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Natural gas use in the U.S. building sector in global low carbon pathways

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Executive summary

Achieving the Paris Agreement goals of limiting global average warming to well below 2°C, and pursuing efforts to limit warming to 1.5°C, implies that global greenhouse gas emissions must be reduced to net zero this century. A wide range of studies have examined the implications of meeting these global goals for energy use and emissions at the country and sector level. We drew on results of those studies, and carried out new modeling analyses, to assess the outlook for the use of natural gas in residential and commercial buildings ("buildings") in the U.S. in scenarios consistent with the Paris Agreement goals. Broadly, we find continued but declining natural gas use in buildings in these scenarios. Pathways of building gas use cover a wide range, with the speed and extent of reductions strongly influenced by the overall U.S. emissions goal, progress made in other sectors, and the use of negative emissions technologies. Regional gas use in buildings may vary as well due to differences in climate and other factors.

Our approach included two main types of analyses. We examined two databases of published global emissions scenarios that were used to support a recent report of the Intergovernmental Panel on Climate Change (IPCC 2018). We selected a subset of these scenarios that were consistent with the Paris Agreement warming goals, and in which U.S. CO_2 emissions (or emissions for industrialized countries as a group, where U.S. results were not available) were reduced by 2050 sufficiently to be meaningful for current policy discussions: at least 80% in 2°C scenarios, and 100% in 1.5°C scenarios, relative to 2005. We then examined outcomes in these scenarios for natural gas consumption in buildings to draw conclusions about pathways consistent with Paris Agreement goals.

Analyzing a large number of scenarios from different models is useful for producing robust conclusions, but variations in assumptions across models and scenarios can make it difficult to isolate the role of single factors. We therefore also developed new scenarios with the Global Change Analysis Model (GCAM) to investigate questions such as how the availability of negative emissions options could influence the use of natural gas in U.S. buildings.

Results show that in 2°C scenarios, residential and commercial building gas use in the U.S. is reduced 0-20% by 2030 and 30-75% by 2050. In 1.5°C scenarios, reductions are steeper: 0-30% by 2030 and 55-85% in 2050. Results from a larger ensemble of scenarios looking across the industrialized countries suggest a wider range and larger reductions, but the implications for the U.S. are unclear. Reductions in gas use tend to be larger when U.S. net CO_2 emissions reductions are larger, and when the use of negative emissions options is constrained. Building gas use tends to be more persistent than the use of fossil fuels in other sectors and may be more persistent in colder states.

Summary of key findings:

1. Scenarios limiting global warming to 1.5 or 2°C find continued but declining emissions from natural gas use in U.S. residential and commercial buildings through 2050.
2. Natural gas use in buildings in these scenarios spans a broad range of possible pathways. The speed and extent to which it declines depends to a large degree on the overall U.S. emissions goal and the use of negative emissions technologies.
3. Natural gas use in buildings tends to continue longer than fossil fuel use in other sectors of the economy and may continue longer in colder states.

Key findings and supporting analysis

In the remainder of this report, we discuss each key finding in turn, describing the supporting analysis of the scenarios database and GCAM model simulations. We also describe the methodology underlying these two approaches to the analysis.

Introduction: Scientific and policy framing

A new scientific and policy framing has emerged around climate mitigation over the last several years. This new framing is based on the timing of net-zero CO_2 or GHG emissions. This is now the framing for international and national policy discussions.

The Paris Agreement goals are to limit global average warming to well below 2°C, and to pursue efforts to limit warming to 1.5°C. The scientific community has concluded that net global CO_2 emissions need to reach zero around 2070 to limit warming to 2°C without relying extensively on negative emissions technologies. A comparable conclusion regarding 1.5°C is driving 2050 net-zero commitments from countries, states, cities, and businesses around the world. Discussions in the U.S. are now focused on meeting a 1.5°C goal, and states, cities, businesses, and the federal government are looking to eliminate CO_2 or GHG emissions by 2050. These net-zero targets are an evolution from the Obama Administration's target of 80% GHG reductions by 2050, which was intended at the time to be consistent with 2°C. Although there are 2°C studies with less ambitious reductions in 2050, net CO_2 reductions of less than 80% by 2050 would be a step back even from these previous national goals for 2°C, and they are well outside of the scientific consensus associated with 1.5°C. A meaningful assumption for engagement in policy discussions around 2°C is therefore that total net CO_2 emissions be reduced by at least 80% in 2050, and an assumption of net-zero emissions would be consistent with the current framing around 1.5°C.

