Strategies for Achieving Net-Zero Emissions in Nevada

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Executive Summary

As part of a larger effort to mitigate climate change, Nevada has pledged to achieve net-zero emissions of greenhouse gases (GHGs) by 2050. In 2017, GHG emissions totaled 53.8 metric tons of carbon dioxide equivalent ($MtCO_2e$), and these emissions are expected to rise to 71.3 $MtCO_2e$ by 2050 if no efforts are made to manage carbon emissions. This report investigates options for carbon reduction (emitting smaller amounts of GHG), avoidance (capturing CO_2 from large industrial sources and storing it), and removal (capturing CO_2 from the air and storing it) in order to meet Nevada's climate goals. We examine five scenarios ranging from no action to aggressive strategies.

In order to reduce the use of fossil fuels that emit GHGs, primarily carbon dioxide, when they are burned, we need to shift our energy generation to more sustainable sources. Electrification of industries has a major role to play in the decarbonization of all sectors of the economy and will displace the burden of decarbonization toward the electricity generation sector, while raising the demand for electricity. To meet our climate goals, it is essential to lower the carbon intensity of the grid. Other strategies to reduce carbon emissions include improving the efficiency of processes and buildings, reducing the amount of waste produced, and reducing the use of highly potent GHGs in cooling systems.

Major CO_2 emitters like natural gas power plants and cement and lime facilities can be retrofitted with carbon capture to avoid releasing most of their CO_2 into the atmosphere. Making these improvements could capture up to 8.3 $MtCO_2$ in Nevada. We view direct air capture of carbon (DAC) as a complement to other decarbonization strategies and it is required in all the scenarios we considered to reach net-zero emissions in 2050. The amount of carbon that would need to be captured by DAC varies from a minimum of 4.3 $MtCO_2$/yr (if significant progress was achieved using other strategies) to 49.6 $MtCO_2$/yr (if little effort is made using other decarbonization strategies). Our results, examined alongside the "Power of Place" study published in 2019, indicate that all land used to generate renewable energy to meet the future electricity demand and to provide energy to DAC systems can comply with the highest environmental restriction levels; thus, these systems could be deployed with minimal environmental impact.

Once captured, CO_2 has to be stored permanently and securely in order to achieve climate change mitigation. One option is injection in the subsurface of sedimentary basins or basaltic formations, while another is carbon mineralization with non-carbonated alkaline materials, such as industrial wastes, mine tailings, or rocks. Carbon mineralization of industrial wastes such as cement kiln dust and lime kiln dust could store about 50 $ktCO_2$/yr, and mineralization of mine tailings at three major mines could store about 23 $ktCO_2$/yr. This is about two orders of magnitude below the needed amount of CO_2 storage in the state, but Nevada has multiple sedimentary basins and basalt outcrops, so more CO_2 storage sites could be found in the future. Also, carbonated mine tailings can be used as aggregates and reduce emissions from mining.

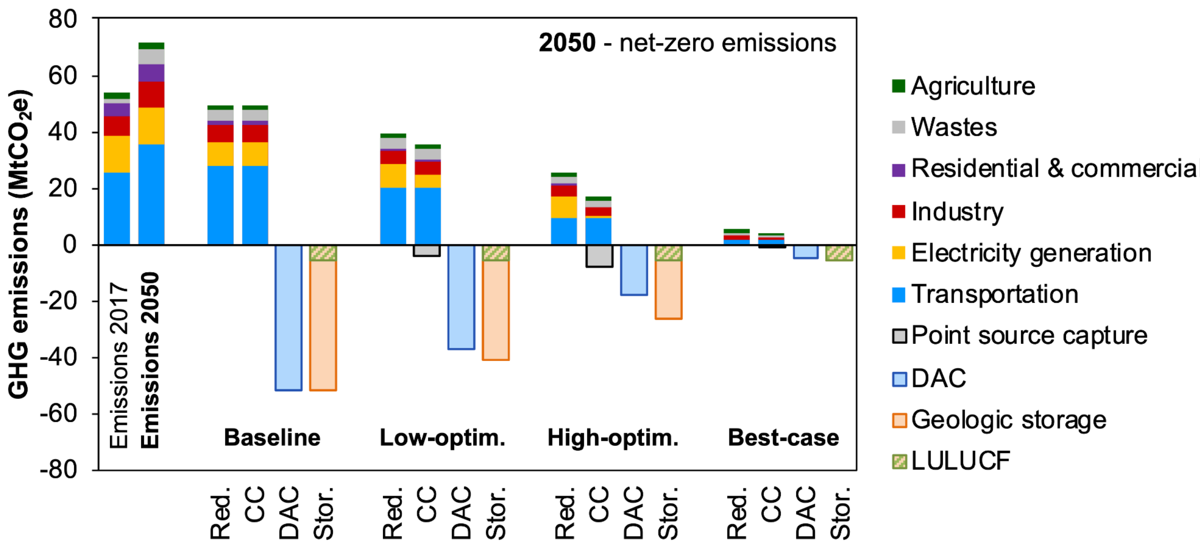

Figure 1. Greenhouse gas (GHG) emissions and carbon management needed to reach Nevada's climate goals by 2050. Estimated GHG emissions are broken down by sector in the bars above the x-axis, and captured emissions (point source capture or DAC) and CO_2 storage are the bars below the x-axis. A business-as-usual scenario is shown on the far left-hand side, followed by the baseline, low-optimistic, high-optimistic, and best-case carbon management scenarios. The scenarios are broken down into total emissions after emission mitigation (reduction, Red.), and after emissions avoided by point source capture (carbon capture, CC), and amount of direct air capture (DAC) and CO_2 storage (Stor.) necessary to meet the climate goals. The green hashed portions show the amount of CO_2 that could be captured and stored byland use, land use change, and forestry (LULUCF) approaches according to a Nevada Division of Environmental Protection (NDEP) 2019 report, which could lower the need for geologic storage.

Glossary of Terms

afforestation **–** planting new forests in regions where they did not previously exist

anthropogenic emissions **–** emissions that are directly caused by human activity, such as those from the industrial, residential and commercial, transportation, agricultural, and waste management sectors

annual vehicle miles traveled (AVMT) **–** total number of miles traveled by specified vehicles over a one-year time frame

business-as-usual (BAU) **–** predictive scenarios in which no additional efforts are made to reach Nevada's net-zero by 2050 goal or to reduce GHG emissions beyond current efforts

carbon capture and storage (CCS) **–** the removal and storage of CO_2 from the atmosphere, including both point source capture from large emitters and direct air capture

carbon dioxide removal (CDR) **–** general term for the removal of CO_2 from the atmosphere, which includes nature-based solutions such as afforestation and reforestation and engineered solutions such as DAC

carbon intensity **–** the amount of CO_2-equivalent emissions per unit of product made or consumed

carbon mineralization (CM) **–** the engineered reaction of CO_2 with alkaline minerals, industrial waste, or mine tailings to form solid products for permanent storage

coefficient of performance (COP) **–** ratio of useful heat output to energy input; a 1000-W heat pump with a COP of 3.5 will output 3500 W of heat

concentrated solar power (CSP) **–** these systems of mirrors and lenses concentrate the sun rays towards a receiver where the solar energy warms up a working fluid that is then used to generate electricity

CO_2-equivalent emissions (CO_2e) **–** a measure of overall GHG emissions normalized such that emissions for non-CO_2 gases are reported in terms of the equivalent amount of CO_2 that would be required for the same global warming potential (GWP); for example, 1 ton of CH_4 emissions is equal to 25 tons CO_2-equivalent emissions

decarbonization **–** the transition from the current carbon-emitting and fossil fuel–based energy economy to the use of renewable energy and proactive minimization of GHG emissions

direct air capture (DAC) – the removal of CO_2 directly from the atmosphere

electrification – transition of an energy-consuming sector or technology away from fossil fuel use and toward the use of electricity (e.g., replacement of gas-powered heating with electric-resistive heating)

emission reduction – strategies to decrease total GHG emissions that prevent emissions from occurring in the first place

emission scope – classification of the responsibility for emissions, with scope 1 being emissions directly created due to an organization's activity, scope 2 being indirect emissions from the generation of purchased energy, and scope 3 being all other indirect emissions

greenhouse gas (GHG) – any atmospheric gas that contributes to the greenhouse effect and global warming, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs)

grid carbon intensity – the amount of CO_2-equivalent emissions per unit of energy generated and supplied to an energy grid

in-situ CO_2 storage – permanent geologic storage of CO_2 through injection into deep underground aquifers and geologic formations

landfill gas to energy (LFGTE) – the extraction and use of landfill gas for energy use

legacy emissions – greenhouse gases emitted in the last several hundred years that remain in the atmosphere and contribute to global warming

life cycle assessment (LCA) – an overall engineering and social analysis of a process or operation to determine its lifetime resource intensity and environmental impacts

mole percent (mol.%) – amount of a particular component (in moles) relative to the total amount of all components (in moles) in a mixture, expressed in percentages

net-zero emissions – the state achieved when emission reductions and CDR are used to capture or remove the same amount of CO_2-equivalents as the amount emitted, thereby not changing the total amount of GHGs in the atmosphere

***ozone-depleting substances (ODS)* –** pollutants that react with and contribute to the breakdown of the Earth's atmospheric ozone layer

***photovoltaic (PV)* –** this technology converts the light from the sun into electricity using semiconducting materials

***point source capture* –** the capture of CO_2 or other pollutants from a concentrated emission source such as the stack of a power plant or other industrial facility, sometimes referred to as *post-combustion capture*

***reforestation* –** the active replanting of forests that have been cut down or no longer exist

***reversibility* –** an assessment of how permanent a CO_2 removal strategy is and whether these removed emissions may be released back into the atmosphere in the near future

***technology readiness level (TRL)* –** a measure of how readily a proposed technology or system can be deployed in the present day

1. Introduction

1.1. A state of emergency

The levels of greenhouse gas (GHG) emissions in the atmosphere have risen steadily in the last several decades, even as global awareness of their potential impacts on climate change has increased[1]. Climate change is affecting human society through rising sea levels, increased storms, extreme weather patterns that disrupt agriculture, and impacts on biodiversity. It has been estimated that globally, nearly 83 million people will die by the end of this century due to the adverse impacts of climate change[2].

In order to reduce these impacts and protect biodiversity on Earth, as well as the health and safety of human society, we must keep global temperatures stable. The Intergovernmental Panel on Climate Change (IPCC) has noted that keeping global temperatures within 1.5°C of preindustrial levels will necessitate the annual net removal of 10 gigatons (Gt) of CO_2 from the atmosphere by 2050. Therefore, we need to understand and address unchecked GHG emissions as quickly as possible to lessen the consequences of increasing global temperatures and to eventually reverse climate change. To fully address this multifaceted problem and reach both local and global emissions goals, we need to deploy strategies involving comprehensive scientific, social, and political solutions.

In 2004, Pacala and Socolow released a study that detailed several strategies aimed at reducing carbon emissions to achieve stable atmospheric levels (500 ppm) by 2050[3]. These solutions encompassed efficient use of vehicles, reduced vehicle use, efficient buildings, carbon capture on large emitters, increased use of renewable energy, advanced low-carbon practices in agriculture, and reduced deforestation in combination with reforestation and afforestation[I]. All of the proposed solutions are still relevant and can be deployed to reduce emissions going forward. However, little progress has been made in deploying the solutions since that study was released, which has severely shifted the priorities in order to achieve emission mitigation and climate stabilization by mid-century. Notably, emission avoidance solutions like point source carbon capture and storage (CCS) must now carry a much greater burden; likewise, carbon dioxide removal (CDR) strategies may play a significant role in "making up for lost time" and reconciling any residual emissions that would have otherwise contributed to atmospheric CO_2 concentrations in line with potentially irreversible climate-related impacts.

[I] Reforestation refers to the planting of trees where forests recently stood; afforestation describes the planting of new forests in locations where there were no previous forests.

1.2. Net-zero emissions

The concept of *net-zero* or carbon neutrality is fairly straight-forward in theory: the declaring entity must ensure that by a given deadline, there are no net emissions of CO_2e[II] to the atmosphere. Nevada has pledged to reach net-zero emissions by 2050[4]. The various approaches to reach this goal are often complementary: emission reduction, emission avoidance, and emission removal. The approach that has been the most widely developed is emission reduction, which focuses on emitting fewer emissions in the first place. To do so, it is necessary to develop low-carbon sources of energy (e.g., solar, wind, geothermal, biomass), electrify cars and homes, increase the energy efficiency of processes and buildings, and decommission power generation systems that use fossil fuels, especially coal. While this approach is absolutely essential for a sustainable world, we cannot use it alone to reach carbon neutrality and will have to also use carbon capture and storage.

CO_2 can be captured from large emitters before it is released to the atmosphere (point source capture) to avoid emissions, or it can be captured from the air (direct air capture) to remove emissions. Carbon capture can only produce a climate benefit if the captured CO_2 is subsequently put into long-term storage. The higher CO_2 concentration of natural gas power plants (i.e., 3–5 mol%) and industrial exhaust streams (>15 mol%) compared with air (~0.04 mol%) means that it costs less per unit of CO_2 to capture carbon from these plants[5,6]. While the lower costs of point source capture are attractive, at its best this process can only achieve carbon neutrality, and carbon removal is needed to offset the emissions that cannot be reduced or avoided, like those from certain parts of the transportation, industrial, and agricultural sectors.

CDR approaches can address current and legacy emissions and can be divided into two categories: nature-based approaches and technology-based approaches. Nature-based approaches include reforestation, afforestation, and soil organic carbon enhancement. These approaches are often cheaper and have co-benefits such as ecosystem restoration. However, the adapted environments must be deployed successfully, and the carbon storage can be reversed by environmental changes like forest fires or droughts, which are becoming increasingly common in Nevada. The Nature Conservancy of Nevada is currently investigating the carbon capture and storage potential of land management and nature-based approaches in the state. The present report focuses on technological CDR approaches, which involve direct air capture (DAC) of CO_2, storage of the captured CO_2, and eventually transportation. DAC requires large energy inputs that could be met with renewable sources of energy like geothermal and solar in Nevada. It is essential to select CO_2 storage solutions that are durable and limit the risks of reversibility, in order to have a positive impact on climate.

[II] In this report and elsewhere, CO_2e stands for CO_2 *equivalent* emissions, and takes into account other greenhouse gases, namely CH_4 and N_2O, as well as refrigerants.

This report will discuss the most relevant options for carbon emission reduction, avoidance, and removal in Nevada for the different sectors of the economy.

1.3. Emissions landscape

In 2017, the gross emissions in Nevada totaled 43.8 $MtCO_2e$[III], with net emissions reaching 38.1 $MtCO_2e$ after removal of 5.7 $MtCO_2e$ through land use, land-use change, and forestry (LULUCF) approaches[7]. The transportation sector was the largest contributor (36%), followed by electricity generation (30%), industry (15%), residential and commercial (11%), waste (4%), and agriculture (4%) (Fig. 2)[7]. The transportation, residential and commercial (R&C), and agriculture sectors are characterized by small distributed emissions, while the electricity generation and the industrial sectors are large point sources of greenhouse gases located mostly in the vicinity of the larger population centers of Las Vegas and Reno.

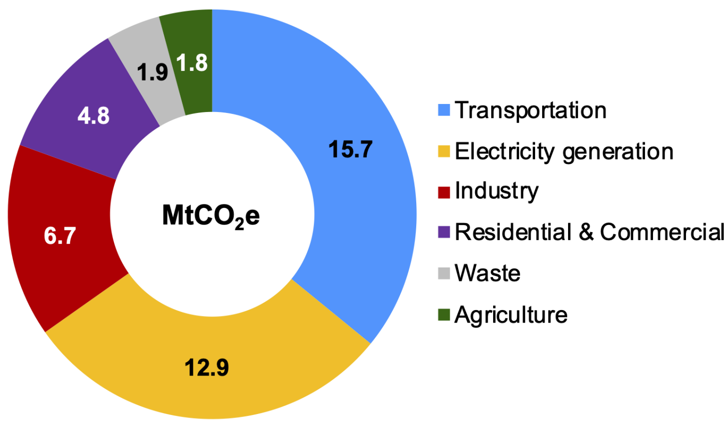

Figure 2. Greenhouse gas (GHG) emissions by sector, in metric tons of carbon dioxide equivalent ($MtCO_2e$), for 2017 in Nevada[7].

The year 2005 marked a peak in GHG emissions in Nevada, with 56.4 $MtCO_2e$ in gross emissions and 49.4 $MtCO_2e$ in net emissions[7]. This peak was primarily due to the emissions from the electricity generation sector, which was dominant from 1990 to 2005. The electricity generation sector saw a sharp decline in emissions in 2006, due to the retirement of the 1580-MW Mohave generating station in 2005[8] and reached a similar level of GHG emissions as the transportation sector. The transportation sector saw a peak in emissions in 2006–2007. All other sectors have been slowly increasing over the years[7].

[III] Gross GHG emissions from the NDEP 2019 report (43.8 $MtCO_2e$) differ from gross GHG emissions considered for this report (53.8 $MtCO_2e$). The present report aims to account for all emissions that could be impacted by a change of policy in Nevada, which includes out-of-state upstream emissions of fuel production and refining for the transportation sector.

The majority of the GHG emissions are CO_2 (>85% of gross emissions). The remaining contributions from other GHGs like CH_4 and N_2O are roughly equal to the emissions offset by LULUCF approaches. While methane emissions predominantly come from the agriculture and waste sectors, the emissions from hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) used in refrigeration and air conditioning systems is a growing concern due to the increasing average temperatures in the state.

Nevada is also experiencing fast population growth, which is expected to increase emissions in most sectors: electricity generation, transportation, residential and commercial, agriculture, and wastes. The emissions from the industrial sector were not impacted in the past 20 years by population growth and are expected to stay roughly the same, with the exception of emissions from the use of HFCs and PFCs, which are expected to keep growing. A business-as-usual (BAU) emission trajectory would likely follow population growth, with the exception of the industrial sector, for which the trajectory is a projection of past trends.

1.4. Decarbonization strategies

The sectors of the economy are bound by different constraints, which affect the decarbonization strategies that can be used: small, distributed emission sources versus large emitters, ability to use renewable sources of energy, potential for electrification, potential for increasing energy efficiency, and availability of land.

Transportation is considered a harder-to-abate sector because its emission sources are millions of fossil fuel–powered vehicles that release GHGs, as opposed to a few large emission sources where existing point source capture technology can be used. A start-up company is developing point source capture for heavy-duty vehicles, but this technology is not yet proven to economically scale[9,10]. Thus, most emission reduction pathways focus on decreasing the use of fossil fuels in transportation altogether. The carbon intensity of fuels can be decreased by blending gasoline with biofuels and synthetic fuels or by improving the fuel economy of internal combustion engine vehicles (ICEVs), so that smaller amounts of GHGs are emitted to travel the same distance. Another option is decreasing the miles traveled by ICEVs altogether. This can be done by replacing ICEVs with electric vehicles (EVs), such as the battery electric vehicle, or by decreasing the total miles traveled by all vehicles through advancements in public transport. The degree to which EV deployment will decrease GHG emissions depends on the carbon intensity of the electric grid from which EVs source their power.

The R&C sector contributes roughly 11% of total greenhouse gas emissions in Nevada, with approximately 2.6 $GtCO_2e$/year coming from residential usage and 2.5 $GtCO_2e$/year coming from commercial usage. These emissions are largely generated from space and water heating, appliance use, lighting, and cooking. The majority of these uses are considered basic needs for a standard quality of living; thus, while reduced consumption should be considered part of a portfolio of emission reduction strategies (e.g., turning off lights, using eco-friendly settings on thermostats, unplugging appliances that have higher "vampire consumption"[IV]), this report does not consider reduced consumption by the public as a mitigation strategy. To assure a standard quality of life, baseline emissions from the R&C sector are expected to increase along with population and economic growth, the latter of which is assumed to trend linearly with projected population growth. Further, climate change feedback exists in the form of more *excessively* hot days (i.e., days in which the temperature is over 100˚F) that will place increased stress on R&C cooling systems.

A number of strategies can be applied to reduce emissions in the R&C sector. First, a tremendous amount of new infrastructure must be constructed to accommodate the increase in both population and economic activity over the next three decades. Each new construction brings an opportunity to build efficient energy shells and achieve green building certification (e.g., the LEED designation, which has shown to reduce energy consumption by more than 30%[11]).

Secondly, there are several viable routes for electrification of the R&C sector, reducing and potentially eliminating the use of natural gas or wood as an energy source in building use, which can not only achieve notable reductions in CO_2 emissions but can eliminate harmful criteria pollutants like $PM_{2.5}$ that otherwise can accumulate indoors and present health risks for building occupants. Furnaces that use fossil fuels can be replaced with high-efficiency heat pumps, which can have a coefficient of performance[V] (COP) of ~3.5 in the warm climate of Nevada. Likewise, heat pumps can replace natural gas–fired water heaters, providing similar gains in efficiency. Cooking via electric cook-top, or the more efficient induction cook-top, can replace use of gas stoves. In each instance, the replacement of an appliance or service that uses fossil fuels with an electrified counterpart not only reduces fossil fuel consumption, but also provides efficiency gains, leading to lower overall energy consumption.

Much like the transportation sector, due to the high level of electrification, emission reductions in the R&C sector are heavily dependent on grid carbon intensity. A breakdown of the energy consumption by end use for the R&C sector is provided in Figure 3. Note that in both subsectors, space heating is the largest consumer of energy, further supporting the strategy of replacing traditional furnaces with heat pumps to achieve deep emission reductions in buildings.

Since electrification of processes is an essential part of the decarbonization scenarios of many sectors, it is crucial to lower the carbon intensity of the grid. The largest emitters are the two coal power plants. Valmy is planned for decommission by 2025, and TS Power will be upgraded to a

[IV] Vampire consumption of energy refers to devices that continue to pull power from the grid even when they are turned off. It is estimated that these devices can add up to 20% of monthly electricity consumption.

[V] The coefficient of performance (COP) is a ratio of the useful heat output to energy input. A 1000-W heat pump with a COP of 3.5 will output 3500 W of heat.

dual coal-natural gas power plant in 2022[4,12]. No new fossil-fueled power plants are planned in the state, and the natural gas power plants can be retrofitted with post-combustion carbon capture and storage. The growing power demand can be met by new solar and geothermal power plants, which will gradually replace the natural gas power plants as they are decommissioned to facilitate the transition to a zero-carbon grid.

