350 PPM PATHWAYS FOR THE UNITED STATES

May 8, 2019

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DEEP DECARBONIZATION PATHWAYS PROJECT

DDPP

350 PPM Pathways for the United States

U.S. Deep Decarbonization Pathways Project

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List of Terms

1.0°C – One degree Celsius (1.8°F) of global warming over pre-industrial temperatures.

1.5°C – One-and one-half degrees Celsius (2.7°F) of global warming over pre-industrial temperatures, an aspirational goal in the Paris Agreement climate accord.

2°C – Two degrees Celsius (3.6°F) of global warming over pre-industrial temperatures. The Paris Agreement states the intention of parties to remain "well under" this upper limit.

350 ppm – An atmospheric CO_2 concentration of 350 parts per million by volume

80 x 50 – A target for reducing CO_2 emissions used in U.S. states and in other countries, referring to an 80% reduction below 1990 levels by 2050.

AEO – The Annual Energy Outlook, a set of modeled results released annually by the U.S. government that forecasts the energy system under current policy for the next three decades.

AZNM – eGRID region comprising most of Arizona and New Mexico

Base Case – The primary deep decarbonization pathway with all technologies and resources available according to best scientific estimates.

Baseline – A scenario derived from the U.S. Department of Energy's *Annual Energy Outlook* projecting the future evolution of the energy system given current policies

BECCS – Bioenergy with carbon capture and geologic sequestration

BECCU – Bioenergy with carbon capture and utilization of that carbon somewhere in the economy

Bioenergy – Primary energy derived from growing biomass or use of organic wastes

CAMX – eGRID region comprising most of California

CCE – Circular carbon economy, a term that refers to the capture and reuse of CO_2 within the energy system

CCS – Carbon capture and storage (also called carbon capture and sequestration)

CCU – Carbon capture and utilization (for economic purposes)

CO_2 – Carbon dioxide, the primary greenhouse gas responsible for human caused warming of the climate

DAC – Direct air capture, a technology that captures CO_2 from ambient atmosphere

DDPP – Deep Decarbonization Pathways Project

DOE – U.S. Department of Energy

EER – Evolved Energy Research, LLC.

eGRID – Emissions & Generation Resource Integrated Database maintained by the Environmental Protection Agency. eGRID divides the country into regions used in this study that are relevant for electricity planning and operations

EnergyPATHWAYS – An open-source, bottom-up energy and carbon planning tool for use in evaluating long-term, economy-wide greenhouse gas mitigation scenarios.

EPA – U.S. Environmental Protection Agency

ERCOT – Electricity interconnection and balancing authority comprising most of Texas

Gt(C) – Gigatons (billions of metric tons) of carbon

GW – Gigawatt (billion watts)

GWh – Gigawatt hour (equivalent to one million kilowatt hours)

IAM – Integrated Assessment Model, a class of model that models the energy system, economy, and climate system, to incorporate feedback between the three.

Intertie – Electric transmission lines that connect different regions

IPCC – Intergovernmental Panel on Climate Change, an international organization mandated to provide policy makers with an objective assessment of the scientific and technical information available about climate change.

Land NET – Negative CO_2 emissions as the result of the update of carbon in soils and terrestrial biomass

Low Biomass – A scenario that limits the use of biomass for energy

Low Electrification – A scenario with a slower rate of switching from fuel combustion technologies to electric technologies on the demand-side of the energy system

Low Land NETs – A scenario with a lower uptake of carbon in land sinks, resulting in a more restricted emissions budget for the energy system.

MMT – Million metric tonnes

N-1 – A test to determine the reliability of a system by ensuring any single component of the system can fail without jeopardizing the system as a whole

NET – Negative emissions technology, one that absorbs atmospheric CO_2 and sequesters it

Net-zero – A condition in which human-caused carbon emissions equal the natural uptake of carbon in land, soils, and oceans such that atmospheric CO_2 concentrations remain constant.

No New Nuclear – A scenario that disallows new nuclear construction

No Tech NETs – A scenario that disallows use of the specific technologies of biomass with carbon capture and geologic sequestration and direct air capture with geologic sequestration

NWPP – Northwest power pool

Pg(C) – Peta (10^{15}) grams

ppm – parts per million

ReEDS – Renewable Energy Deployment System – a capacity planning and dispatch model build by the National Renewable Energy Laboratory

RFC – Three separate eGRID regions in the mid-Atlantic and extending west through Michigan

RIO – Regional Investment and Operations Platform, an optimization tool built by Evolved Energy Research to explore electricity systems and fuels

SDSN – Sustainable Development Solutions Network

SR – eGRID region composing all of the Southeastern United States outside of Florida

TBtu – Trillion British thermal units, an energy unit typically applied to in power generation natural gas

Tech NET – Negative emission technologies composed of either biomass with carbon capture and sequestration or direct air capture with sequestration.