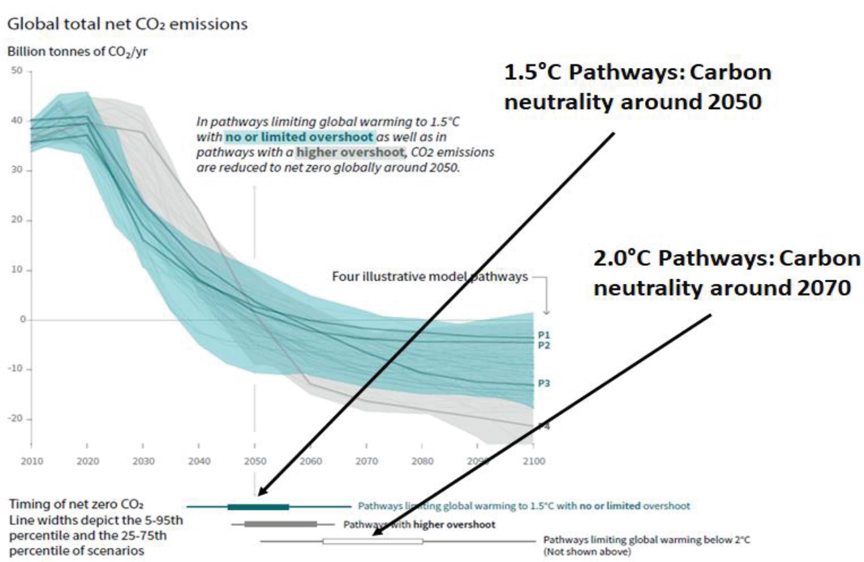

Figure 1: Global net CO_2 emissions scenarios consistent with limiting warming to 2°C (green range) or 1.5°C (gray range) along with years by which net emissions reach zero. Source: IPCC (2018).

1. Scenarios limiting global warming to 1.5°C or 2°C find continued but declining emissions from natural gas use in U.S. residential and commercial buildings through 2050.

We identified pathways of natural gas use in U.S. buildings consistent with the Paris Agreement targets by first identifying all global scenarios in the databases that were likely to remain below 2°C, or more likely than not to remain below 1.5°C. These scenarios were those available to support the 2018 IPCC report on global warming of 1.5 C (IPCC, 2018). However this set included many scenarios in which U.S. net CO_2 emissions were not reduced to levels consistent with current policy discussions. We therefore selected a subset of these scenarios in which not only were global warming goals achieved, but U.S. net CO_2 emissions were reduced at least 80% in 2°C scenarios and at least 100% (net zero) in 1.5°C scenarios by 2050, relative to 2005.

In this subset of scenarios, pathways of natural gas use in U.S. buildings (for all end uses) show eventual declines in the coming decades (Figure 2). For example, in 2°C scenarios, building gas use in the U.S. is reduced 0-20% by 2030, and 30-75% by 2050. In 1.5°C scenarios, reductions are steeper: 0-30% by 2030 and 55-85% in 2050. These reductions are in net terms; it is not possible from the scenario results to identify specific locations where gas use may be increasing or decreasing, but only the net result that overall use declines.

These results for the U.S. are the most relevant outcomes available from global scenario databases for informing U.S. utility-scale planning. However they are limited to four scenarios for each warming target that meet our selection criteria. Results are more robust when based on a larger number of scenarios, since they can differ based on varying assumptions across scenarios about future population and economic growth driving energy demand, technology costs, types of mitigation policies implemented, and other factors. We therefore repeated the analysis for a larger number of scenarios (11 for 2°C, 7 for 1.5°C) that had outcomes available for the industrialized countries as a whole. While not as relevant as U.S. results, they still provide an indication of building gas use in economies similar to the US.

In this larger set of scenarios, reductions in natural gas use cover a somewhat wider range, particularly on the low end, compared to those for the U.S. (Figure 2). For example, in 2°C scenarios, building gas is reduced 0-40% by 2030, and 30-95% by 2050. In 1.5°C scenarios, reductions are 20-65% by 2030 and 55-90% in 2050. It is unclear whether the differences from U.S. results reflect real differences in energy systems in the two regions or simply reflect a wider set of scenario assumptions used in the studies underlying the industrialized country results.

In addition to indicating the range of reductions that occur in a given year, these pathways can also be used to indicate the range of years by which time a given reduction occurs. This framing can help understand the pace of change represented across scenarios. For example, in 2°C scenarios, 20% reductions in U.S. building gas use occur between about 2030 and 2040 in the U.S. (2025 to 2040 in industrialized countries). Reductions of 50% occur as early as 2040 in the U.S. (shortly after 2030 in industrialized countries). In 1.5°C scenarios, these same levels of reduction occur earlier: 20% reductions in the U.S. do not occur later than 2035, and 50% reductions are reached in 2035-2045.

