 or 10) provide a consumer lifecycle benefit compared to electric resistance scenarios but are considerably more costly than each natural gas scenario.

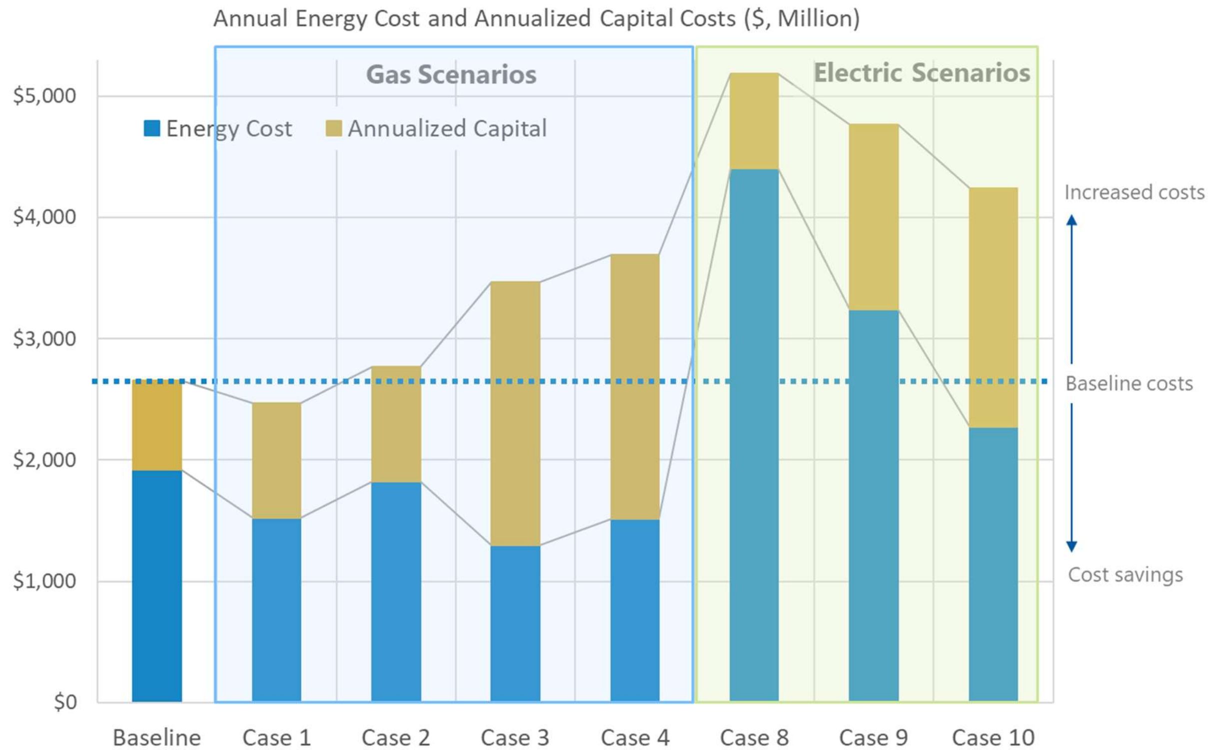


Figure 41: Annual Energy & Annualized Capital Costs ($, Million)

Figure 42 shows a typical annual energy cost comparison between an average single-family home in Colorado (1,885 ft^2) based on Case 1 (98% efficient furnace) and Case 9 (HSPF 9 electric heat pump) assumptions for space heating, water heating, cooking, and drying. For these home uses, energy costs would more than double for an all-electric home.

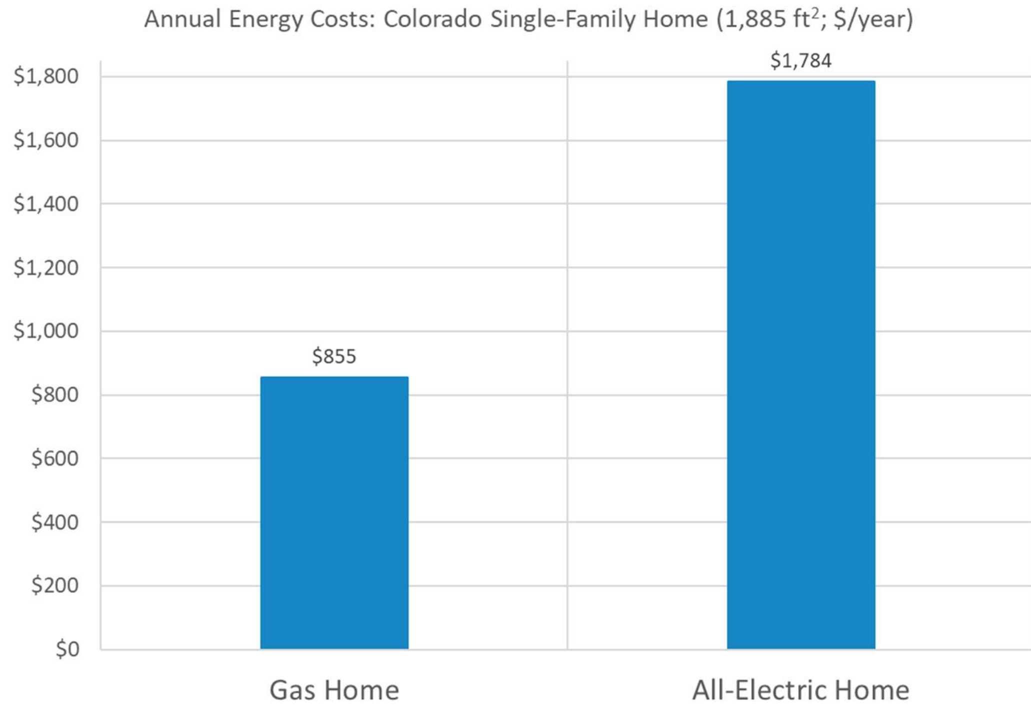


Figure 42: Annual Energy Cost Comparison for Typical Colorado Single-Family Home

Figure 43 shows CO_2 and CO_2e (CO2 equivalent) for each of these scenarios. The gas scenarios provide a combination of reductions from improvements in energy efficiency and, for two cases, using 50% blends of renewable natural gas. Operating electric equipment with the current grid in Colorado results in significant GHG emission increases in two cases and a neutral outcome with higher efficiency heat pumps. The proposed grid for the 2030-2040 timeframe provides emission benefits compared to the existing natural gas baseline.

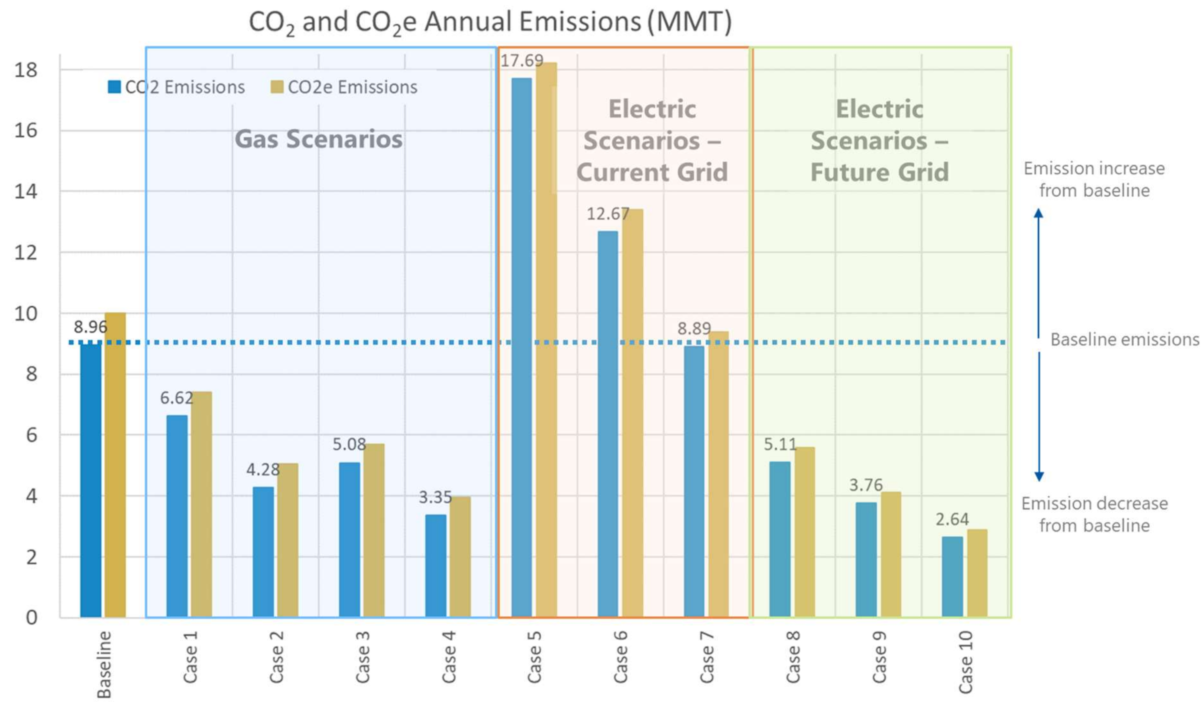


Figure 43: GHG Emission Level Comparison

There is an additional topic to account for when determining real-world measures of GHG abatement cost effectiveness: the probability that an appreciable portion of electric winter space heating will be met using marginal seasonal generation (i.e., dispatchable gas generation) with higher GHG emission rates than the future average grid mix. This impacts the % GHG reduction and the GHG abatement cost calculation.

Figure 44 is a modified version of Figure 43, using updated CO_2 emission estimates based on a 50% future 2030-2040 grid scenario with 50% of the electric space heating load being powered by unmitigated dispatchable gas generation. This assumes gas generation at 48% higher heating value (HHV) efficiency; note, the current Colorado gas-fired power plant fleet average is closer to 39% HHV, based on EPA eGRID data. Under this alternate scenario, the electrification benefits may be reduced due to winter generation limitations of wind and solar power. This is presented not as a prescriptive scenario, but as a cautionary depiction of the likely real-world challenges with electric space heating. This underscores the need to consider: (1) hybrid heating systems where natural gas furnaces carry heating loads during colder temperatures or (2) decarbonization of gas generation with renewable gas or carbon capture. The hybrid heating approach has the added benefit of avoiding the need for excessive investment in electric generating capacity and transmission & distribution assets to peak winter peaks.

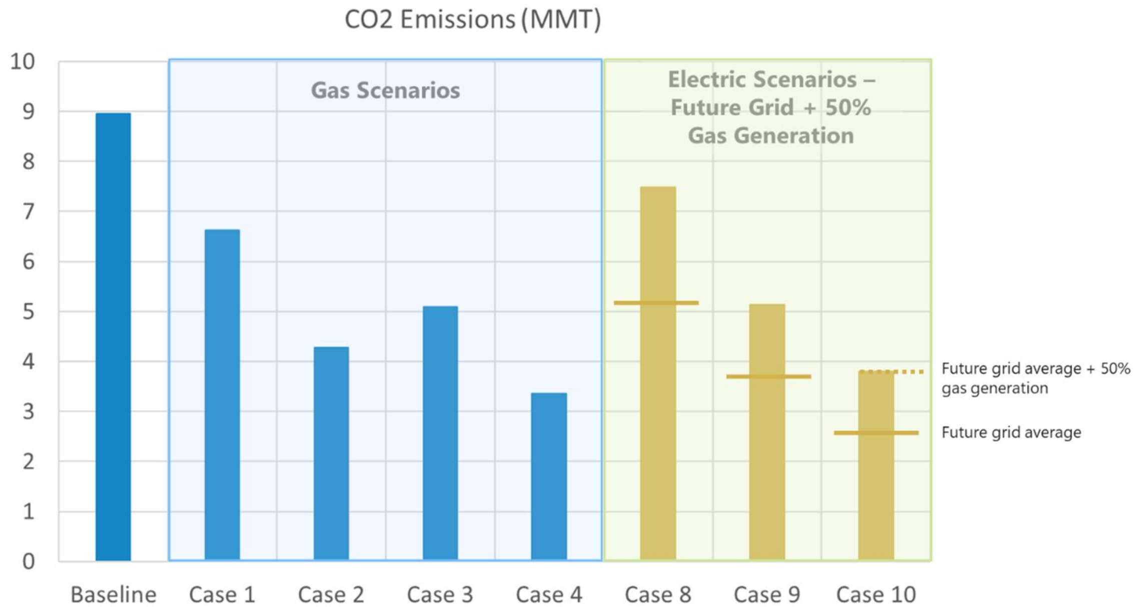


Figure 44: CO_2 Emissions With 50% of Electric Space Heating Power from Gas Generation

Figure 45 shows a comparison of the primary natural gas and electric GHG reduction options. Note that this graph excludes current power generation scenarios (i.e., Cases 5, 6 and 7) which would increase CO_2 emissions. Case 8 (using the proposed future grid with electric resistance equipment) is also excluded due to high CO_2 abatement costs (over $600/metric ton of CO_2). The four natural gas cases are lower in cost than the two electric cases using electric heat pumps, with varying levels of CO_2 reductions. Using high-efficiency furnaces results in net consumer savings (-$83/metric ton CO_2) and about 26% CO_2 reductions. That scenario with 50% blended RNG has a cost of $46/metric ton CO_2 reduced and 52% CO_2 emissions reduction. Gas heat pumps without and with 50% RNG blend can achieve 43%-63% reduction at costs of $189-$204/metric ton CO_2.

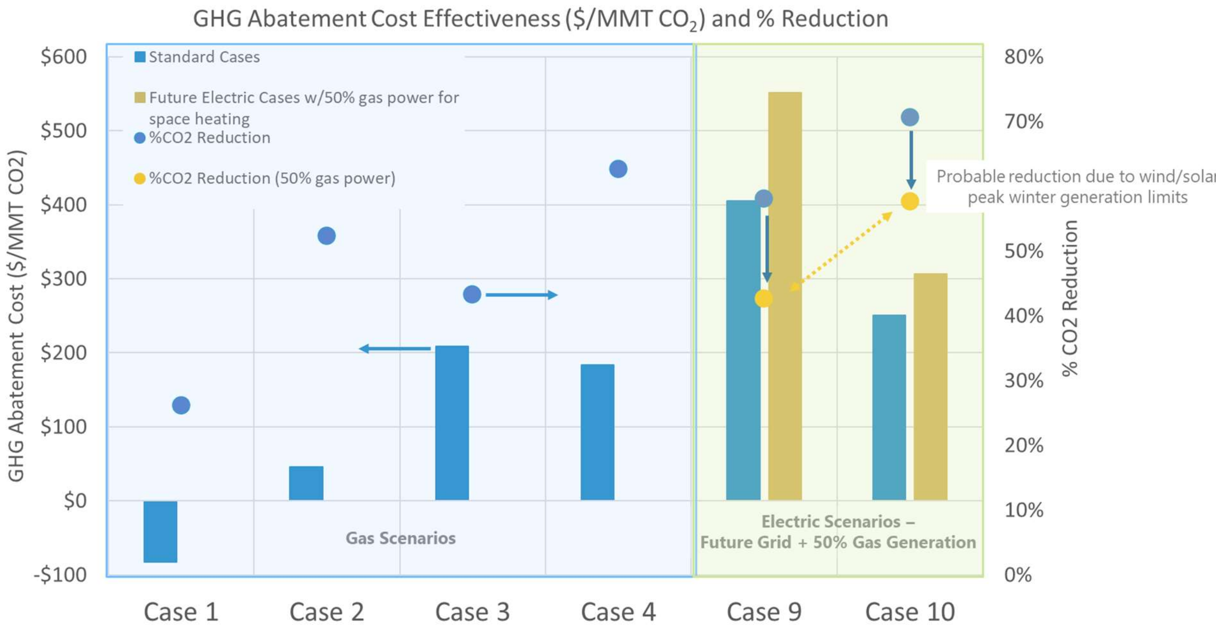


Figure 45: GHG Abatement Cost Comparison

Electrification scenarios with the future grid power generation mix (Case 9 using HSPF 9.0 electric heat pumps and Case 10 using HSPF 13 electric heat pumps) can in theory achieve 58-71% CO_2 reductions. In practice, however, these cases are more likely to operate using at least 50% of the winter season on dispatchable gas generation (as illustrated previously in Figure 34) and see practicable CO_2 reduction levels in the 42%-58% range, with CO_2 abatement costs ranging from about $305-$550/metric ton of CO_2.

The electrification scenarios are each more expensive in terms of energy costs for consumers (as shown in Figure 41) and for societal CO_2 abatement costs as shown in the above figure. The scenario using 50% dispatchable gas generation could realize higher GHG reduction levels if decarbonization measures (e.g., operating on renewable gas or carbon capture and storage) are used. These measures will have added costs so the modified GHG abatement costs (shown in the gold bars in Figure 45 may still be suitable estimates.