TX – Transmission

VMT – Vehicle miles traveled

WECC – Western electricity coordinating council

Executive Summary

This report describes the changes in the U.S. energy system required to reduce carbon dioxide (CO_2) emissions to a level consistent with returning atmospheric concentrations to 350 parts per million (350 ppm) in 2100, achieving net negative CO_2 emissions by mid-century, and limiting end-of-century global warming to 1°C above pre-industrial levels. The main finding is that 350 ppm pathways that meet all current and forecast U.S. energy needs are technically feasible using existing technology, and that multiple alternative pathways can meet these objectives in the case of limits on some key decarbonization strategies. These pathways are economically viable, with a net increase in the cost of supplying and using energy equivalent to about 2% of GDP, up to a maximum of 3% of GDP, relative to the cost of a business-as-usual baseline. These figures are for energy costs only and do not count the economic benefits of avoided climate change and other energy-related environmental and public health impacts, which have been described elsewhere.[1]

This study builds on previous work, *Pathways to Deep Decarbonization in the United States* (2014) and *Policy Implications of Deep Decarbonization in the United States* (2015), which examined the requirements for reducing GHG emissions by 80% below 1990 levels by 2050 ("80 x 50").[2] These studies found that an 80% reduction by mid-century is technically feasible and economically affordable, and attainable using different technological approaches. The main requirement of the transition is the construction of a low carbon infrastructure characterized by high energy efficiency, low-carbon electricity, and replacement of fossil fuel combustion with decarbonized electricity and other fuels, along with the policies needed to achieve this transformation. The findings of the present study are similar but reflect both a more stringent emissions limit and the consequences of five intervening years without aggressive emissions reductions in the U.S. or globally.

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[1] See e.g. *Risky Business: The Bottom Line on Climate Change,* available at https://riskybusiness.org/
[2] Available at http://usddpp.org/.

The 80 x 50 analysis was developed in concert with similar studies for other high-emitting countries by the country research teams of the Deep Decarbonization Pathways Project, with an agreed objective of limiting global warming to 2°C above pre-industrial levels.[3] However, new studies of climate change have led to a growing consensus that even a 2°C increase may be too high to avoid dangerous impacts. Some scientists assert that staying well below 1.5°C, with a return to 1°C or less by the end of the century, will be necessary to avoid irreversible feedbacks to the climate system.[4] A recent report by the IPCC indicates that keeping warming below 1.5°C will likely require reaching net-zero emissions of CO_2 globally by mid-century or earlier.[5] A number of jurisdictions around the world have accordingly announced more aggressive emissions targets, for example California's recent executive order calling for the state to achieve carbon neutrality by 2045 and net negative emissions thereafter.[6]

In this study we have modeled the pathways – the sequence of technology and infrastructure changes – consistent with net negative CO_2 emissions before mid-century and with keeping peak warming below 1.5°C. We model these pathways for the U.S. for each year from 2020 to 2050, following a global emissions trajectory that would return atmospheric CO_2 to 350 ppm by 2100, causing warming to peak well below 1.5°C and not exceed 1.0°C by century's end.[7] The cases modeled are a 6% per year and a 12% per year reduction in net fossil fuel CO_2 emissions after 2020. These equate to a cumulative emissions limit for the U.S. during the 2020 to 2050 period of 74 billion metric tons of CO_2 in the 6% case and 47 billion metric tons in the 12% case. (For comparison, current U.S. CO_2 emissions are about 5 billion metric tons per year.) The emissions in both cases must be accompanied by increased extraction of CO_2 from the atmosphere using land-based negative emissions technologies ("land NETs"), such as reforestation, with greater extraction required in the 6% case.

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[3] Available at http://deepdecarbonization.org/countries/.