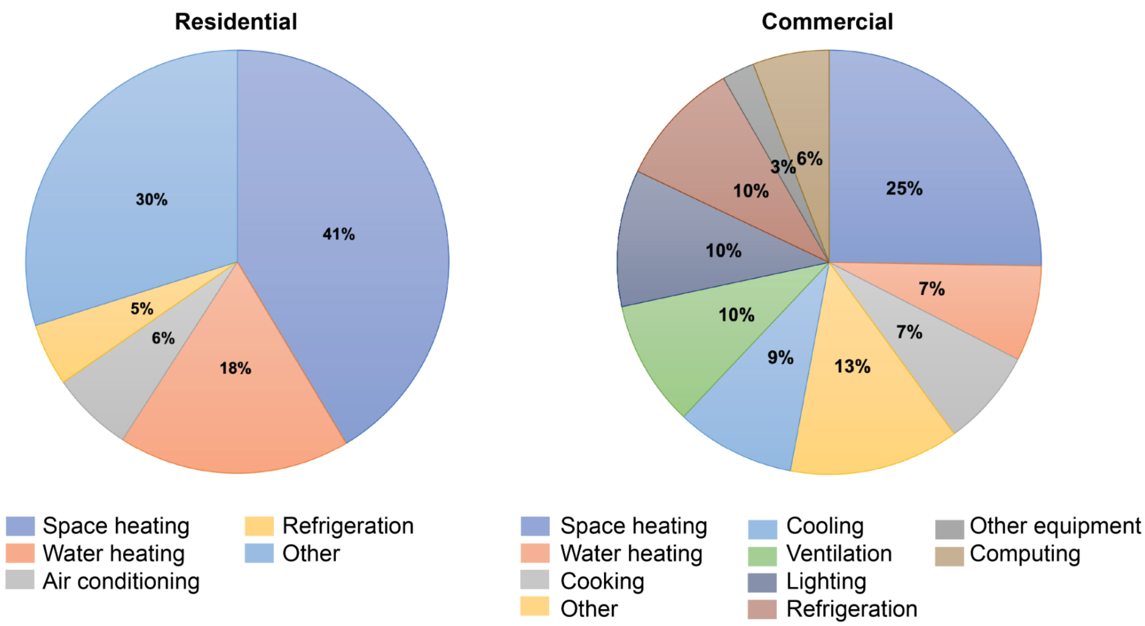

Figure 3. Breakdown of energy consumption by end use in the residential (left) and commercial (right) sectors[13].

The industrial sector faces different challenges: process emissions, the need for high-grade heat, and the leakage of highly potent GHGs. Cement and lime plants face both of the first two challenges. The process emissions are CO_2 emissions resulting from chemical reactions, like the calcination of limestone in cement and lime kilns, which will require decarbonization through point source capture. A common solution to supply heat is the use of electric kilns; however, processes like cement and lime use high-grade heat for which kilns are not currently available on the market, complicating the transition to electrification in the short term. High-grade heat is best supplied today by natural gas and coal due to their high energy density. The replacement of coal by natural gas or biomass (co-fired) would reduce emissions. The emissions from fuel combustion are combined with process emissions in cement and lime kilns and could be captured with the same point source capture unit. SF_6 and ozone-depleting substances (HFCs and PFCs) used in electrical transmission and distribution systems and in refrigeration and cooling systems, respectively, are very potent GHGs that are leaking into the atmosphere. Due to the warming climate, the use of refrigeration systems and air conditioners is expected to rise. Net emissions could be lowered either by capturing their equivalent in CO_2 with direct air capture, or by using substitutes that have lower global warming potential.

Emissions in the agricultural sector include CO_2, CH_4, and N_2O and come from several distinct subsectors in Nevada: liming of soils, agricultural residue burning, enteric fermentation, manure management, and agricultural soil management. The latter three make up the bulk of emissions in the sector and are the primary areas that would be addressed by a cohesive net-zero strategy. Agricultural emissions make up about 4% of emissions in the state, and their nominal amount is expected to remain relatively constant over the coming decades. It is difficult to use carbon capture or emission reductions in the agricultural sector, unlike the industrial sector, and therefore the best options are the use of mitigation strategies such as changes in fertilizer use, improved low-till and no-till land management practices, the use of cover crops or silvopasture, and improvements to livestock feed. These approaches could potentially offset a significant fraction of anticipated emissions and minimize the need for negative emissions to achieve net-zero in the sector. The reduction of emissions from enteric fermentation through changes in livestock management (a combination of improved grazing conditions and changes to cattle feed) is likely to be the most realistic pathway to emission reductions.

Like emissions from the agricultural sector, emissions from the production and management of waste differ from other sectors because very few anthropogenic CO_2 emissions are actually produced; nearly all the sector's contributions come from CH_4 and N_2O emissions. Emissions come from municipal solid waste, industrial solid waste, and municipal wastewater treatment. While these emissions account for only about 4% of the total share in Nevada, there are still opportunities to reduce emissions without relying entirely on CDR to achieve net-zero. Reducing the per-capita production of waste through sensible changes in consumption is an important part of any plan for reducing emissions, but legacy waste in landfills will continue to emit GHGs long after it was deposited. The flaring and capture of landfill gas (composed of CH_4 and CO_2) is one demonstrated pathway to reduce emissions from waste management and has already been implemented at the Lockwood and Apex Regional Landfills near Sparks and Las Vegas, respectively. Increasing statewide deployment of landfill gas capture at both Nevada Division of Environmental Protection (NDEP) Class I and II municipal landfills and Class III industrial landfills will be key to reducing emissions from the waste sector. Another important potential strategy is establishing new infrastructure to capture emissions from wastewater treatment.

1.5. CDR strategies

CDR strategies involve removing CO_2 from the atmosphere and storing it in a suitable subsystem (e.g., the lithosphere, the technosphere). Such storage must achieve long-term sequestration, and the CDR strategy should not release more CO_2 (or equivalent emissions) to the atmosphere than it removes over its lifecycle. There are multiple ways to implement CDR strategies, depending on the local resources. A previous report estimated that 5.7 $MtCO_2$ was removed through natural CO_2 sinks in 2017, and this number is expected to remain stable in the coming decades[7]. As discussed above (see part 1.2), this report explores technological CDR only, due to the local climate and the unknown potential for nature-based CDR solutions in Nevada[14]. The large potential for energy generation from geothermal[15] and solar[16] also works in favor of technological DAC solutions in Nevada.

Higher TRL[VI] DAC technologies require heat and electricity, with sorbent-based DAC technologies and solvent-based DAC technologies requiring temperatures around 100ºC and 900ºC, respectively[17,18]. Requirements for solvent-based DAC systems will be difficult to fulfill with renewable energy sources, but the needs of sorbent-based DAC systems could be met by geothermal energy or concentrated solar power (CSP). Some lower TRL DAC technologies require only electrical input. Minor variations of the more mature sorbent-based approach with similar infrastructural needs could work, except that instead of desorbing CO_2 from the capture agent using steam, the solid sorbent would be heated by resistive heating. Other emerging options use electrochemistry to selectively sorb and desorb CO_2[19]. These approaches are not tethered to low-carbon thermal sources and have flexible siting options; for example, they can be located at sites that can produce renewable electricity but do not have renewable sources of heat.

We see carbon removal approaches as complementary to efforts to reduce and avoid emissions. Due to the high dilution of CO_2 in the air, technological CDR approaches require large energy inputs and are more costly than point source carbon capture. DAC paired with storage has the potential to be carbon negative, which would also address legacy emissions.

1.6. Challenges of carbon storage

Decarbonization approaches using point source carbon capture and carbon removal approaches using engineered DAC must include a CO_2 storage strategy. There are multiple CO_2 storage options, and the best option in a given situation depends on the local geology and feedstocks.

Conventional CO_2 storage, which is at the commercial stage, is done by injecting CO_2 into sedimentary formations deeper than ~1000 meters, either depleted oil and gas reservoirs or deep saline aquifers. Such formations exist within Nevada, but the subsurface will have to be investigated further to locate them, to understand their potential for carbon storage, and to evaluate the risks. More data are needed on the physical and chemical characteristics of potential reservoirs to estimate their capacity and to assess the risks, given that Nevada is a seismically active state. An alternative to sedimentary rock formations are basalts, and the technology to store carbon in these rocks is being piloted. As with sedimentary formations, CO_2 is injected into basaltic formations deeper than ~1000 meters, where it interacts with the basalt rock and forms carbonate rock. Basaltic formations exist at these depths in Nevada, but again, detailed investigations of the

[VI] TRL, or technical readiness level, describes the stage of technical development on a scale from 1 to 9, where 1–3 typically represents lab scale research and proof of concept, 4–6 represents pilot and demonstration stage, and 7–9 approaches small and full commercial deployment.

subsurface are needed to identify appropriate locations and estimate their potential storage capacity.

Another possibility is to react CO_2 with feedstocks containing large amounts of magnesium and calcium to mineralize CO_2 into carbonate rocks. These feedstocks may be industrial byproducts (e.g., cement kiln dust, lime kiln dust), mine tailings of basaltic or ultramafic composition, or basaltic or ultramafic rocks from mines that are dedicated to provide feedstocks for carbon mineralization. Nevada has numerous outcrops of basalts and a few outcrops of serpentinites and greenstone, so carbon mineralization might be a promising method for CO_2 storage in the state.

1.7. Nevada-specific considerations

Nevada has a population of 3.17 million persons in 2021[20] and one of the highest population growth rates in the country, with a projected population of 3.79 million persons in 2040[20]. It is also one of the most urbanized states, with over 90% of its population living in cities[21]. Nevada is also the driest state in the country[22] and receives only 250 mm of average rainfall per year[23]. Due to water scarcity, the local ecosystems are composed of 74% desert and semi-desert, 15% forests and woodlands, 7% shrub and herb vegetation, and 5% other ecosystems[24]. This desertic environment is appropriate for solar power generation, with an average horizontal solar irradiance of 4.5–5.25 $kWh/m^2/day$ in the northern half of the state and of 5.25–5.75 $kWh/m^2/day$ in the southern part of the state with seasonal variation[16]. Nevada also has one of the highest amounts of geothermal resources in the country[15].

Nearly 87% of the land in the state is publicly owned by the federal government[25], and 63% of the state is managed by the Bureau of Land Management (BLM)[26]. Nevada has extensive mining operations that extract gold, silver, copper, diatomite, lime, sand, and gravel[27,28]. The mining sub-sector consumed over 60 trillion Btu in 2018 (including energy from electricity)[29] and generated over $8B in 2019[28], the highest amount of any state.

Nevada shares borders with two states that have both statutory and executive net-zero targets for 2050: California and Oregon. This could have strong implications on a Nevada-specific strategy. First, economic leakage can occur when there is a strong discrepancy between GHG regulations in neighboring regions. This risk is minimized when neighboring regions share a common pledge (to reach net-zero emissions) and have similar goals, as there is less incentive for businesses to move to avoid stricter regulations on their GHG emissions. However, this also means that Nevada must keep pace (or set the pace) in decarbonization to avoid potential economic leakage *into* the state, which would directly counteract efforts to reduce emissions.

2. Scope and Methodology of This Study

We identified potential realistic pathways by which Nevada could achieve a goal of net-zero emissions by 2050. Generally, this goal can be accomplished by mitigating emissions in the first place, performing point source capture of necessary emissions, and balancing the remainder of emissions with adequate carbon removal, through either nature-based solutions such as afforestation/reforestation or engineered solutions like DAC. Emissions from the primary sectors investigated in the 2019[30] and 2020 NDEP[7] state inventory reports are projected to 2050, and pathways for mitigation, reduction, and removal are described for each. The sectors of interest defined by the NDEP GHG state emissions inventories are transportation, energy generation, industry, residential and commercial, waste, and agriculture. The different areas of the emissions portfolio of Nevada each present unique challenges to decarbonization and emission reductions, as the sources of emissions, types of GHGs emitted, and predicted changes in emissions over the next several decades vary considerably from sector to sector.

In the pages that follow, we have outlined the most promising strategies for reducing GHG emissions. Their deployment varies, depending on which scenario Nevada follows to achieve its goal of net-zero emissions by 2050. In each case, the total emission reduction for each sector is quantified and the goal of net-zero emissions is met by offsetting the remaining emissions with carbon removal.

2.1. Scenarios

Projection out to 2050 is difficult because it is uncertain whether current trends will maintain the same trajectory, different levels of economic investment are required, it is unclear what impacts actions and decisions (political and otherwise) will have on neighboring states, and unknown climate feedbacks may induce a shift in priorities. We recognize that there are many pathways to achieve net-zero, and thus we make no prescriptive recommendations based on single outcomes. To address these inherent uncertainties, we define a business-as-usual scenario and four unique decarbonization scenarios with progressive assumptions and actions:

> *Business as usual (BAU) scenario.* In this "pre-baseline" case, all growth trajectories are held at pre-goal levels. It assumes a future where no net-zero goal has been established and there are zero concerted efforts toward decarbonization of any sector, beyond what would be considered normal practice. In this scenario, natural gas–fired power plants remain active without carbon capture technologies, and residential and commercial locations continue to optimize activities toward least-cost options (e.g., cheaper but less efficient appliances, no efficient building shells, transportation technologies mirror 2019). It represents the collective impact of counterfactual outcomes (absence of action) linked to the decarbonization strategies set forth in the remaining scenarios.

Baseline scenario. In the baseline case, a call to action has been established, but movement proceeds without urgency. Sectors transition toward lower-carbon outputs on a voluntary basis, and comply at the bottom end of projected ranges. This case can be interpreted as the BAU scenario with extended, marginal efforts in the direction of net-zero. It is likely to prevail if there are no incentives to increase efforts early and throughout the 2020–2050 timeframe. This scenario can still achieve net-zero emissions but relies *heavily* on CDR to offset non-mitigated emissions.

Low-optimistic scenario. In this scenario, actions are notably more aggressive than in the baseline. Mitigation efforts, including carbon capture and sequestration of industrial and power exhaust streams, are undertaken to prevent over-reliance on engineered CDR in 2050. Although very high compliance standards may be set, actual compliance remains lower than anticipated due to lack of support and slow dissipation of initiatives.

High-optimistic scenario. This scenario represents extreme action, fueled by compliance mandates and aggressive initiatives, likely backed by strong governmental support. It sets out to minimize the amount of CDR required by making a heavy investment in emission reduction, through CCS and near-full electrification of the transportation and residential and commercial sectors. This scenario is best viewed as a realistic-ideal case, in which 100% compliance is aggressively sought but, due to various factors like minimal active resistance by some actors, or difficulty in full transitioning in certain remote locations, the actual compliance falls short.

Best-case scenario. This borderline fictitious scenario is designed to represent the incremental extension of the high-optimistic scenario to ideal conditions. Electrification of homes and businesses achieves 100%, ICEVs are fully replaced by EVs, and all residual fossil-firing power is spontaneously committed to retirement at 2050. This case is less instructive for informing actual mitigation efforts, but represents the absolute minimal amount of CDR required in 2050 to achieve net-zero under ideal conditions.

2.2. Sectoral strategies

2.2.1. Transportation sector

Many of the emissions from Nevada's transportation sector are not directly produced by the state. In 2019, Nevada produced 268,000 barrels of crude oil, less than 0.01% of total production in the United States[31]. In this same year, Nevada imported 58,555,000 barrels of petroleum products, and 86% of them went to the transportation sector[32]. Nevada was not directly involved in the production of these products, but their life cycle emissions are factored in because Nevada could avert these emissions by switching to alternative vehicle fuels.

Emissions from the production of vehicles are not incorporated into projections. It is difficult to quantify these emissions because they come from many different sources. For instance, the Tesla Gigafactory in Sparks, Nevada, is entirely powered by renewable energy, but it will likely produce scope 3 emissions (indirect emissions) from vehicle and battery manufacture[33,34]. Transportation supply chains could decarbonize as well, to approach a net-zero emissions future.

The majority of transportation sector emissions result from the combustion of fossil fuels in ICEVs. The three major fuel types used in Nevada are gasoline, diesel, and jet fuel. Of these, gasoline has the greatest impact on GHG emissions because it is widely used by most light-duty vehicles, as well as by some medium-duty and heavy-duty vehicles. Diesel fuel is rarely used by light-duty vehicles in the United States, but the majority of medium-duty and heavy-duty vehicles use it. Lastly, the overwhelming majority of airplanes run on jet fuel. Other fuels are used in Nevada, such as aviation gas, lubricants, and natural gas, but these have little effect compared with gasoline, diesel, and jet fuel.

Table 1. Summary of assumptions for calculations related to the transportation sector.

Parameter (2050 Target)	Baseline	Low-Optimistic	High-Optimistic	Best-Case
Change in light-duty AVMT (%)	25.4% (equal to population growth)			
Change in medium-duty and heavy-duty AVMT (%)	25.4% (equal to population growth)			
Change in aviation AVMT (%)	70%	70%	20%	-20%
EV penetration (% of stock, light-duty)	20	50	75	100
EV penetration (% of stock, medium-duty and heavy-duty)	5	10	20	60
Alternate fuels penetration (% of stock, medium-duty and heavy-duty)	0 (no major R&D breakthroughs)		25	20
Alternate fuels penetration (% of stock, aviation)	0 (no major R&D breakthroughs)		25	50
Gasoline C.I. (gCO_2e/BTU)	0.084	0.071	0.058	0.029
Diesel C.I. (gCO_2e/BTU)	0.085	0.076	0.066	0.033
Jet fuel C.I. (gCO_2e/BTU)	0.085	0.072	0.058	0.029

AVMT = annual vehicle miles traveled; EV = electric vehicle; C.I. = carbon intensity

To determine transportation sector emissions projections for 2050, we considered four main factors. The first was annual vehicle miles traveled (AVMT), which describes the total distance traveled by all vehicles that use a given type of fuel in a year. Nevada's population is expected to increase by 20.4% by 2040[20]. If the trend predicted by the Nevada Department of Taxations persists, the population growth should reach 25.4% by 2050. So we used a 25.4% population increase to estimate AVMT increases, and thus increases in gasoline and diesel consumption. Jet fuel demand is expected to increase even more, as the Energy Information Administration's 2020 Annual Energy Outlook projected that rising personal incomes and desire for connectivity would increase air travel AVMT by 70%[35]. These AVMT values may fluctuate if there are unexpected changes to Nevada's population or economic strength. If the income distribution changes, there will also be changes in the demand for personal vehicle use or delivery services, which could affect gasoline and diesel fuel consumption, respectively.

The second factor we considered, EV penetration, is an alternative to fossil fuels. It refers to the percentage of vehicles in Nevada that will be battery-powered electric vehicles (BEVs) by 2050. In 2018, the transportation sector in Nevada only used 30 billion BTU of electricity, compared with 230 trillion BTU of energy for all sectors in the state[36]. EV sales are expected to take off with increased government support and further research and scaling, which increases fuel economy and decreases price. The success of EVs in lowering GHGs is heavily dependent on EV technology improvements. EVs are currently a viable replacement for light-duty vehicles like passenger cars, but large battery sizes and range anxiety means that further development is necessary before EVs can replace medium-duty and heavy-duty vehicles. Fuel economy for EVs has improved considerably over the past decade, but it may be near its limit, and the scenario builder takes this into account[37]. The potential of EVs to lower GHGs also depends on electric grid carbon intensity (gCO_2e/BTU), which can be lowered by producing electricity from renewable sources.

The third factor we considered, also an alternative to fossil fuels, is alternative fuel penetration. It refers to hydrogen fuel cell vehicles (FCVs) or carbon-neutral synthetic fuels. These would have substantial impact on vehicles that are difficult to electrify, such as airplanes and medium-duty and heavy-duty vehicles. Carbon-neutral synthetic fuels could replace fossil fuels, prolonging ICEV production. This would be important if EVs failed to scale or to accommodate for Nevadans who do not want to purchase a new vehicle. Because of the extensive research and development necessary for these technologies to scale, we consider these fuels only as a replacement for diesel and jet fuel in the high-optimistic and best-case scenarios.

The fourth factor affecting transportation sector emissions is the carbon intensity of fossil fuels, measured in gCO_2e/BTU. Improvements in internal combustion engines can improve the efficiency of vehicles (the fuel economy), so that more of the energy contained in the fuel is ultimately used to move the vehicle. Modification of the fuel itself, such as by mixing in carbon-neutral biofuels, can also decrease gCO_2e/BTU. Improvements in extraction and refinement of fossil fuels before combustion can decrease gCO_2e/BTU as well. Future carbon intensity benchmarks for 2050 were extrapolated from California's Carbon Intensity Benchmarks from 2011 to 2030[38].

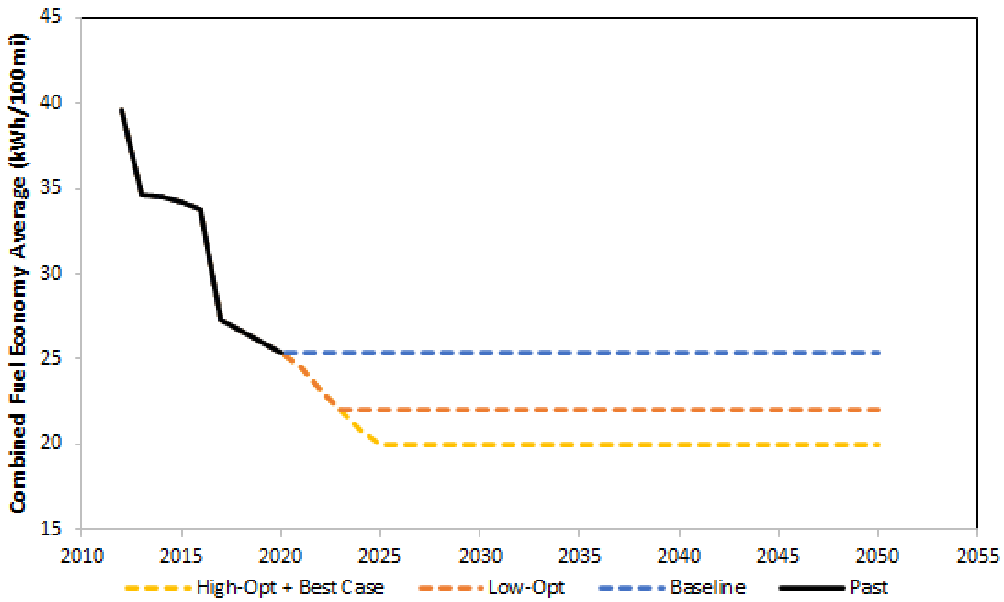

Figure 4. Past and projected fuel economy of electric vehicles on the market.