The costs outlined above are from a consumer's perspective (annual energy and capital investment in equipment and products used in the home) and societal perspective (i.e., GHG abatement costs). What has not been included are electric utility costs or an estimation of the impact of electrification on consumer electricity prices. Figure 46 shows analysis by Black Hills Energy on various clean power planning scenarios, including two with broad-scale electrification. Notably, the two most expensive options are the electrification scenarios which include electric space heating. A specific assumption in their electrification space heating analysis is that 50% of the heating load would be met with electric resistance heating (on the coldest days) and 50% by legacy natural gas furnaces (what is referred to in this report as a hybrid heating solution. Explicit in this analysis is a recognition of the severe peak electricity demand levels that would result from widespread electrification of space heating. By relying on direct natural gas use for space heating on cold days, Black Hills can avoid excessive investment in electric infrastructure (i.e., the costs shown in this figure would be considerably higher) and elevated risks of electric grid outages. Further, they avoid the practical reality that most of the generation on peak cold days would come from dispatchable generators with little to no GHG reduction benefit. One final note is the higher costs for electrification would likely lead to electricity prices increases (which is not assumed in this analysis) that would further increase consumer costs and raise electrification GHG abatement costs.

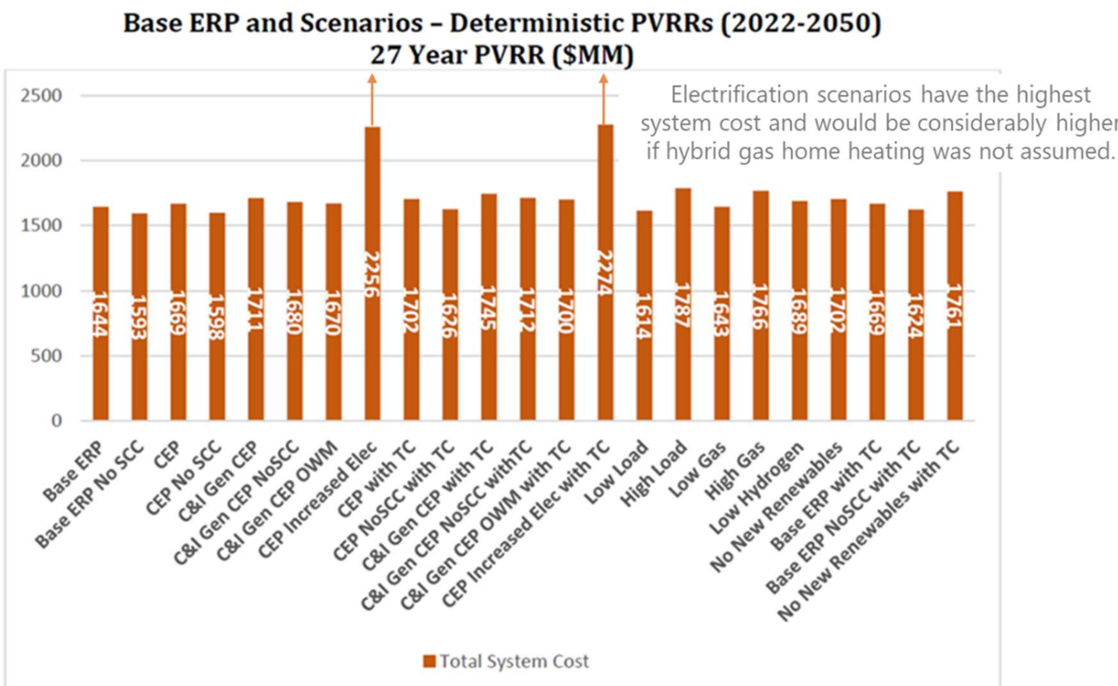


Figure 46: Black Hills Energy Electric System Investment Scenarios

Using the matching principle that a meaningful portion of winter seasonal peak electricity demand will be met with dispatchable natural gas generation, GHG reductions are likely to be less than anticipated for electric space heating options. The four gas scenarios involve considerably lower consumer (and utility sector or societal) costs, disruptions, and risk, with the potential for appreciable levels of GHG reduction. Where electrification may be pursued, hybrid gas and electric space heating is a very cost-effective and prudent strategy to avoid the high costs and risks associated with all-electric space heating in cold-weather environments.

Table 7: Energy and Environmental Cost and Benefit Data

Case	Description	Annual Energy Costs ($MM/yr)	Annualized Capital Costs ($MM/yr)	Total Annualized Costs ($MM/yr)	Annual CO_2 Emissions (MMT/yr)	Annual CO_2e Emissions (MMT/yr)	$/Metric Ton CO_2 Reduced	$/Metric Ton CO_2e Reduced	% CO_2 Reduction
--	Baseline: Natural Gas Systems	$1,922	$737	$2,659	8.96	9.99	--	--	--
1	Case 1. Typical High-Efficiency Gas	$1,525	$942	$2,467	6.62	7.41	-$83	-$75	26.1%
2	Case 2 Case 1 with 50% RNG	$1,825	$942	$2,767	4.28	5.05	$46	$45	52.3%
3	Case 3 Emerging High-Efficiency Gas	$1,298	$2,170	$3,468	5.08	5.68	$209	$188	43.2%
4	Case 4 Case 3 with 50% RNG	$1,519	$2,170	$3,689	3.35	3.94	$184	$170	62.6%
5	Case 5 All Electric Resistance Current Power Generation	$4,407	$777	$5,184	17.69	18.21	GHG Increase	GHG Increase	GHG Increase
6	Case 6 HSPF 9 Current Power Generation	$3,239	$1,528	$4,767	12.67	13.39	GHG Increase	GHG Increase	GHG Increase
7	Case 7 HSPF 13 Current Power Generation	$2,274	$1,969	$4,243	8.89	9.39	$24,942	$2,645	0.7%
8	Case 8 Electric Resistance Equipment Future Power Generation (w/50% gas generation for space heat)	$4,407	$777	$5,184	5.11 (7.48)	5.59	$655 ($1,702)	$574	43.0% (16.6%)
9	Case 9 HSPF 9 Future Power Generation (w/50% gas generation for space heat)	$3,239	$1,528	$4,767	3.76 (5.14)	4.11	$405 ($552)	$358	58.1% (42.6%)
10	Case 10 HSPF 13 Future Generation (w/50% gas generation for space heat)	$2,274	$1,969	$4,243	2.64 (3.80)	2.88	$250 ($307)	$223	70.6% (57.6%)

Colorado Home Electrification Considerations and Challenges

This section discusses additional challenges or issues pertaining to the expanded use of electricity as a natural gas replacement in Colorado homes. These center around energy transmission, distribution, and storage systems as well as the growing consumer importance placed on home energy service reliability and resilience.

Natural Gas and Electric Energy Delivery Systems

Figure 47 shows the impact of space heating electrification on peak winter demand in the 48 continental states based on a GTI Energy analysis. This data highlights the substantial scale-up and investment in electric transmission and delivery capacity required to support switching residential gas heating to electricity.

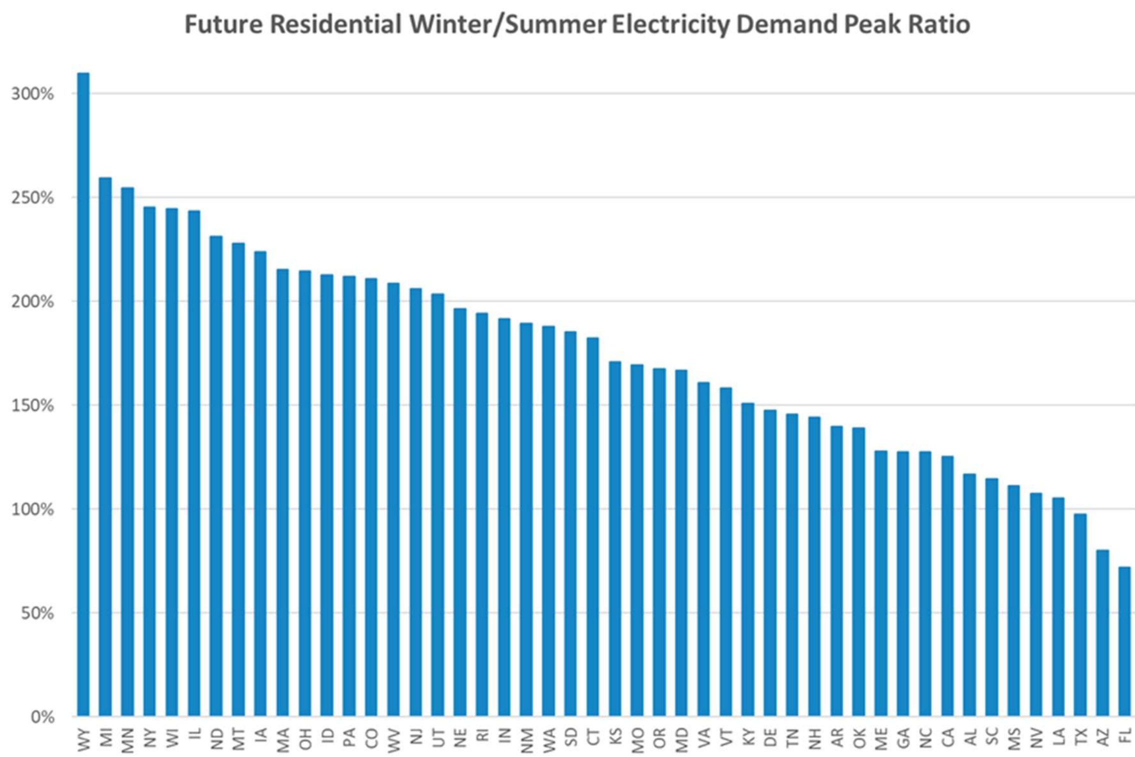


Figure 47: Impact of Electrification on Peak Winter Demand (Source: GTI Energy)

While some electrification advocates may point to distributed PV systems as a potential answer, the decreased solar PV output during winter months severely limits the ability of distributed solar PV systems to ameliorate this seasonal electric peaking challenge.

The success of the natural gas energy delivery system in meeting severe peak demand during cold weather is due to the combination of the major energy-carrying capacity of gas pipelines and natural gas storage (discussed in the next section). Figure 48 and Table 8 illustrate the typical rated energy delivery capacity of an interstate natural gas pipeline relative to electric transmission lines. A typical gas transmission pipeline has 10-50 times the energy delivery capacity of electric transmission lines.

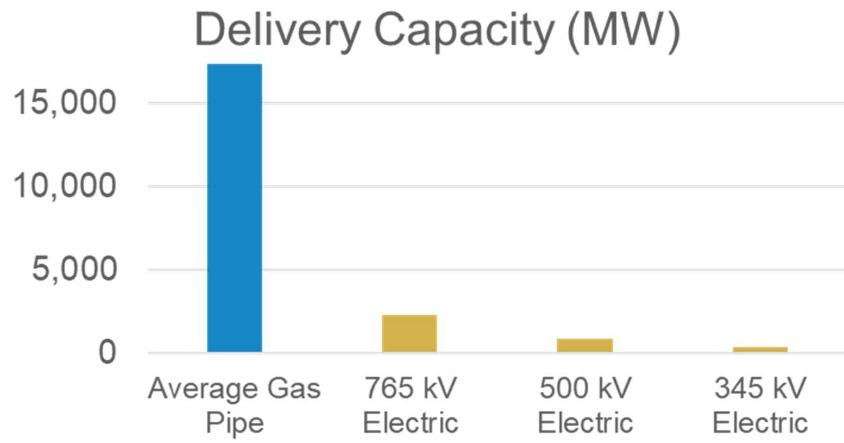


Figure 48: Major Natural Gas and Electric Transmission System Capacity (DOE, AEP)

Table 8: Major Natural Gas and Electric Transmission System Capacity (DOE, AEP)

350 US Gas Transmission Pipelines	Delivery Capacity, MW
Average Pipeline	17,386
90th Percentile	~32,000
Electric Transmission Lines	**Capacity, MW**
765 kV	2,300
500 kV	900
345 kV	400

In addition to challenges with winter peak demand power generation – and the lack of suitable dispatchable power generation other than natural gas combined cycle plants – substantial upgrades to electric transmission and distribution systems would be needed to meet high peak day/peak month demand requirements.

Natural Gas and Electric Energy Storage Systems

Energy storage systems are used in natural gas and electric energy delivery systems to assist in managing peak demand periods or to provide other services. Table 9 summarizes key metrics for three main US energy storage systems: underground natural gas storage, pumped hydro energy storage, and battery energy storage (BES); the latter two are employed for electric energy storage. Natural gas underground storage systems are demonstrably larger than electric storage systems based on delivery capacity (over 15X larger) and empirically demonstrated peak monthly energy delivery (over 100X larger). While gas underground storage and pumped hydro can provide seasonal energy storage capability to offset winter or summer peak space conditioning loads, battery energy systems lack this capability and are mainly used for short-term applications less than 24-hours. In terms of cycle efficiency and energy losses, natural gas underground storage systems are substantially more efficient (97-99%) than both battery electric (around 82%) or pumped hydro (79%) energy storage systems.

Table 9: Representative Gas and Electric Energy Storage Size and Performance Metrics (DOE-EIA 2022 data, GTI Energy)

	Underground Gas Storage	Pumped Hydro Energy Storage	Battery Energy Storage
Nominal Capacity (GW)	495	23	8.6
Peak Monthly Energy Delivered, GWh	331,800	2680	354
Peak Month Capacity Factor	23%	15.9%	5.7%
Annual Capacity Factor	--	11.1%	5.0%
Cycle Efficiency (Losses) (%)	98.4% (1.6%)	79% (21%)	82% (18%)

Figure 49 illustrates the much larger demonstrated energy delivery capacity possible with natural gas underground storage when compared to pumped hydro or battery energy storage systems. This scale of natural gas storage has evolved due to the unique requirements of the winter heating loads outlined in this report. Replicating this capacity with electric systems – particularly considering the high seasonality of space heating loads – would be extraordinarily expensive and may only be technically feasible with pumped hydro systems or using natural gas turbines with renewable gas energy storage.

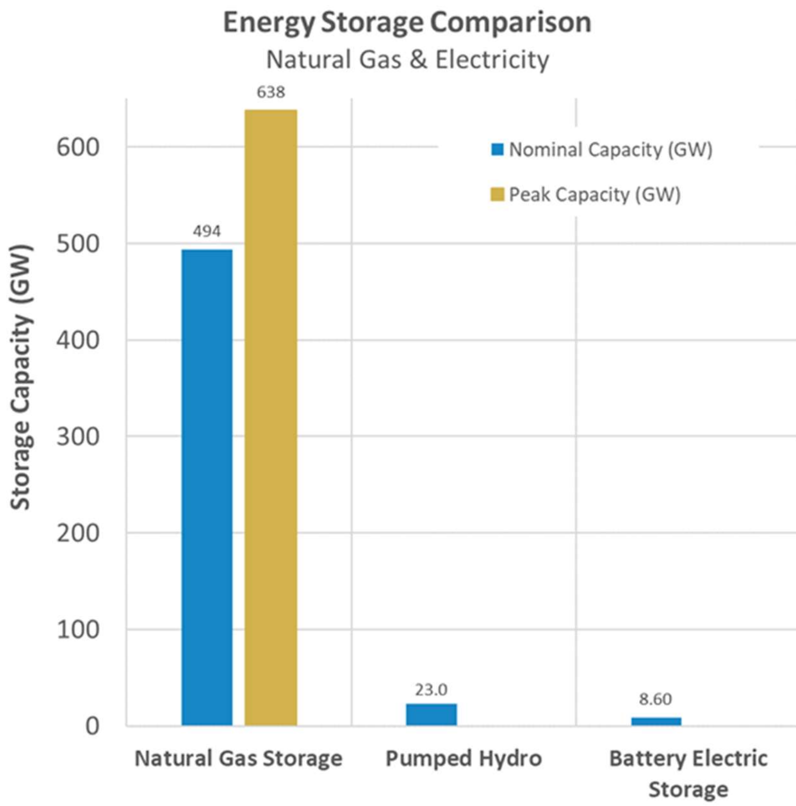


Figure 49: Nominal Energy Storage Capacity (DOE-EIA)

Battery energy storage lacks the seasonal storage capability needed to meet the increased demand from winter space heating. Figure 50 compares the monthly capacity factors for these three forms of energy storage. Natural gas storage has demonstrated high seasonal storage capabilities as does pumped hydro to a lesser extent (i.e., ramping up to support summer space cooling loads). Battery energy storage however has no demonstrated seasonal differences in capacity factor; in practice, battery energy storage typically has its lowest monthly capacity factor in January. The low capacity factor for battery energy storage also has implications in terms of its cost effectiveness.