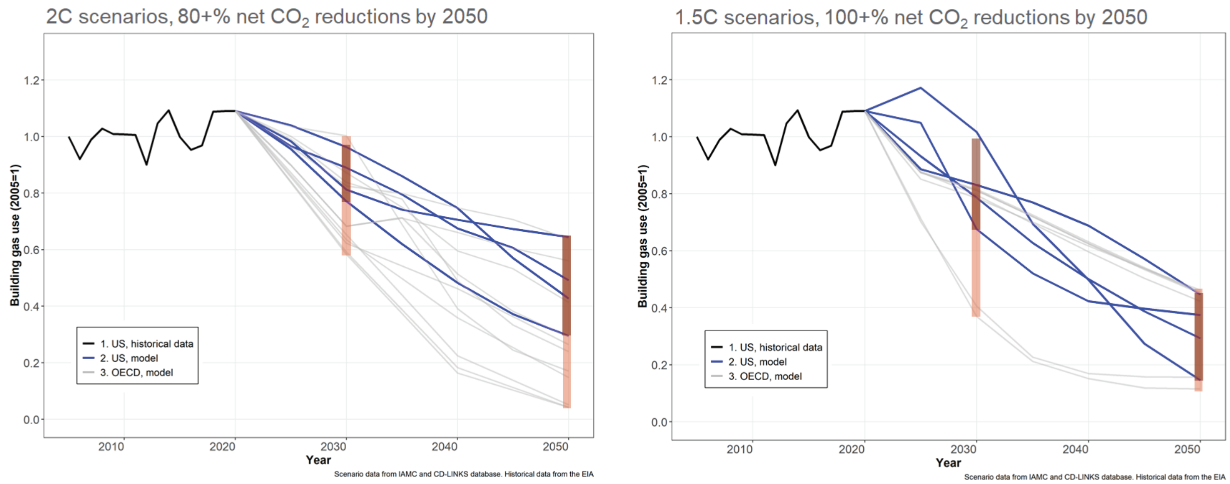

Figure 2: U.S. and industrialized country residential and commercial gas use for all end uses in 2°C scenarios in which net CO_2 emissions in the U.S. are reduced by at least 80% by 2050, relative to 2005 (left), and in 1.5 C scenarios in which net CO_2 emissions in the U.S. are reduced by at least 100% by 2050, relative to 2005 (right). A small number of scenarios include contributions from alternative gases (see Methodology). Ranges of reductions for 2030 and 2050 are indicated for the U.S. (dark red) and industrialized countries (light red).

The primary substitute for gas in buildings across modeling studies is electricity. Electric substitutes already exist for heating, water heating, clothes drying, and cooking. At the same time, there is increasing national and international interest in alternative fuels such as hydrogen or bioenergy. Some models include these alternatives, incorporating estimates of their relative costs, finding that they do not play a major role in substituting for gas or electricity in buildings. However, these alternatives are not sufficiently explored across the modeling literature to draw robust conclusions about their potential.

Results from the scenario databases are available for building gas use, not for emissions from that use. However, emissions reductions in these scenarios would be at least as large as reductions in building gas use, with emissions defined as those resulting from the combustion of gas within the buildings. In most scenarios in Figure 2, all building gas use is fossil-based natural gas, and therefore emissions reductions are exactly the same as reductions in gas use, because the emissions per unit of gas used is identical for all natural gas. In the small number of scenarios in which renewable sources of gas become part of total building gas use over time, emissions reductions will be greater than reductions in total gas use.

2. Natural gas use in buildings in these scenarios spans a broad range of possible pathways. The speed and extent to which it declines depends to a large degree on the overall U.S. emissions goal and the use of negative emissions technologies.

The range of reductions in building gas use in either 1.5°C or 2°C scenarios depends on a number of different factors. Two principal influences are the overall reductions in net CO_2 emissions occurring in the U.S. by 2050, and the extent of the use of negative emissions technologies.

Deeper reductions in economy-wide net CO_2 emissions are generally associated with larger reductions in natural gas use in buildings. Figure 3 demonstrates this relationship for 2°C scenarios. As a rough approximation, an 80% reduction in net U.S. CO_2 emissions in 2050, associated with a 2°C goal, would imply a central estimate of around a 50% reduction in building gas use; a 100% reduction, associated with a 1.5°C goal, would imply a central estimate of around a 70% reduction in building gas use. While near-term reductions focus on electricity and other, easier to decarbonize areas, deeper economy-wide reductions require meaningful action across all sectors.

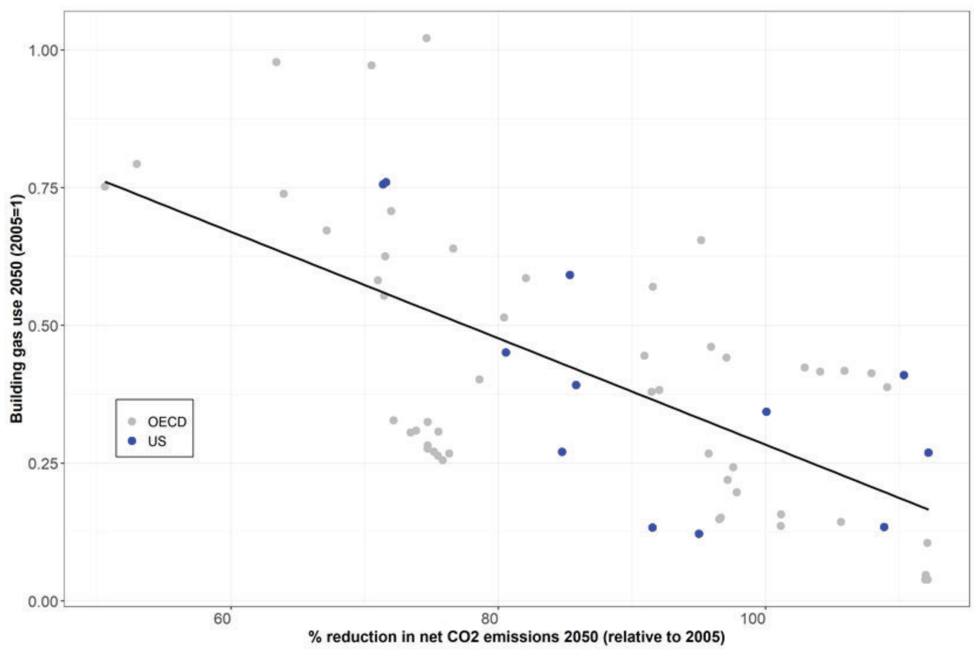

Figure 3: The relationship in 2050 between building gas use and economy-wide net CO_2 reductions in the U.S. (blue dots) and industrialized countries (gray dots) in scenarios limiting warming to either 1.5°C or 2°C. Solid line is a best fit trend line.

Deeper reductions of natural gas use are also associated with more limited availability of negative emissions options. This occurs because continued use of natural gas in buildings, within the context of scenarios in which global emissions must eventually fall to zero, depends on the availability of negative emissions options to offset natural gas emissions. Negative emissions options can include carbon uptake in natural systems such as forests (i.e., the "land sink"), or it can include engineered methods such as bioenergy with carbon dioxide capture and storage (BECCS) or direct air capture (DAC).