2.2.2. Electricity generation sector

The electricity generation profile has changed significantly over the past two decades, as shown in Figure 5[39]. In 2001, coal-fired power plants were producing about half of the electricity in the state. Coal has been gradually replaced by energy sources with lower carbon intensity: it was surpassed by natural gas in 2005 and renewable sources of energy (excluding large hydroelectric) in 2015. In 2020, 66% of the state's energy was produced by natural gas power plants, 24% by renewable energy sources (excluding large hydroelectric dams), 5% by coal power plants, and 5% by large hydroelectric dams. As shown in Figure 5, the change in the energy generation profile has resulted in a reduction of the grid intensity by half, compared with its early-2000s level.

The EPA listed 15 natural gas power plants and two coal power plants in Nevada in 2019[40]. The North Valmy coal power plant is scheduled to decommission by 2025, while the TS Power Plant will transition to a dual coal–natural gas power plant in 2022[4,12]. The first natural gas units were built in the 1960s and 1970s, but most of the capacity was built in the 1990s and 2000s. These units should retire between 2040 and 2060, assuming a lifetime of 50 years (Fig. 6)[41,42].

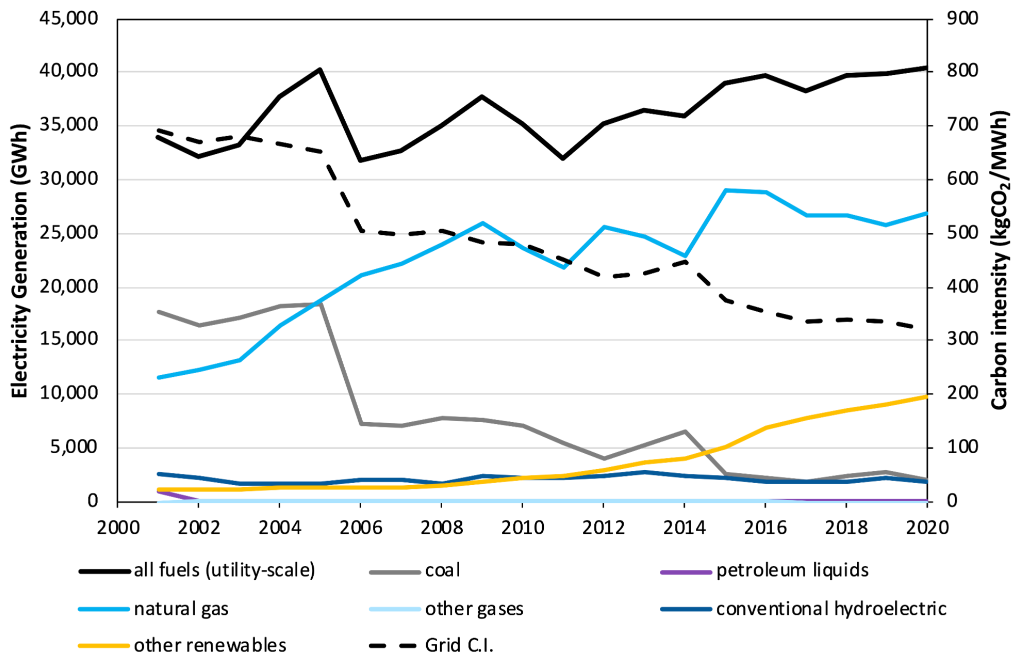

Figure 5. Breakdown of electricity generation by fuel for the last two decades, and carbon intensity of the grid[39].

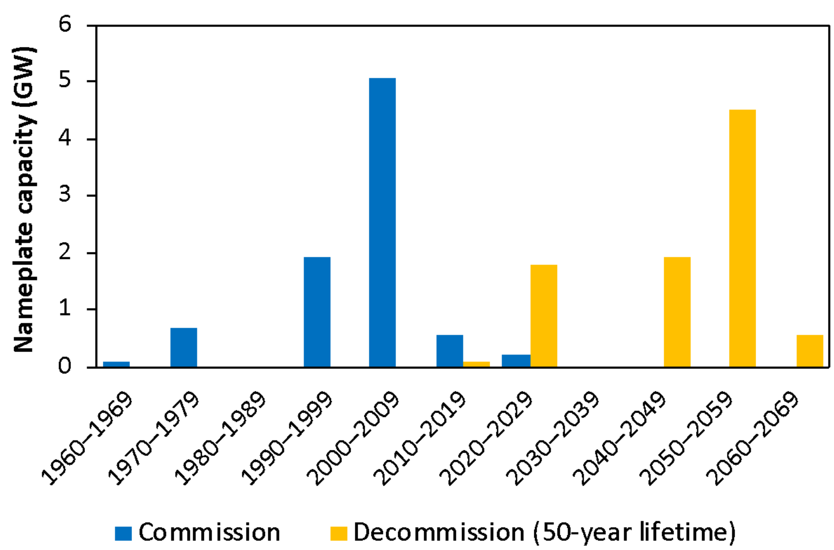

Figure 6. Timeline of the commissioning and decommissioning of natural gas power plants (assuming a lifetime of 50 years when no decommission data are available)[41,42].

No new natural gas power plants are planned in the state, and the growing demand is expected to be met by renewable sources of energy. Conventional hydroelectric power generation has been stable around 2000 MWh for the past 20 years[39] and projections to 2050 assume that it will remain stable. However, water scarcity is worsening and might lead to a decline in electricity generation from hydroelectric dams. Lake Mead, the largest human-made reservoir in the United States, which is closed by the Hoover Dam, is currently filled to only 40% of its capacity[23]. Our projections thus include both the possibility that hydropower generation will remain stable and that hydropower generation will drop to zero.

Other forms of renewable energy are increasing production in Nevada, which is one of the leaders in geothermal and solar energy resources in the United States. In 2020, Nevada produced over 4000 MWh of electricity from geothermal power plants and 5000 MWh from utility-scale solar farms[39]. While solar energy has developed extensively in the past few years due to low capital costs, the development of geothermal energy has been slower due to the high capital cost of drilling the wells and building the power plants. There are vast amounts of untapped geothermal energy potential in the state and surrounding region, possibly in the order of tens of gigawatts[VII], which is more than ten times the capacity of all power plants in Nevada today. Geothermal presents other advantages compared with solar, including a smaller surface area per unit of electricity generated, the continuous generation of electricity, and the option to use the heat directly for various uses like greenhouses, resorts, district heating[VIII], and space heating.

We estimated the carbon intensity of the grid using the electricity generation per fuel type and the carbon intensity of fuels. We used a carbon intensity of 1,002.4 gCO_2/kWh for coal and 412.8 gCO_2/kWh for natural gas for this calculation, and assumed a carbon intensity of zero for conventional hydroelectric and other renewable energy sources. To estimate past carbon intensity of the grid, we used data from the EIA[39], and to estimate future carbon intensity, we used projected electricity demand in 2050, as described below. The carbon intensity of the grid also depends on the deployment of carbon capture technologies at natural gas power plants, as described in Table 2.

Table 2. Summary of assumptions for calculations related to the electricity generation sector.

Parameter (2050 target)	Baseline	Low-optimistic	High-optimistic	Best-case
New fossil-fueled power plants	No			
Lifetime of natural gas power plants	50 years			all power plants phased out
Future of coal power plants	Valmy: decommissioned (2025) / TS Power: full conversion to natural gas (2022)			all power plants phased out
RE capacity	match with the estimate of the total generation capacity			unlimited
New generation capacity (% RE)	depends on RE capacity; RE covers all new needs for electricity generation			100%
Point source capture (CC) at natural gas plants (%)	no CC	50% CC	100% CC	no CC (because all power plants are phased out)

[VII] Personal communication: James Faulds, Nevada Bureau of Mines and Geology.
[VIII] District heating describes the distribution of centrally produced thermal energy through insulated piping to broad residential and/or commercial areas.

The demand for electricity in Nevada is expected to rise due to the growing population and increased electrification in all sectors of the economy. The demand for electricity in the coming decades was estimated using assumptions that are specific to each sector.

In the industrial sector, only a fraction of the emissions can be reduced by electrification due to process emissions. We calculated additional electricity needs in 2050 from electrification in the industrial sector using the projected emissions of CO_2 sources that can be electrified (e.g., kilns, boilers, heaters, engines) and the carbon intensity of fossil fuels (92.1 gCO_2/MJ for coal, 50.3 gCO_2/MJ for natural gas, and 69.3 gCO_2/MJ for diesel fuel). As electric kilns are not yet available on the market, their electricity demand was calculated separately, and kiln electrification was considered only in the high-optimistic and best-case scenarios. The other combustion emissions were split into two categories: emissions from natural gas and emissions from petroleum. The systems using natural gas follow the same electrification compliance as the residential and commercial sector, whereas the systems using petroleum follow the same electrification compliance as heavy-duty trucks, since most petroleum users are likely hauling trucks in the mining industry.

Though the transportation sector currently makes up only a small fraction of Nevada's electricity demand, this portion is expected to change due to the scaling up of EV production and government action[43]. To estimate the electric grid GWh required by 2050 for the transportation sector, we estimated the percentage of light-duty, medium-duty, and heavy-duty vehicle stock that would be electric by 2050 for each scenario. Aviation was not considered because to date, no economical method to electrify air transport has been developed. These values vary because electrification of heavier vehicles is more difficult, given current range limits and large battery sizes. Using Nevada's AVMT data from 2019 and considering expected population growth, we estimated AVMTs for 2050, as well as the percentage of those vehicle miles that would be traveled using EVs. We also considered the energy-efficiency of EVs (compared with ICEVs), comparing the average fuel economy of ICEVs to average fuel economy projections for EVs in 2050.

The residential and commercial sectors consumed 13.5 and 12.1 TWh of electricity in 2019, representing roughly 47% and 48% of sector energy consumption, respectively. The remaining energy came from natural gas, biomass, petroleum, and renewable energy (e.g., solar, geothermal). Electricity consumption per building unit in the residential and commercial sectors reached 10,400 kWh/yr and 177,000 kWh/yr, respectively. Most of the electricity in these sectors powered cooling operations, appliances, equipment, and lighting. Conversely, space heating, water heating, and cooking were mainly powered by natural gas, at 80% of the total energy share. Heating also constituted the greatest demand for energy in both residential and commercial units, commanding 65% and 42% of total energy, respectively.

To estimate the increase in electricity demand in the R&C sector, we carried forward baseline electricity use from established housing and businesses, assuming periodic upgrading of appliances and consumption devices to reflect incremental gains in efficiency (see Table 5 for 2050 efficiency targets across various scenarios). New construction was assumed to have all-electric, high-efficiency appliances and thus scaled with current electric demand. Existing construction saw two important and counteracting considerations, namely a decrease in per-unit electricity consumption due to enhanced efficiencies, and an increase in per-unit electricity consumption due to the replacement of natural gas sourcing with electricity, for example through replacement of a gas furnace (COP of 0.8 to 0.9) with a heat pump (COP of 3.5).

Future demand for electricity will have to be met by building new power plants. We assumed that new builds would use exclusively renewable energy, and used the capacity factors reported in Table 3 to estimate the capacity needed to meet the future demand for various sources of renewable energy. The capacity factor range is provided by the National Renewable Energy Lab[44]; when no specific capacity factors were found for Nevada, we used the median of the range in the calculations. The capacity factors for solar photovoltaic (PV) capacity and wind in the current study fall out of the range, because Nevada has particularly high solar potential and particularly low wind speeds compared with the rest of the United States.

Table 3. Capacity factors for various renewable energy sources[44,45].

Source of energy	Capacity factor (%)	
	IQR	Value used in the current study
Solar PV	18.0–25.3	27.8
Solar CSP	29.0–44.6	38.5
Geothermal	75.0–94.3	85.0
Wind	30.0–40.9	28.2

PV = photovoltaic; CSP = concentrated solar power; IQR = interquartile range (in a ranked dataset, the median is the middle value of the dataset, and the interquartile range represent 50% of the data included in the two quarters surrounding the median)

2.2.3. Industrial sector

The process emissions from the industrial sector stayed relatively stable over the last two decades, with the exception of substitutes for ozone-depleting substances (ODS). The projections of emissions through 2050 thus assume that emissions will remain constant for most subsectors (cement manufacturing, lime manufacturing, limestone and dolomite use, and soda ash production) and some ODS substitutes (aerosols, fire extinguishers, and foams). Emissions projections from subsectors that showed emissions variations in the past (electric power transmission and distribution systems, refrigerators and air conditioners, and other applications of ODS substitutes) were estimated by generating a linear fit for emissions from the past 10 years. For the past 20 years, the ratio of industrial process emissions to total industrial emissions has stayed stable at 0.35, so it was used to estimate the total emissions from the industrial sector in 2050. Also, emissions from the natural gas and oil systems stabilized around 0.98 $MtCO_2e$ and are assumed to remain constant in our projections.

Facility-level emissions breakdowns were retrieved from the EPA database Facility Level Information on GreenHouse gases Tool[40]. For the calculations of fuel switching in cement and lime kiln, we used fuel intensities of 92.1 gCO_2/MJ for sub-bituminous coal and 50.3 gCO_2/MJ for natural gas. Biomass has the same fuel intensity as coal, the only difference being that the resulting emissions are biogenic. Due to the different types of emissions and the variability in emission sizes, different strategies should be used to abate emissions from the industrial sector. The assumptions for the calculations are summarized below (Table 4).

Table 4. Summary of assumptions for calculations related to the industrial sector.

Parameter (2050 target)	Baseline	Low-optimistic	High-optimistic	Best-case
Decarbonization strategies for fuel combustion emissions, outside of cement and lime plants				
Electrification compliance (replacing natural gas use)	60%	75%	90%	100%
Electrification compliance (replacing petroleum use)	5%	10%	20%	60%
Decarbonization strategies at cement and lime plants				
Fuel switching (maximum coal replacement)	biomass to replace 20% of coal natural gas to replace 100% of coal			
Fuel switching (biomass)	at 2 facilities	at 1 facility	-	-
Fuel switching (natural gas)	at 1 facility	at 2 facility	at 2 facilities	-
Electrification	-	-	at 1 facility	at all facilities
Point source carbon capture efficiency	-	90%		
Point source capture at industrial facilities ($MtCO_2/yr$)	no CC	CC at cement plant	CC at cement + 1 lime plant	CC at all plants
Decarbonization strategies for process emissions, outside of cement and lime plants				
Growth in electrical transmission and distribution	match to electricity demand in 2050			
Replacement of SF_6 by CO_2 in electrical equipment	50%	70%	90%	100%
Replacement of ODS by CO_2 in refrigeration and air conditioning equipment	50%	70%	90%	100%

2.2.4. Residential and commercial sector

Emission growth in the R&C sector is largely anchored by population growth over the next three decades, which will ultimately place new infrastructure into existence and place an increased burden on energy consumption to meet basic needs and ensure both a standard quality of life and standard business practices. These needs are slightly exacerbated by a projected increase in the number of hot days (over 100˚F) each year by approximately +15% over the next 30 years. Since emissions in this sector are tied heavily to building infrastructure and operational decisions regarding choice of equipment, growth in the sector is divided into two categories: existing builds and new builds.

Table 5. Summary of assumptions for calculations related to the residential and commercial sector.

Parameter	Baseline	Low-optimistic	High-optimistic	Best-case
% building units with high-efficiency shells (2030)	11	18	25	31
% building units with high-efficiency shells (2040)	25	38	50	63
% building units with high-efficiency shells (2050)	50	63	75	100
% of building units with all-electric appliances (2030)	30	44	58	73
% of building units with all-electric appliances (2040)	50	70	90	95
% of building units with all-electric appliances (2050)	75	85	95	100
% of building units with high-efficiency appliances (2030)	20	30	40	50
% of building units with high-efficiency appliances (2040)	40	50	60	75
% of building units with high-efficiency appliances (2050)	60	75	90	100
% New home efficiency savings (2030)	20			
% New home efficiency savings (2040)	25			
% New home efficiency savings (2050)	30			
% High-efficiency gains (2030)	95			
% High-efficiency gains (2040)	90			
% High-efficiency gains (2050)	85			

Nevada had a 2020 baseline population of 3,145,184 people in 1,098,602 households, according to the most recent census data[20,46]. The mean number of persons per household is 2.67, which is expected to hold steady for the growth period under study. According to the U.S. Census Bureau building permit survey, Nevada filed for 19,716 building permits in 2020. Based on population growth between 2019 and 2020, approximately 14,355 new housing units needed to be constructed to accommodate the increased population at a fixed household density. Hence, it is reasonable to expect that all new population growth will be accommodated by new housing units. The slight discrepancy in building permits over projected new housing suggests a small turnover in older housing. However, given that Nevada *leads the nation* in terms of youngest median age of owner-occupied homes at 23 years[47], this study assumes that all new housing will be dedicated to new residents, and existing housing will be upgraded systematically to keep pace with state-of-the-art emission reduction strategies in the sector, including retrofitting to more efficient building shells via insulation, double-pane high-efficiency windows, and other improvements, implemented periodically.

For existing infrastructure, building efficiency is improved systematically over the next 30 years, from moderate in the baseline scenario to highly aggressive in the best-case scenario (achieving 100% retrofit by 2050). These modifications improve building efficiency by 20–30%, which can help offset incremental energy consumption levied by warming conditions. Over the same period, existing buildings will undergo a gradual transition to electrification, systematically replacing all fossil-fuel consuming appliances and services with higher efficiency electrical counterparts. Existing electrical appliances will also be upgraded to higher efficiency (Energy Star–rated[IX]) appliances over time, and average appliance lifetime means that continual upgrading to state-of-art efficiency will occur over the next three decades. The four scenarios parallel-build shell efficiency, where appliance upgrading is viewed as moderate in the baseline case and ultra-aggressive (to 100% compliance in 2050) in the best-case scenario.

For new buildings, this study takes the bold stance that all new infrastructure can be constructed to achieve at least 20% efficiency gains over baseline (existing) builds, meeting progressive benchmarks of 25% in 2040 and 30% in 2050. Likewise, all new housing and businesses will feature all-electric, high-efficiency appliances rather than appliances that use fossil fuels.

Nevada had 68,567 establishments that employed people in 2019, employing an average ~45 people per establishment[47]. We took a similar approach in terms of fixed employment density and new infrastructure to accommodate population-driven economic growth in the state. Likewise, we took an analogous approach to the residential sector for decarbonization of existing and new buildings.

[IX] Energy Star is a government-backed labeling for consumer products that achieve requisite benchmarks in efficiency gains over standard products and practices.

2.2.5. Waste management sector

The primary method for reducing emissions in the waste sector is landfill gas-to-energy (LFGTE) combustion, combined with CO_2 capture. Based on the technical specifications of the gas capture system in place at the Apex Regional Landfill, we assumed that 75% of emissions produced at a landfill may be utilized via LFGTE when a system is present. As there is currently no planned expansion of landfill gas flaring or LFGTE in Nevada, the baseline scenario assumes that the total capture capacity remains constant, and the capture capacity scales upward in the low-optimistic, high-optimistic, and best-case scenarios, in the last of which 100% of Nevada's landfills will incorporate capture systems. Landfill gas flaring, which does not produce energy, has fewer potential social benefits than GTE systems and is therefore omitted as a pathway in the optimistic and best-case scenarios. We also assumed that emissions from wastewater treatment operations may be reduced in the enhanced scenarios through gas capture and flaring systems, although the potential for energy generation from these has not been quantified.

Waste sector emissions were projected based on the 2019 NDEP GHG emissions report[30]. Production of municipal solid waste (MSW) following recent annual trends was regressed using historical population data, and available data on waste in landfills was taken from the NDEP for the years 2012–2019 (2020 was discounted due to potential confounding impacts of COVID-19). Emissions from the decomposition of waste were estimated with a first-order decay model utilized by the EPA State Inventory Tool (SIT) for the waste sector that was used in the NDEP study[30]. Data for legacy waste-in-place at Nevada landfills were taken from the estimates used by the SIT for 1960–2004, and data from 2005–2020 were taken from available NDEP reporting. For the years 2021–2050, produced MSW was estimated using the regressed data from 2012–2019 and the predicted population growth over that period. Industrial solid waste (ISW) projections were generated following the same procedure. Methane emissions in the first-order decay model are based on the total tons of waste added to landfills each year.

Table 6. Summary of assumptions for calculations related to the waste management sector.

Parameter (2050 target)	Baseline	Low-optimistic	High-optimistic	Best-case
Waste diversion goal rate (%)	25	40	50	60
Waste diversion goal achieved	2025	2050	2045	2040
LFGTE deployment (%)	40	50	65	100
Wastewater gas flaring capacity (%)	0	20	40	50

The baseline scenario in this analysis assumes that Nevada will achieve its long-standing goal to recycle 25% of its waste statewide, which will reduce the total amount of emissions generated by adding waste to landfills. In addition, it assumes LFGTE capacity will remain roughly constant over the next several decades, and existing infrastructure will be capable of processing 40% of the state's landfill methane emissions with an efficiency of 75%. Improved scenarios investigate the effects of not only improved waste diversion rates (40%, 50%, and 60% overall) but also an accelerated timeline for achieving these rates (by 2050, 2045, and 2040). The fraction of landfill methane emissions that will be processed by LFGTE systems increases to 50%, 65%, and 100% in the three improved scenarios. Of the methane emissions which are reduced to CO_2, 90% are captured and added to the state total of stored CO_2. In addition, the 2019 NDEP GHG inventory suggests that the flaring of wastewater emissions can reduce waste sector emissions by reducing CH_4 emissions to CO_2[30]; thus, flaring from wastewater could reduce emissions by 20%, 40%, and 50% in the improved pathways, over zero in the baseline.

2.2.6. Agriculture sector

In the agricultural sector, emissions may be reduced from agricultural soil management, enteric fermentation in livestock, and manure management. Other subsectors considered in the 2019 NDEP GHGs inventory total a very small fraction of emissions in this hard-to-reduce sector and will likely be challenging to reduce[30].

Table 7. Summary of assumptions for calculations related to the agriculture sector.