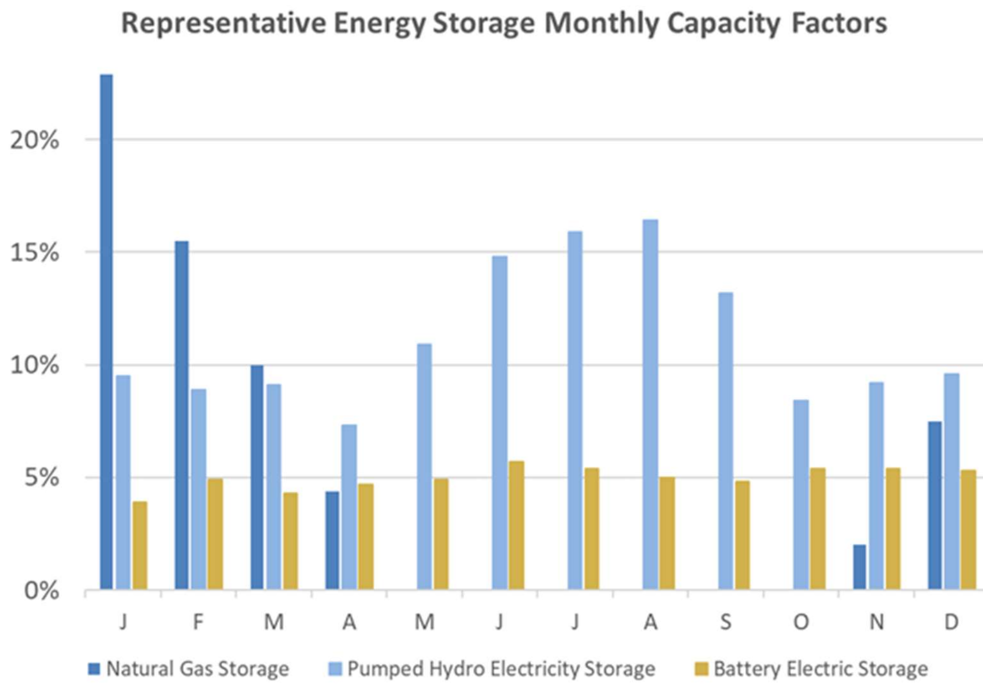


Figure 50: Representative Energy Storage System Capacity Factors (DOE-EIA; 2022 data for electric storage)

Figure 51 illustrates the challenges with electric energy storage in meeting long-duration winter space heating peak electricity demands. Only pumped hydro systems come close to having the system scale and operating attributes (e.g., discharge time) that are congruent with space heating loads. While larger battery energy storage systems are being deployed, they remain relatively small compared to pumped hydro and lack the fundamental technical capability of extended duration (e.g., weeks, months) discharge times (Figure 52).

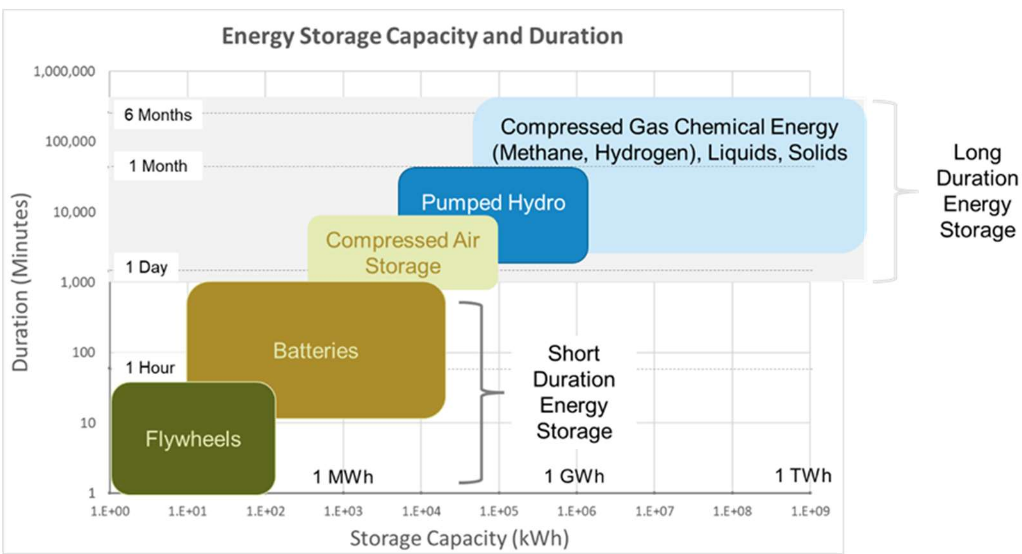


Figure 51: Size and Duration of Energy Storage Systems (adapted from National Hydropower Association report)

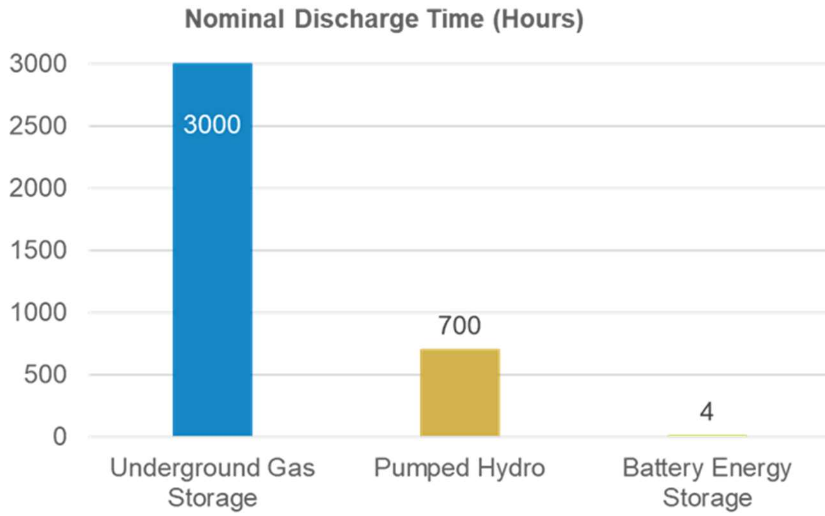


Figure 52: Nominal Discharge Times of Energy Storage Options

Main Finding: Electric energy storage options have higher cycle losses than natural gas systems and battery energy storage systems lack the seasonal capability needed to meet winter electricity loads resulting from large-scale residential electrification. Pumped hydro storage has seasonal capabilities but has not had new investment in recent years.

Home Energy Supply Reliability and Resilience

Home energy system reliability and resilience have become increasingly important to residential homeowners, driving more consumers to install home emergency generators to ensure electricity is available at all times, especially during extreme weather events (Figure 53).

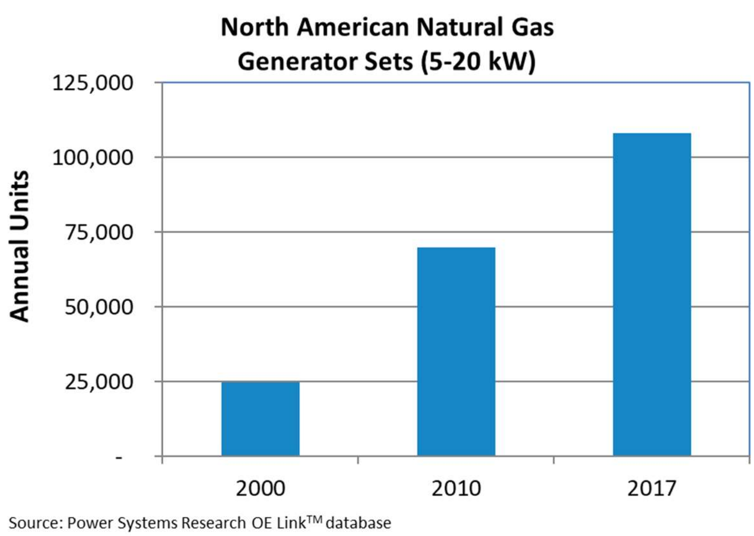
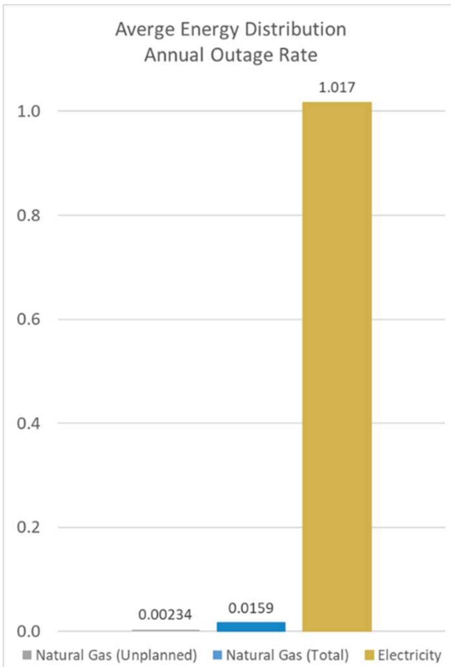


Figure 53: Trends in North American Residential Natural Gas Generators Units

Figure 54 highlights the main reasons consumers look to install equipment like natural gas home generators: (1) higher electricity outage rates and (2) concomitant lower levels of reliability (when compared to natural gas distribution service for example). Installing a natural gas generator in homes and businesses makes sense because natural gas distribution service is highly robust and rarely has unplanned service outages or weather events. The extreme notion of removing natural gas service to homes and businesses not only substantially increases their annual energy bills, it also removes a key consumer solution for ensuring their home's energy supply reliability and resilience (Figure 55). These are comparable to the following IEEE 1366 Guide for Electric Power Distribution Reliability metrics: (1) System Average Interruption Frequency Index (SAIFI, left) and (2) Average Service Availability Index (ASAI, right).



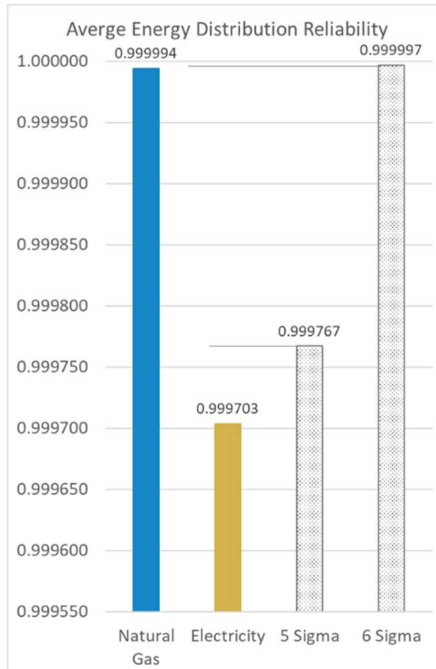


Figure 54: Natural Gas and Electric Distribution Outage Rates and Service Reliability

Figure 55: Example Residential and Commercial/Industrial Natural Gas Generator Sets

Colorado Home GHG Reduction Recommendations

The following is a strategic framework for achieving near-term feasible and cost-effective GHG reductions in Colorado natural gas homes over the next two decades, predicated on the perspective that:

- Natural gas is an important and abundant natural resource that provides tremendous value to consumers in Colorado and the nation as a whole
- Two energy delivery systems – natural gas and electricity – can provide an optimized approach to energy delivery and reliability
- Residential gas and electric equipment can be complementary, within a smart energy system, to allow energy consumers, energy utility operators, and other stakeholders the option to choose gas or electricity to optimize cost, energy system reliability, and GHG reductions (and avoid expensive investments to meet peak energy demand)
- Pipeline energy storage and delivery systems are important to society in the context of reliably delivering large quantities of energy to homes and businesses – especially during cold weather
- Long-term renewable gas options can produce low GHG methane or hydrogen while helping leverage society's cumulative investment in gaseous pipeline and energy storage assets
- GHG reductions are appropriate to reduce the potential future threats of climate change. Selecting the most feasible and cost-effective approaches should be based on objective economic analyses and metrics such as $/metric ton of GHG reduction
- More information and progress in energy and environmental innovation will evolve over the next 10 to 20 years that help inform and guide future GHG reduction policy direction

The following approach looks to leverage current investments in a cost-effective manner while enabling optionality value to make critical future energy policy choices based on new information that reflects greater certainty and reduced chances of unintended consequences.

Recommended steps and measures for Colorado residential GHG reductions:

- An emphasis on building envelope efficiency improvements that help consumers reduce their annual energy costs, improve indoor comfort, reduce natural gas and electric energy consumption (including peak energy demand), reduce GHG emissions, and improve future optionality for electrification scenarios
- Incentives for cost-effective GHG abatement options such as high-efficiency natural gas equipment (e.g., 95-98% efficient gas furnaces and water heaters) and emerging gas heat pumps (130%+ efficiency) for space and water heating
- Encouraging use of renewable gases using low-carbon sources of methane or hydrogen (including power-to-gas) that lower the carbon intensity of gaseous energy delivered to homes
- Expanded use of hybrid space conditioning systems using high-efficiency gas furnaces or boilers combined with and electric heat pump system as an upgrade to a conventional air conditioning system, working together with smart controls at the home and utility level to optimize cost, energy delivery asset utilization, and GHG reductions.

Summary and Conclusions

There is an active dialogue on policy considerations pertaining to future pathways for reducing GHG emissions. This report focuses on energy use and future GHG reduction pathways for the Colorado residential sector, with quantitative and qualitative information on consumer costs and environmental benefits as well as a review of real-world challenges and potential unintended or unanticipated consequences of residential electrification.

The following is a summary of key findings, conclusions, and recommendations:

- **Natural gas is a cost-effective energy choice for Colorado homeowners.** The residential cost of electricity relative to natural gas has grown in Colorado over the past 15 years. In 2022, Colorado homeowner electricity prices were 3.35 times higher than natural gas on an energy-equivalent basis.
- **Consumer surveys across the US report that most homeowners prefer natural gas** over electricity, particularly for space heating, water heating, and cooking.
- **Electrification of Colorado homes will more than double consumer annual energy costs.** Annual energy costs for Case 1 (natural gas including a 98% efficient gas furnace) are $1,525 million compared to Case 6 (electricity including an HSPF 9 electric heat pump) at $3,239 million. This represents an over $2 billion increase in annual energy bills for current homes using natural gas in the state (112% higher).
- **Electrification of Colorado homes will raise consumer annualized capital costs for energy equipment.** Annualized equipment costs for Case 1 are $942 million and for Case 6 $1,528 million. This represents a $586 million increase in annualized capital costs with electrification (62% higher).
- **Natural gas pathways for GHG reductions have lower consumer and societal costs when measured in $/metric ton of CO_2 reduced.** Using currently available high-efficiency gas equipment results in cost effective GHG reductions ("negative costs" of -$83/metric ton of CO_2). Using renewable gas with existing high-efficiency equipment and next-generation natural gas heat pumps increase total GHG reduction potential, albeit at higher costs ($46 to $209/metric ton of CO_2).
- **Electric GHG abatement costs are higher than the natural gas cases; today's most popular electric heat pumps (HSPF 9.0) correspond to GHG abatement costs ranging between $405 to $552/metric ton of CO_2.** Higher efficiency cold-climate electric heat pumps (e.g., HSPF 13.0) improve GHG abatement costs, dropping to $250 to $307/metric ton CO_2.
- Current all-electric Colorado homes using electric resistance heating or HSPF 9 heat pump with today's power generation mix in the state result in higher CO_2 emission rates than a natural gas home.
- **A significant issue with residential electrification scenarios in cold-climate regions centers on the intense seasonal energy use required for space heating**. Report data highlights the large increase in peak winter electricity use that would occur in the Colorado residential sector with widespread electrification (see Figure 34). The potential power

generation required, the electric infrastructure cost, and the potential reliability implications for consumers and society are significant.

- **There is no evidence wind or solar resources can address prospective seasonal energy-intensive space heating electricity peaks during Colorado winters**. These systems have a meaningful drop in winter output (e.g., during January).
- Using the matching principle and reasonable options at this juncture, **most new winter seasonal peak electricity demand that arises from electric space heating will be met with dispatchable natural gas generation**. Without GHG mitigation for this scenario, potential GHG reductions from electric space heating will be less than anticipated.
- There is no evidence battery energy storage can play a value-added role in meeting elevated long-duration winter electricity demands. Pumped hydro systems have demonstrated seasonal, long-duration storage ability but are not an active area of market expansion. Batteries do provide short-duration value-added services but are not suited to delivering sustained (multiple days to months) energy for space heating demand.
- Using hybrid space heating systems whereby electric heat pumps operate at milder temperatures and natural gas heating systems operate at cold temperatures avoids a host of issues associated the use of only electric heat pumps
- Gas distribution systems have quantifiably higher service reliability and lower outage rates than electric distribution systems. An increasing number of homes in Colorado and nationally are installing natural gas generators to avoid the cost and concerns with grid power interruptions.

The following is a suggested set of energy efficiency and GHG reduction measures that offer a cost-effective multi-faceted pathway – as well as high optionality value and flexibility to respond to future information and innovations:

1. A core focus emphasis on building envelope efficiency improvements that help consumers reduce their annual energy costs, improve indoor comfort, reduce natural gas and electric energy consumption (including peak energy demand), and reduce GHG emissions
2. Incentives for cost-effective GHG abatement options such as high-efficiency natural gas equipment (e.g., 95-98% efficient gas furnaces and water heaters) and gas heat pumps (130%+ efficiency) for space and water heating
3. Encouraging the expanded use of renewable natural gas (RNG) and related pathways for producing and using low-carbon sources of methane or hydrogen (including power-to-gas) that can lower the carbon intensity of gaseous energy delivered to homes
4. Expanded use of hybrid space conditioning systems based on the concept of a high-efficiency natural gas furnace and an electric heat pump system as an upgrade to a conventional whole house air conditioning system, working together with smart controls at the home and utility level to optimize cost, energy delivery system asset utilization, and GHG reductions.