To illustrate and quantify this dependence, we modeled a set of 2°C scenarios using a single model, GCAM, in which we kept all scenario assumptions the same except for that availability of negative emissions options, in this case uptake in terrestrial systems and BECCS. We produced scenarios that met the global warming goal with a series of increasingly strict constraints on negative emissions:

- No constraints: negative emissions options are available in all countries and sectors.
- No net negative, Global: net CO_2 emissions are not allowed to fall below zero globally, but can be negative in any particular country or sector.

- No net negative, Global, US: net CO_2 emissions are not allowed to fall below zero globally or in the U.S., but can be negative in any particular U.S. sector or other countries.
- No net negative, Global, U.S., electricity sector: net CO_2 emissions are not allowed to fall below zero globally, in the U.S. (economy-wide), or in the U.S. electricity sector, but can be negative in other U.S. sectors or countries.
- No negative emissions: negative emissions options are not available anywhere in any sector, and carbon capture and storage (CCS) is not allowed even with fossil fuels (zero emissions technologies).

These scenarios show (Figure 4) that as negative emissions constraints become stricter, natural gas use in buildings is reduced earlier, and when such options are not available at all, it is reduced much more extensively by 2050. For example, a 20% reduction in building gas use is reached in 2040 in the scenario without constraints on negative emissions, but occurs in 2025 when such options are constrained to a subset of U.S. sectors. In these scenarios, some negative emissions options remain available, and therefore natural gas use persists in the longer term, declining by 35-40% by 2050. If such options are not available at all, natural gas use in buildings declines much more extensively, by about 85% by 2050 and eventually to zero by around 2090.

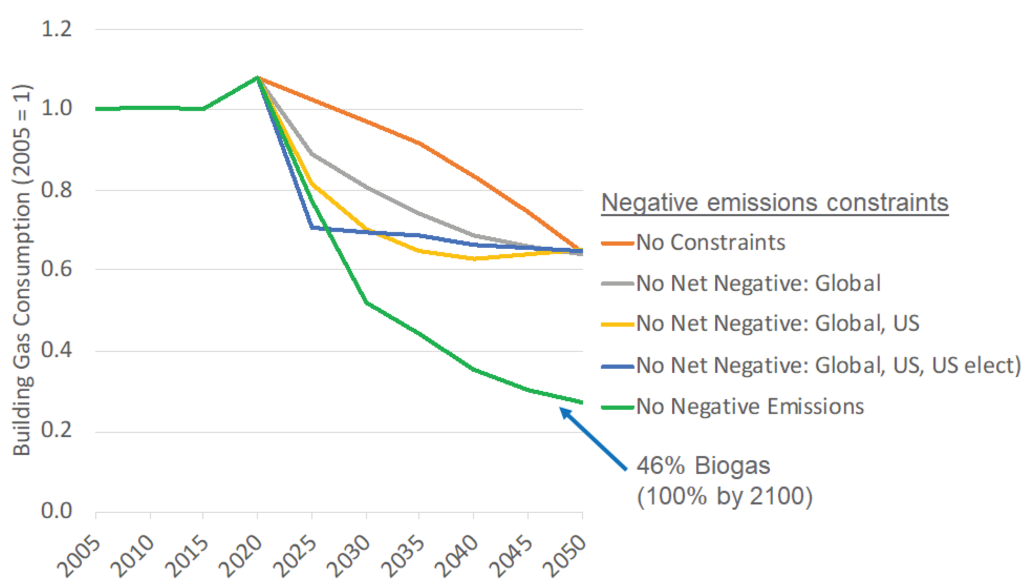

Figure 4: U.S. building gas use in 2°C scenarios for all end uses produced with the GCAM model, with increasingly strict constraints on the availability of negative emissions options. The "No negative emissions" scenario excludes the use of carbon capture and storage, including with fossil fuels. In that scenario, biogas use increases to reach 46% of total gas use by 2050, and 100% of gas use by 2100.

3. Natural gas use in buildings tends to continue longer than fossil fuel use in other sectors of the economy, and may continue longer in colder states.

Results from both the scenario databases and the GCAM analysis support the idea that natural gas use in buildings typically continues longer than fossil fuel use in other sectors. For example, Figure 3 shows that reductions in building gas use are generally smaller than emissions reductions for the economy as a whole. This is illustrated by the fact that 80% reductions in net CO_2 emissions for the economy are associated with about 50% reductions in building gas use, implying larger than 80% reductions in some other sectors.

The GCAM scenarios shown in Figure 4 also indicate the persistence of natural gas use in buildings. They indicate that if negative emissions options are available, natural gas use in buildings persists because it is cheaper to remove CO_2 from the atmosphere than to remove gas from buildings. Figure 5 illustrates that in the GCAM scenario with no constraints on negative emissions (left panel), building sector emissions persist while the electricity sector begins to employ negative emissions before 2050, with extensive net negative emissions in the second half of the century (see appendix). Even when such options in the electricity sector are not allowed (right panel), emissions are reduced much more substantially in the industrial and transportation sectors, including with negative emissions, while emissions from buildings persist.