Parameter (2050 target)	Baseline	Low-optimistic	High-optimistic	Best-case
Low-till and no-till soil management (%)	0	35	60	100
Lower-emitting cattle feed (%)	0	20	45	100
Grazing land improvements (%)	0	10	25	50
Efficient fertilizer usage (%)	0	40	75	100

The 2050 emissions from the agricultural sector were estimated using the EPA SIT Agricultural Module and the associated projection tool. Historic agricultural data are utilized for the GHG inventory portion, and appropriate population estimates are used to predict changes in emissions over the next several decades. The total amount of agricultural emissions is not estimated to change dramatically despite population growth (about a 2.2% increase in CO_2e emissions from 2016), but the share of emissions from each subsector is predicted to shift. The sector share of enteric fermentation and manure management emissions is predicted to shrink following nationally expected trends and as water scarcity makes livestock farming in Nevada more challenging. Increased emissions from agricultural soil management will offset these losses and present an opportunity for alternative fertilizer usage and land management strategies. The improved emissions scenarios demonstrate the potential impacts of improved cattle feed quality, minimum-tillage agriculture, improvements to grazing lands for livestock, and improvements to the efficiency of fertilizer usage as possible pathways for emission reduction in the sector.

2.3. Carbon dioxide removal and storage

2.3.1. Direct air capture

Given estimates in each sector using the methodologies defined above, we evaluated the potential to offset residual emissions in 2050 with engineered CDR through DAC. First, we tallied the sum of all residual emissions across the aforementioned sectors, assuming a 3% loss due to transportation (powering, transport, and fugitive loss)[X] and a 1% loss during storage to meet the minimum storage requirement targets set forth by the US Department of Energy[48]. These emissions must be offset with DAC, which can leverage existing resources in the state to remove CO_2 directly from the air and provide a negative credit in the overall accounting to reach net-zero emissions.

The current state of DAC commercialization affords two technical approaches: a solvent-based system and a sorbent-based system. These technologies have advantages and disadvantages that can play into regional variability. For example, a large solvent-based DAC system requires a significant amount of water but may take up less land area than the more modular-based sorbent approach. Meanwhile, the sorbent system requires less water to operate, an important consideration in water-scarce regions, and requires a much lower quality of heat for regeneration, at around 100–120˚C, which makes it a prime candidate for integration with geothermal heat. For these reasons, the modular sorbent-based approach seems most suitable for deployment in Nevada. We calculated net carbon removal by identifying the thermal source, electric source, and embodied emissions in the DAC infrastructure and capture media (e.g., sorbent and monolith support). Captured CO_2 is compressed to transport specifications based on the mode of transport (rail, trucking, or pipeline) for delivery to reliable storage.

As of 2021, the only major sorbent-based DAC with commercial operations is Climeworks, and the largest scale of operation in planning was their Orca Plant, at 4,000 tCO_2/yr. The solvent-based Carbon Engineering, on the other hand, is planning a 1MtCO_2/yr scale plant in the Permian Basin. It is expected that by the time Nevada needs considerable DAC, both technologies will have proven commercially at scale.

2.3.2. CO_2 storage

Storage through mineral carbonation of industrial alkaline waste and mine tailings. Processes for *ex-situ* carbon mineralization (CM) are anticipated to improve over the several decades and may present an opportunity for the storage of captured CO_2. CM involves either ambient uptake into or engineered carbonation of industrial and mining waste materials that have already undergone several mechanical or chemical processing steps that may enhance reactivity.

[X] While transport-related emissions largely depend on haul distance and mode, emissions generally fall around 3%, or 0.03 kgCO_2e per kg CO_2 transported (authors' calculations).

Cement kiln dust, lime kiln dust, and mafic or ultramafic mine tailings all present sources of alkalinity via calcium and magnesium cations and can react with CO_2 to form mineral carbonates. These carbonated wastes could be either sold as pure carbonates if market demand exists or reused as synthetic construction aggregates, offsetting the production and associated emissions of some mined aggregates in the state. Nevada is home to one cement plant and two lime plants[40] that can serve as reliable sources of industrial alkalinity over the next several decades. Data for the production of mine tailings and CO_2 storage capacity offered by the mining sector may be inferred from available GIS information on the locations of operating mines, the geology of Nevada, geochemical studies on regions near mines of interest, and reported production and ore grades of mining activities in the state. In addition, the opportunities for carbon mineralization through projected increases in lithium mining activity over the next several decades may be investigated through spatial analysis of active lithium mining claims in the state.

In-situ storage. In-situ storage of CO_2 is done at a commercial scale in sedimentary reservoirs, and at a pilot scale in basaltic formations. In order to store more CO_2 and to reduce the risks of leakages, the CO_2 needs to be stored in its supercritical form, deeper than 800 meters in the Earth's crust.

Appropriate sedimentary reservoirs are depleted oil and gas reservoirs and deep saline aquifers. Depleted reservoirs present the advantage that they are already well known due to earlier exploration and might have infrastructure in place that could be used for injecting CO_2 into the subsurface. Knowledge of deep saline aquifers might be more limited, but commercial-scale injection of CO_2 into these types of reservoir has proven successful since the Sleipner project in offshore Norway that started in 1996[49]. Since then, 51 CO_2 injection projects have been developed around the world, storing about 94 $MtCO_2/yr$[50]. Basaltic formations can also host CO_2, as shown by two successful pilot projects: CarbFix in Iceland[51-54] and Wallula in Washington state[55]. CO_2 is reactive with basalt, and CO_2 has been shown to mineralize into carbonates in less than two years in basaltic formations[52]. The geology is very location-specific, so having a portfolio of geologic formations that can be used for storing CO_2 increases the probability of having appropriate formations nearby. Also, each geologic setting is unique and each location will need to be evaluated in order to determine whether CO_2 can be injected and stored there.

Depths compatible with supercritical CO_2 are much greater than the depths of drinkable water reserves, which should not be polluted by CO_2 storage. Also, geological reservoirs targeted for CO_2 storage should not be connected to reservoirs used to retrieve geothermal energy. In some cases, water availability can be a limiting factor for the CO_2 injection process, as the CO_2 needs to be dissolved in water before being injected at depth. For instance, the CarbFix project uses 27 tons of water per ton of CO_2 injected[54]. Water can also be a limiting factor in the case of sedimentary formations; the injection of CO_2 in depleted oil and gas reservoirs can be alternated with the injection of water to better distribute the CO_2 in the reservoir. In the case of deep saline aquifers, water availability might be less critical as targeted formations are already filled with brine, in which the CO_2 should dissolve.

Nevada has a complex geology and includes many basins of varying sizes and geometry. The basins generally contain thick sequences of sediments, commonly exceeding 1,000 meters and in some cases reaching several kilometers in thickness[XI]. These basins should be investigated further, especially Neogene basins, as some of them contain evaporites[56], which can act as caprocks. Nevada is seismically active, especially the western portion of the state. Southern Nevada is the least seismically active part of the state, so it might be the best place to evaluate for in-situ CO_2 injection and storage in Neogene basins. As sedimentary and basalt formations suitable for CO_2 injections still need to be further investigated and characterized in Nevada, this report explores options in neighboring states, where the CO_2 could be transported and stored.

Transport of captured CO_2 can occur via tanker trucking, pipeline, rail, or some combination of these modes. The correct choice of mode can be set by physical and economic considerations, with trucking generally reserved for volumes under 300,000–500,000 tCO_2/yr[57,58]. Trucking is also sometimes necessary for the front- and back-end of rail transport to deliver CO_2 to and from terminals. The unit costs are higher for trucking than for rail, at \$0.18/t-mile and \$0.07/t-mile, respectively[58]. However, rail transport is expected to cost an additional \$2/tCO_2 transported to cover staging, loading, and unloading operations.

Pipeline transport is more economical for higher volumes of material, though planning and implementation can face geophysical challenges and cost escalators when traversing mountainous terrain and can face social acceptance and right-of-way barriers when routed near or through populated regions. Unit costs for pipeline transport are more variable due to factors such as change in elevation, pipeline diameter, pressure and booster spacing, labor, and right-of-way permitting. Generally, the unit cost of pipeline CO_2 transport is around \$0.05/t-mile at scale (over 1 million tonnes transported), with higher costs incurred at lower volumes.

2.4. Land area

The scale of the future energy demand raises concerns about the availability of land where future renewable energy projects may be developed, considering local environmental concerns. Factors used to estimate the land area of these future projects and the energy needed for DAC are reported in Tables 8 and 9. Solvent-DAC systems have lower land footprints than sorbent-DAC systems, due to the high temperatures needed for the calcination step that require the use of natural gas; meanwhile, thermal energy needs of sorbent-DAC systems can be entirely met by renewable sources of energy. This report primarily explores the potential and needs of sorbent-based DAC, as its energy needs can be fully met by renewable energy sources. However, the land area required

[XI] Jim Faulds, personal communication.

for a DAC plant and the associated source of energy can be significantly higher for sorbent-based DAC than for solvent-based DAC, depending on the source of energy (Table 9). If land availability is a limiting factor, options that use natural gas can be considered, as these solvent-based DAC plants also capture the CO_2 emissions from the natural gas combustion process.

Table 8. Land area per MW for various renewable energy sources[59-61].

Source of energy	Land area range (km^2/MW)	Land area used in the current study (km^2/MW)
Solar PV	0.030–0.034	0.032
Solar CSP	0.019–0.040	0.040
Geothermal	0.004–0.032	0.018
Wind	0.043–0.045	0.044

PV = photovoltaic; CSP = concentrated solar power

Table 9. Summary of assumptions regarding land area required for DAC[62].

DAC energy configuration			Land area ($km^2/MtCO_2$)		
Type of DAC	Heat source	Electricity source	DAC plant	Energy source	Total
Solvent-based	Natural gas	Natural gas	0.4	0	0.4
		Solar PV	0.4	7.7	8.1
		Geothermal	0.4	1.5	1.9
Sorbent-based	Solar PV	Solar PV	1.5	23	24.5
	Geothermal	Geothermal	1.5	4.7	6.2

DAC = direct air capture; PV = photovoltaic

The deployment of renewable energy projects must consider types of land and potential impacts on wildlife and human activities. Information about land availability for the present study was based on the "Power of Place" study published in 2019[63] that investigated which land could be used for developing clean energy pathways while respecting land conservation needs. That study was primarily focused on California, but also explored potential siting of renewable energy in other western states, including Nevada. Not all lands can be considered for new renewable energy projects, and the study differentiated four types of exclusions: legally protected lands, administratively protected lands, lands with high conservation value, and lands representing intact landscapes.

Then, the “Power of Place” study used the RESOLVE model[63,64], an electricity sector capacity expansion model, to determine which localities were best suited for the development of renewable energy projects to avoid impacts on natural and working lands and to meet the climate goals of California. For future solar and wind projects, the “Power of Place” study determined area size (km^2), potential capacity (MW), and capacity factor. For geothermal projects, it used the results of a previous study assessing renewable resources potential in the western United States[65]. The geothermal potential was based on known and quantifiable conventional hydrothermal resources, where enough information existed to estimate the volume of heat in place. This excluded the potential from undiscovered conventional geothermal resources and enhanced geothermal systems.

The “Power of Place” study differentiated between constrained and unconstrained areas[63]. Constrained cases were identified by the RESOLVE model as areas that may be used to meet California’s climate goals, whereas unconstrained cases expand resource development to the rest of the state and do not impose maximum limits[64]. The goal of the present study is to understand which resources lie within Nevada, to meet the state’s own climate goals. Thus, we used the unconstrained dataset to show the full extent of Nevada’s potential in developing renewable energy projects.

3. Results

3.1. Transportation sector

Transportation combustion emissions in Nevada increased from 9.778 $MtCO_2e$ in 1990 to 15.722 $MtCO_2e$ in 2017[7]. These emissions peaked at 18.444 $MtCO_2e$ in 2007, decreasing over the following years due to the Great Recession and stricter fuel economy standards. After 2011, these emissions began to increase again, driven by increases in air travel and highway vehicle use. Unless there are substantial behavioral changes in transport use post-pandemic, increases in air travel demand (causing fuel consumption) are expected to continue through 2050. Population growth in Nevada is also expected to increase gasoline and diesel fuel consumption, and thus increase emissions.

Assuming that transportation technology remains the same as in 2019 (business as usual) and that fuel demand increases as predicted, life-cycle emissions from transportation fuels in 2050 will be 35.3 $MtCO_2e$. This is a larger increase than NDEP projected because NDEP included combustion emissions alone, whereas our projection includes combustion emissions and emissions from fuel production, which includes extracting and refining processes out of state. Changes in total emissions for 2050 are driven by decreases in carbon intensity and AVMT, as well as increases in transportation methods that do not involve fossil fuels. To attain net-zero emissions by 2050 under any of these scenarios, all of the remaining GHG emissions would have to be captured through DAC.

The results of varying transportation mitigation strategies indicate that population-wide deployment of existing technological advancements could have a substantial impact on Nevada's yearly GHG emissions. EVs make it possible to remove nearly all emissions from gasoline fuel in the transportation sector, as they are viable replacements for all light-duty ICEVs that run on gasoline. The best-case scenario assumes 100% EV penetration for gasoline-powered vehicles, but other scenarios are less optimistic due to existing cost and political barriers to EVs and the widespread charging network they require. Carbon intensity of the electric grid in varying scenarios is detailed in the electricity generation sector and not the transportation sector, but it is also critical to consider if EVs are to serve as a technology that decreases GHG emissions.

Since the consumption of gasoline for motor vehicles is easier to mitigate than the consumption of other fuel types, in the more-optimistic scenarios jet fuel consumption contributes the most to GHG emissions, of all the fuel types. The largest decreases to jet fuel consumption occur when air travel is avoided altogether, such as in the best-case scenario, in which aviation AVMT decreases 20% from pre-pandemic levels in 2019. Alternative fuel use and decreases in jet fuel carbon intensity are also promising alternatives, but since much of this technology is currently still under development, it is unlikely that transportation GHG emissions can be brought to zero by 2050.

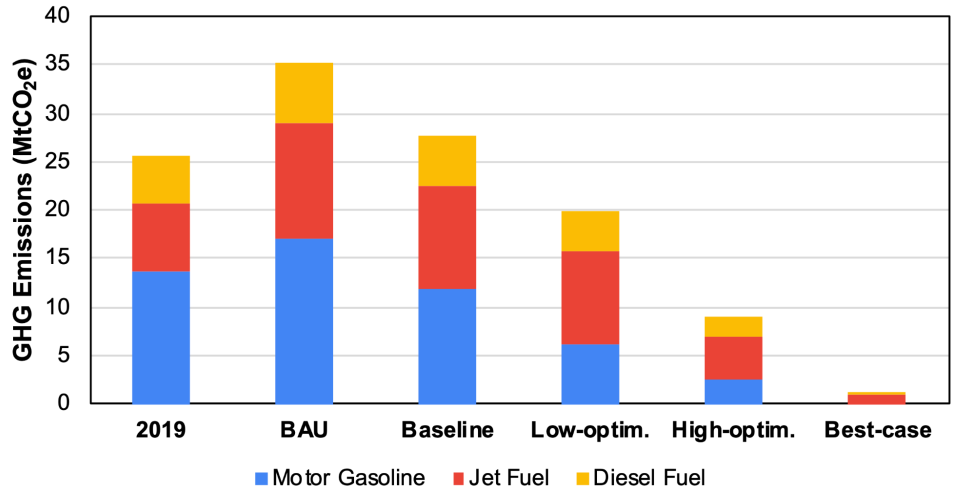

Figure 7. 2050 transportation sector greenhouse gas (GHG) emissions ($MtCO_2e$) by fuel type, for the business-as-usual (BAU), baseline, low-optimistic, high-optimistic, and best-case scenarios. The emissions for the year 2019 are given for reference.

3.2. Electricity generation sector

To calculate the additional electricity demand in 2050, we accounted for the growing population and increasing electrification of all sectors of the economy. Figure 8 shows that in 2050, the needs for electricity generation will roughly double current needs, from 157% for the baseline scenario to 227% for the best-case scenario. The carbon intensity of the grid in 2020 was about 320 gCO_2/kWh, considering only electricity sources within Nevada. Studies that consider imports and exports of energy might find higher carbon intensity for Nevada's grid electricity[66]. Assuming that all future electricity generation additions will be met by renewable energy sources, all scenarios result in lower grid carbon intensity. The best-case scenario, which assumes retirement of all fossil sources, would have a carbon-neutral grid in 2050 (excluding embedded emissions), as shown on Figure 8. If fully renewable electricity generation is not feasible, carbon capture at natural gas power plants can also very significantly reduce the grid intensity, as shown by the high-optimistic scenario. In a context of increasing electricity demand and higher electrification, lowering the grid carbon intensity is essential for lowering scope 2 emissions across all sectors and meeting climate goals.

To meet energy demand in 2050, new power plants will need to be built. Between the baseline and best-case scenario, the additional energy demand roughly doubles, with a jump in demand between the high-optimistic and the best-case scenarios, due to the retirement of all fossil-fueled power plants in the best-case scenario. Figure 9 compares the additional capacity and land area needed for various sources of renewable energy and for each scenario.

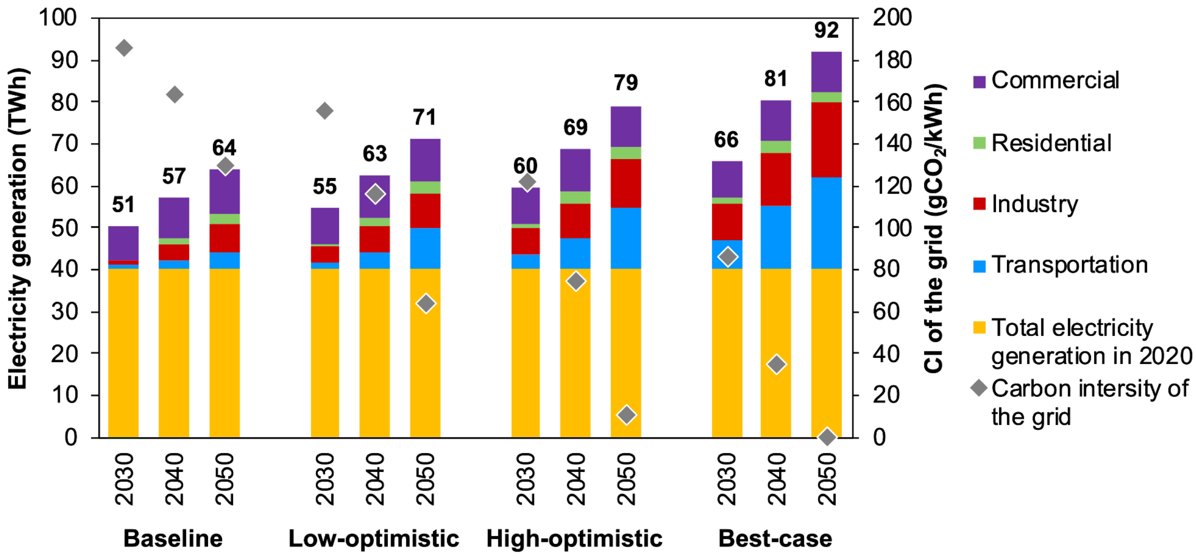

Figure 8. Estimates of the electricity generation demand in 2030, 2040, and 2050 for each scenario and sector, and carbon intensity (CI) of the grid.

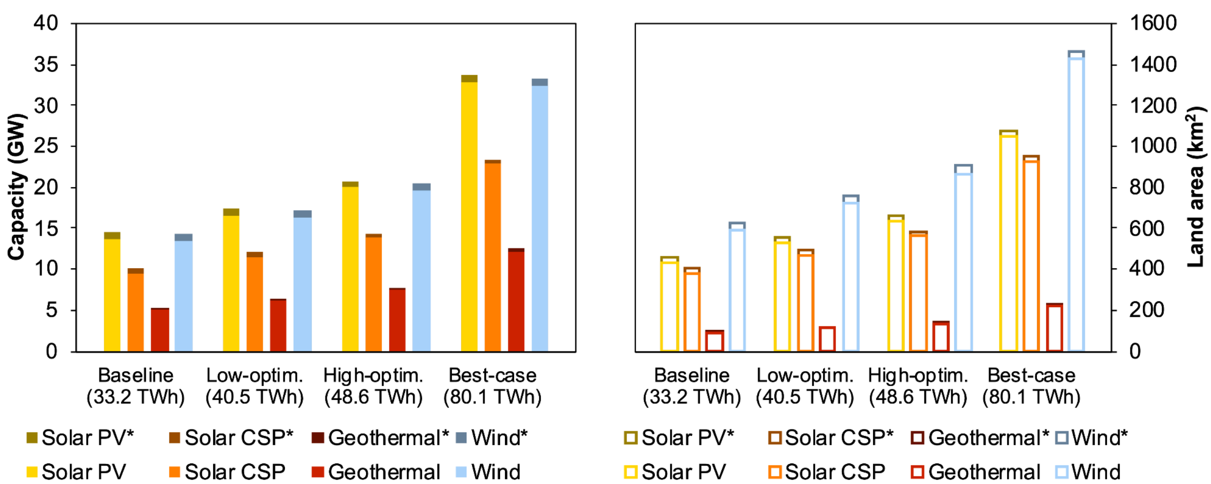

Figure 9. Comparison of the additional capacity (GW) and land area (km^2) needed to meet the estimated electricity demand (TWh) in 2050 for four renewable energy sources—solar PV (photovoltaic), solar CSP (concentrated solar power), geothermal, and wind—and for each scenario. Each bar of the graph corresponds to the total capacity or the total land area that would be needed if each renewable energy source was used to cover the entire demand. Data with a star show the additional capacity and land area that would be needed if large hydroelectric sources are no longer able to generate electricity. Nevada is likely to develop a portfolio of renewable energy sources, so each bar should be considered as the maximum capacity or land area that would be needed for each energy source.

With its higher capacity factor and lower footprint, geothermal energy projects require less than 50% of the capacity and less than 20% of the land area compared with other renewable energy sources to meet the same electricity demand. Nevada will likely develop a portfolio of renewable energy sources; the geothermal case thus indicates the minimal capacity and land area that would be needed in 2050. The higher bound is indicated by solar for the maximum capacity and by wind for the maximum land area. Figure 9 does not show the total amount of energy that would be needed to meet the 2050 goals. It only illustrates the consequences of the growing electricity demand for utility companies and excludes the capacity and land requirements of carbon dioxide removal that are developed later in this report.

As shown in Figure 10, operating power plants in 2020 are located mostly close to major cities, in particular solar and natural gas power plants. Geothermal power is more dependent on local resources, and geothermal power plants are located in northwestern Nevada where the geothermal potential is higher[67,68]. Figure 10 also depicts the areas that would be appropriate for clean energy development according to the "Power of Place" study[63]. The best locations for solar power, which would comply with the most environmental restrictions, are mostly in northern and western Nevada, along the border with California. There are few good opportunities for wind, but they are mostly in the northeast and very northwest of the state, and the opportunities for geothermal energy are concentrated in western to northwestern Nevada[69]. The low deployment potential of geothermal energy used in the "Power of Place" study (584 MW with the least environmental restrictions) contrasts with other estimates of geothermal power potential in the state, on the order of tens of gigawatts[XII].