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GTI Energy is an independent, non-profit research & development organization with an 80-year history focused on developing new energy and environmental technologies and providing education and training services for the energy industry and its customers. The following biographies include GTI Energy personnel that contributed directly and indirectly to this report and the underlying tools, data, and analysis used in compiling this publication. This includes a team of engineers, data analysts, and programmers which developed and refined GTI Energy's publicly accessible Energy Planning and Analysis Tool (EPAT) over multiple years. These personnel are part of GTI Energy's building energy efficiency team that is developing and validating a range of technologies and building envelope solutions aimed at reducing the energy and environmental impact of energy use in buildings.

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Appendix A: Energy Planning Analysis Tool (EPAT) Results

Case 1 & 3

Energy Planning Analysis Tool

Building Location and Configuration

State:	Colorado	Population:	5,029,196	Total State Home:	1,910,146

State Residential Electric Houses

Included?	House Type	Number of Units	Average Size (ft2)	Number of People per Unit
x	Moblile	80,000	0	3
x	Single Fam. Detached	1,270,000	1,885	3
x	Single Fam. Attached	135,000	1,185	3
x	Apt. Building 2 to 4 units	85,000	851	3
x	Apt. Building 5+ units	380,000	895	3
	All Residential Electric Houses	1,950,000	1,521	3

State Energy Price *

Electric Price (Cents/kWh)	Natural Gas Price ($/Therm)	Renewable Natural Gas Price ($/Therm)	Propane Price ($/Gal)	Renewable Propane Price ($/Gal)
14.29	1.25	1.60	1.69	3.50

*Note: User-Specified prices

Select Building Configurations

All Houses — Equipment Cost Basis: Retrofit

		Baseline	Alternative
Included?	Application	Equipment and Appliances	Equipment and Appliances
x	Space Heating	Natural Gas, AFUE 98% Electric Consumption: 46 (10^6 kWh) Gas Consumption: 694 (10^6 Therm) Installed Cost: 2,807 $/Unit + 3.86 $/kBtuh Unit Capacity: 80 kBtuh	1.4 AFUE Natural Gas Absorption Heat Pump (Prototype) Electric Consumption: 363 (10^6 kWh) Gas Consumption: 464 (10^6 Therm) Installed Cost: 5,500 $/Unit + 2,750 $/Unit Unit Capacity: 80 kBtuh
	Space Cooling	13 SEER(11.07 EER) A/C Electric Consumption: 673 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 2,588 $/Unit + 42.00 $/kBtu Unit Capacity: 30 kBtuh	13 SEER(11.07 EER) A/C Electric Consumption: 673 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 2,588 $/Unit + 42.00 $/kBtu Unit Capacity: 30 kBtuh
x	HVAC Blower	Electric Consumption: 794 (10^6 kWh)	Electric Consumption: 722 (10^6 kWh)
x	Water Heating	Natural Gas EF 0.95 - Condensing Tankless Electric Consumption: 102 (10^6 kWh) Gas Consumption: 287 (10^6 Therm) Installed Cost: 2,515 $/Unit	Natural Gas EF 1.30 - Absorption Heat Pump Electric Consumption: 764 (10^6 kWh) Gas Consumption: 231 (10^6 Therm) Installed Cost: 2,250 $/Unit

		Unit Capacity: 199 kBtu/h	Unit Capacity: 60 Gal
	Lighting & Plug-in Loads	Electric Consumption: 4,301 (10^6 kWh)	Electric Consumption: 4,301 (10^6 kWh)
x	Cooking Range	Gas Standard Electric Consumption: 60 (10^6 kWh) Gas Consumption: 60 (10^6 Therm) Installed Cost: 823 $/Unit	Gas Standard Electric Consumption: 60 (10^6 kWh) Gas Consumption: 60 (10^6 therm) Installed Cost: 823 $/Unit
	Refrigerator	How many: 1 Electric Consumption: 0 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
	Dishwasher	How many: 1 Electric Consumption: 335 (10^6 kWh)	How many: 1 Electric Consumption: 335 (10^6 kWh)
	Washer	How many: 1 Electric Consumption: 172 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
x	Clothes Dryer	Gas Standard EF 3.84 Electric Consumption: 148 (10^6 kWh) Gas Consumption: 48 (10^6 Therm) Installed Cost: 1,100 $/Unit	Gas Standard EF 3.84 Electric Consumption: 148 (10^6 kWh) Gas Consumption: 48 (10^6 Therm) Installed Cost: 1,100 $/Unit
x	Electrical Service Upgrade	No Electrical Upgrade 0 $/house	New Electrical Panel 2,000 $/house
	Photovoltaic	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System
	Micro CHP	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW

Source Energy Factors And Composite Emission Factors

Geographic Area:	State: Colorado
Plant Level Database:	All Plants
eGrid Database:	2020 data
eGrid Level:	eGRID 2020 data State database
Renewable Conversion Efficiency:	Captured

Source Energy Factors

	Electric	Natural Gas	Renewable Natural Gas	Propane	Renewable Propane
Btu/Btu	1.63	1.09	1.28	1.15	1.27

Composite Emission Factors

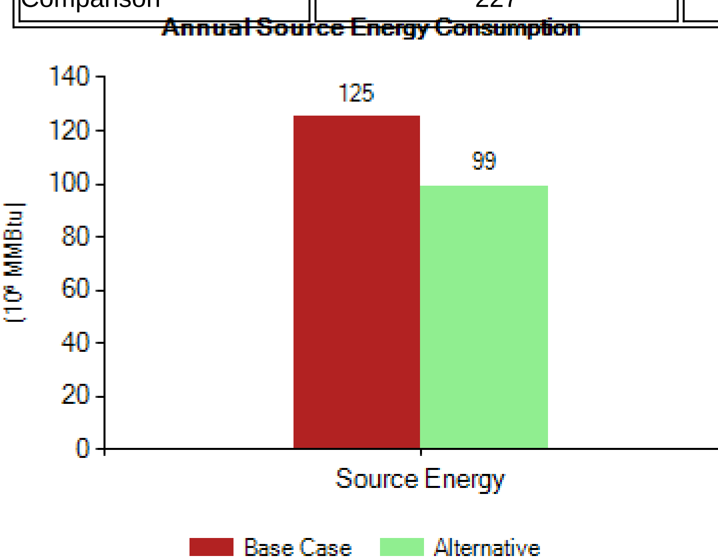
Energy Form	CO2	SO2	NOx	CH4	N2O	CO2e
Electricity (lb/MWh)	365.2	0.073	0.236	1.227	0.0010	399.7
Natural Gas (Building Used, lb/MMBtu)	130.2	0.029	0.172	0.526	0.0030	145.7
Renewable Natural Gas (Building Used, lb/MMBtu)	35.2	0.084	0.281	0.507	0.0030	50.2
Propane (lb/MMBtu)	163.2	0.055	0.225	0.083	0.0110	168.5
Renewable Propane (Building Used, lb/MMBtu)	43.6	0.101	0.281	0.009	0.0110	46.9
Natural Gas (mCHP NG Engine Used, lb/MMBtu)	137.2	0.029	1.892	1.389	0.0000	176.2
Natural Gas (mCHP Fuel Cell Used, lb/MMBtu)	128.9	0.028	0.055	0.524	0.0000	143.7

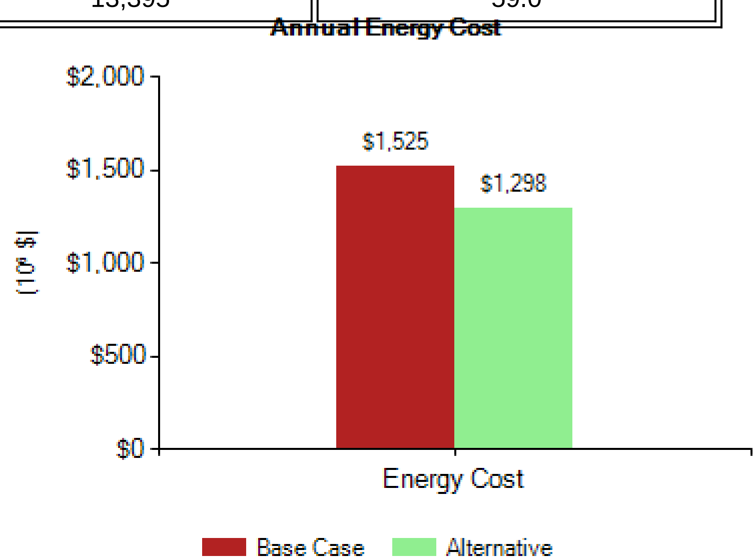
Source Energy and Emission Factors are calculated for CO: Energy conversion efficiency and specific emission data for electricity generated using fossil fuels and biomass are based on eGRID 2020 data State database. Electric distribution efficiency data are based on eGRID 2020 data State database. Electricity generation fuel mix distribution data are based on user custom data All other default data are based on EIA, NREL, and ANL (GREET 1 2012) data sources.

Energy Consumption and Cost

	Energy	Annual Site Consumption	Annual Site Consumption	Annual Source Consumption	Annual Energy Cost	Equipment Invest Cost
			(10^6 MMBtu)	(10^6 MMBtu)	(10^6 $)	(10^6 $)
Baseline	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	1,150 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 1,089 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	3.92 0.00 0.00 108.90 0.00 0.00 0.00 0.00 112.82	6.40 0.00 0.00 118.70 0.00 0.00 0.00 0.00 125.10	164 0 0 1,361 0 0 0 0 1,525	14,730
Alternative	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	2,057 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 803 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	7.02 0.00 0.00 87.53 0.00 0.00 0.00 0.00 87.32	11.44 0.00 0.00 87.53 0.00 0.00 0.00 0.00 98.97	294 0 0 1,004 0 0 0 0 1,298	28,125

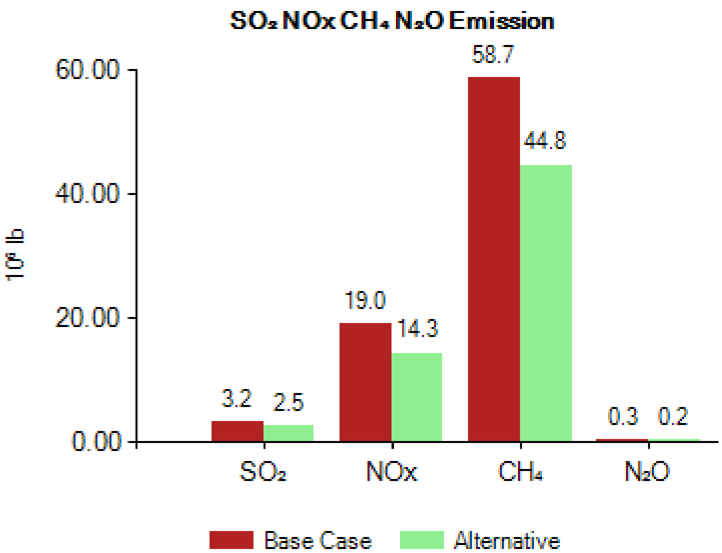
	Energy Cost Savings (Baseline-Alternative)	Equipment Invest Cost (Alternative-Baseline)	Simple Payback (Year)
	(10^6 $)	(10^6 $)	(Year)
Comparison	227	13,395	59.0

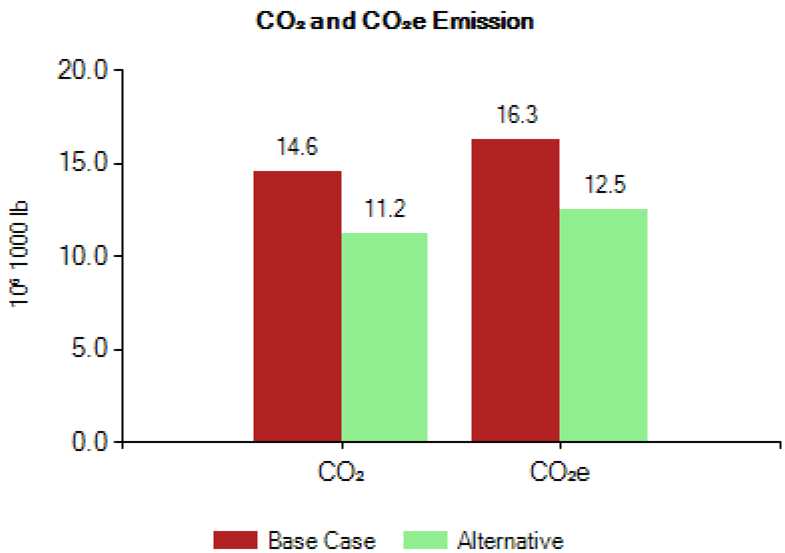




Annual Source Emissions

	SO2 (10^6 lb)	NOx (10^6 lb)	CO2 (10^9 lb)	CH4 (10^6 lb)	N2O (10^6 lb)	CO2e (10^9 lb)
Baseline	3.24	19.00	14.60	58.69	0.33	16.33
Alternative	2.48	14.30	11.21	44.76	0.24	12.52





Case 2 and Case 4

Energy Planning Analysis Tool

Building Location and Configuration

State:	Colorado	Population:	5,029,196	Total State Home:	1,910,146

State Residential Electric Houses

Included?	House Type	Number of Units	Average Size (ft2)	Number of People per Unit
x	Moblile	80,000	0	3
x	Single Fam. Detached	1,270,000	1,885	3
x	Single Fam. Attached	135,000	1,185	3
x	Apt. Building 2 to 4 units	85,000	851	3
x	Apt. Building 5+ units	380,000	895	3
	All Residential Electric Houses	1,950,000	1,521	3

State Energy Price *

Electric Price (Cents/kWh)	Natural Gas Price ($/Therm)	Renewable Natural Gas Price ($/Therm)	Propane Price ($/Gal)	Renewable Propane Price ($/Gal)
14.29	1.25	1.80	1.69	3.50

*Note: User-Specified prices

Select Building Configurations

All Houses Equipment Cost Basis: Retrofit

		Baseline	Alternative
Included?	Application	Equipment and Appliances	Equipment and Appliances
x	Space Heating	Natural Gas, AFUE 98% Electric Consumption: 46 (10^6 kWh) Gas Consumption: 694 (10^6 Therm) Installed Cost: 2,807 $/Unit + 3.86 $/kBtuh Unit Capacity: 80 kBtuh	1.4 AFUE Natural Gas Absorption Heat Pump (Prototype) Electric Consumption: 363 (10^6 kWh) Gas Consumption: 464 (10^6 Therm) Installed Cost: 5,500 $/Unit + 2,750 $/Unit Unit Capacity: 80 kBtuh
x	Space Cooling	14 SEER(12.06 EER) A/C Electric Consumption: 618 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 2,711 $/Unit + 42.00 $/kBtu Unit Capacity: 30 kBtuh	13 SEER(11.07 EER) A/C Electric Consumption: 673 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 2,588 $/Unit + 42.00 $/kBtu Unit Capacity: 30 kBtuh
x	HVAC Blower	Electric Consumption: 794 (10^6 kWh)	Electric Consumption: 722 (10^6 kWh)
x	Water Heating	Natural Gas EF 0.95 - Condensing Tankless Electric Consumption: 102 (10^6 kWh) Gas Consumption: 287 (10^6 Therm) Installed Cost: 2,515 $/Unit	Natural Gas EF 1.30 - Absorption Heat Pump Electric Consumption: 764 (10^6 kWh) Gas Consumption: 231 (10^6 Therm) Installed Cost: 2,250 $/Unit

		Unit Capacity: 199 kBtu/h	Unit Capacity: 60 Gal
	Lighting & Plug-in Loads	Electric Consumption: 4,301 (10^6 kWh)	Electric Consumption: 4,301 (10^6 kWh)
x	Cooking Range	Gas Standard Electric Consumption: 60 (10^6 kWh) Gas Consumption: 60 (10^6 Therm) Installed Cost: 823 $/Unit	Gas Standard Electric Consumption: 60 (10^6 kWh) Gas Consumption: 60 (10^6 therm) Installed Cost: 823 $/Unit
	Refrigerator	How many: 1 Electric Consumption: 0 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
	Dishwasher	How many: 1 Electric Consumption: 335 (10^6 kWh)	How many: 1 Electric Consumption: 335 (10^6 kWh)
	Washer	How many: 1 Electric Consumption: 172 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
x	Clothes Dryer	Gas Standard EF 3.84 Electric Consumption: 148 (10^6 kWh) Gas Consumption: 48 (10^6 Therm) Installed Cost: 1,100 $/Unit	Gas Standard EF 3.84 Electric Consumption: 148 (10^6 kWh) Gas Consumption: 48 (10^6 Therm) Installed Cost: 1,100 $/Unit
	Electrical Service Upgrade	No Electrical Upgrade 0 $/house	No Electrical Upgrade 0 $/house
	Photovoltaic	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System
	Micro CHP	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW

Source Energy Factors And Composite Emission Factors

Geographic Area:	State: Colorado
Plant Level Database:	All Plants
eGrid Database:	2020 data
eGrid Level:	eGRID 2020 data State database
Renewable Conversion Efficiency:	Captured

Source Energy Factors

	Electric	Natural Gas	Renewable Natural Gas	Propane	Renewable Propane
Btu/Btu	1.63	1.09	1.28	1.15	1.27

Composite Emission Factors

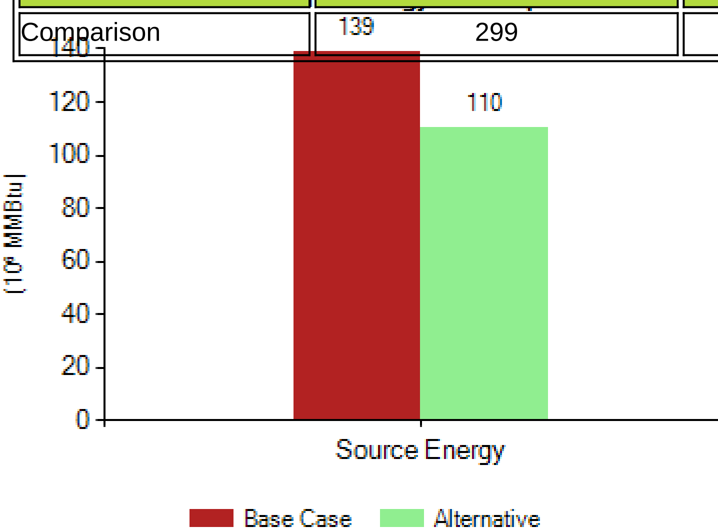
Energy Form	CO2	SO2	NOx	CH4	N2O	CO2e
Electricity (lb/MWh)	365.2	0.073	0.236	1.227	0.0010	399.7
Natural Gas (Building Used, lb/MMBtu)	130.2	0.029	0.172	0.526	0.0030	145.7
Renewable Natural Gas (Building Used, lb/MMBtu)	35.2	0.084	0.281	0.507	0.0030	50.2
Propane (lb/MMBtu)	163.2	0.055	0.225	0.083	0.0110	168.5
Renewable Propane (Building Used, lb/MMBtu)	43.6	0.101	0.281	0.009	0.0110	46.9
Natural Gas (mCHP NG Engine Used, lb/MMBtu)	137.2	0.029	1.892	1.389	0.0000	176.2
Natural Gas (mCHP Fuel Cell Used, lb/MMBtu)	128.9	0.028	0.055	0.524	0.0000	143.7

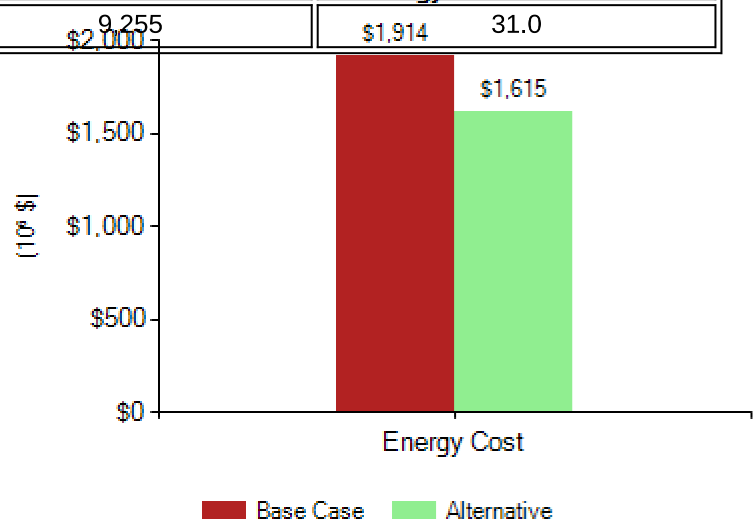
Source Energy and Emission Factors are calculated for CO: Energy conversion efficiency and specific emission data for electricity generated using fossil fuels and biomass are based on eGRID 2020 data State database. Electric distribution efficiency data are based on eGRID 2020 data State database. Electricity generation fuel mix distribution data are based on user custom data All other default data are based on EIA, NREL, and ANL (GREET 1 2012) data sources.

Energy Consumption and Cost

	Energy	Annual Site Consumption	Annual Site Consumption	Annual Source Consumption	Annual Energy Cost	Equipment Invest Cost
			(10^6 MMBtu)	(10^6 MMBtu)	(10^6 $)	(10^6 $)
Baseline	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	1,768 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 545 (10^6 Therm) 0 (10^6 Therm) 545 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	6.03 0.00 0.00 54.45 0.00 54.45 0.00 0.00 114.93	9.83 0.00 0.00 59.35 0.00 69.70 0.00 0.00 138.88	253 0 0 681 0 980 0 0 1,914	22,473
Alternative	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	2,730 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 402 (10^6 Therm) 0 (10^6 Therm) 402 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	9.31 0.00 0.00 43.76 0.00 43.76 0.00 0.00 89.61	15.18 0.00 0.00 43.76 0.00 43.76 0.00 0.00 110.34	390 0 0 502 0 723 0 0 1,615	31,728

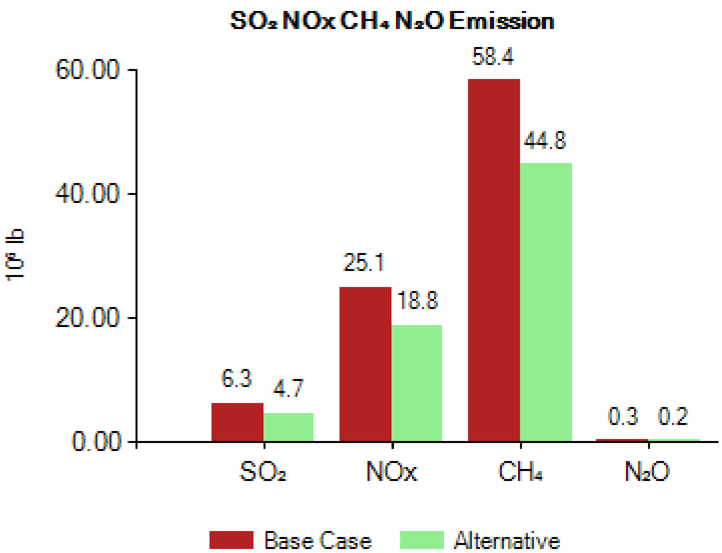
	Energy Cost Savings (Baseline-Alternative)	Equipment Invest Cost (Alternative-Baseline)	Simple Payback (Year)
	(10^6 $)	(10^6 $)	(Year)
Comparison	299	9,255	31.0

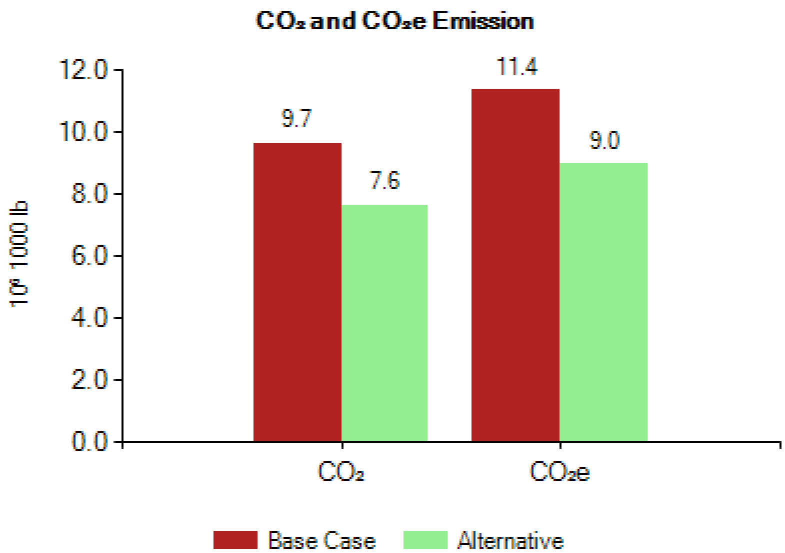




Annual Source Emissions

	SO2 (10^6 lb)	NOx (10^6 lb)	CO2 (10^9 lb)	CH4 (10^6 lb)	N2O (10^6 lb)	CO2e (10^9 lb)
Baseline	6.28	25.08	9.65	58.42	0.33	11.37
Alternative	4.74	18.83	7.64	44.82	0.24	8.96





Gas Baseline and Case 5

Energy Planning Analysis Tool

Building Location and Configuration

State:	Colorado	Population:	5,029,196	Total State Home:	1,910,146

State Residential Electric Houses

Included?	House Type	Number of Units	Average Size (ft2)	Number of People per Unit
x	Moblile	80,000	0	3
x	Single Fam. Detached	1,270,000	1,885	3
x	Single Fam. Attached	135,000	1,185	3
x	Apt. Building 2 to 4 units	85,000	851	3
x	Apt. Building 5+ units	380,000	895	3
	All Residential Electric Houses	1,950,000	1,521	3

State Energy Price *

Electric Price (Cents/kWh)	Natural Gas Price ($/Therm)	Renewable Natural Gas Price ($/Therm)	Propane Price ($/Gal)	Renewable Propane Price ($/Gal)
14.29	1.25	1.60	1.69	3.50

*Note: User-Specified prices

Select Building Configurations

All Houses Equipment Cost Basis: Retrofit

		Baseline	Alternative
Included?	Application	Equipment and Appliances	Equipment and Appliances
x	Space Heating	Natural Gas, AFUE 80% Electric Consumption: 76 (10^6 kWh) Gas Consumption: 850 (10^6 Therm) Installed Cost: 1,881 $/Unit + 2.70 $/kBtuh Unit Capacity: 100 kBtuh	Electric, Efficiency 100% Electric Consumption: 18,847 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 450 $/Unit + 10.00 $/kBtuh Unit Capacity: 80 kBtuh
	Space Cooling	13 SEER(11.07 EER) A/C Electric Consumption: 673 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 2,588 $/Unit + 42.00 $/kBtu Unit Capacity: 30 kBtuh	13 SEER(11.07 EER) A/C Electric Consumption: 673 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 2,588 $/Unit + 42.00 $/kBtu Unit Capacity: 30 kBtuh
x	HVAC Blower	Electric Consumption: 722 (10^6 kWh)	Electric Consumption: 722 (10^6 kWh)
x	Water Heating	Natural Gas EF 0.62 - Min. Eff. Storage Electric Consumption: 0 (10^6 kWh) Gas Consumption: 444 (10^6 Therm) Installed Cost: 728 $/Unit + 10.00 $/gal Unit Capacity: 60 Gal	Electric Resistance EF, 0.95 Electric Consumption: 8,502 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 591 $/Unit + 3.50 $/gal Unit Capacity: 60 Gal

	Lighting & Plug-in Loads	Electric Consumption: 4,301 (10^6 kWh)	Electric Consumption: 4,301 (10^6 kWh)
x	Cooking Range	Gas Standard Electric Consumption: 60 (10^6 kWh) Gas Consumption: 60 (10^6 Therm) Installed Cost: 823 $/Unit	Electric Standard EF 0.74 Electric Consumption: 874 (10^6 kWh) Gas Consumption: 0 (10^6 therm) Installed Cost: 923 $/Unit
	Refrigerator	How many: 1 Electric Consumption: 0 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
	Dishwasher	How many: 1 Electric Consumption: 335 (10^6 kWh)	How many: 1 Electric Consumption: 335 (10^6 kWh)
	Washer	How many: 1 Electric Consumption: 172 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
x	Clothes Dryer	Gas Standard EF 2.75 Electric Consumption: 148 (10^6 kWh) Gas Consumption: 68 (10^6 Therm) Installed Cost: 1,000 $/Unit	Electric Standard EF 3.1 Electric Consumption: 1,893 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 760 $/Unit
x	Electrical Service Upgrade	No Electrical Upgrade 0 $/house	New Electrical Panel 2,000 $/house
	Photovoltaic	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System
	Micro CHP	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW

Source Energy Factors And Composite Emission Factors

Geographic Area:	State: Colorado
Plant Level Database:	All Plants
eGrid Database:	2020 data
eGrid Level:	eGRID 2020 data State database
Renewable Conversion Efficiency:	Captured

Source Energy Factors

	Electric	Natural Gas	Renewable Natural Gas	Propane	Renewable Propane
Btu/Btu	2.49	1.09	1.28	1.15	1.27

Composite Emission Factors

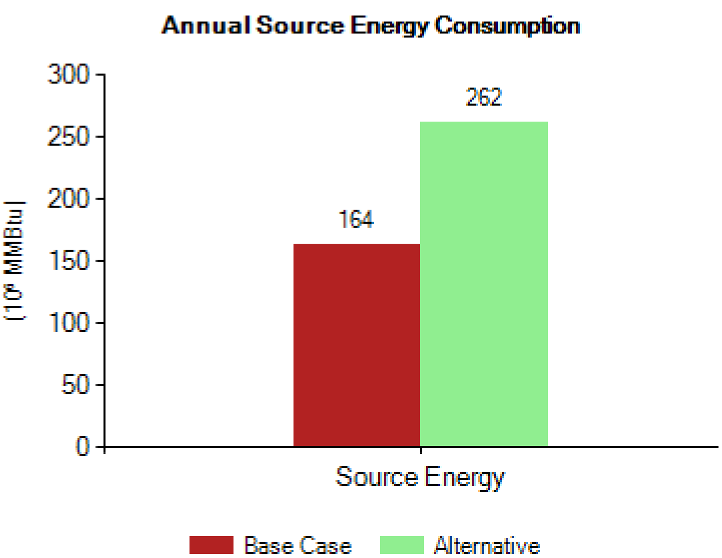
Energy Form	CO2	SO2	NOx	CH4	N2O	CO2e
Electricity (lb/MWh)	1,232.6	0.470	0.857	2.350	0.0140	1,302.0
Natural Gas (Building Used, lb/MMBtu)	130.2	0.029	0.172	0.526	0.0030	145.7
Renewable Natural Gas (Building Used, lb/MMBtu)	35.2	0.084	0.281	0.507	0.0030	50.2
Propane (lb/MMBtu)	163.2	0.055	0.225	0.083	0.0110	168.5
Renewable Propane (Building Used, lb/MMBtu)	43.6	0.101	0.281	0.009	0.0110	46.9
Natural Gas (mCHP NG Engine Used, lb/MMBtu)	137.2	0.029	1.892	1.389	0.0000	176.2
Natural Gas (mCHP Fuel Cell Used, lb/MMBtu)	128.9	0.028	0.055	0.524	0.0000	143.7

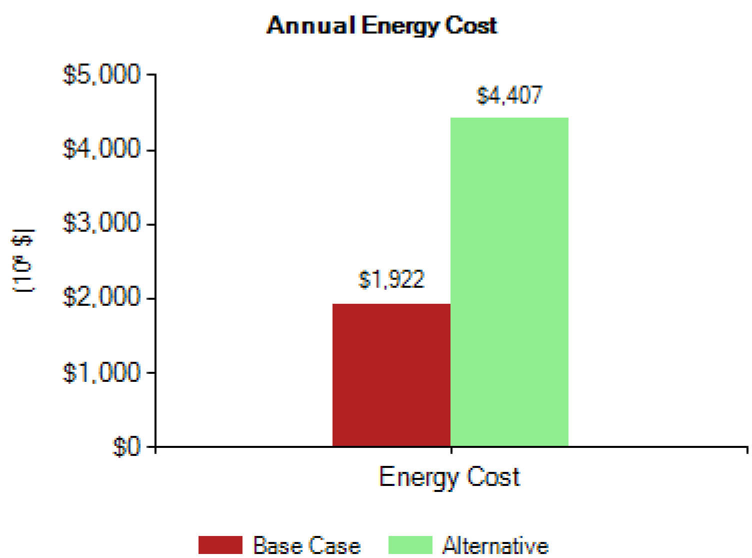
Source Energy and Emission Factors are calculated for CO: Energy conversion efficiency and specific emission data for electricity generated using fossil fuels and biomass are based on eGRID 2020 data State database. Electric distribution efficiency data are based on eGRID 2020 data State database. Electricity generation fuel mix distribution data are based on user custom data All other default data are based on EIA, NREL, and ANL (GREET 1 2012) data sources.