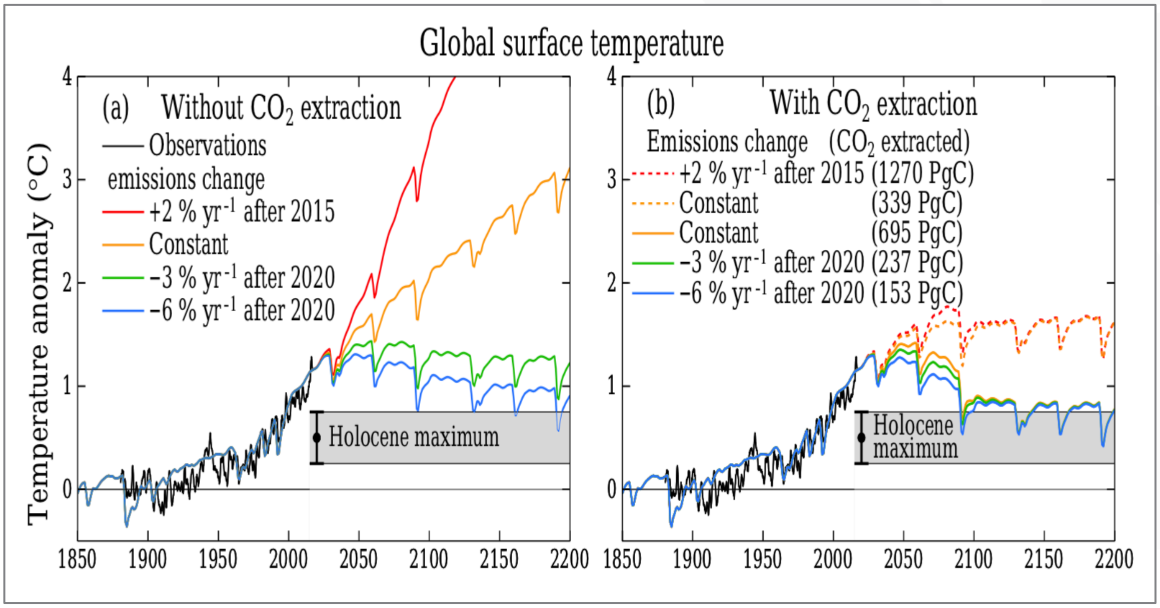
[4] James Hansen, et al. (2017) "Young people's burden: requirement of negative CO2 emissions," *Earth System Dynamics*, https://www.earth-syst-dynam.net/8/577/2017/esd-8-577-2017.html.

[5] Available at https://www.ipcc.ch/sr15/.

[6] Available at https://www.gov.ca.gov/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf.

[7] Hansen et al. (2017).

Figure ES1 Global surface temperature and CO2 emissions trajectories. Hansen et al, 2017.



We studied six different scenarios: five that follow the 6% per year reduction path and one that follows the 12% path. All reach net negative CO_2 by mid-century while providing the same energy services for daily life and industrial production as the *Annual Energy Outlook (AEO)*, the Department of Energy's long-term forecast. The scenarios explore the effects of limits on key decarbonization strategies: bioenergy, nuclear power, electrification, land NETs, and technological negative emissions technologies ("tech NETs"), such as carbon capture and storage (CCS) and direct air capture (DAC).

Table ES1. Scenarios developed in this study

Scenario	Average annual rate of CO_2 emission reduction	2020-2050 maximum cumulative fossil fuel CO_2 (million metric tons)	Year 2050 maximum net fossil fuel CO_2 (million metric tons)	Year 2050 maximum net CO_2 with 50% increase in land sink (million metric tons)
Base	6%	73,900	830	-250
Low Biomass	6%	73,900	830	-250
Low Electrification	6%	73,900	830	-250
No New Nuclear	6%	73,900	830	-250
No Tech NETS	6%	73,900	830	-250
Low Land NETS	12%	57,000	-200	-450

The scenarios were modeled using two new analysis tools developed for this purpose, EnergyPATHWAYS and RIO. As extensively described in the Appendix, these are sophisticated models with a high level of sectoral, temporal, and geographic detail, which ensure that the scenarios account for such things as the inertia of infrastructure stocks and the hour-to-hour dynamics of the electricity system, separately in each of fourteen electric grid regions of the U.S. The changes in energy mix, emissions, and costs for the six scenarios were calculated relative to a high-carbon baseline also drawn from the *AEO*.