The "Mining the Sun" study also presented an interesting perspective for developing clean energy projects[70]. This study identified mining sites and brownfields that could host renewable energy projects, prioritizing lands that have been already disturbed over pristine environments. Developing renewable energy on mine sites could also benefit the mining industry and make the mines independent from the grid, or mines could become receivers and producers of electricity according to their needs. The study developed several scenarios with different levels of integration of electricity produced on mining sites with the grid. For each location, the study assessed the direct normal irradiance and the wind power class[70] to understand which locations were more suitable for the development of clean electricity projects. However, it is difficult to know the land area available for such projects, and for this reason no estimates of the capacity were available. Such estimates might have to be done on a case-by-case basis.

The land area to develop renewable energy to meet the estimated electricity demand in 2050 is on the order of magnitude of hundreds to thousands of square kilometers (Fig. 9), geothermal energy having the smallest footprint. About two-thirds of the locations identified in the "Mining the Sun" study, and most of the available land with the least environmental impact identified in the "Power of Place" study, are located in northern or central Nevada and are connected to the northern grid, but a large portion of the demand is located in southern Nevada. As shown in Figure 10,

[XII] Jim Faulds, personal communication.

connections between the northern and southern grids are limited, but new high-voltage transmission lines are planned—Greenlink West and Greenlink North[42]—to improve transmission within the state. The completion of these transmission lines should speed the development of renewable energy projects close to existing or planned transmission lines to take advantage of the infrastructure. However, they might have adverse impact on the high-quality lands that would be opened to more development.

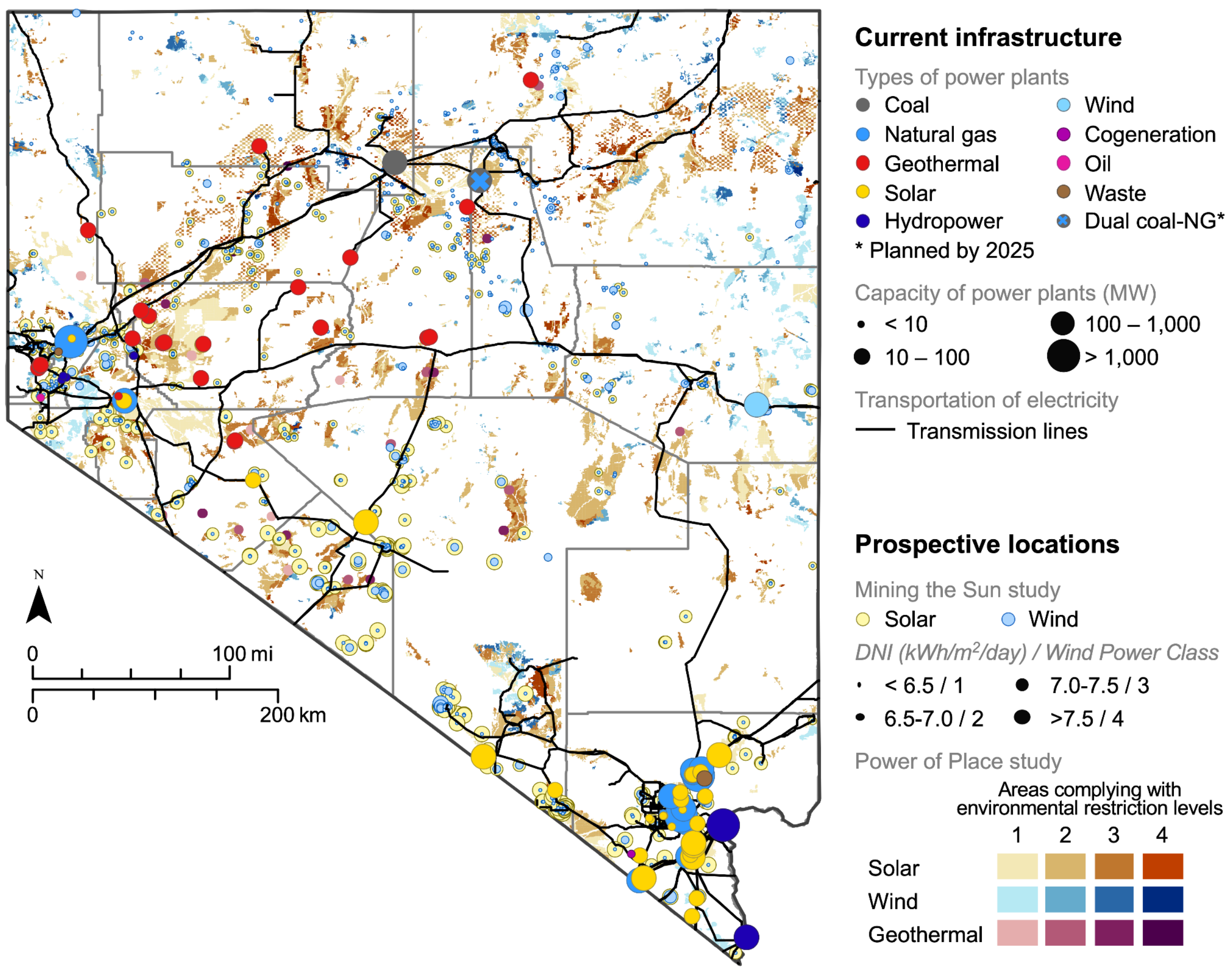

Figure 10. Map of operating power plants in Nevada, along with potential sites where renewable energy projects could be developed. Prospective development includes the areas from the "Power of Place" study that were defined as unconstrained and mining locations, which could be rehabilitated into clean energy farms identified in the "Mining the Sun" study[63,70,71].

3.3. Industrial sector

The industrial sector emitted 6.69 $MtCO_2e$ in 2017[7], constituting 15% of the emissions in Nevada. These emissions are distributed between process emissions (2.26 $MtCO_2e$), stationary fuel combustion (3.45 $MtCO_2e$), and natural gas and oil systems (0.98 $MtCO_2e$). Process emissions are the hardest to abate, because these emissions are the result of chemical reactions during the industrial processes. For instance, the calcination of limestone in the cement and lime manufacturing processes is a reaction that produces lime and CO_2.

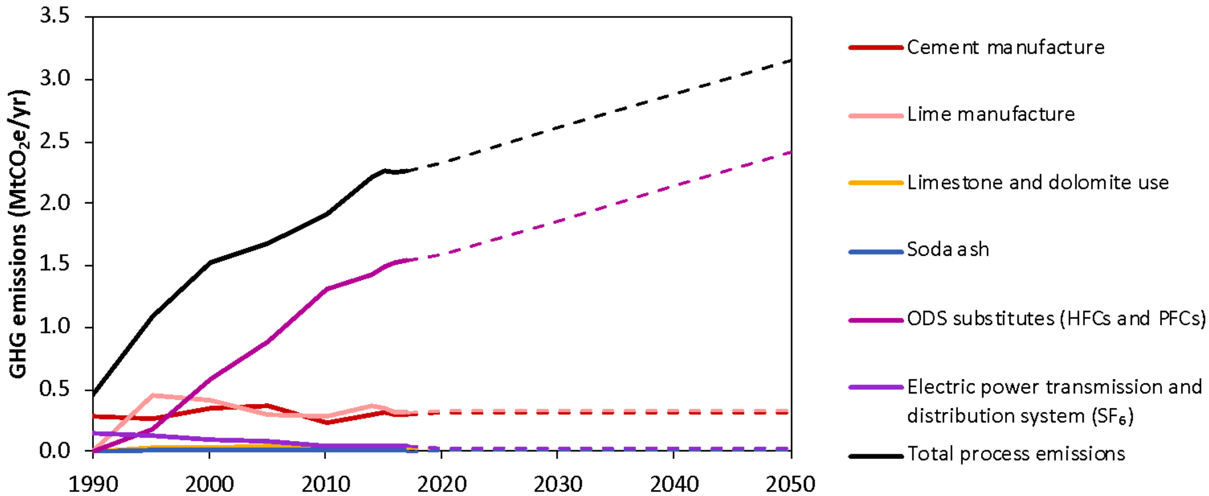

Figure 11. Past and projected process emissions of greenhouse gases (GHGs) for the industrial sector. ODS = ozone-depleting substances, HFCs = hydrofluorocarbons, PFCs = perfluorocarbons

These emissions are expected to grow to about 9.03 $MtCO_2e$ in 2050. Fuel combustion emissions will be roughly 5.87 $MtCO_2e$ in 2050 if no effort is made regarding electrification. The process emissions will be roughly 3.15 $MtCO_2e$ and will be dominated by the ODS substitutes (Fig. 11) if no other substitutes are used that are harmless for the ozone layer and that have a low global warming potential. The cement and lime industries will be the highest emitters, with process emissions from limestone calcination projected to roughly equal current emissions, around 0.65 $MtCO_2e$/yr.

3.3.1. Cement and lime facilities

The largest industrial emitters are the cement plant in Lyon County and the two lime plants in Clark and Elko Counties[40]. Process emissions make up about 50% and 60% of the total emissions at these cement and lime facilities, respectively. The fuel combustion emissions make the rest of the emissions and are mainly due to coal combustion[40]. Thus, diverting from coal is not restricted to decommissioning coal-fired power plants, but also applies to other sectors.

Most of the current infrastructure is well over 30 years old: the cement facility started production in 1964 with the addition of a new kiln in 1970, the lime facility in Clark County opened in 1974 with its fourth and last kiln built in 1996, and the lime facility in Elko County started its activity in 1989[7,72-75]. The kilns may be upgraded in the near future, which can be opportunities for additional changes to decarbonize the facilities.

The need for high-grade heat in the cement and lime industries (above 800°C) complicates the electrification of kilns, and electrified cement and lime kilns are not expected to be on the market in the next decade[76]. However, these technologies could be on the market in 2050 and could reduce the dependence of this industry on fossil fuels, while requiring over 2,000 GWh of electricity generation to power the three facilities in Nevada. With electrification, part of the burden of carbon management is passed to the electricity generation sector.

Cement and lime facilities in Nevada use primarily coal as their source of heat. Current alternative solutions to reduce emissions from coal burning include co-firing coal with biomass or replacing coal by natural gas (Table 10). Up to 20% of biomass can be co-fired without requiring infrastructure updates or preprocessing of biomass[77]. This would reduce emissions from coal by 0.12 $MtCO_2$. However, the use of biomass can result in the release of GHG elsewhere if it is not managed properly, and the transportation of biomass is uneconomical over long distances. We thus investigated the availability of waste biomass in counties within 50 km of the cement and lime facilities (Fig. 12)[78-80]. Information about waste biomass is available by county, which makes it difficult to accurately estimate whether enough biomass would be available close to the cement and lime plants. The plants in Clark County should have waste biomass available according to the billion-ton report[78], if the biomass is not used for some other purpose. Co-firing biomass might not be feasible at the lime plant in Elko County, due to low availability of waste biomass locally. Switching from coal to natural gas could also reduce emissions by 0.27 $MtCO_2e$ or almost 40% of fuel combustion emissions. Again, this option might be more difficult to implement at the lime plant in Elko County, as this facility is not currently using natural gas and might not have the appropriate burners installed at its facility. Installing them would require additional investments.

Carbon capture and storage is often cited as the most promising option in decarbonization roadmaps[81,82]. This is supported by the large share of difficult-to-abate emissions from the process itself and the design of cement and lime kilns, which combine the emissions from the calcination reaction and the combustion of fuel in a single stream. As shown in Figure 13, if carbon capture is implemented at the exhaust of all three facilities without any fuel change and assuming a 90% capture efficiency, it has the potential to avoid 1.51 $MtCO_2e$.

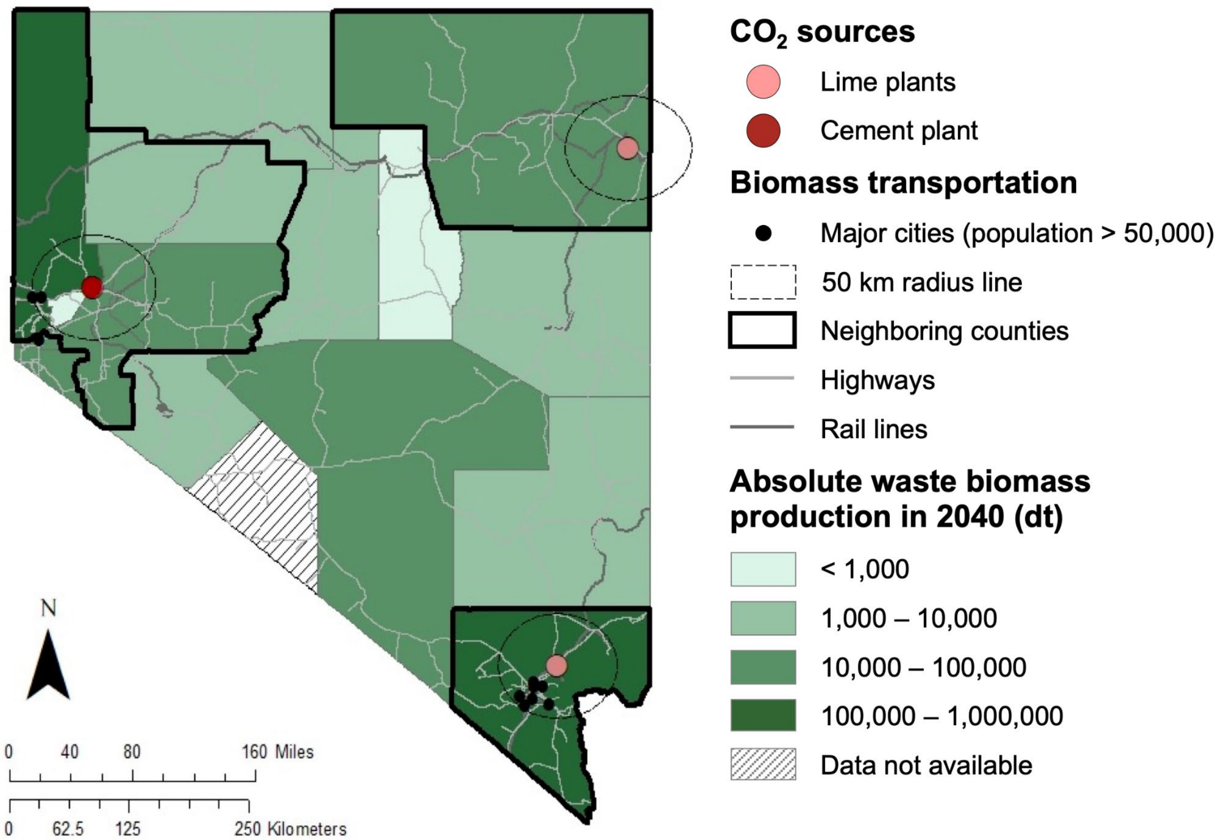

Figure 12. Map of biomass availability close to cement and lime plant in Nevada[78-80].

This potential stays the same if biomass is co-fired with coal. However, biomass (plant material) removes CO_2 from the air during its growth, so its use in kilns would result in the capture of 0.12 $MtCO_2e$ of biogenic CO_2. If the capture and storage of biogenic CO_2 during the growth phase is higher than the net emissions from the facility, the use of biomass can result in negative emissions. Achieving negative emissions would require using more than 20% biomass in the kiln, which might not be possible if not enough biomass is available locally and would require preprocessing the biomass. The preprocessing of biomass might emit some CO_2 and thus would reduce the efficiency of biomass use. A full life cycle assessment would have to be conducted to confirm any claim of negative emissions.

The carbon capture potential falls to 1.27 $MtCO_2e$ if coal is replaced by natural gas in the kiln, which makes this a good option if no or limited CO_2 storage is available locally. All three facilities emit well over 100,000 tCO_2e/yr and will qualify for the federal tax credit 45Q for capturing their CO_2 emissions.

Table 10. Breakdown of the emissions from cement and lime facilities with options for fuel switching.

Facility	Nevada Cement Company	Lhoist North America Apex plant	Graymont Western U.S. (inc. Pilot Peak plant)
Commodity	Cement	Lime	Lime
County	Lyon	Clark	Elko
Total emissions (tCO_2e)	336,015	688,004	655,862
Process emissions (tCO_2e)	173,778	416,776	410,411
Fuel combustion emissions (tCO_2e)	162,238	271,228	245,451
Fuel switching (tCO_2e): 80% coal + 20% biomass	-31,211	-38,844	-48,894
Amount of biomass (dt)	80,000 - 100,000	100,000 - 120,000	125,000 - 150,000
Waste biomass available within 50 km	Possibly	Possibly	No
Fuel switching (tCO_2e): 100% natural gas	-70,853	-88,182	-110,998
Currently using natural gas	Yes	Yes	No
Carbon capture potential (tCO_2e) - no fuel switching	-302,414	-619,204	-590,276
Carbon capture potential (tCO_2e) - fuel switching to natural gas	-238,646	-539,840	-490,377
Carbon capture potential (tCO_2e) - electric kilns	-156,400	-375,099	-369,369

Figure 13 compares different options for carbon capture to abate carbon emissions from cement and lime plants. The combination of co-firing biomass and using carbon capture results in the lowest net emissions (excluding biogenic emissions). Even if the implementation of carbon capture takes some time, co-firing biomass could be done in the very near future, provided that waste biomass is available for use locally. The combination of kiln electrification and carbon capture and storage results in the lowest tonnage of emissions that must be captured and stored. However, the technology for electrification of cement and lime kilns is not yet available. The best current option to minimize the tonnage of emissions that must be captured is natural gas fueling and carbon capture, but this option would result in higher net emissions than options combining electrification or biomass cofiring with carbon capture. Also, all facilities are located nearby or connected to the railroad network, making it feasible to transport biomass and CO_2 to and from the facilities.

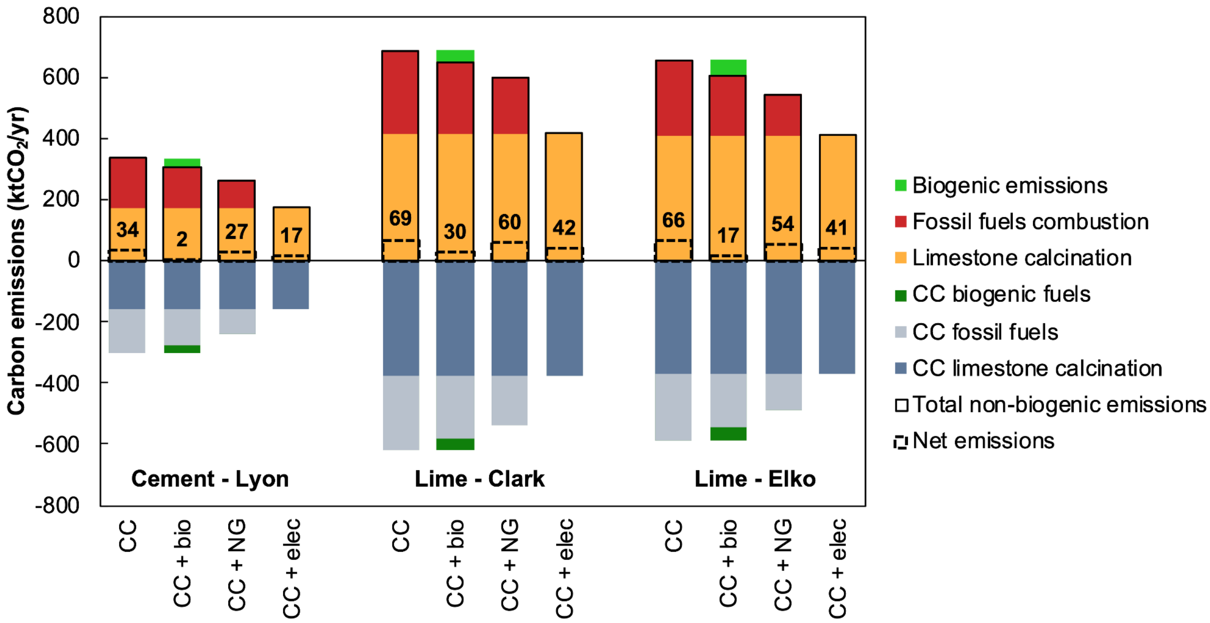

Figure 13. Breakdown of emissions from the cement and the two lime plants in Nevada, with four options for decarbonization of the kiln exhaust: carbon capture (CC), CC using biomass to replace 20% of the coal (CC + bio), CC with replacement of coal by natural gas (CC + NG), and CC with electrification of the kiln (CC + elec). The emissions and carbon capture potential are broken down by source: limestone calcination (process emissions), fossil fuels combustion, and biomass combustion (biogenic emissions). The net emissions (black dotted outline) correspond to the non-biogenic emissions (black solid outline) minus the total carbon capture potential from limestone calcination, fossil fuels combustion, and biogenic fuels combustion.

Industrial CCS is often targeted, as process emissions mean that many exhaust streams have a greater fraction of CO_2, leading to more efficient point source capture and, by virtue, lower levelized costs of capture. It is estimated that given the specific composition and volumetric flow rates of CO_2 in these three industrial facilities, the levelized cost of capture could be as low as \$30/t CO_2[5]. Compression for transport can add another \$9–\$11/tCO_2, and injection into the subsurface generally cost between \$7 and \$13/tCO_2[83], though actual costs vary depending on reservoir characteristics, level of preparation, post-injection site care, and injection rate. The transportation leg can also add significant costs, depending on mode (which in turn depends on volume transported), and haul distance.

3.3.2. Process emissions from leakages

The use of HFCs and PFCs (ODS substitutes) in refrigeration and air conditioning systems, of SF_6 in electrical transmission and distribution systems, and of natural gas in all sectors of the economy, results in leakages that increase the total GHG emissions in Nevada.

HFCs and PFCs were adopted as replacements for ODS to avoid the depletion of the ozone layer, but some of these chemicals are very potent greenhouse gases, ranging between 138–12,400 tCO_2e per tonne of HFC or PFC, at a global warming potential (GWP[XIII]) of 100. The emissions attributed to ODS substitutes tripled in the past 20 years and are expected to keep increasing. Refrigerants and air conditioning systems could replace HFCs and PFCs with CO_2, which could greatly reduce the emissions from these systems, currently estimated on the order of 1,000–10,000 tCO_2e, and could achieve $MtCO_2e$ levels without mitigation. For example, replacement of a traditional HFC refrigerant like R-404A or R-134A (GWPs of 3,922 and 1,430, respectively) with CO_2 (R-744) could reduce emissions via leakage by 99.9%[84]. Adopting CO_2 as the main coolant would have its own challenges, partly because of high operating pressures. However, its high volumetric efficiency (more than six times the cooling effect per volume as R22), low compression ratio, and low viscosity, present advantages compared to traditional coolants.