Energy Consumption and Cost

	Energy	Annual Site Consumption	Annual Site Consumption	Annual Source Consumption	Annual Energy Cost	Equipment Invest Cost
			(10^6 MMBtu)	(10^6 MMBtu)	(10^6 $)	(10^6 $)
Baseline	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	1,006 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 1,422 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	3.43 0.00 0.00 142.20 0.00 0.00 0.00 0.00 145.63	8.55 0.00 0.00 155.00 0.00 0.00 0.00 0.00 163.54	144 0 0 1,778 0 0 0 0 1,922	10,339
Alternative	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	30,838 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	105.22 0.00 0.00 0.00 0.00 0.00 0.00 0.00 105.22	262.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 262.00	4,407 0 0 0 0 0 0 0 4,407	11,181

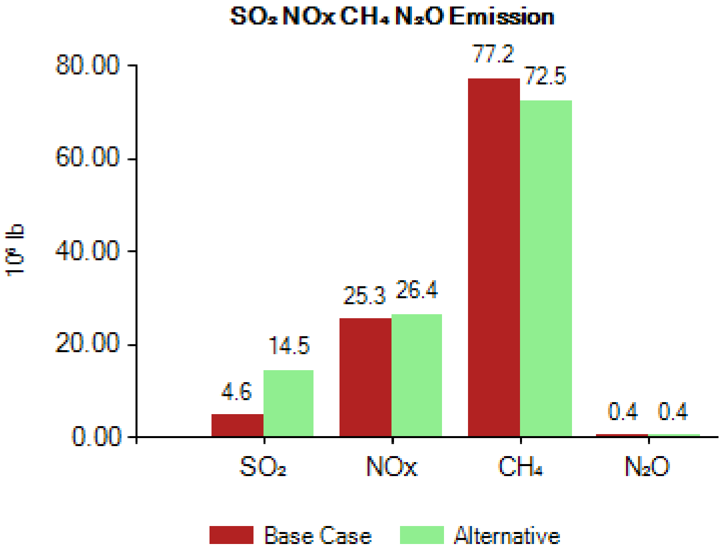
	Energy Cost Savings (Baseline-Alternative)	Equipment Invest Cost (Alternative-Baseline)	Simple Payback (Year)
	(10^6 $)	(10^6 $)	(Year)
Comparison	-2,485	842	Never

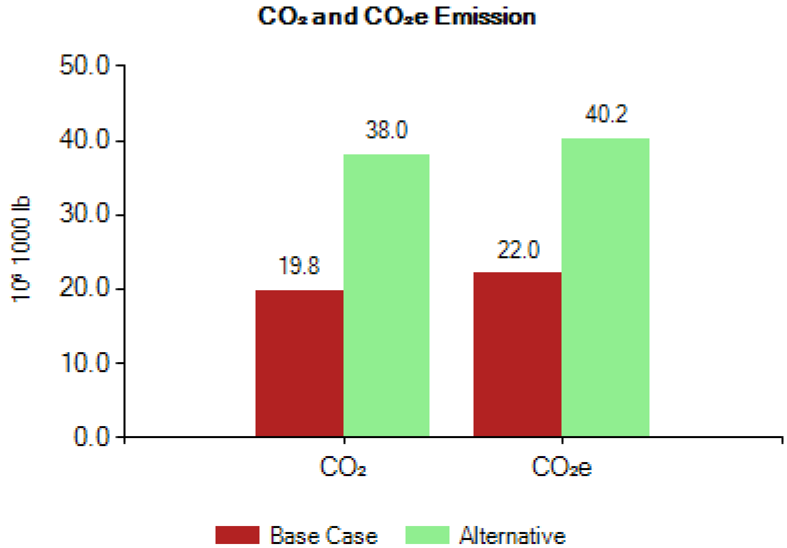




Annual Source Emissions

	SO2 (10^6 lb)	NOx (10^6 lb)	CO2 (10^9 lb)	CH4 (10^6 lb)	N2O (10^6 lb)	CO2e (10^9 lb)
Baseline	4.60	25.32	19.75	77.16	0.44	22.03
Alternative	14.49	26.43	38.01	72.47	0.43	40.15





Cases 6 & 7

Energy Planning Analysis Tool

GTI ENERGY

Building Location and Configuration

State:	Colorado	Population:	5,029,196	Total State Home:	1,910,146

State Residential Electric Houses

Included?	House Type	Number of Units	Average Size (ft2)	Number of People per Unit
x	Moblile	80,000	0	3
x	Single Fam. Detached	1,270,000	1,885	3
x	Single Fam. Attached	135,000	1,185	3
x	Apt. Building 2 to 4 units	85,000	851	3
x	Apt. Building 5+ units	380,000	895	3
	All Residential Electric Houses	1,950,000	1,521	3

State Energy Price *

Electric Price (Cents/kWh)	Natural Gas Price ($/Therm)	Renewable Natural Gas Price ($/Therm)	Propane Price ($/Gal)	Renewable Propane Price ($/Gal)
14.29	1.25	1.60	1.69	3.50

*Note: User-Specified prices

Select Building Configurations

All Houses — Equipment Cost Basis: Retrofit

		Baseline	Alternative
Included?	Application	Equipment and Appliances	Equipment and Appliances
x	Space Heating	16 SEER /9.0 HSPF Heat Pump Electric Consumption: 10,674 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 3,873 $/Unit +42.00 $/kBtuh Unit Capacity: 90 kBtuh	20.5 SEER /13 HSPF Heat Pump Electric Consumption: 8,886 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 4,745 $/Unit +42.00 $/kBtuh Unit Capacity: 100 kBtuh
	Space Cooling	16 SEER /9.0 HSPF Heat Pump Electric Consumption: 532 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 0 $/Unit +0.00 $/kBtu Unit Capacity: 30 kBtuh	20.5 SEER /13 HSPF Heat Pump Electric Consumption: 406 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 0 $/Unit +0.00 $/kBtu Unit Capacity: 30 kBtuh
x	HVAC Blower	Electric Consumption: 722 (10^6 kWh)	Electric Consumption: 722 (10^6 kWh)
x	Water Heating	Electric Resistance EF, 0.95 Electric Consumption: 8,502 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 591 $/Unit +3.50 $/gal Unit Capacity: 60 Gal	Electric Heat Pump EF, 2.00 Electric Consumption: 4,038 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 1,900 $/Unit Unit Capacity: 50 Gal

	Lighting & Plug-in Loads	Electric Consumption: 4,301 (10^6 kWh)	Electric Consumption: 4,301 (10^6 kWh)
x	Cooking Range	Electric Standard EF 0.74 Electric Consumption: 874 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 923 $/Unit	Electric Induction EF 0.84 Electric Consumption: 770 (10^6 kWh) Gas Consumption: 0 (10^6 therm) Installed Cost: 1,879 $/Unit
	Refrigerator	How many: 1 Electric Consumption: 0 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
	Dishwasher	How many: 1 Electric Consumption: 335 (10^6 kWh)	How many: 1 Electric Consumption: 335 (10^6 kWh)
	Washer	How many: 1 Electric Consumption: 172 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
x	Clothes Dryer	Electric Standard EF 3.1 Electric Consumption: 1,893 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 760 $/Unit	Electric Standard EF 3.93 Electric Consumption: 1,494 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 930 $/Unit
x	Electrical Service Upgrade	New Electrical Panel 2,000 $/house	New Electrical Panel 2,000 $/house
	Photovoltaic	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System
	Micro CHP	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW

Source Energy Factors And Composite Emission Factors

Geographic Area:	State: Colorado
Plant Level Database:	All Plants
eGrid Database:	2020 data
eGrid Level:	eGRID 2020 data State database
Renewable Conversion Efficiency:	Captured

Source Energy Factors

	Electric	Natural Gas	Renewable Natural Gas	Propane	Renewable Propane
Btu/Btu	2.49	1.09	1.28	1.15	1.27

Composite Emission Factors

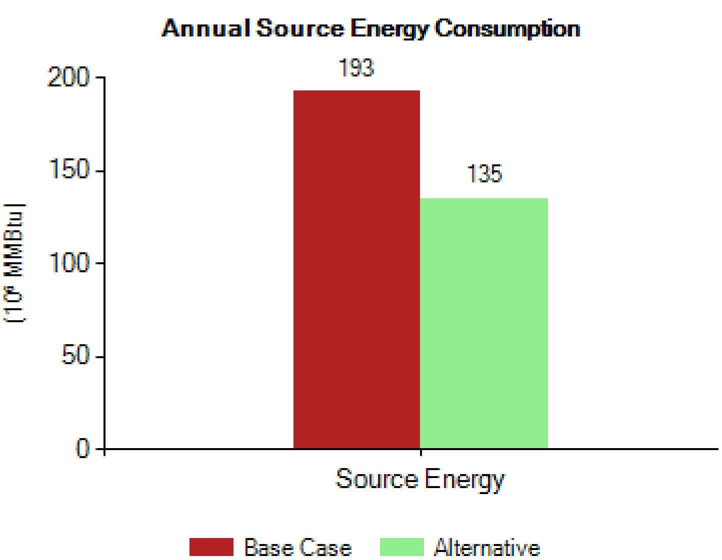
Energy Form	CO2	SO2	NOx	CH4	N2O	CO2e
Electricity (lb/MWh)	1,232.6	0.470	0.857	2.350	0.0140	1,302.0
Natural Gas (Building Used, lb/MMBtu)	130.2	0.029	0.172	0.526	0.0030	145.7
Renewable Natural Gas (Building Used, lb/MMBtu)	35.2	0.084	0.281	0.507	0.0030	50.2
Propane (lb/MMBtu)	163.2	0.055	0.225	0.083	0.0110	168.5
Renewable Propane (Building Used, lb/MMBtu)	43.6	0.101	0.281	0.009	0.0110	46.9
Natural Gas (mCHP NG Engine Used, lb/MMBtu)	137.2	0.029	1.892	1.389	0.0000	176.2
Natural Gas (mCHP Fuel Cell Used, lb/MMBtu)	128.9	0.028	0.055	0.524	0.0000	143.7

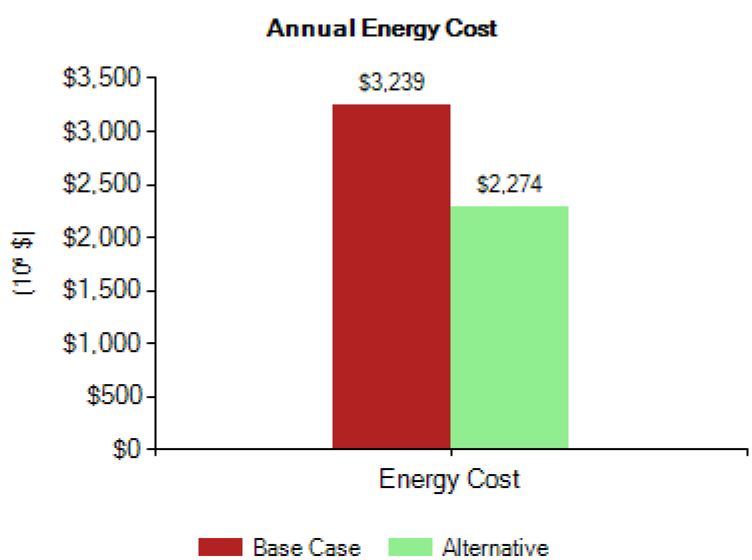
Source Energy and Emission Factors are calculated for CO: Energy conversion efficiency and specific emission data for electricity generated using fossil fuels and biomass are based on eGRID 2020 data State database. Electric distribution efficiency data are based on eGRID 2020 data State database. Electricity generation fuel mix distribution data are based on user custom data All other default data are based on EIA, NREL, and ANL (GREET 1 2012) data sources.

Energy Consumption and Cost

	Energy	Annual Site Consumption	Annual Site Consumption	Annual Source Consumption	Annual Energy Cost	Equipment Invest Cost
			(10^6 MMBtu)	(10^6 MMBtu)	(10^6 $)	(10^6 $)
Baseline	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	22,665 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	77.33 0.00 0.00 0.00 0.00 0.00 0.00 0.00 77.33	192.56 0.00 0.00 0.00 0.00 0.00 0.00 0.00 192.56	3,239 0 0 0 0 0 0 0 3,239	23,667
Alternative	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	15,910 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	54.28 0.00 0.00 0.00 0.00 0.00 0.00 0.00 54.28	135.17 0.00 0.00 0.00 0.00 0.00 0.00 0.00 135.17	2,274 0 0 0 0 0 0 0 2,274	30,525

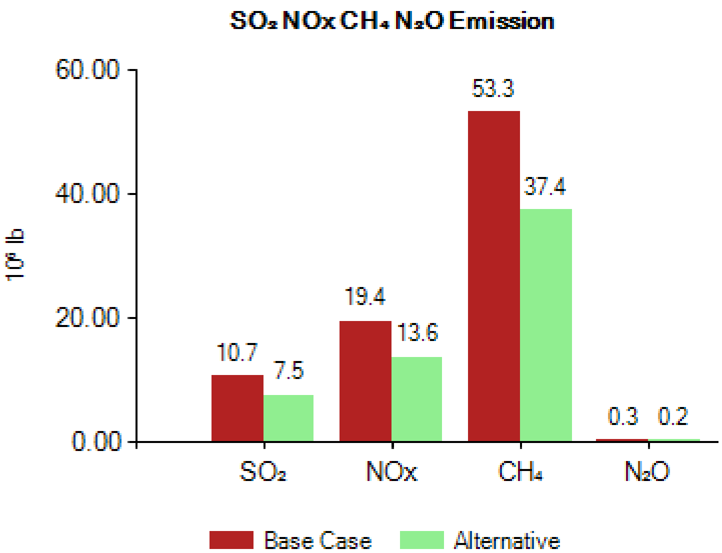
	Energy Cost Savings (Baseline-Alternative)	Equipment Invest Cost (Alternative-Baseline)	Simple Payback (Year)
	(10^6 $)	(10^6 $)	(Year)
Comparison	965	6,858	7.1

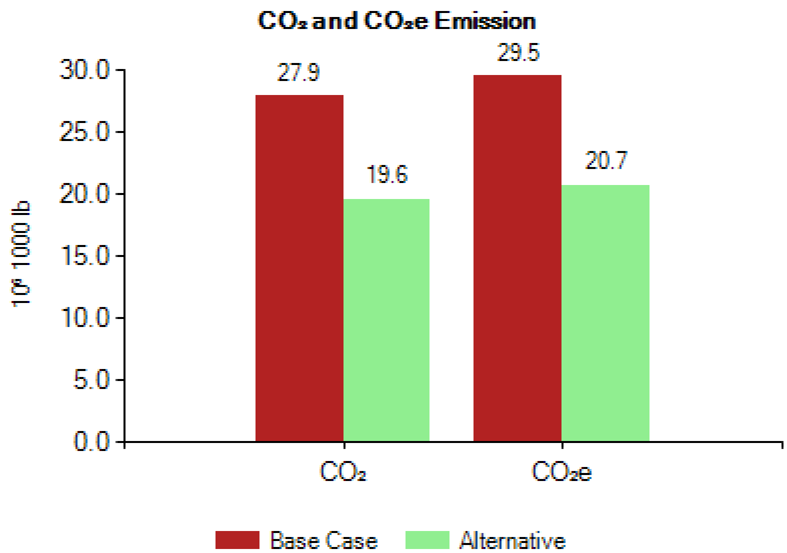




Annual Source Emissions

	SO2 (10^6 lb)	NOx (10^6 lb)	CO2 (10^9 lb)	CH4 (10^6 lb)	N2O (10^6 lb)	CO2e (10^9 lb)
Baseline	10.65	19.42	27.94	53.26	0.32	29.51
Alternative	7.48	13.63	19.61	37.39	0.22	20.71





Energy Planning Analysis Tool

Building Location and Configuration

State:	Colorado	Population:	5,029,196	Total State Home:	1,910,146

State Residential Electric Houses

Included?	House Type	Number of Units	Average Size (ft2)	Number of People per Unit
x	Moblile	80,000	0	3
x	Single Fam. Detached	1,270,000	1,885	3
x	Single Fam. Attached	135,000	1,185	3
x	Apt. Building 2 to 4 units	85,000	851	3
x	Apt. Building 5+ units	380,000	895	3
	All Residential Electric Houses	1,950,000	1,521	3

State Energy Price *

Electric Price (Cents/kWh)	Natural Gas Price ($/Therm)	Renewable Natural Gas Price ($/Therm)	Propane Price ($/Gal)	Renewable Propane Price ($/Gal)
14.29	1.25	1.60	1.69	3.50