Relative to 80 x 50 trajectories, a 350 ppm trajectory that achieves net negative CO_2 by mid-century requires more rapid decarbonization of energy plus more rapid removal of CO_2 from the atmosphere. For this analysis, an enhanced land sink 50% larger than the current annual sink of approximately 700 million metric tons was assumed.[8] This would require additional sequestration of 25-30 billion metric tons of CO_2 from 2020 to 2100. The present study does not address the cost or technical feasibility of this assumption but stipulates it as a plausible value for calculating an overall CO_2 budget, based on consideration of the scientific literature in this area.[9]

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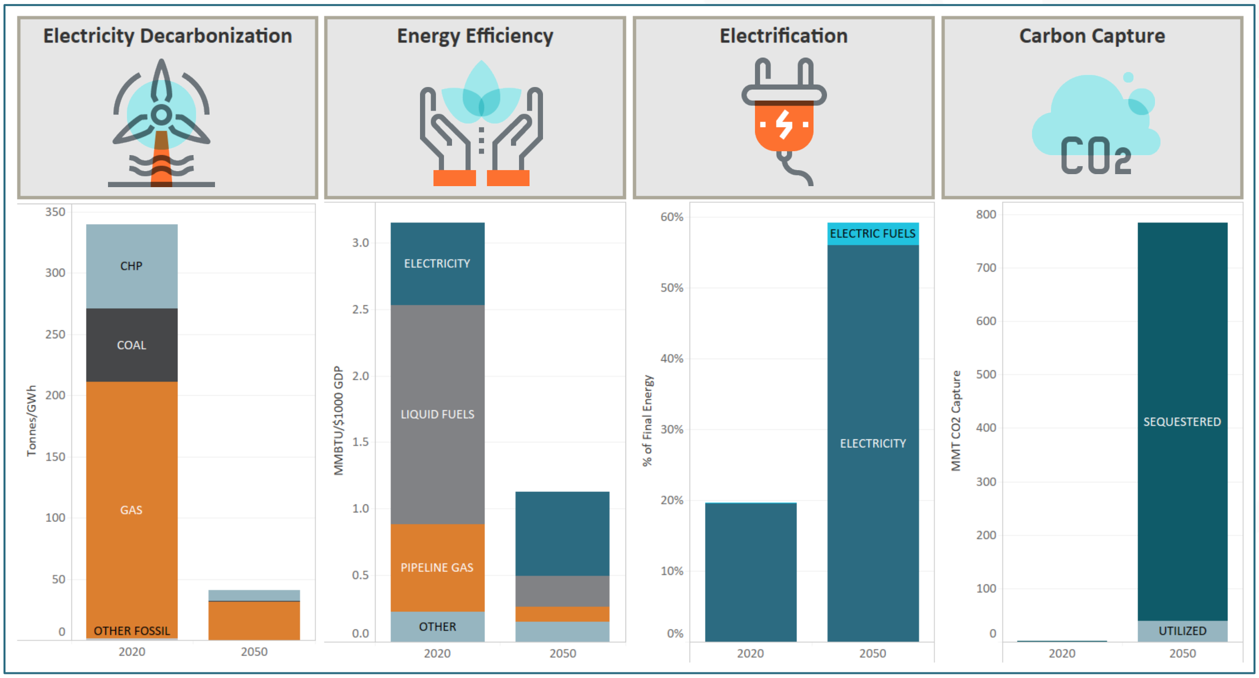
[8] U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016,* available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016

[9] Griscom, Bronson W., et al. (2017) "Natural climate solutions." *Proceedings of the National Academy of Sciences* 114.44 (2017): 11645-11650; Fargione, Joseph E., et al. (2018) "Natural climate solutions for the United States." *Science Advances* 4.11: eaat1869.

Figure ES2 Four pillars of deep decarbonization - Base case



Energy decarbonization rests on the four principal strategies ("four pillars") shown in Figure ES2: (1) electricity decarbonization, the reduction in emissions intensity of electricity generation by about 90% below today's level by 2050; (2) energy efficiency, the reduction in energy required to provide energy services such as heating and transportation, by about 60% below today's level; (3) electrification, converting end-uses like transportation and heating from fossils fuels to low-carbon electricity, so that electricity triples its share from 20% of current end uses to 60% in 2050; and (4) carbon capture, the capture of otherwise CO_2 that would otherwise be emitted from power plants and industrial facilities, plus direct air capture, rising from nearly zero today to as much as 800 million metric tons in 2050 in some scenarios. The captured carbon may be sequestered or may be utilized in making synthetic renewable fuels.