SF_6 is used as an insulator in electrical transmission and distribution systems. It is responsible for emissions of about 41,000 tCO_2e in 2017. The emissions from SF_6 have been decreasing over the past years, and this trend is expected to continue, reaching about 25,000 tCO_2e in 2050, due to the development of better practices to avoid SF_6 leakage[85]. Like ODS substitutes, SF_6 is very potent (23,500 tCO_2e/tSF_6 at GWP 100) and its replacement by CO_2 would result in emissions in the order of 1–10 tCO_2e.

Emissions from natural gas and oil systems are close to 1 $MtCO_2e$/yr, with over 99% of it coming from natural gas systems. With the electrification of all sectors and diversion from fossil fuels, the emissions from the distribution of natural gas are expected to decrease. In the baseline, low-optimistic, and high-optimistic scenarios, during which natural gas power plants are still operating, current emissions are expected to be reduced by 40–50% in 2050. The largest emission reduction occurs in the best-case scenario, which assumes the retirement of all fossil fuel power plants, and in which the emissions are expected to be as low as 26,000 tCO_2e in 2050.

3.3.3. Fossil fuel combustion

Industrial emissions from fossil fuel combustion should reach about 4.9 $MtCO_2e$ in 2050 under a business-as-usual scenario, including 2.4 $MtCO_2e$ from petroleum combustion; 1.8 $MtCO_2e$ from other sources, mainly natural gas; and 0.7 $MtCO_2e$ from cement and lime kilns. These emissions can be reduced mainly by the electrification of heaters, boilers, engines, and kilns, which would result in emission reductions of 1.2 $MtCO_2e$ in the baseline scenario, 1.6 $MtCO_2e$ in the low-optimistic scenario, 2.3 in the high-optimistic scenario, and 3.9 $MtCO_2e$ in the best-case scenario.

[XIII] GWP, or global warming potential, describes the warming impact of a greenhouse gas relative to CO_2 which is arbitrarily set to a GWP of 1. A GWP of 50 would mean that the per-molecule warming effect of that gas is 50 times greater than CO_2.

3.3.4. Mining industry considerations

The mining industry in Nevada uses about two thirds of the total energy of the industrial sector, provided primarily by electricity, diesel, and pipeline gas[30]. A 2018 report from the Rocky Mountain Institute on decarbonization of the mining sector indicates that the most promising pathways overall for reducing emissions are changes in the electricity supply to renewables, efficiency increases through process improvement and technology improvements, electrification of processes, and changes to mining transportation fleets to use more fuel-efficient or electric vehicles[86]. Available energy usage data from 2018 indicates that about 57% of the energy used by the mining industry comes from electricity, indicating that decarbonization of electricity generation is a critical step to reducing the overall emissions from mining[29]. The conversion of the Nevada Gold Mines TS Power Plant to a dual natural gas and coal power plant, in addition to the potential construction of substantial solar power infrastructure for mining, are key efforts currently underway that will reduce emissions in the sector[87]. The electrification of mining vehicles that consume gasoline and diesel fuel will also help decrease emissions from mining.

The Nevada Mining Association (NVMA) reported in an April 2014 survey that major efforts to reduce emissions from the sector include the transition to lower-power LED lighting in mines and switching to solar and geothermal energy where possible[88]. The NVMA affirms its commitment to promoting efficiency in its fossil fuel-burning vehicles until electrification of the state's mining fleet is possible[27]. Monetary incentives such as the NV Energy SureBet program could be used to promote reduced energy uses and efficiency increases and therefore reduce total emissions; in addition to changing mine lighting to LEDs, the Rawhide gold mine saved money by installing automated variable-speed drives for its ore crusher and conveyor systems[89]. Promoting both improvements in mining process efficiency and a shift from fossil fuels to renewable electricity will be major keys to reducing the carbon emissions of Nevada's mining industry.

3.4. Residential and commercial sector

Residential and commercial sector emissions are heavily tied to two factors: 1) the extent of building electrification, and 2) the progressive decarbonization of grid electricity. Since the latter lies largely outside of measures that can be directly controlled through specific action in the R&C sector, this section focuses on the mechanisms for—and effects of—electrifying building operations. Results for each sub-sector are displayed in Figure 14.

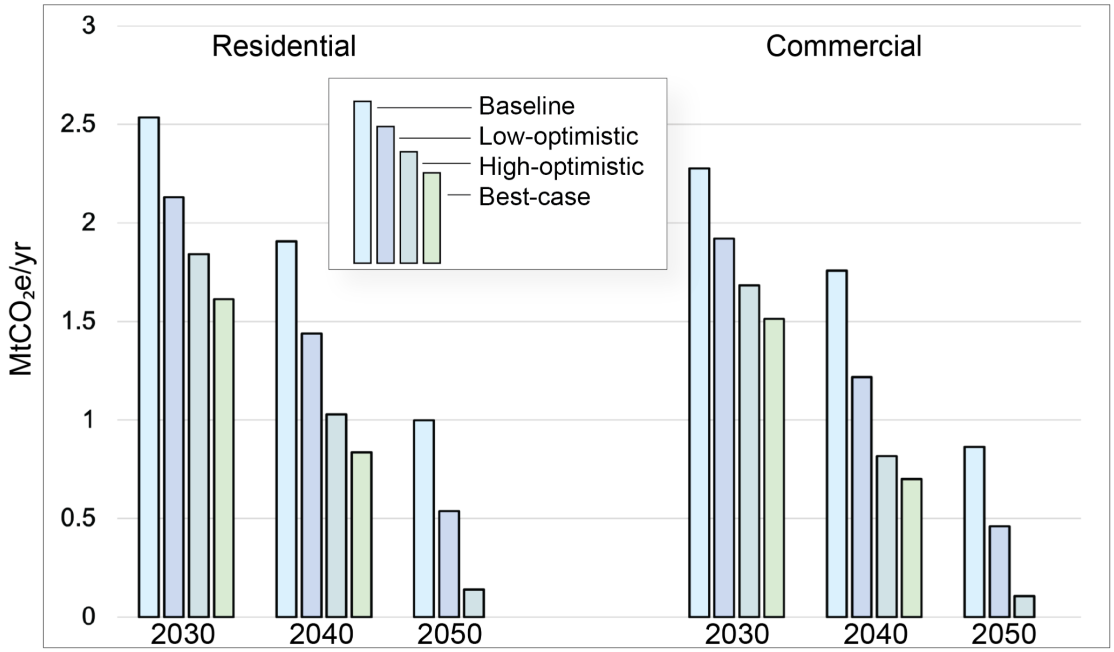

Figure 14. Projected emission reductions in the residential and commercial sector over three decades. Emissions in the best-case scenario vanish in 2050 as 100% electrification is achieved on a zero carbon grid.

Both residential and commercial sectors show a similar progression in emission reductions across scenarios and by decade, on account of the analogous emission reduction strategies applied to all buildings. In the residential sector, space heating contributes the most to sector emissions (38%), followed by cooking, appliances, lighting, and electronics at 24%. The primary mechanism for reduction in space heating–related emissions is replacement of a natural gas–fired furnace with a heat pump. A traditional natural gas–fired furnace has an 80% annual fuel utilization efficiency (AFUE), but higher efficiency furnaces are shown to have an AFUE of 90–95%. A heat pump operating in Nevada, however, has an average COP of 3.5, meaning that a heat pump is 350% efficient in terms of converting an energy input into usable heat.

This has two significant implications in the building sector: 1) the primary source of natural gas consumption is eliminated, and 2) less overall energy is required to provide the same basic necessity. Natural gas releases 227 gCO_2e/kWh for use in heating; thus, replacement of a natural gas furnace with a heat pump will reduce emissions in any region where the ratio of grid carbon intensity to heat pump COP is *lower* than the ratio of natural gas heating intensity to furnace efficiency. To make this less abstract through example, consider the Nevada baseline grid carbon intensity of (353 gCO_2e/kWh) and a heat pump COP of 3.5: this yields a ratio of 353/3.5 = ~100. Next consider natural gas heating is (227 gCO_2e/kWh) and an optimistic furnace efficiency of 0.95: this yields a ratio of 227/0.95 = ~239. By these numbers, any heat pump with a COP of at least 1.48 will yield emission reductions in Nevada[XIV]. Since it has already been established that heat pumps operating in Nevada have a COP of 3.5, this strategy clearly has the potential for great emission reductions within the sector.

Heat pumps can also replace natural gas or electric water heaters, offering even greater energy and emission savings (the efficiency of a natural gas–fired water heater is lower than that of a furnace, at roughly 60%). It is important to note, however, that water heating generally represents a much lower percentage of emissions in both sectors, at 15% for residential use and only 4% for commercial use. Hence, replacing water heaters with heat pumps will have a smaller overall impact on emissions in both sectors. A breakdown of the impact on emissions from replacement of appliances with heat pumps in the residential sector is shown in Figure 15. In an unmitigated scenario, emissions from heating alone are almost 2 $MtCO_2e$ in 2050. Conversely, even the moderate *baseline* scenario shows 80% emission reductions with respect to baseline, further illustrating the importance of heat pumps in the decarbonization of buildings.

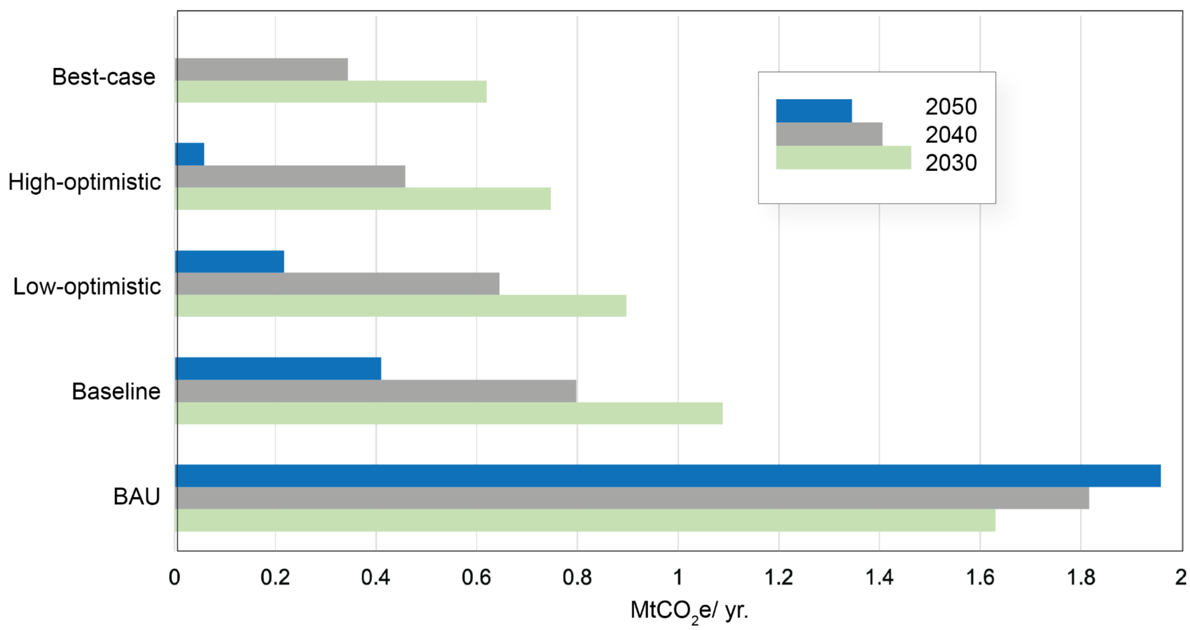

Figure 15. Impact of replacing fossil-fired furnaces and water heaters with high COP (3.5) heat pumps in the residential sector. The business-as-usual (BAU) case assumes no replacements. All other scenarios follow the replacement schedule outlined in Table 5 (heat-pump replacement is an assumed upgrade in all-electric housing).

As shown, a key strategy in this sector is shifting the burden away from fossil fuel sourcing and onto the electric grid. However, electricity consumption already represented 47% and 48% of

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[XIV] Of note, with an anticipated reduction in Nevada grid intensity over time (through increased renewable energy penetration), this ratio will continue to land in increasing favor to heat pump replacements, resulting in larger emission reductions over time.

energy consumption by the residential and commercial sectors, respectively, in 2019. Hence, it is important to recognize emission reduction strategies aimed at lowering existing—and new—electricity consumption, through improvements in efficiency. The Energy Star rating system provides consumers and businesses with information regarding efficiency to help them make informed decisions, particularly in reducing energy-related costs and emissions. Moderate upgrades in efficiency can be achieved by replacing gas stoves with electric stoves (from approximately 40% to 74%), and even higher efficiency gains can be achieved with new induction cooktops, which have efficiency ratings as high as 90%. It is also anticipated that appliances (e.g., refrigerators, washers, dryers, dishwashers, lights, electronics) will continue to see marginal improvements in efficiency over the next three decades. A breakdown of electricity efficiency–related improvements that lead to emission reductions in the commercial sector is shown in Table 11. Improvements in energy efficiency only yield modest improvements in electricity consumption per business unit over time; hence, decarbonization of this sector remains heavily tied to decarbonization of the electric power sector.

Table 11. Projected average electricity consumption per Nevada business in MWh per year.

	BAU	Baseline	Low-optimistic	High-optimistic	Best-case
2030	182	181	180	178	177
2040	181	120	118	116	113
2050	181	109	107	105	103

BAU = business-as-usual

3.5. Waste management sector

Reductions in the emissions of landfilled waste were estimated through two potential pathways: diversion of waste from landfills (through reduced consumption or increased recycling and composting) and through the deployment of additional landfill gas capture in the state. The recycling rates in 2020 are assumed to be 22% for MSW and 50% for ISW based on available data. The baseline scenario assumes that Nevada will meet its 25% recycling rate goal by 2025 and will make no further improvements in annual recycling rates. The improved scenarios feature improved waste diversion rates and accelerated timelines for these.

Based on results from emissions projections to 2050, the waste sector may account for up to 5.42 $MtCO_2e$ emitted annually in the business-as-usual scenario. Of these emissions, the total reduction from baseline possible is estimated to range from 1.59 $MtCO_2e$ in the baseline scenario to 4.24 $MtCO_2e$ in the best-case scenario through a combination of reduced waste landfilling and generation and improved LFGTE with CO_2 post-combustion capture. The remaining emissions that must be reduced using DAC offsetting would total 3.82 $MtCO_2e$ in the baseline scenario down to 1.18 $MtCO_2e$ in the best-case scenario.

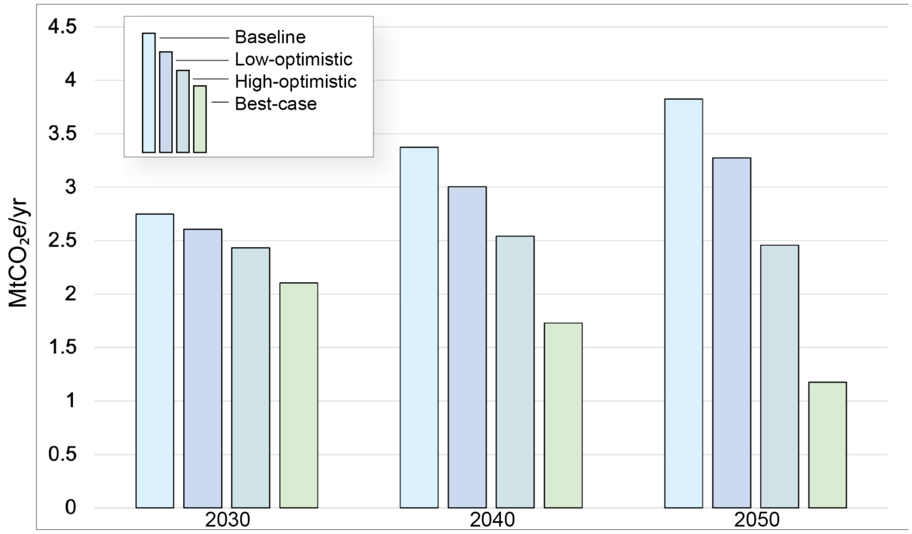

Figure 16. Predicted net emissions after reductions from the waste sector in 2030, 2040, and 2050. Net emissions will need to be offset by carbon removal. Aggressive deployment of landfill gas to energy and waste reduction lead to a decrease over time in the best-case scenario despite population growth.

The siting of future LFGTE systems is important in waste management planning, as there are only two such systems currently in place in Nevada at large urban landfills: the Apex Regional Landfill near Las Vegas and the Lockwood Regional Landfill near Sparks. (An additional collection and flaring system exists at the closed Sunrise Landfill near Las Vegas but has been identified as having low potential for energy generation.) Using data from the NDEP waste management resources and the EPA Landfill Methane Outreach Program (LMOP), potential landfills for deploying gas collection systems have been examined. While some have been previously identified as having future potential for deployment, many sites have not been examined sufficiently through the LMOP. Landfills in Nevada that close before 2050 should be priorities for deploying LFGTE systems, as it is reasonable to assume that having constant waste-in-place will allow capture to take place with fewer potential disruptions. New landfills that are constructed to replace these closing sites may also be fitted from inception with LFGTE systems to avoid having to build them later. The use of waste incineration or waste-to-energy pathways has not been explored for Nevada, as there are no such systems currently in place and no plans for development.

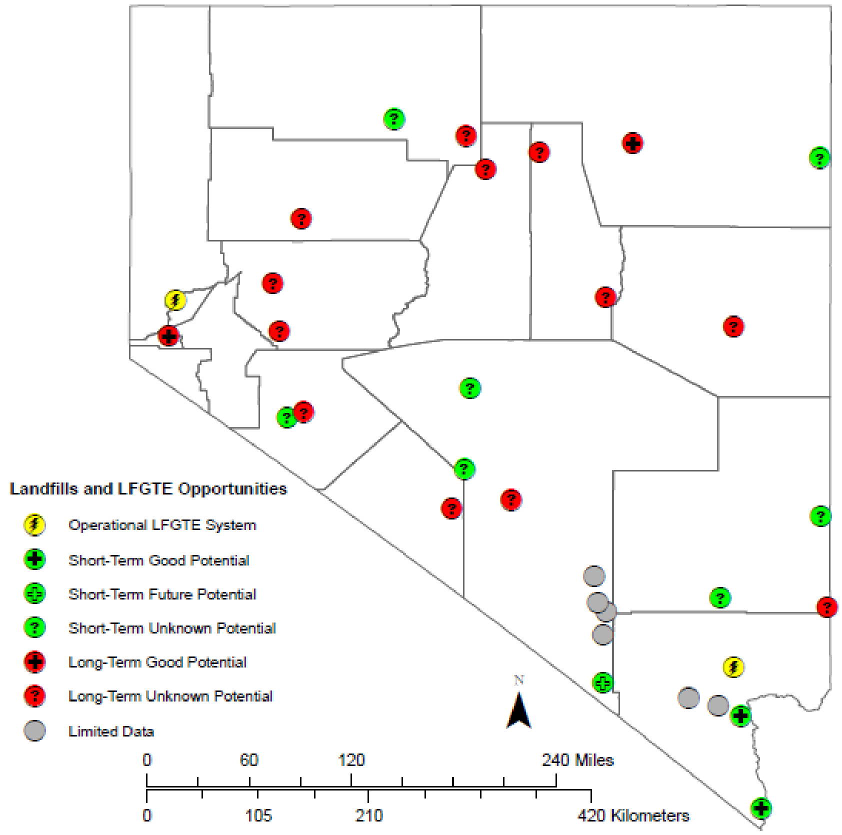

Figure 17. Existing operational landfills and landfill gas-to-energy (LFGTE) systems in Nevada. Landfills closing before 2050, indicated by green symbols, are priority candidates for deploying gas capture or further studying its feasibility[40,90].

3.6. Agriculture sector

Emission reduction opportunities in the agricultural sector will be driven primarily by changes in standard cattle management and land-use practices. Realistic improvements in fertilizer efficiency through either decreased total usage or lower-nitrogen formulations (up to 20% reduced emissions) and improvements in land tillage to low- and no-till agriculture (up to 30% reduced emissions) could decrease emissions from agricultural soil management by nearly 50% in a best-case scenario. Improvements in the quality of available cattle feed and the grazing land conditions available to livestock through increased cover cropping or the introduction of silvopasture practices may allow for reductions of up to 35% from enteric fermentation. Emissions could be further reduced by reducing livestock farming in Nevada, but it is difficult to predict how both national- and state-level trends in meat and dairy consumption may change over the next several decades, and it would be very challenging to mandate a reduction in the total number of cattle in the state simply to meet emissions goals.

Figure 18. Summary of predicted net emissions after reductions from the agriculture sector in 2030, 2040, and 2050. Net emissions will need to be offset by carbon removal. Key reductions will come from changes in land and livestock management practices.

While the total emissions from the agricultural sector are anticipated to remain small despite population growth, it is important to acknowledge that more sustainable and climate-focused practices can be adopted to reduce the state's overall GHG impact and reach the emissions goals that have been set for 2050. Sustainable farming will increase the quality and longevity of agriculture in Nevada and allow for more consistent production over time as the state grows. It is reasonable to predict that emission reductions of 20% from the sector baseline can be achieved through positive changes in agricultural practices instead of through full reliance on direct air capture of CO_2.

3.7. Carbon dioxide removal and direct air capture

Figure 19 shows the results of the four scenarios developed in this study. Four reference cases are presented that inventory the emissions from 2017 and the projected emissions from 2030, 2040, and 2050 if no carbon management is done. The total emissions in 2030, 2040, and 2050 are shown for each scenario after emission reduction and point source capture. In order to meet the state's climate goal of emitting only 45% of 2005 emissions by 2030 and achieving net-zero emissions by 2050, the rest of the emissions have to be captured using DAC. An arbitrary goal of 80% of 2005 emissions has been used for the 2040 midpoint. The calculation also accounts for leakages during transportation and CO_2 storage, which explains why the amount of DAC on the 2050 panel of Figure 19 is larger than the total amount of emissions under the baseline scenario. The best-case scenario in 2030 shows a positive DAC, which means that this scenario would outperform the 2030 climate goals and that no DAC would be needed for the first decade. However, all the other scenarios for 2030, and all scenarios for the following years, will need some amount of DAC to meet their goals, and an increasing amount of DAC over the years to meet the 2050 net-zero target.