*Note: User-Specified prices

Select Building Configurations

All Houses

Equipment Cost Basis: Retrofit

		Baseline	Alternative
Included?	Application	Equipment and Appliances	Equipment and Appliances
x	Space Heating	Natural Gas, AFUE 80% Electric Consumption: 76 (10^6 kWh) Gas Consumption: 850 (10^6 Therm) Installed Cost: 1,881 $/Unit + 2.70 $/kBtuh Unit Capacity: 100 kBtuh	Electric, Efficiency 100% Electric Consumption: 18,847 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 450 $/Unit + 10.00 $/kBtuh Unit Capacity: 80 kBtuh
	Space Cooling	13 SEER(11.07 EER) A/C Electric Consumption: 673 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 2,588 $/Unit + 42.00 $/kBtu Unit Capacity: 30 kBtuh	13 SEER(11.07 EER) A/C Electric Consumption: 673 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 2,588 $/Unit + 42.00 $/kBtu Unit Capacity: 30 kBtuh
x	HVAC Blower	Electric Consumption: 722 (10^6 kWh)	Electric Consumption: 722 (10^6 kWh)
x	Water Heating	Natural Gas EF 0.62 - Min. Eff. Storage Electric Consumption: 0 (10^6 kWh) Gas Consumption: 444 (10^6 Therm) Installed Cost: 728 $/Unit + 10.00 $/gal Unit Capacity: 60 Gal	Electric Resistance EF, 0.95 Electric Consumption: 8,502 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 591 $/Unit + 3.50 $/gal Unit Capacity: 60 Gal

	Lighting & Plug-in Loads	Electric Consumption: 4,301 (10^6 kWh)	Electric Consumption: 4,301 (10^6 kWh)
x	Cooking Range	Gas Standard Electric Consumption: 60 (10^6 kWh) Gas Consumption: 60 (10^6 Therm) Installed Cost: 823 $/Unit	Electric Standard EF 0.74 Electric Consumption: 874 (10^6 kWh) Gas Consumption: 0 (10^6 therm) Installed Cost: 923 $/Unit
	Refrigerator	How many: 1 Electric Consumption: 0 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
	Dishwasher	How many: 1 Electric Consumption: 335 (10^6 kWh)	How many: 1 Electric Consumption: 335 (10^6 kWh)
	Washer	How many: 1 Electric Consumption: 172 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
x	Clothes Dryer	Gas Standard EF 2.75 Electric Consumption: 148 (10^6 kWh) Gas Consumption: 68 (10^6 Therm) Installed Cost: 1,000 $/Unit	Electric Standard EF 3.1 Electric Consumption: 1,893 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 760 $/Unit
x	Electrical Service Upgrade	No Electrical Upgrade 0 $/house	New Electrical Panel 2,000 $/house
	Photovoltaic	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System
	Micro CHP	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit +0 $/kW	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit +0 $/kW

Source Energy Factors And Composite Emission Factors

Geographic Area:	State: Colorado
Plant Level Database:	All Plants
eGrid Database:	2020 data
eGrid Level:	eGRID 2020 data State database
Renewable Conversion Efficiency:	Captured

Source Energy Factors

	Electric	Natural Gas	Renewable Natural Gas	Propane	Renewable Propane
Btu/Btu	1.63	1.09	1.28	1.15	1.27

Composite Emission Factors

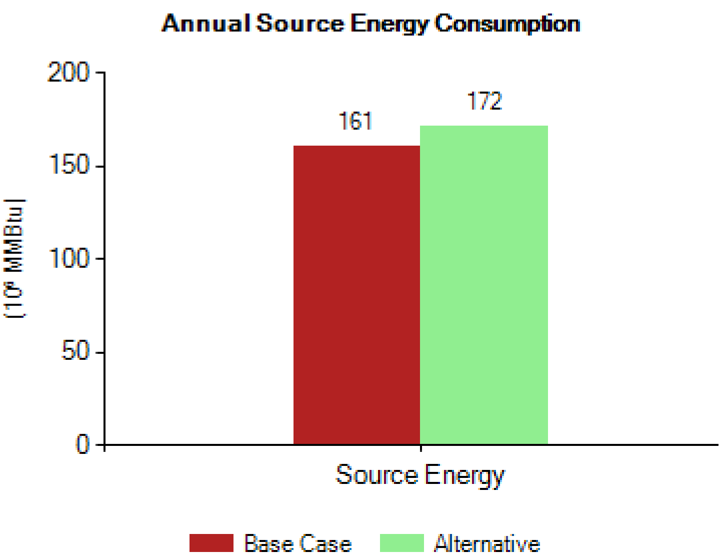
Energy Form	CO2	SO2	NOx	CH4	N2O	CO2e
Electricity (lb/MWh)	365.2	0.073	0.236	1.227	0.0010	399.7
Natural Gas (Building Used, lb/MMBtu)	130.2	0.029	0.172	0.526	0.0030	145.7
Renewable Natural Gas (Building Used, lb/MMBtu)	35.2	0.084	0.281	0.507	0.0030	50.2
Propane (lb/MMBtu)	163.2	0.055	0.225	0.083	0.0110	168.5
Renewable Propane (Building Used, lb/MMBtu)	43.6	0.101	0.281	0.009	0.0110	46.9
Natural Gas (mCHP NG Engine Used, lb/MMBtu)	137.2	0.029	1.892	1.389	0.0000	176.2
Natural Gas (mCHP Fuel Cell Used, lb/MMBtu)	128.9	0.028	0.055	0.524	0.0000	143.7

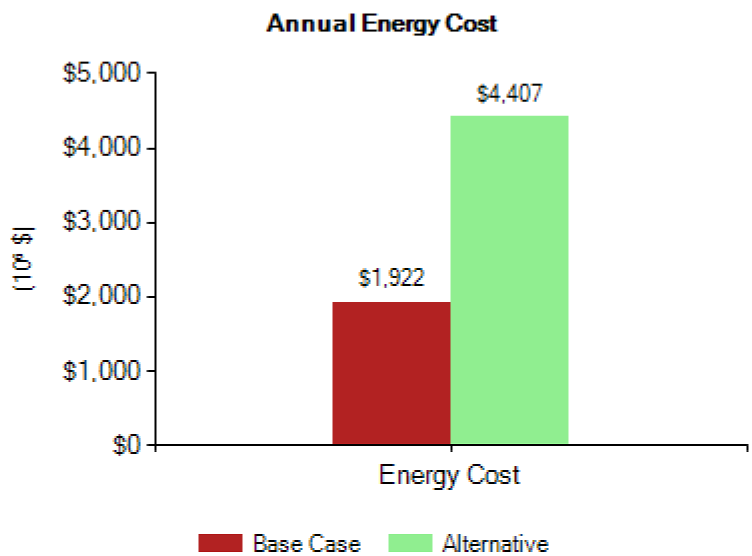
Source Energy and Emission Factors are calculated for CO: Energy conversion efficiency and specific emission data for electricity generated using fossil fuels and biomass are based on eGRID 2020 data State database. Electric distribution efficiency data are based on eGRID 2020 data State database. Electricity generation fuel mix distribution data are based on user custom data All other default data are based on EIA, NREL, and ANL (GREET 1 2012) data sources.

Energy Consumption and Cost

	Energy	Annual Site Consumption	Annual Site Consumption	Annual Source Consumption	Annual Energy Cost	Equipment Invest Cost
			(10^6 MMBtu)	(10^6 MMBtu)	(10^6 $)	(10^6 $)
Baseline	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	1,006 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 1,422 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	3.43 0.00 0.00 142.20 0.00 0.00 0.00 0.00 145.63	5.59 0.00 0.00 155.00 0.00 0.00 0.00 0.00 160.59	144 0 0 1,778 0 0 0 0 1,922	10,339
Alternative	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	30,838 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	105.22 0.00 0.00 0.00 0.00 0.00 0.00 0.00 105.22	171.51 0.00 0.00 0.00 0.00 0.00 0.00 0.00 171.51	4,407 0 0 0 0 0 0 0 4,407	11,181

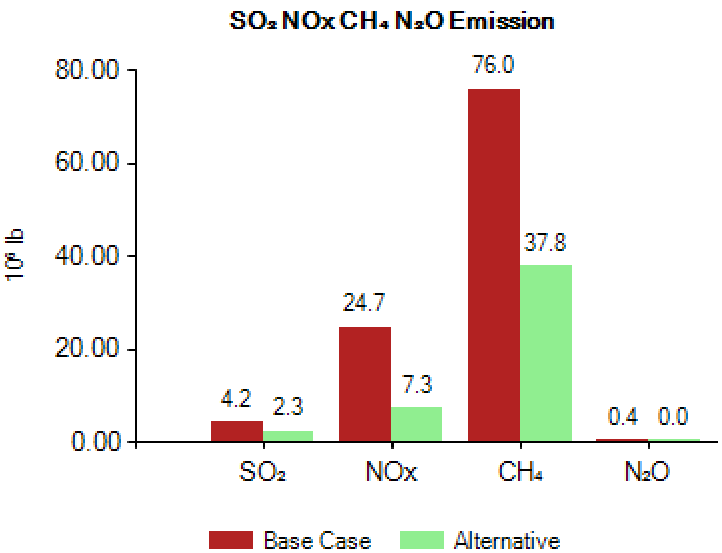
	Energy Cost Savings (Baseline-Alternative)	Equipment Invest Cost (Alternative-Baseline)	Simple Payback (Year)
	(10^6 $)	(10^6 $)	(Year)
Comparison	-2,485	842	Never

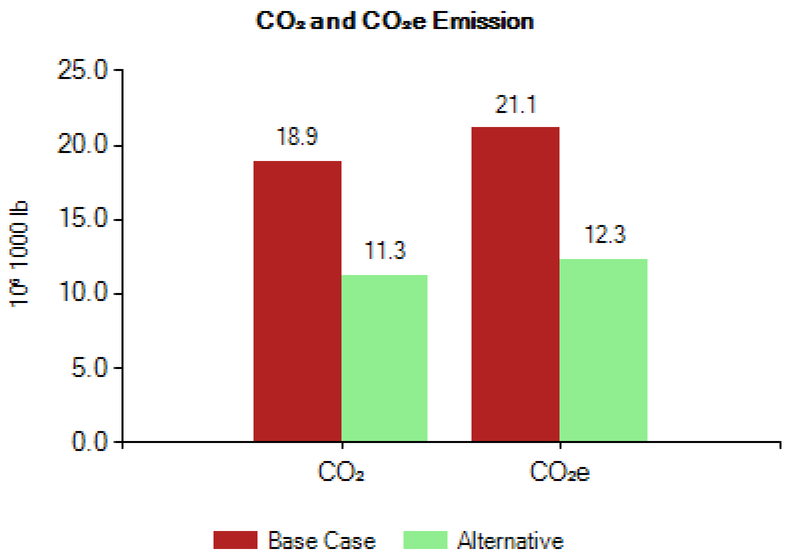




Annual Source Emissions

	SO2 (10^6 lb)	NOx (10^6 lb)	CO2 (10^9 lb)	CH4 (10^6 lb)	N2O (10^6 lb)	CO2e (10^9 lb)
Baseline	4.20	24.70	18.88	76.03	0.43	21.12
Alternative	2.25	7.28	11.26	37.84	0.03	12.33





Case 9 & 10

Energy Planning Analysis Tool

Building Location and Configuration

State:	Colorado	Population:	5,029,196	Total State Home:	1,910,146

State Residential Electric Houses

Included?	House Type	Number of Units	Average Size (ft2)	Number of People per Unit
x	Moblile	80,000	0	3
x	Single Fam. Detached	1,270,000	1,885	3
x	Single Fam. Attached	135,000	1,185	3
x	Apt. Building 2 to 4 units	85,000	851	3
x	Apt. Building 5+ units	380,000	895	3
	All Residential Electric Houses	1,950,000	1,521	3

State Energy Price *

Electric Price (Cents/kWh)	Natural Gas Price ($/Therm)	Renewable Natural Gas Price ($/Therm)	Propane Price ($/Gal)	Renewable Propane Price ($/Gal)
14.29	1.25	1.60	1.69	3.50

*Note: User-Specified prices

Select Building Configurations

All Houses　　Equipment Cost Basis: Retrofit

		Baseline	Alternative
Included?	Application	Equipment and Appliances	Equipment and Appliances
x	Space Heating	16 SEER /9.0 HSPF Heat Pump Electric Consumption: 10,674 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 3,873 $/Unit +42.00 $/kBtuh Unit Capacity: 90 kBtuh	20.5 SEER /13 HSPF Heat Pump Electric Consumption: 8,886 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 4,745 $/Unit +42.00 $/kBtuh Unit Capacity: 100 kBtuh
	Space Cooling	16 SEER /9.0 HSPF Heat Pump Electric Consumption: 532 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 0 $/Unit +0.00 $/kBtu Unit Capacity: 30 kBtuh	20.5 SEER /13 HSPF Heat Pump Electric Consumption: 406 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 0 $/Unit +0.00 $/kBtu Unit Capacity: 30 kBtuh
x	HVAC Blower	Electric Consumption: 722 (10^6 kWh)	Electric Consumption: 722 (10^6 kWh)
x	Water Heating	Electric Resistance EF, 0.95 Electric Consumption: 8,502 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 591 $/Unit +3.50 $/gal Unit Capacity: 60 Gal	Electric Heat Pump EF, 2.00 Electric Consumption: 4,038 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 1,900 $/Unit Unit Capacity: 50 Gal

	Lighting & Plug-in Loads	Electric Consumption: 4,301 (10^6 kWh)	Electric Consumption: 4,301 (10^6 kWh)
x	Cooking Range	Electric Standard EF 0.74 Electric Consumption: 874 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 923 $/Unit	Electric Induction EF 0.84 Electric Consumption: 770 (10^6 kWh) Gas Consumption: 0 (10^6 therm) Installed Cost: 1,879 $/Unit
	Refrigerator	How many: 1 Electric Consumption: 0 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
	Dishwasher	How many: 1 Electric Consumption: 335 (10^6 kWh)	How many: 1 Electric Consumption: 335 (10^6 kWh)
	Washer	How many: 1 Electric Consumption: 172 (10^6 kWh)	How many: 1 Electric Consumption: 0 (10^6 kWh)
x	Clothes Dryer	Electric Standard EF 3.1 Electric Consumption: 1,893 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 760 $/Unit	Electric Standard EF 3.93 Electric Consumption: 1,494 (10^6 kWh) Gas Consumption: 0 (10^6 Therm) Installed Cost: 930 $/Unit
x	Electrical Service Upgrade	New Electrical Panel 2,000 $/house	New Electrical Panel 2,000 $/house
	Photovoltaic	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (10^6 kWh) Battery Offsets: 0 (10^6 kWh) Electricity Exported to Grid: 0 (10^6 kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System
	Micro CHP	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW	None Electric Reduced: 0 (10^6 kWh) Electric Export to Grid: 0 (10^6 kWh) NG Building Used Reduction: 0 (10^6 therm) mCHP NG Consumption: 0 (10^6 therm) Installed Cost: 0 $/Unit + 0 $/kW

Source Energy Factors And Composite Emission Factors

Geographic Area:	State: Colorado
Plant Level Database:	All Plants
eGrid Database:	2020 data
eGrid Level:	eGRID 2020 data State database
Renewable Conversion Efficiency:	Captured

Source Energy Factors

	Electric	Natural Gas	Renewable Natural Gas	Propane	Renewable Propane
Btu/Btu	1.63	1.09	1.28	1.15	1.27

Composite Emission Factors

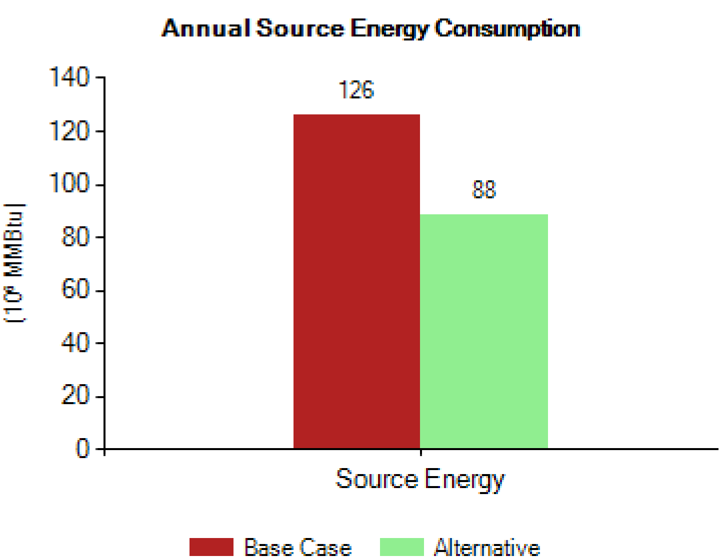
Energy Form	CO2	SO2	NOx	CH4	N2O	CO2e
Electricity (lb/MWh)	365.2	0.073	0.236	1.227	0.0010	399.7
Natural Gas (Building Used, lb/MMBtu)	130.2	0.029	0.172	0.526	0.0030	145.7
Renewable Natural Gas (Building Used, lb/MMBtu)	35.2	0.084	0.281	0.507	0.0030	50.2
Propane (lb/MMBtu)	163.2	0.055	0.225	0.083	0.0110	168.5
Renewable Propane (Building Used, lb/MMBtu)	43.6	0.101	0.281	0.009	0.0110	46.9
Natural Gas (mCHP NG Engine Used, lb/MMBtu)	137.2	0.029	1.892	1.389	0.0000	176.2
Natural Gas (mCHP Fuel Cell Used, lb/MMBtu)	128.9	0.028	0.055	0.524	0.0000	143.7

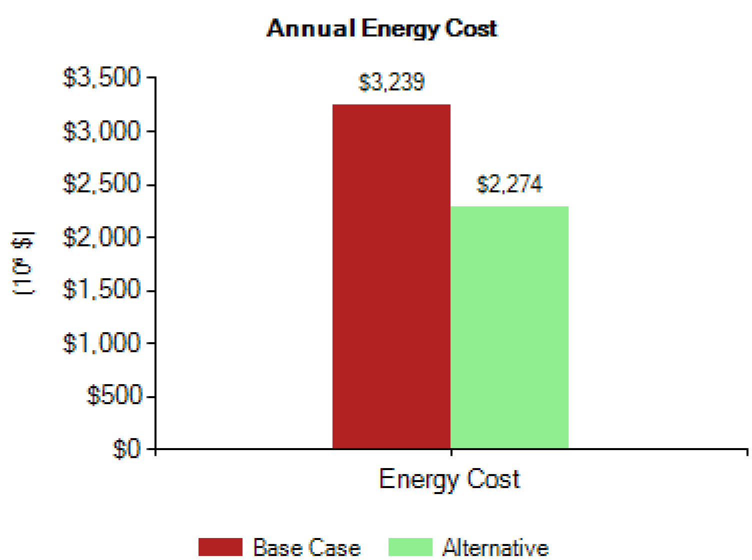
Source Energy and Emission Factors are calculated for CO: Energy conversion efficiency and specific emission data for electricity generated using fossil fuels and biomass are based on eGRID 2020 data State database. Electric distribution efficiency data are based on eGRID 2020 data State database. Electricity generation fuel mix distribution data are based on user custom data All other default data are based on EIA, NREL, and ANL (GREET 1 2012) data sources.