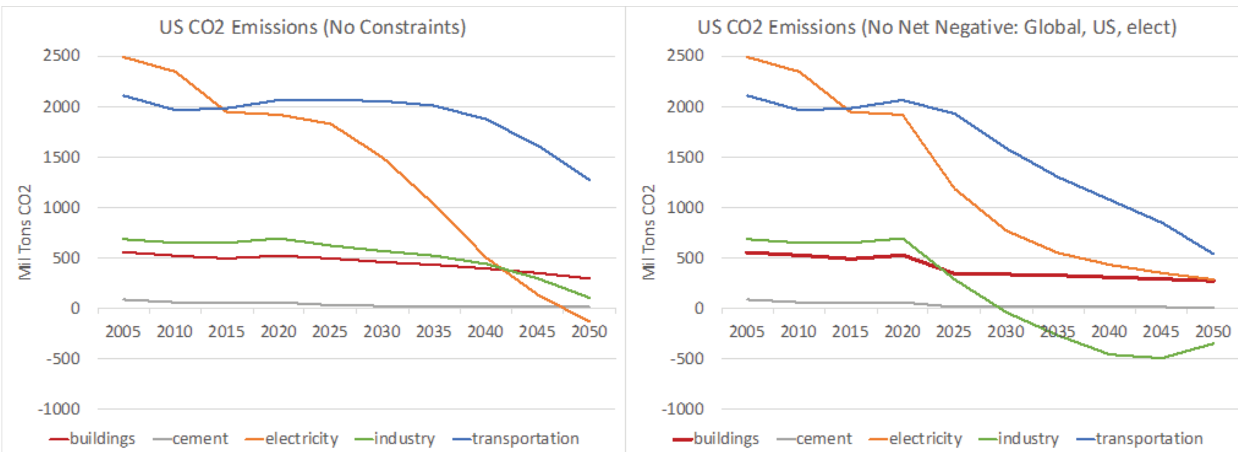

Figure 5: U.S. CO_2 emissions by sector from GCAM for 2°C scenarios in which there are no constraints on negative emissions options (left), and net emissions are not allowed to be negative either for the U.S. economy as a whole or in the electricity sector (right).

Natural gas use in buildings can also be expected to vary across U.S. states, for several reasons. Current levels of building gas use vary across states of different population size, income levels, mixes of end uses, access to gas, and trends in demand driven by these factors. Climate plays a role by affecting the demand for heating and also affects the efficiency of heating technologies such as electric heat pumps. Since electrification (and decarbonization of electricity supply) is a key option for reducing emissions from the building sector, it is possible that reductions in building natural gas use could be expected to occur at different rates across states. For example, natural gas use might be expected to persist in states with colder climates due to greater demand for heating and the decreased efficiency of heat pumps in colder weather.

To assess this possibility we obtained state-specific results from an existing study that employed a version of the GCAM model that represents all 50 states (Feijoo et al, 2020). While the scenario in that study is not exactly the same as the GCAM scenarios in Figures 4 and 5, it is a global 2°C scenario with similar cumulative net CO_2 emissions for the U.S.

Results show that reductions in natural gas use in buildings does vary across states, ranging from approximately a 25% increase to a 20% decrease (relative to 2005) by 2030, and from 60% to 85% decrease by 2050 (Figure 6). In this particular scenario, sharper reductions in building gas use occur after 2035, while earlier reductions occur predominantly in the electricity and industrial sectors. However other scenarios find different timings of building gas reductions, as discussed in Key Finding 1.

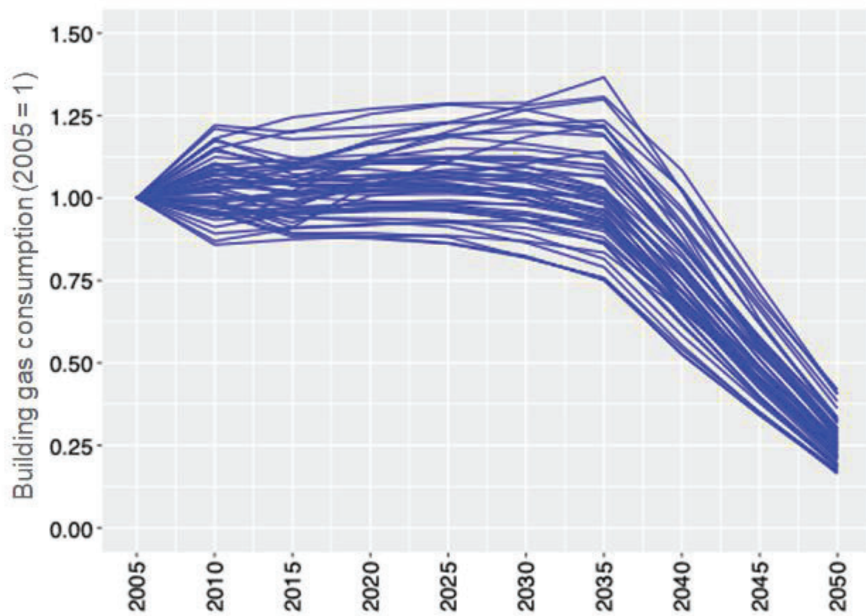

Figure 6: Natural gas use in buildings by state in a 2°C scenario, as modeled in GCAM-USA. Data from Feijoo et al., 2020. Outcomes from 2005 to 2010 are from historical data, with model outcomes beginning in 2010.