Part of the CDR could be accomplished through land use, land-use change, and forestry; however, due to the uncertainties regarding its potential and its permanence, this carbon management strategy has not been included in the calculations.

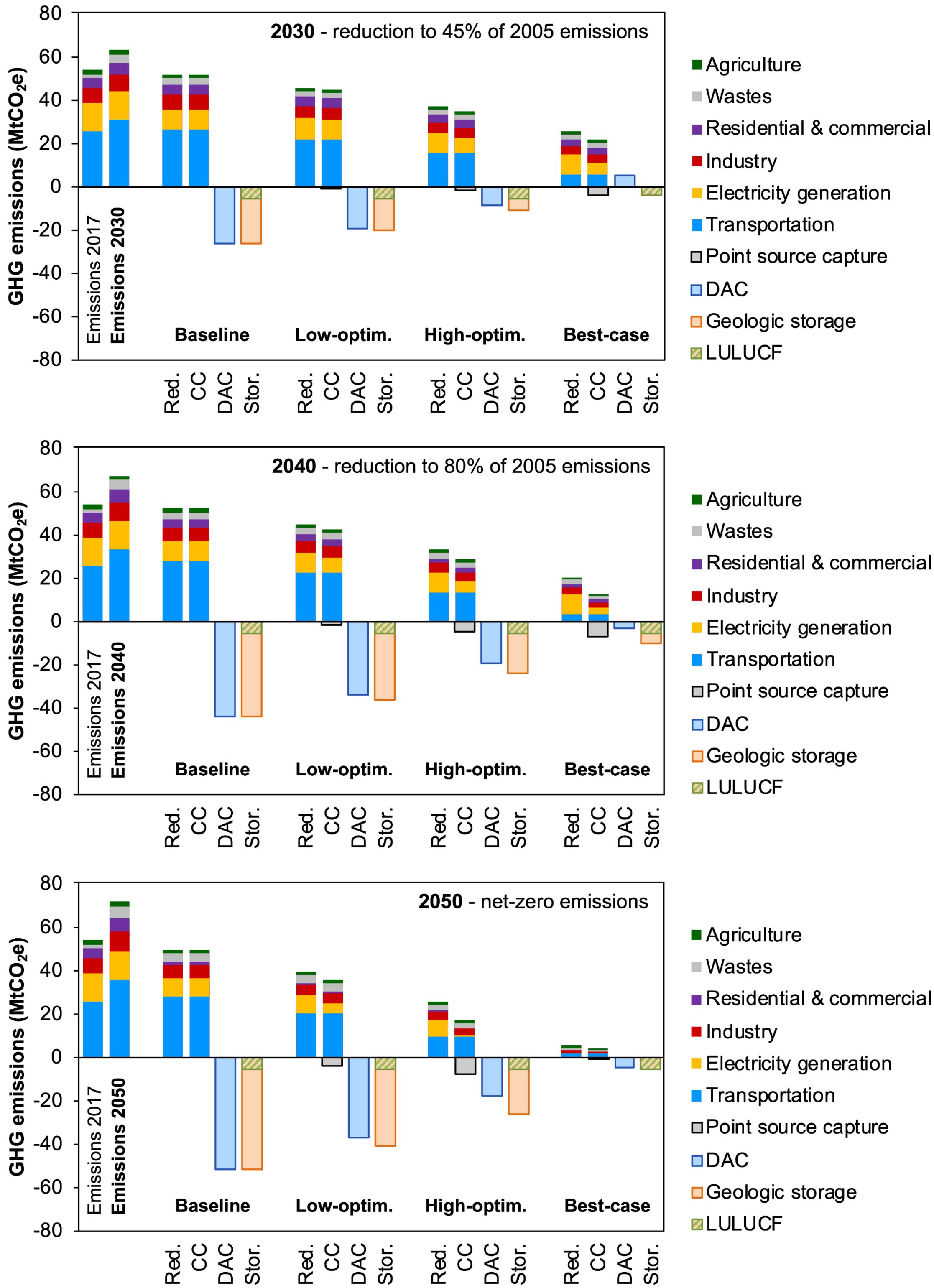

Figure 19. Summary of greenhouse gas (GHG) emissions and carbon management implementation needed for reaching the climate goals in 2030, 2040, and 2050. Each panel of the figure shows the breakdown of estimated GHG emissions by sector in the positive direction and captured emissions (point source capture or direct air capture, DAC) and CO_2 storage in the negative direction. A business-as-usual scenario is shown on the left-hand side, and each carbon management scenario is broken down into total emissions after emission mitigation (Red.), after emissions avoided by point source capture (CC), and amount of DAC (DAC) and CO_2 storage (Stor.) necessary to meet the climate goals. The green hashed feature shows the amount of CO_2 that could be captured through land use, land-use change and forestry (LULUCF) according to the Nevada Division of Environmental Protection 2019 report[30], which could lower the need for geologic storage; however, uncertainties remain in LULUCF potential and permanence. In the best-case scenario for 2030, DAC is positive, which means that no DAC is needed for that scenario, and that this particular scenario will outperform 2030 climate goals.

Figure 19 shows that less aggressive efforts in emission reductions increase the burden on carbon capture, both through point source capture and DAC. The need for carbon capture also raises the question of CO_2 storage, either in the subsurface or by making products that can store CO_2 for a long period of time. In the baseline scenario, significant amounts of DAC are required to reach net-zero in 2050, at 51.6 $MtCO_2$/year on a net basis. Because in the baseline scenario the grid carbon intensity does not reach 0.0 gCO_2e/kWh but rather 130 gCO_2e/kWh, no DAC operation will be considered 100% efficient in removal of CO_2. In addition to energy-related emissions, there are also embodied emissions in the materials, including sorbents, support materials, and structural components. Our previous analyses illustrated that pairing DAC with geothermal energy—of which Nevada has an abundance—can greatly maximize the net removal of CO_2 by minimizing lifecycle emissions, particularly in the excessive thermal requirement, and also can potentially reduce the *net removed cost*, which is defined as the gross removal cost corrected by lifecycle emissions, on a per tonne CO_2 basis[91-93].

Cost projections for sorbent-based DAC cover a wide range, from the ultra-optimistic <\$100/tCO_2 to the more sobering \$1,000/tCO_2. Climeworks, with 15 plants in operation or planned worldwide in 2021, has publicly claimed \$600/tCO_2 and claims to have a technical roadmap to reduce the cost to under \$200/tCO_2. A recent analysis shows that the cost of DAC may approach \$100 to \$200/tCO_2 by mid-century[94]. Still, even optimistic projections for DAC show that it is always a more expensive option than point source capture, which typically falls under \$100/tCO_2 and less than \$50/tCO_2 for more concentrated streams[95].

In the context of 2050 net-zero emissions goals, the more that renewable energy sources can replace fossil fuel power plants and mitigate GHG emissions, the less carbon dioxide removal is needed. Earlier in this report, Figure 8 showed that 5–33 GW of new electric capacity will need to be deployed by 2050 to meet utility needs. An additional 1–37 GW would be needed to supply

DAC plants, totaling 12–51 GW to meet utility and DAC energy needs, depending on the renewable energy type and the scenario followed.

Figure 20 illustrates the land area that would be needed to meet the 2050 goal using solar and geothermal energy. Due to higher capacity factors and lower footprint per megawatt or per tonne of CO_2 captured, geothermal energy would require about a fourth of the land area that solar photovoltaic would need. Data points correspond to the land area taken by clean energy power plants and DAC plants if the energy demand of the facilities were met solely by solar or geothermal energy. As Nevada is likely to develop a portfolio of clean energy, including solar and geothermal energy, solar data could be considered the higher bound of land area needed, while geothermal data indicates the lower bound.

The baseline scenario would require the largest land area to reach net-zero GHG emissions, due to the lower development of renewable energy and the lower electrification of the economy, leading to greater needs for DAC (Fig. 19). The high-optimistic and best-case scenarios have similar total footprints, showing that greater mitigation of GHG emissions would be rewarded by a smaller land footprint. It is also possible that future DAC design will have lower energy and water requirements, leading to a lower footprint for DAC plants.

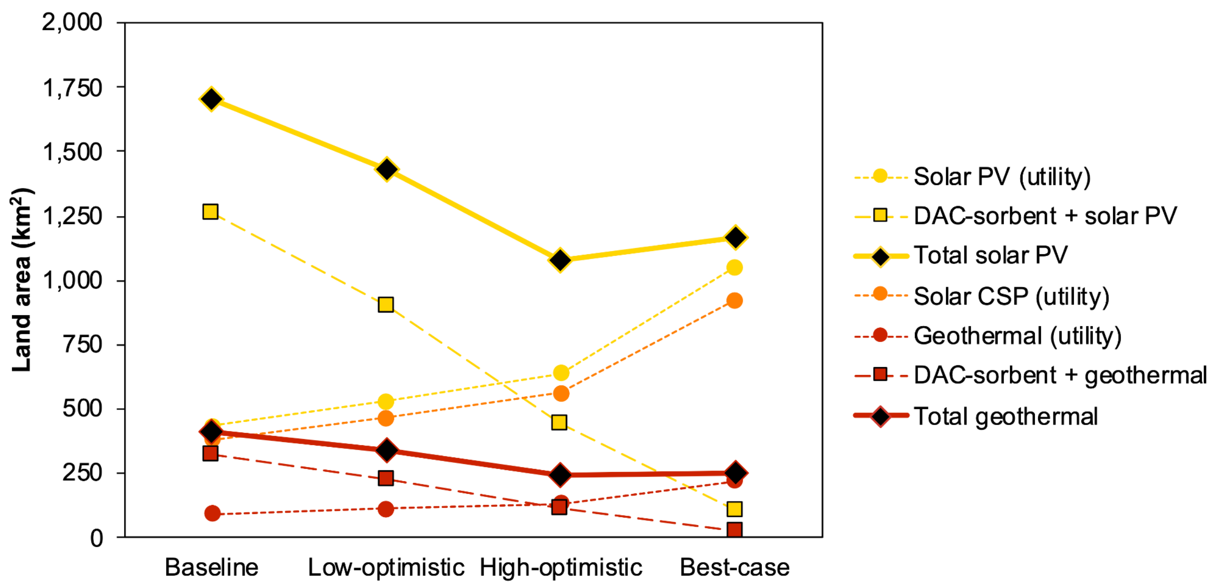

Figure 20. Comparison of the land area needed to reach net-zero emissions goals in 2050 for solar and geothermal energy under the four scenarios, with a breakdown between utilities and direct air capture (DAC) needs. PV = photovoltaic; CSP = concentrated solar power

These land area estimates need to be compared with the availability of land that would comply with environmental restrictions. Figure 21 compares the land available according to the "Power of Place" study[63] and the needs for land area, electric capacity, and DAC identified in the present study. Solar has the largest deployment potential by far and could cover the totality of the electricity needs for the grid and DAC, while complying with all environmental restrictions identified in the “Power of Place” study. This result indicates that Nevada should be able to develop a portfolio of energy sources to reach its 2050 goals while protecting its environment. Geothermal has a very small development potential according to the “Power of Place” study. However, geothermal can produce energy at all times, compensating for intermittent sources of energy, and in the case of DAC it can supply heat directly to regenerate the capture agent, increasing the efficiency of energy use. More in-depth studies of the geothermal potential in places with low environmental impacts might raise the potential of this energy source in the future.

In the present study, we investigated only solar PV for supplying energy to DAC; alternatively, solar CSP can be deployed on the same areas as solar PV, especially in southern Nevada where the direct normal irradiance is higher. One advantage of solar CSP is that this energy source can have a smaller footprint than solar PV, depending on the technology used[59,60,96]. Like geothermal sources, solar CSP could supply heat directly to the DAC plant, whose energy needs are 80% thermal energy, instead of only generating electricity. Using the heat directly would increase the efficiency of the process and lower the land area required for the energy source of the DAC plant.

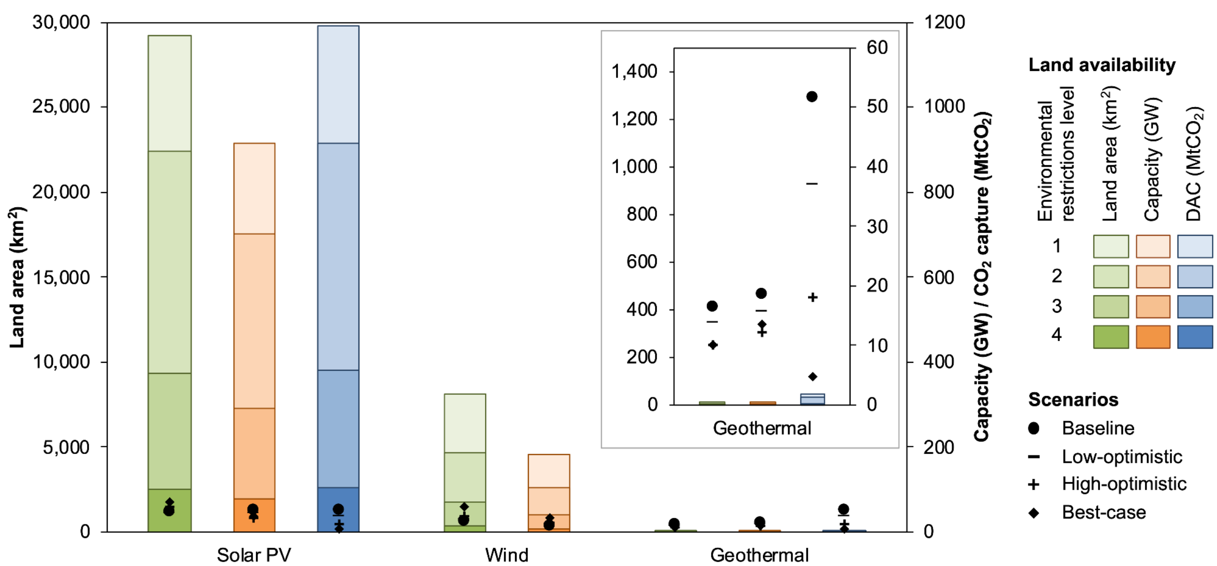

Figure 21. Comparison of the land area available according to the “Power of Place” study for the deployment of clean energy and direct air capture (DAC), and the needs identified for the four scenarios in this study. The capacity bars for solar photovoltaic (PV), wind, and geothermal energy cover the energy needs of the grid and the DAC plants, with the exception of wind, for which only the electricity needs of the grid were considered. The DAC bar covers the needs of the DAC plant itself and of its energy source. Due to the large difference in scale between solar and geothermal energy, an inset was added for geothermal data with the same scale ratio as the main graph[63].

Once captured from the air, the CO_2 needs to be stored securely and permanently, and preferentially close to its capture location. For increased carbon removal efficiency, future DAC plants need to be located close to a renewable source of energy and to reliable storage. Sedimentary formations in Nevada need to be explored further to assess their capacity for sequestering CO_2; currently, there is no obvious CO_2 storage location within the state, but rather a set of options with various technological readiness levels and various data availability.

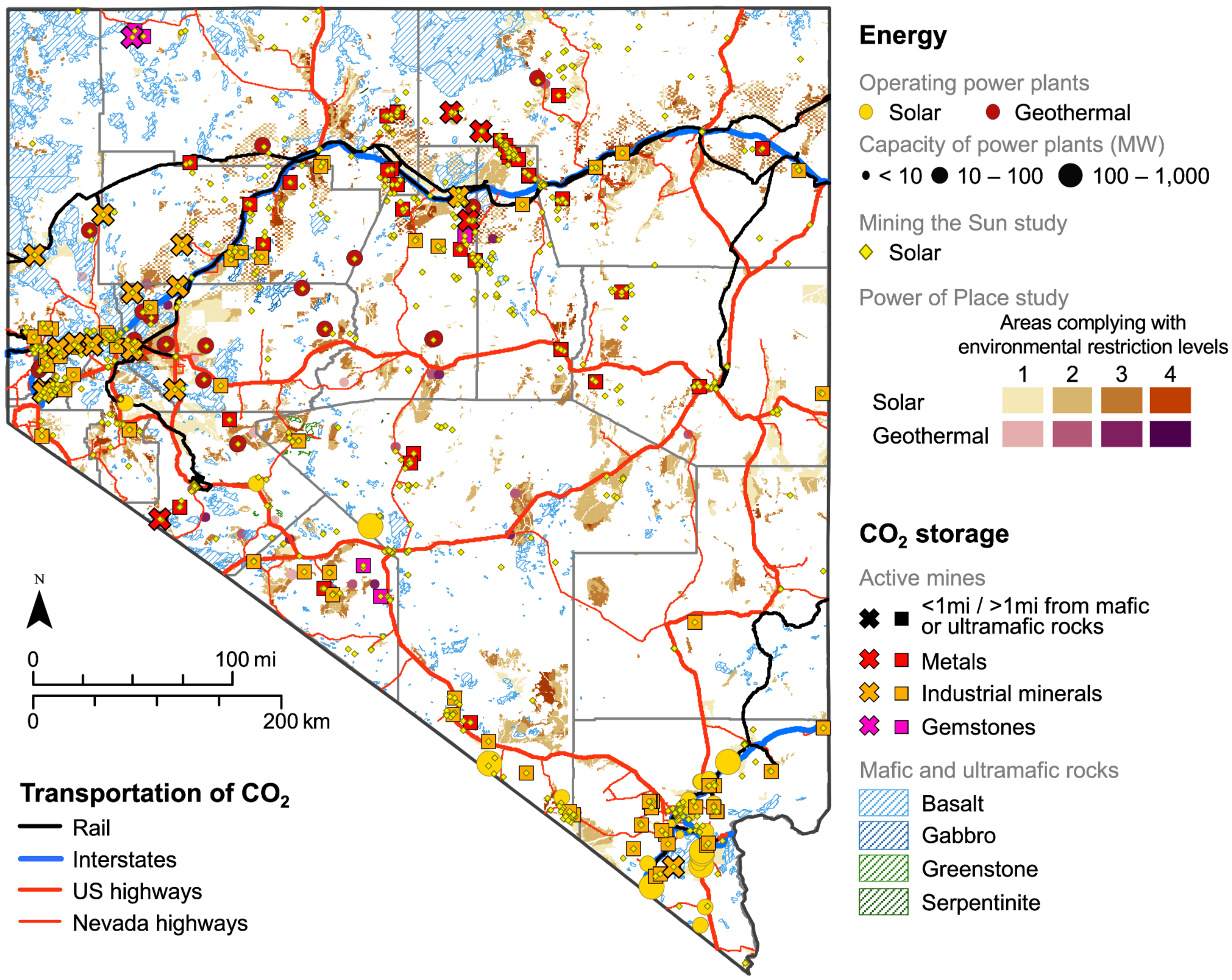

Figure 22. Opportunities for carbon dioxide removal in Nevada[63,71,97-102]. Land restriction levels from the "Power of Place" study indicates areas that would comply with (1) legal protections, (2) administrative protections, (3) high conservation value preservation, and (4) landscape intactness preservation.

As noted in section 3.3.4. ("Mining industry considerations"), some mines might have tailings that are reactive with CO_2 and could store carbon via carbon mineralization processes. Figure 22 overlaps current renewable energy power plants and areas for potential renewable energy development from the "Power of Place" and the "Mining the Sun" studies, including active mines and mafic and ultramafic geologic formations (e.g., basalt, gabbro, serpentinite, greenstone) that could be used in a carbon mineralization process. About four metal mines in the north and west parts of Nevada might be able to both host solar energy installations and use mine tailings rich in calcium and magnesium for carbon mineralization. About three locations for potential geothermal energy development on top of basaltic formations are found in the western part of the state. The basalt would have to be mined and ground specifically for carbon sequestration, or, if the basaltic formations are deep enough and appropriate for CO_2 storage, the CO_2 could be injected into the subsurface, provided that it does not interfere with the geothermal reservoir. Even if strict co-locations of renewable energy deployment sites and CO_2 storage options at existing mines are difficult to find, multiple opportunities exist close to one another, especially in the north and the west where most of the mining activities and the basalt outcrops are located.

3.8. Carbon storage options

Like carbon removal, the storage of captured CO_2 may be achieved through either engineered or nature-based solutions. An issue of critical importance in the selection of a CO_2 storage option is its permanence; some choices for carbon storage may not be able to keep CO_2 sequestered permanently (or at least not for several hundred years). Geologic storage of CO_2 through either subsurface injection of supercritical CO_2 into underground formations (*in-situ* storage) or the reaction of minerals on the surface with CO_2 into solid carbonates (*ex-situ* storage) are two options that serve as engineered analogs to the natural ambient mineral weathering process. They can offer increased permanence over options such as soil carbon sequestration or afforestation/reforestation. Storage of carbon either through underground injection of CO_2 or surficial carbonation of mineral wastes may occur in the state of Nevada and in neighboring states, providing potential sinks for CO_2 captured either from industrial processes or through DAC.

3.8.1. Mineral carbonation of alkaline waste and mine tailings

Nevada produces cement kiln dust (CKD) and lime kiln dust (LKD) from three major industrial sources: the Nevada Cement Company plant, the Lhoist North America lime plant, and the Graymont Pilot Peak lime plant. We assessed the process emissions from these sources reported to the EPA FLIGHT database for 2019[40]. While coal fly ash may also serve as a potential source of alkalinity, we assumed that no coal plants will be operating in Nevada by 2050 and that it will not be a reliable source of alkalinity for CO_2 storage. Average data for the composition of CKD and LKD are taken from Collins & Emery[103], and we assumed that high-calcium (high-reactivity) LKD will be available as it is freshly produced by the plant. We used a production factor for CKD of 0.060 tons CKD/ton CO_2 emitted, based on the work of Kirchofer et al.[104]. We used a production factor for LKD of 0.175 tons LKD/ton CO_2, derived from the 2003 reported domestic production of 18.2 million tons of lime[105], concurrent LKD production estimates of 2.5 millions tons[105], and a production factor of 0.785 tons CO_2/ton lime produced (process emissions basis) based on the 2009 EU Emissions Trading Scheme[106]. We assumed that about 77% of the total carbonation capacity may be achieved for both CKD and LKD, based on work with CKD by Huntziger et al.[107]. Total estimates for annual CO_2 storage capacity in Nevada via carbon mineralization of industrial kiln dusts and the associated equivalent production of synthetic aggregates are listed in the table below (Table 12).

Table 12. Assessment of mineralization potential across heavy emitters in Nevada's industrial sector.