Energy Consumption and Cost

	Energy	Annual Site Consumption	Annual Site Consumption	Annual Source Consumption	Annual Energy Cost	Equipment Invest Cost
			(10^6 MMBtu)	(10^6 MMBtu)	(10^6 $)	(10^6 $)
Baseline	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	22,665 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	77.33 0.00 0.00 0.00 0.00 0.00 0.00 0.00 77.33	126.05 0.00 0.00 0.00 0.00 0.00 0.00 0.00 126.05	3,239 0 0 0 0 0 0 0 3,239	23,667
Alternative	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	15,910 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 kWh) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Therm) 0 (10^6 Gal) 0 (10^6 Gal)	54.28 0.00 0.00 0.00 0.00 0.00 0.00 0.00 54.28	88.48 0.00 0.00 0.00 0.00 0.00 0.00 0.00 88.48	2,274 0 0 0 0 0 0 0 2,274	30,525

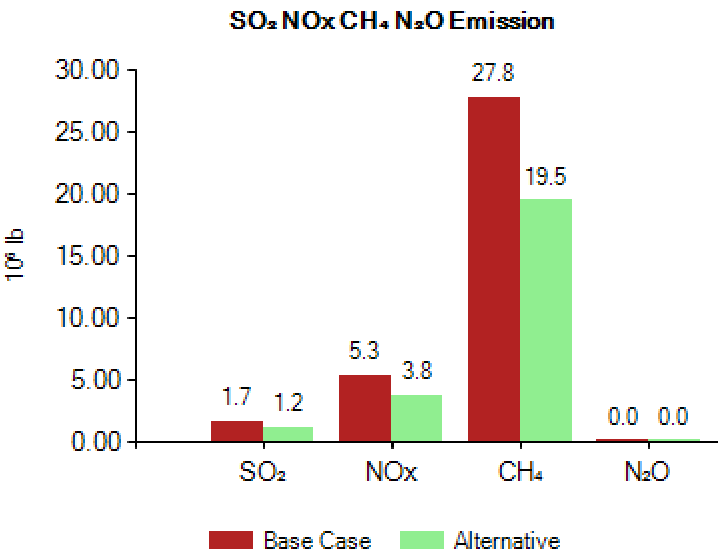
	Energy Cost Savings (Baseline-Alternative)	Equipment Invest Cost (Alternative-Baseline)	Simple Payback (Year)
	(10^6 $)	(10^6 $)	(Year)
Comparison	965	6,858	7.1

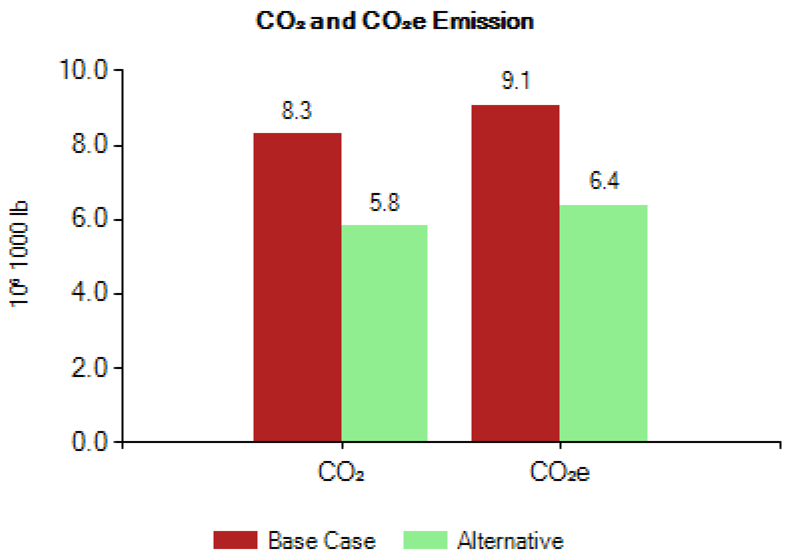




Annual Source Emissions

	SO2 (10^6 lb)	NOx (10^6 lb)	CO2 (10^9 lb)	CH4 (10^6 lb)	N2O (10^6 lb)	CO2e (10^9 lb)
Baseline	1.65	5.35	8.28	27.81	0.02	9.06
Alternative	1.16	3.75	5.81	19.52	0.02	6.36





Single-family home example; current grid

Energy Planning Analysis Tool

Building Location and Configuration

State:	Colorado	Population:	5,029,196	Total State Home:	1,910,146

State Residential Electric Houses

Included?	House Type	Number of Units	Average Size (ft2)	Number of People per Unit
	Moblile	80,000	0	3
x	Single Fam. Detached	1,270,000	1,885	3
	Single Fam. Attached	135,000	1,185	3
	Apt. Building 2 to 4 units	85,000	851	3
	Apt. Building 5+ units	380,000	895	3
	All Residential Electric Houses	1,270,000	1,885	3

State Energy Price *

Electric Price (Cents/kWh)	Natural Gas Price ($/Therm)	Renewable Natural Gas Price ($/Therm)	Propane Price ($/Gal)	Renewable Propane Price ($/Gal)
14.29	1.25	1.80	1.69	3.50

*Note: User-Specified prices

Select Building Configurations

Single House

Equipment Cost Basis: Retrofit

		Baseline	Alternative
Included?	Application	Equipment and Appliances	Equipment and Appliances
x	Space Heating	Natural Gas, AFUE 98% Electric Consumption: 27 (kWh) Gas Consumption: 408 (Therm) Installed Cost: 2,807 $/Unit +3.86 $/kBtuh Unit Capacity: 100 kBtuh	16 SEER /9.0 HSPF Heat Pump Electric Consumption: 6,296 (kWh) Gas Consumption: 0 (Therm) Installed Cost: 3,873 $/Unit +42.00 $/kBtuh Unit Capacity: 120 kBtuh
	Space Cooling	13 SEER(11.07 EER) A/C Electric Consumption: 362 (kWh) Gas Consumption: 0 (Therm) Installed Cost: 2,588 $/Unit +42.00 $/kBtu Unit Capacity: 36 kBtuh	16 SEER /9.0 HSPF Heat Pump Electric Consumption: 286 (kWh) Gas Consumption: 0 (Therm) Installed Cost: 0 $/Unit +0.00 $/kBtu Unit Capacity: 36 kBtuh
x	HVAC Blower	Electric Consumption: 449 (kWh)	Electric Consumption: 408 (kWh)
x	Water Heating	Natural Gas EF 0.95 - Condensing Tankless Electric Consumption: 52 (kWh) Gas Consumption: 147 (Therm) Installed Cost: 2,515 $/Unit Unit Capacity: 199 kBtu/h	Electric Resistance EF, 0.95 Electric Consumption: 4,360 (kWh) Gas Consumption: 0 (Therm) Installed Cost: 591 $/Unit +3.50 $/gal Unit Capacity: 60 Gal
	Lighting &	Electric Consumption: 2,733 (kWh)	Electric Consumption: 2,733 (kWh)

	Plug-in Loads		
x	Cooking Range	Gas Standard Electric Consumption: 31 (kWh) Gas Consumption: 31 (Therm) Installed Cost: 823 $/Unit	Electric Standard EF 0.74 Electric Consumption: 448 (kWh) Gas Consumption: 0 (therm) Installed Cost: 923 $/Unit
	Refrigerator	How many: 1 Electric Consumption: 0 (kWh)	How many: 1 Electric Consumption: 0 (kWh)
	Dishwasher	How many: 1 Electric Consumption: 172 (kWh)	How many: 1 Electric Consumption: 172 (kWh)
	Washer	How many: 1 Electric Consumption: 88 (kWh)	How many: 1 Electric Consumption: 0 (kWh)
x	Clothes Dryer	Gas Standard EF 3.84 Electric Consumption: 76 (kWh) Gas Consumption: 25 (Therm) Installed Cost: 1,100 $/Unit	Electric Standard EF 3.1 Electric Consumption: 971 (kWh) Gas Consumption: 0 (Therm) Installed Cost: 760 $/Unit
	Electrical Service Upgrade	No Electrical Upgrade 0 $/house	No Electrical Upgrade 0 $/house
	Photovoltaic	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (kWh) Battery Offsets: 0 (kWh) Electricity Exported to Grid: 0 (kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System	PV Installed : No PV Array Size : 0 (kW) Battery Installed: No Battery Size: 0 (kWh) Economics: Net Metering Electricity Retail Rate Multiplier : 0 Direct Solar Offsets: 0 (kWh) Battery Offsets: 0 (kWh) Electricity Exported to Grid: 0 (kWh) PV Cost: 0 $/kW Battery Cost: 0 $/kWh Total Cost: 0 $/System
	Micro CHP	None Electric Reduced: 0 (kWh) Electric Export to Grid: 0 (kWh) NG Building Used Reduction: 0 (therm) mCHP NG Consumption: 0 (therm) Installed Cost: 0 $/Unit + 0 $/kW	None Electric Reduced: 0 (kWh) Electric Export to Grid: 0 (kWh) NG Building Used Reduction: 0 (therm) mCHP NG Consumption: 0 (therm) Installed Cost: 0 $/Unit + 0 $/kW

Source Energy Factors And Composite Emission Factors

Geographic Area:	State: Colorado
Plant Level Database:	All Plants
eGrid Database:	2020 data
eGrid Level:	eGRID 2020 data State database
Renewable Conversion Efficiency:	Captured

Source Energy Factors

	Electric	Natural Gas	Renewable Natural Gas	Propane	Renewable Propane
Btu/Btu	2.49	1.09	1.28	1.15	1.27

Composite Emission Factors

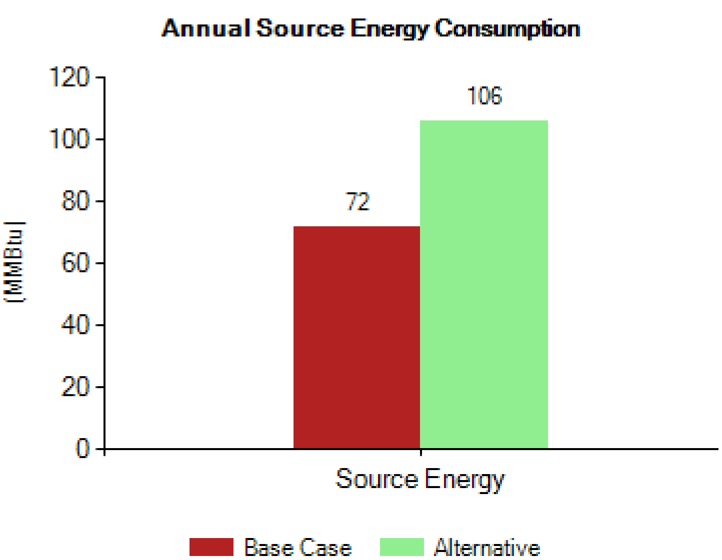
Energy Form	CO2	SO2	NOx	CH4	N2O	CO2e
Electricity (lb/MWh)	1,232.6	0.470	0.857	2.350	0.0140	1,302.0
Natural Gas (Building Used, lb/MMBtu)	130.2	0.029	0.172	0.526	0.0030	145.7
Renewable Natural Gas (Building Used, lb/MMBtu)	35.2	0.084	0.281	0.507	0.0030	50.2
Propane (lb/MMBtu)	163.2	0.055	0.225	0.083	0.0110	168.5
Renewable Propane (Building Used, lb/MMBtu)	43.6	0.101	0.281	0.009	0.0110	46.9
Natural Gas (mCHP NG Engine Used, lb/MMBtu)	137.2	0.029	1.892	1.389	0.0000	176.2
Natural Gas (mCHP Fuel Cell Used, lb/MMBtu)	128.9	0.028	0.055	0.524	0.0000	143.7

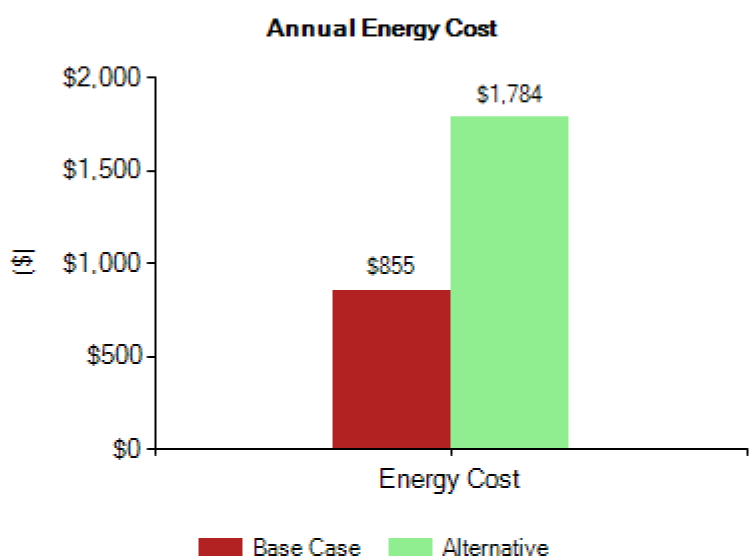
Source Energy and Emission Factors are calculated for CO: Energy conversion efficiency and specific emission data for electricity generated using fossil fuels and biomass are based on eGRID 2020 data State database. Electric distribution efficiency data are based on eGRID 2020 data State database. Electricity generation fuel mix distribution data are based on user custom data All other default data are based on EIA, NREL, and ANL (GREET 1 2012) data sources.

Energy Consumption and Cost

	Energy	Annual Site Consumption	Annual Site Consumption	Annual Source Consumption	Annual Energy Cost	Equipment Invest Cost
			(MMBtu)	(MMBtu)	($)	($)
Baseline	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	635 (kWh) 0 (kWh) 0 (kWh) 611 (Therm) 0 (Therm) 0 (Therm) 0 (Gal) 0 (Gal)	2.17 0.00 0.00 61.10 0.00 0.00 0.00 0.00 63.27	5.39 0.00 0.00 66.60 0.00 0.00 0.00 0.00 71.99	91 0 0 764 0 0 0 0 855	7,631
Alternative	Electricity (Total Building Used) Electricity Offset (Distributed Generation) Electricity (Distributed Generation) Natural Gas (Building Used) Natural Gas (mCHP Used) Renewable Natural Gas (Building Used) Propane (Building Used) Renewable Propane (Building Used) Total	12,483 (kWh) 0 (kWh) 0 (kWh) 0 (Therm) 0 (Therm) 0 (Therm) 0 (Gal) 0 (Gal)	42.59 0.00 0.00 0.00 0.00 0.00 0.00 0.00 42.59	106.05 0.00 0.00 0.00 0.00 0.00 0.00 0.00 106.05	1,784 0 0 0 0 0 0 0 1,784	11,397

	Energy Cost Savings (Baseline-Alternative)	Equipment Invest Cost (Alternative-Baseline)	Simple Payback (Year)
	($)	($)	(Year)
Comparison	-929	3,766	Never





Annual Source Emissions

	SO2 (lb)	NOx (lb)	CO2 (1000 lb)	CH4 (lb)	N2O (lb)	CO2e (1000 lb)
Baseline	2.07	11.05	8.74	33.63	0.19	9.73
Alternative	5.87	10.70	15.39	29.34	0.17	16.25