We assessed how the extent of reductions in natural gas use in buildings (for all end uses) in 2050 varied with climate by comparing reductions to the number of heating degree days (HDDs) in each state. Heating degree days are an index measuring the need for heating, so are a measure of how cold winters are in a given state. We find that colder states (higher number of HDDs) reduce building gas use less, although the effect is not strong, with reductions associated with climate ranging from about 70% to a little less than 80% (Figure 7, left panel, see trend line). For example, building gas use is reduced in Louisiana by nearly 80%, while it is reduced by less than 70% in Alaska.

One reason for this relatively modest effect is that natural gas is used for many end uses in buildings, not all of which are climate-sensitive. The same assessment of building gas use only for heating shows a stronger relationship, with reductions associated with climate ranging from nearly 70% to almost 90% (Figure 7, right panel, see trend line). In addition, the model analysis underlying these results does not fully capture differences in the efficiency of heating options across states. The results nonetheless suggest that, even in the absence of climate effects on heating technology efficiency and effectiveness, gas may continue longer in colder states. Climate effects on heating technology efficiency and effectiveness, such as heat pumps, would be anticipated to strengthen this result, but additional analysis would be needed to confirm this hypothesis.

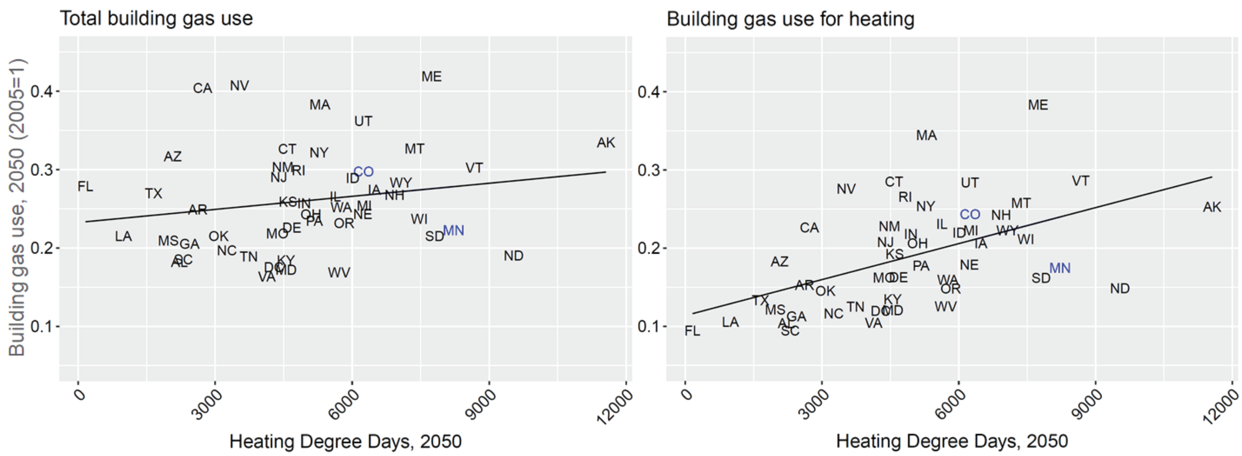

Figure 7: Total building gas use (left) and building gas use for heating (right) versus heating degree days by state in 2050, in a 2°C scenario. States are labeled with two-letter abbreviations. Solid lines are best fit trend lines. Data from Feijoo et al., 2020.

Appendix

Normalizing scenarios to 2005 vs 2020

Figure 2 in the main report shows projected natural gas use relative to 2005, with model results normalized to historical data in 2020. That choice was made to “correct” scenarios with a base year earlier than 2020 for not having correctly anticipated natural gas use in the U.S. through the year 2020. Model results are then used to inform understanding of how gas use changes beginning in 2020 in scenarios achieving 1.5 or 2°C.

For context, we provide here the full set of 1.5°C and 2°C scenarios normalized to 2005, without “correcting” for observed gas use through 2020. This is a larger scenario set than those shown in Figure 2 because it includes all scenarios, not just those in which net CO_2 emissions are reduced by 80%+ (for 2°C) or 100% (for 1.5°C) in 2050. Scenarios cover a wider range in 2030 and 2050 partly because there are more scenarios and partly because the divergence that occurs already by the year 2020 adds to the future range of outcomes.

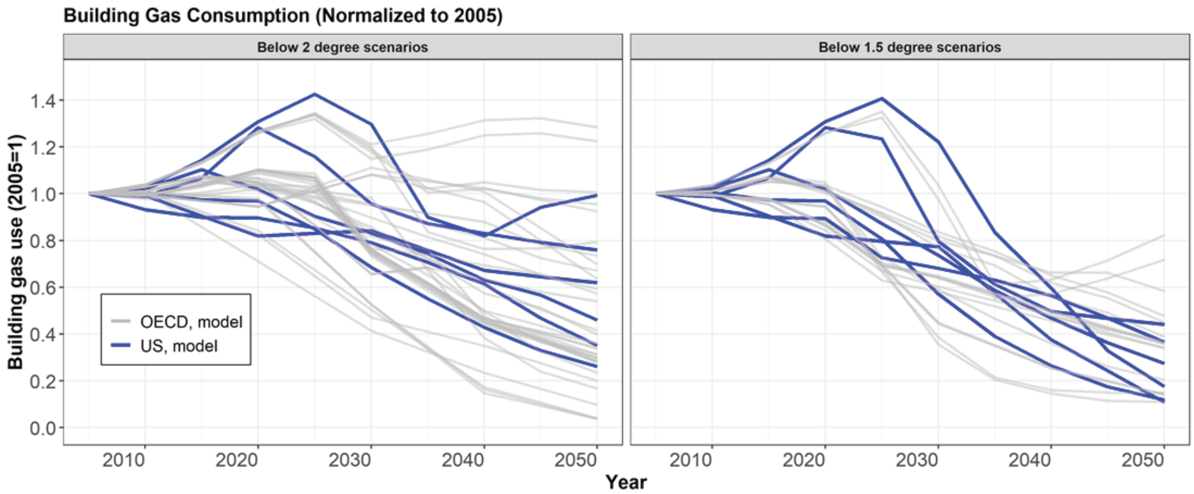

Figure 8: Projected use in the U.S. (blue) and industrialized countries (gray), relative to levels in 2005. Model results are from global scenarios that are likely to remain below 2°C (left) or more likely than not to remain below 1.5°C (right) warming.