Facility	2019 Process Emissions ($ktCO_2/yr$)	Estimated CKD/LKD Production (kt/yr)	CO_2 Storage Capacity (kt/yr)	Total Mass of Carbonated Waste (kt/yr)
Nevada Cement Co. Plant	173.78	10.43	2.96	13.39
Lhoist Apex Lime Plant	416.78	43.60	24.32	97.25
Graymont Pilot Peak Lime Plant	410.41	42.94	23.95	95.76
		Total (kt/yr)	51.23	206.40

CKD = cement kiln dust; LKD = lime kiln dust

The total carbon storage capacity of the combined kiln dusts at current estimated production rates is 5.1% of the total process emissions of the three facilities from which the waste is derived (not including combustion emissions). While this amount of permanent storage is not insignificant, carbon mineralization will not be able to serve as a realistic pathway for the storage of all emissions from these processes in Nevada. As carbon capture is implemented to reduce process and combustion emissions from lime and cement plants, a small fraction of this CO_2 may be diverted for carbon mineralization and essentially the remediation of the wastes produced by these facilities.

It is difficult to fully assess the CM storage potential of mine tailings produced in Nevada without detailed information on the compositions of mine tailings. As a preliminary analysis of storage prospects, we used a geological map of Nevada available from the Nevada Bureau of Mines and Geology (NBMG) and USGS[100] to identify regions with basalt, gabbro, greenstone, and serpentinite geologic formations. GIS data publicly available from the NBMG Active Mines and Energy Producers database[101] was overlaid, and mines located within 1 mile of the favorable geology were identified as possible candidates for carbon mineralization using mine tailings. In particular, the Fire Creek, Hollister, and Midas Mines in central Nevada near Battle Mountain were identified as having potential for carbon storage through basalts in their mine tailings. We used information from the 2019 NBMG report on The Nevada Mineral Industry, which reported tailings primarily composed of basaltic andesite, and data on the total estimated mining reserves for the Fire Creek formation. Average data for MgO and CaO in basaltic andesites in this region were taken from Cousens et al.[108] and used to assess the potential for storage of CO_2 as magnesium and calcium carbonates.

Based on the combined production rates reported in the 2019 NBMG report for the Fire Creek, Midas, and Hollister gold and silver mines, we estimated that the tailings produced in that year could serve as a sink for up to 22.87 ktCO_2, and the carbonated tailings could serve as a synthetic aggregate replacing up to 213.7 kt of mined aggregate. It is important to note that the specific mineralogy of the tailings will need to be analyzed to generate more realistic estimates of the total storage potential at each mine, based on available labile alkalinity and projected process efficiencies for mineral carbonation. In addition, utilizing tailings for carbon mineralization and reuse as synthetic aggregate will likely render any trace minerals that remain in legacy tailings unrecoverable.

Future operations on the underground and open pit reserves of the Fire Creek deposit may produce enough mine tailings to serve as a sink for up to 8.12 MtCO_2 over the remaining lifetime of the operations. This estimate assumes that the Mg and Ca content of the waste may be fully carbonated through an efficient carbon mineralization process. Also, the carbonated mine wastes could serve as synthetic aggregate and replace up to 75.87 Mt of mined aggregate, offsetting further emissions from those mining operations. To fully assess the CM storage potential of mine tailings in Nevada, a compositional analysis should be conducted of tailings from major metal and gemstone mining operations located in regions where basalts, basaltic andesites, serpentinites, and other mafic or ultramafic rocks are known to exist, as indicated on the geologic map.

The reuse of carbonated wastes as synthetic aggregates would also reduce the total emissions from mining aggregates. Woodall et al.[109] reported that the avoided emissions from this practice would be in the range of 0.098 to 0.448 tons CO_2/ton product. The total solid carbonated waste produced from realistic carbonation of CKD and LKD in Nevada totals 206.4 kt/yr, meaning its reuse as synthetic aggregates could reduce overall emissions by between 20.2 and 92.5 ktCO_2/yr. The carbonation of the tailings from the Fire Creek, Hollister, and Midas Mines over their projected lifetimes would total 76.7 Mt, meaning that their reuse as synthetic aggregate could prevent the emission of 7.5–34.4 MtCO_2. This is not an insignificant amount and demonstrates that carbon mineralization and the reuse of its products may provide a valuable means of reducing the emissions from the construction industry for Nevada over the next several decades, while continuing to improve state infrastructure. Data from the USGS as recently as 2017 indicates that the current annual consumption of construction aggregates in Nevada exceeds 30 Mt, meaning that the synthetic aggregates produced from the carbonation of industrial kiln dusts would total less than half a percent of the current market for aggregates. Thus, they could almost certainly be used on existing projects within the state.

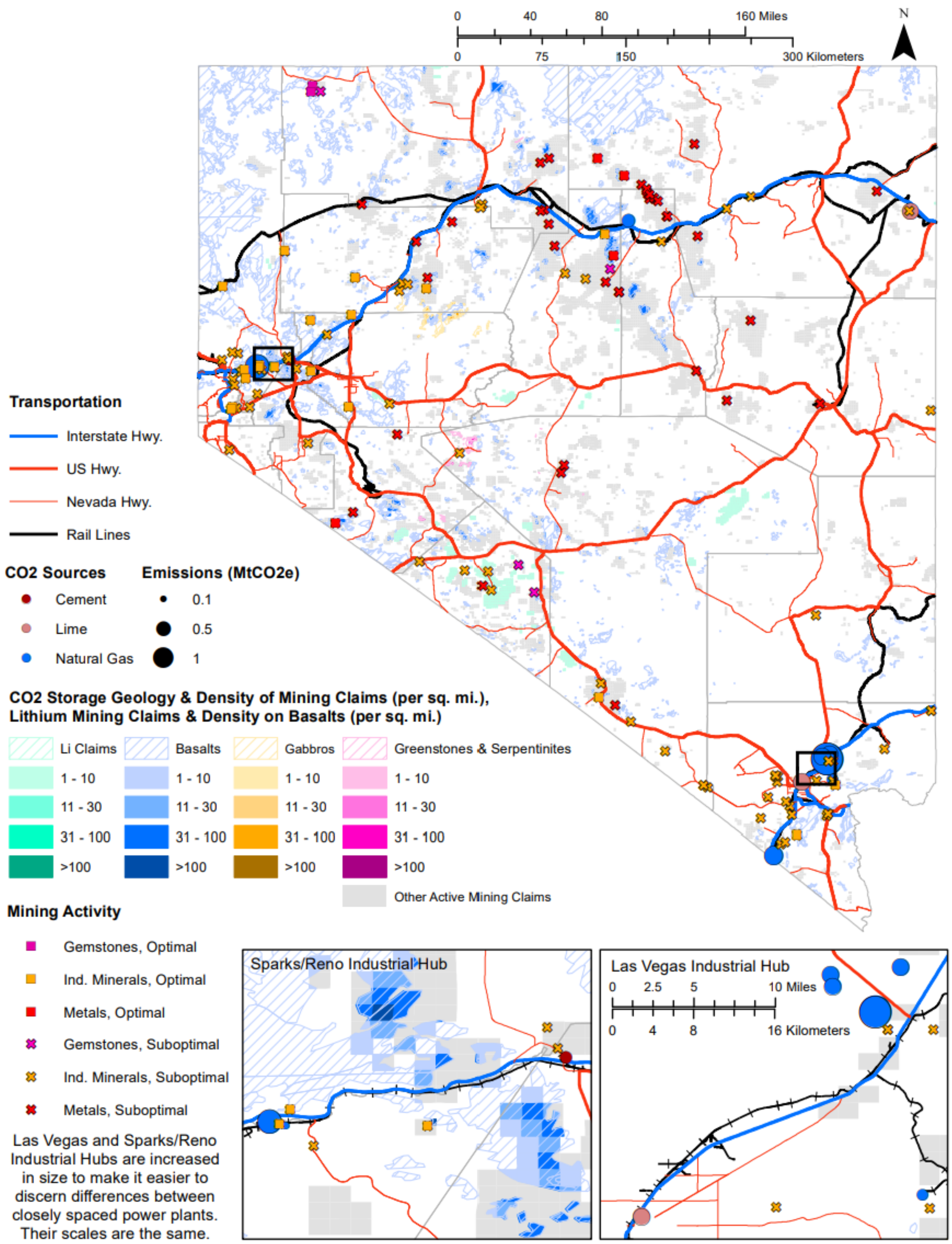

Figure 23. Mineral carbonation storage opportunities in Nevada. Active mines (gemstones, industrial minerals, and metals), geologic formations, transport, density of active mining claims, and major CO_2 sources are indicated[41,98,99,101,102,110,111].

One type of mining activity in Nevada that might increase over the next several decades is lithium mining. Nevada has the only operating lithium mine in the United States, and as the state and country shift toward increased electrification of transportation and increased deployment of renewable energy, sustainable access to domestic lithium resources will be very valuable. It is reasonable to investigate whether a predicted increase in Li production could also lead to an increase in the availability of favorable alkalinity for mineral carbonation. We overlaid the current database of mining claims in Nevada, both general and specific to lithium, with the geographic data for favorable basaltic and ultramafic geology for carbon storage. Lithium claims account for only 3% of total active mining claims in Nevada, and of these, only 1.67% (or 0.05% of total mining claims in the state) lie on geology that is favorable for CO_2 storage. Based on current data, it does not seem likely that CO_2 storage through mineral carbonation spurred by increased lithium mining is a likely pathway for the state in reaching its goals.

Table 13. Breakdown of active mining claims by local geology in Nevada.

Claim Surface Geology	Total Claims	% of Total
Greenstone	1,776	0.38%
Serpentinite	506	0.11%
Basalt	42,504	9.20%
Gabbro	1823	0.39%
Other	415,349	89.91%

Table 14. Breakdown of lithium mining claims intersecting with basaltic geology.

Claim Type	Total Claims	% of Total
Lithium mining, basalts	208	0.05%
Lithium mining, other	13,648	2.95%
Non-lithium claims	448,102	97.00%

3.8.2. Out-of-state options

The conventional way of storing CO_2 is by injection over 800 meters deep in sedimentary formations, either depleted oil and gas reservoirs, or deep saline aquifers. An alternative that is at the pilot phase is to inject CO_2 dissolved in water in basaltic formations. Nevada hosts numerous sedimentary and basaltic formations that would be deep enough for CO_2 injection and storage. However, we must study these formations further to know whether they can technically and economically be used for CO_2 storage. The potential large amount of water that would be used (27 tons of water per ton of CO_2 injected in basaltic formations) and the scarcity of water in Nevada would also be a limiting factor, as over 100% of the perennial yield of water is already committed for over one-third of Nevada's drainage basins[112].

If carbon mineralization options and in-situ CO_2 storage described above do not provide economic opportunities for CO_2 storage, it is worth considering alternative solutions out of state. For instance, subsurface injection of CO_2 in sedimentary formations like depleted oil and gas reservoirs or saline aquifers are available in California, especially in sedimentary reservoirs below the central valley, or in Wyoming[91]. If Nevada has more ambitious climate goals, Wyoming already delivers Class VI well permits, which are specific to dedicated storage of CO_2.

Extensive basaltic formations are located northwest of Nevada, in northern California and Oregon. These formations could be used to develop in-situ CO_2 storage projects similar to the CarbFix project in Iceland, or the Wallula project in the state of Washington. As shown in Figure 24, major CO_2 emitters where CO_2 could be captured (e.g., natural gas power plants, cement and lime plants), are located close to railroads, which could transport the CO_2 to storage sites in sedimentary reservoirs.

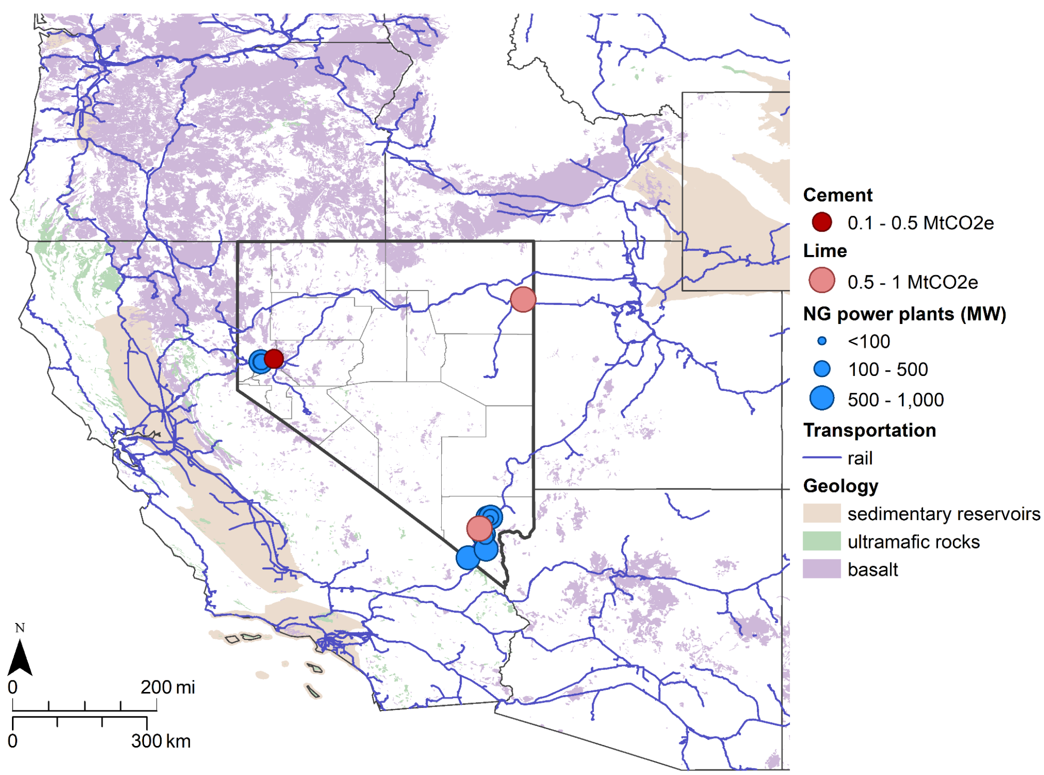

Figure 24. Opportunities for CO_2 storage in Nevada's neighboring states, along with major sources of CO_2 in Nevada and railroads[41,71,98,113,114].

3.9. Areas for further research

The analysis and presentation of net-zero pathways within Nevada has unearthed several interesting topics for further exploration, as well as data gaps that could be filled to help support and solidify future pathways. This section details several such topics.

3.9.1. Emission scoping and interstate considerations

Achieving net-zero starts with an accurate inventory and accounting of current and projected emissions across all sectors. Herein lie several potential complications regarding emission *scope*. According to the GHG Protocol Corporate Standard[115], emissions can be classified into three categories:

> *Scope 1:* emissions from the direct consumption of fossil fuels in any facilities and/or vehicle fleet owned by the entity or state
> *Scope 2:* emissions associated with purchased electricity, heat, steam and cooling; in essence, any form of energy consumption in any entity not controlled or owned by the state
> *Scope 3:* emissions associated with value-chain activities, both upstream and downstream of direct operations

One complication is that one state's scope 1 emissions could be another state's scope 2 or scope 3 emissions. Consider, for example, a power plant in California that supplies electricity to Nevada. These emissions would count as scope 1 in California and scope 2 in Nevada. Likewise, automobiles produced in Nevada could have scope 3 emissions out-of-state. Hence, in emission accounting, it is important to recognize and identify those emissions that are directly under Nevada's control.

Another complication arises from net-zero pathways and the potential for emission leakage. In this sense, leakage does not refer to physical leakage of emissions from storage reservoirs, but rather economic leakage of emissions as a result of local emission reduction efforts. As an example, a lime producer that is placed into a position to decarbonize operations within the state or retrofit their operations with CCS might instead elect to shift operations to other locations, potentially out of state. While this shift in emissions may show favorably on Nevada's ledger toward net-zero, the emissions are not reduced, only shifted outside the accounting boundaries. The reverse situation can also occur, in which the actions of neighboring states could shift emissions into Nevada through induced leakage of economic activity and/or population. Nevada's two western neighbors, California and Oregon, both have net-zero goals. It will be important for Nevada to closely track the policies and efforts in neighboring states to minimize any adverse impacts from interstate leakage.

3.9.2. Ensuring equitable and just transitions

While much of the strategic modeling of CCS and CDR deployment has focused on techno-economic impact categories, these types of analyses can remain blind to the cumulative social and environmental impacts of certain pathways. Many of the strategies identified in this study could place increasing stress on marginalized populations. Fossil-fueled and biomass-fueled cooking are major sources of indoor air pollutants. Switching to electric-based and induction cooktops is an important step for decarbonization of residential and commercial buildings, but these options are often more expensive than their fossil-fueled counterparts and will likely remain out of reach for low-income households without support. It is also important to consider how the cost burden is distributed for residual fossil infrastructure (for generation and distribution), as more residents shift away from natural gas usage.

Care must be taken to ensure that placement of CDR within the state avoids potential harms to local ecosystems and communities[116]. Several CDR options require large amounts of land and water, which could displace local biodiversity or divert resources from other needs. CDR siting should leverage existing resources and infrastructure if possible, but will also need to examine the indirect upstream and downstream impacts. A CO_2 pipeline could present issues in routing with respect to protected lands and raises environmental justice questions, as some communities can exert their political will and capital to sustain NIMBY[XV] resistance, while others cannot.

Implementation of more robust public transportation can help reduce light-duty vehicle miles traveled and benefit members of lower income communities who cannot afford a personal vehicle. Advancements in other technologies, like high-speed trains or hyperloops, could help reduce aviation-related traffic, with a concurrent decrease in emissions in the areas surrounding airports, which are typically lower income neighborhoods.

3.9.3. Data gaps in storage and generation potential

As important as the technology or mechanism for carbon reductions or removals is the safe and secure management of CO_2 from source to storage. A thorough understanding of storage options—*in situ, ex situ*, surficial, and in the technosphere—will increase the flexibility of Nevada's carbon management options as the state strives to reach net-zero emissions while simultaneously avoiding many of the direct and indirect harms described in the previous section.

Given Nevada's robust mining economy, it is worth exploring the utilization of mining waste and byproducts to store CO_2. Chemical analysis of mine tailings can help identify suitable feedstocks for carbon mineralization, as well as potential metals and critical minerals that could be targets for

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[XV] NIMBY stands for *not in my backyard* and is an expression used by those who oppose development that is perceived to be unpleasant or hazardous in their area, such as a landfill, pipeline, or factory.

co-recovery. Likewise, a survey and inventory of the amounts of mine wastes generated and stored on-site can help project developers assess the scale of removal and infrastructure needs on a site-by-site basis.

Nevada's geothermal resources make it a prime candidate for further development of these resources and logical pairing with potential carbon management solutions, like DAC with low-quality heat needs. We need more geothermal data to gain a better understanding of the geothermal potential, as there is a significant discrepancy in the estimates we reviewed.[XVI] Finally, we need more geological data at depth, to determine whether small saline aquifers or basalts could be used for in-situ CO_2 storage.

[XVI] One study claims 584 MW of potential, while personal communications have conveyed vast amounts of untapped geothermal energy potential in the state and surrounding region, possibly in the order of tens of gigawatts.

4. Summary

The present study shows that for Nevada to meet the net-zero goal set by the administration by 2050, we must implement a portfolio of carbon management strategies. Mitigation will play a major role and should be prioritized, but our results show that even with substantial mitigation, carbon capture from large GHG emitters and from the air (through DAC) will be needed to achieve Nevada's carbon neutrality goal.

Electrification is a key mitigation factor for all sectors of the economy and would help divert energy sources from fossil fuels, as long as electricity generation itself shifts toward renewable sources of energy. Solar is an uncontested and growing energy source in the state; PV can supply electricity and CSP can supply both electricity and heat. Geothermal energy has also great potential, especially in the western part of the state. It can supply both electricity and heat and has a smaller footprint than solar. In 2050, we expect that electricity generation will be 150%–230% greater than in 2020. For electrification to be most efficient in mitigating climate change, it is essential to minimize the grid carbon intensity by building only power plants that use renewable energy, replacing fossil fueled power plants with renewable sources of energy, retrofitting recently built natural gas power plants with carbon capture, and offsetting remaining and embedded emissions with CDR.

When electrification is not an appropriate solution, other GHG mitigation strategies can be deployed, such as using efficient energy shells for buildings, finding pathways to decrease waste landfilling in order to reduce compounding annual methane emissions, developing alternative fuels (e.g., hydrogen and carbon-neutral aviation fuels), and replacing leaking and highly potent ODS in refrigeration and air conditioning systems with environmentally benign gases.

Large emitters can also retrofit their systems with carbon capture. This makes sense for natural gas power plants that need to stay online to facilitate the future transition toward a fully renewable electricity generation system, and for cement and lime plants that emit large amounts of CO_2 from the limestone calcination process. Carbon capture could avoid over 90% of the emissions from these sources, which would total to up to 8.3 $MtCO_2$/yr. In the case of the cement and lime industry emissions could be further reduced by fuel switching (use of biomass or natural gas, electrification), which would also reduce the amount of carbon capture needed.

If more efforts are made to mitigate GHG emissions and conduct point source capture on major emission sources, less DAC will be needed to meet Nevada's climate goals. DAC might look like a miracle solution to some, but it comes with costs in terms of energy generation, land use, and CO_2 storage. The baseline scenario would require the most DAC deployment (51.6 $MtCO_2$/yr by mi-century) and is also the one with the largest total energy needs. The high-optimistic and best-case scenarios have lower estimated energy demand, due to lower energy supply needs for DAC (down to 4.5 $MtCO_2$/yr).

In the scenarios we examined, the additional electric capacity and land area that would be needed to develop new renewable energy power plants and DAC plants vary greatly, from 12 to 51 GW and from 250 to 1,900 km^2, depending on the renewable energy source considered and the carbon management strategy followed by the state (i.e., relative amounts of mitigation, point source capture, and DAC). New infrastructure could be deployed only on lands where it would have a low impact on the environment.

In order to mitigate climate change, the CO_2 captured must be stored. Less carbon capture (through point source and DAC) means less CO_2 transportation and storage within or out of state. Nevada has geologic formations that could be used for in-situ storage of CO_2 or ex-situ carbon mineralization. Due to the large mining industry in Nevada, there may be tailings with the appropriate chemical composition that would react with CO_2 and store it in the form of carbonates. Research is needed to develop carbon mineralization processes and evaluate the geologic storage potential for both subsurface CO_2 injection and surface carbon mineralization processes; this research will be a key part of assessing in-state options for permanent storage. Alternative large capacity options that require less investigation might be available in neighboring states, such as California and Oregon, sooner.

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