Achieving this transformation by mid-century requires an aggressive deployment of low-carbon technologies. Key actions include retiring all existing coal power generation, approximately doubling electricity generation primarily with solar and wind power and electrifying virtually all passenger vehicles and natural gas uses in buildings. It also includes creating new types of infrastructure, namely large-scale industrial facilities for carbon capture and storage, direct air capture of CO_2, the production of gaseous and liquid biofuels with zero net lifecycle CO_2, and the production of hydrogen from water electrolysis using excess renewable electricity. The scale of the infrastructure buildout by region is indicated in Figure ES3.

Figure ES3 Regional infrastructure requirements (Low Land NETS scenario)

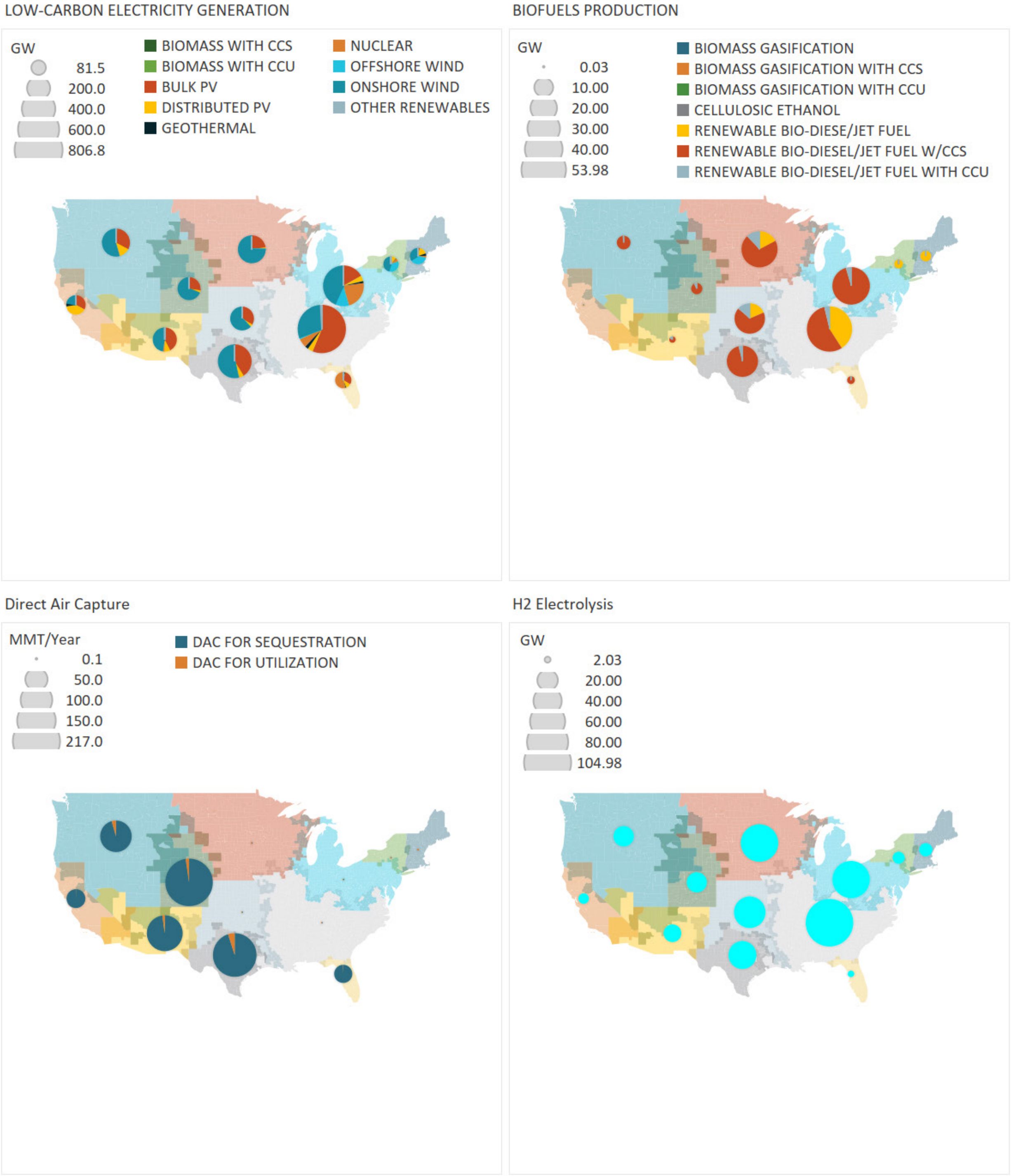


Figure ES4 shows that all scenarios achieve the steep reductions in net fossil fuel CO_2 emissions to reach net negative emissions by the 2040s, given a 50% increase in the land sink, including five that are limited in one key area. This indicates that the feasibility of reaching the emissions goals is robust due to the ability to substitute strategies. At same time, the more limited scenarios are, the more difficult and/or costly they are relative to the base case with all options available. Severe limits in two or more areas were not studied here but would make the emissions goals more difficult to achieve in the mid-century time frame.