Figure 5 in the main report shows projected CO_2 emissions by sector in the GCAM model through 2050. To further illustrate the implications of these scenarios for persistence of gas use in buildings and use of negative emissions technologies, we show results extended through 2100 in Figure 9.

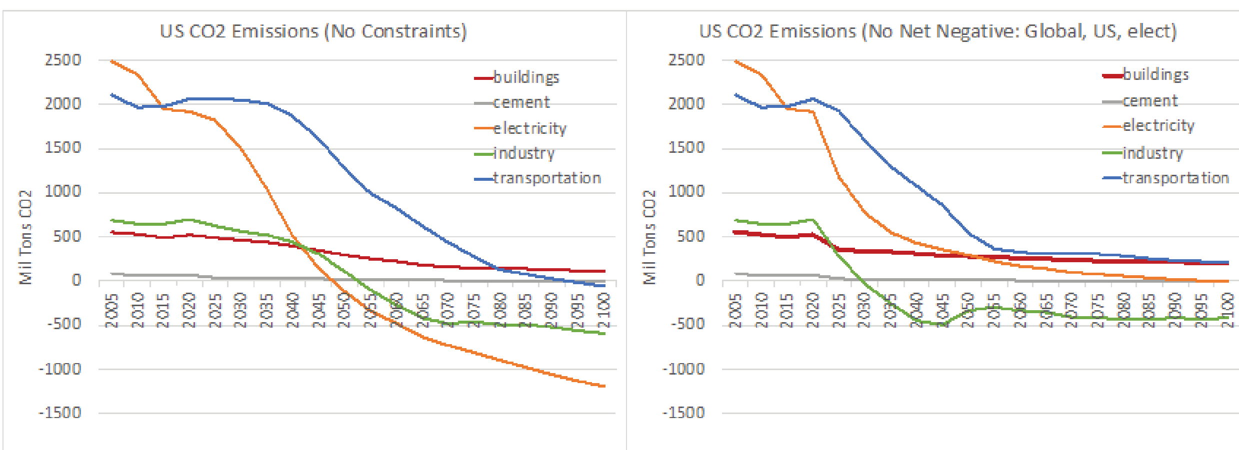

Figure 9: U.S. CO_2 emissions by sector from GCAM for 2°C scenarios in which there are no constraints on negative emissions options (left), and net emissions are not allowed to be negative either for the U.S. economy as a whole or in the electricity sector (right).

Methodology

Scenarios database methodology

We used emissions scenarios from the Integrated Assessment Modeling Consortium (IAMC) 1.5°C Scenario Explorer database (Hupperman et al. 2018)[1] and the CD-LINKS Scenarios Explorer database[2] to assess the use of natural gas in the U.S. building sector through 2050. Both databases present an ensemble of quantitative climate change mitigation pathways underpinning the "Special Report on Global Warming of 1.5°C" (SR15) published by the Intergovernmental Panel on Climate Change (IPCC) in 2018. The CD-LINKS database was used to assess U.S. specific scenarios from six models: AIM (CGE 2.1), IMAGE 3.0.1, MESSAGE (ix-GLOBIOM 1.0), REMIND (MAgPIE 1.7-3.0), WITCH (GLOBIOM 4.4) and POLES (CD-LINKS). The CD-LINKS database consists of globally consistent, national low-carbon development pathways. We complemented these results with a larger set of emissions pathways from the IAMC database (34 scenarios under a below 2°C mitigation pathway and 17 scenarios under a 1.5°C low overshoot mitigation pathway) for a group of industrialized countries consisting of the U.S. and other countries that share similar levels of economic development.[3]

We selected two sets of scenarios from each database: those consistent with achieving the 2°C target, and those consistent with achieving the 1.5°C target. These sets were based on the classification in the IPCC SR15 report (IPCC 2018, see Table 2.SM.11) of "lower 2°C" and "1.5°C return with low overshoot" scenarios. The 2°C scenarios are those that would likely (defined as having a greater than 66% chance) limit peak warming to below 2°C during the 21st century. The 1.5°C scenarios are those that would likely be below 1.5°C in 2100, with a 50–67% probability of temporarily overshooting that level earlier.[4] In the CD-LINKS database, specific scenarios that fell into the 2°C classification were those that would stay within a 1000 $GtCO_2$ budget for the period between 2011 to 2100 ("NPi2020_1000" scenarios), and those that fell into the 1.5°C classification would stay within a 400 $GtCO_2$ budget for the 2011-2100 period ("NPi2020_400" scenarios).

Within these two sets of scenarios, we further selected those scenarios in which net CO_2 emissions in the U.S. (or in industrialized countries) were reduced by at least 80% (for 2°C scenarios) or at least 100% (for 1.5°C scenarios).

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[1] © IAMC 1.5°C Scenario Explorer hosted by IIASA https://data.ene.iiasa.ac.at/iamc-1.5c-explorer

[2] © CD-LINKS Scenario Explorer, https://data.ene.iiasa.ac.at/cd-links. The database was first made available in 2018, with subsequent updates.

[3] We use the phrase "industrialized countries" to refer to the region defined in the IAMC database as "R5OECD90+EU," which contains countries that were members of the Organisation for Economic Co-operation and Development (OECD) as of 1990, as well as current European Union member countries and candidates. Note this does not include Russia and other members of the Former Soviet Union (the "REF" region in the database). Specific countries included are Albania, Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Guam, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, New Zealand, Norway, Poland, Portugal, Puerto Rico, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Turkey, United Kingdom, and the United States of America.

[4] The lower likelihood of achieving the target in the 1.5°C case (50-67%) is used because of the difficulty of achieving it with a higher likelihood.

We used final energy consumption by the residential and commercial sector of gases (which includes natural gas, biogas and coal gas) as our key variable of analysis. To identify whether total gas use contained any significant contributions from alternative gases, we consulted with various CD-LINKS modeling team leads on biogas information availability for the U.S. Three scenarios were confirmed as not having significant biogas in 2050 (POLES, AIM and IMAGE). In one model (MESSAGE), hydrogen accounts for about 13% of total gas in 2050. For the IAMC database results, we used information on secondary energy. Of the 34 OECD region scenarios, 28 have information that allows distinguishing natural gas from biogas; of these, only four[5] have biogas in 2050, ranging from 9-43% of total gas in 2050. We compared the final energy results to net CO_2 emission scenarios. We derived historical emissions data for the U.S. from the U.S. Energy Information Administration (EIA 2021). Tables 1 and 2 provide information on numbers of scenarios and definitions of key variables.

Table 1. Numbers of scenarios used from the CD-LINKS and IAMC scenario databases

Scenario class	U.S. scenario results	OECD scenario results
2˚C scenarios	6	34
2˚C with greater than 80% net CO_2 emissions reduction in 2050	4	11
1.5˚C scenarios	6	17
1.5˚C with greater than 100% net CO_2 emissions reduction in 2050	4	7

Table 2. Key variables from the IPCC databases

Emissions variables	Definitions
Natural gas use in the residential and commercial sector	Final energy consumption (EJ/yr) by the residential and commercial sector of gases ("Final Energy/Residential and Commercial/Gases" variable in the databases), including natural gas, biogas and coal gas. It does not include transmission and distribution losses.
Net CO2 emissions	Total net CO2 emissions ("Emissions/CO2" variable in the databases) from all sources, including energy, industrial, and land use. It is the net CO2 flux to the atmosphere.

[5] This includes all MESSAGE model scenarios, "GEA_Eff_1p5C," "GEA_Eff_AdvNCO2_1p5C," "GEA_Mix_1p5C_AdvNCO2_PartialDelay2020," and "GEA_Mix_1p5C_AdvTrans_PartialDelay2020."

GCAM simulations methodology

GCAM is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. Regional population and labor productivity growth assumptions drive the energy and land-use systems employing numerous technology options to produce, transform, and provide energy services as well as to produce agriculture and forest products, and to determine land use and land cover. Using a run period extending from 1990 – 2100 at 5-year intervals, GCAM has been used to explore the potential role of emerging energy supply technologies and the greenhouse gas consequences of specific policy measures or energy technology adoption including; CO2 capture and storage, bioenergy, hydrogen systems, nuclear energy, renewable energy technology, and energy use technology in buildings, industry and the transportation sectors. The core GCAM has 32 global regions with the U.S. as a separate region. A specialized version of GCAM, GCAM-USA, further disaggregates the representation of the U.S. into fifty states and the District of Columbia. Additional documentation on GCAM is available from Calvin et al. 2019 and on-line at http://jgcri.github.io/gcam-doc/.

Buildings and building energy consumption in GCAM are separated into commercial and residential buildings. Services for cooling, heating, and other, including hot water, cooking, clothes washing and drying, computers, freezers, refrigerators, dishwashers, televisions, and lighting in the case of GCAM-USA, are represented. Building shells are assumed to improve at 0.4% and 0.5% per year for commercial and residential buildings, respectively, reducing the need for cooling and heating services.

The historical energy representation in GCAM is calibrated to the International Energy Agency Energy Balances (IEA, 2019). Methane leakages and losses included as distributional losses in the IEA Energy Balances are included in the GCAM simulations. IEA losses include energy losses from distribution, transmission and transport and do not include gas flaring. The historical methane distributional loss of 2.5% in 2015 for the U.S. is assumed for future periods.

GCAM version 5.3 was utilized for generating the scenarios and results contained in this report. The 2°C climate scenarios for GCAM limit climate forcing to 2.6 Watts/m^2 by 2100 and the mean Earth surface temperature changes do not exceed 2° C throughout the 21st century based on the Hector climate model (Hartin et al., 2015). Cumulative net global industrial CO_2 emissions are fixed to approximately 1,100 gigatons of CO_2 from 2005 to 2100 for all mitigation scenarios with or without net negative emissions pathways. The U.S. CO_2 emissions pathway resulting from the global 2°C scenario was used in alternative scenarios that further restrict total U.S. and sectoral CO_2 emissions. The cumulative net U.S. industrial CO_2 emissions are approximately 165 to 180 gigatons of CO_2 from 2005 to 2100.

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