Figure ES4 2020-2050 CO_2 emissions for the scenarios in this study

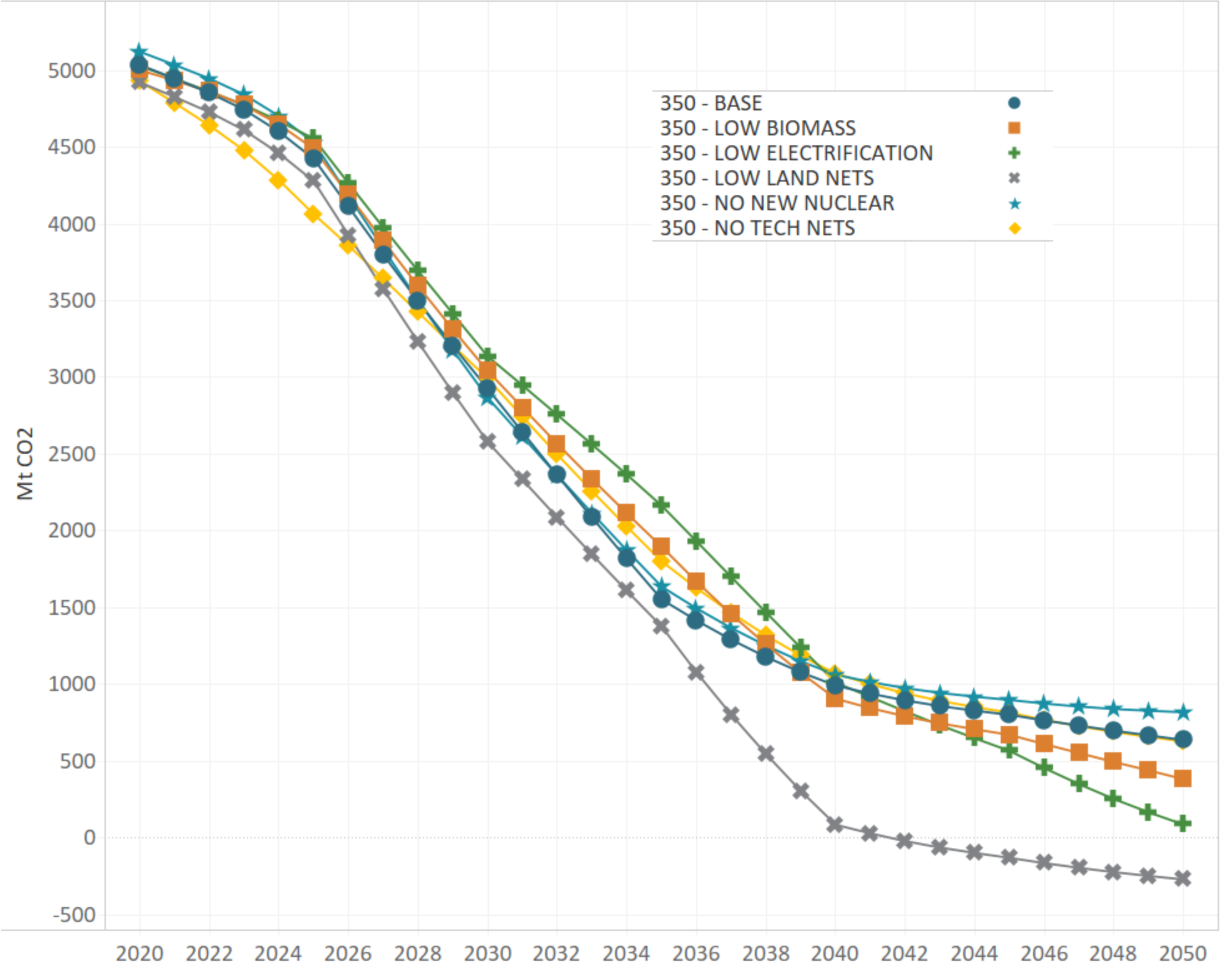
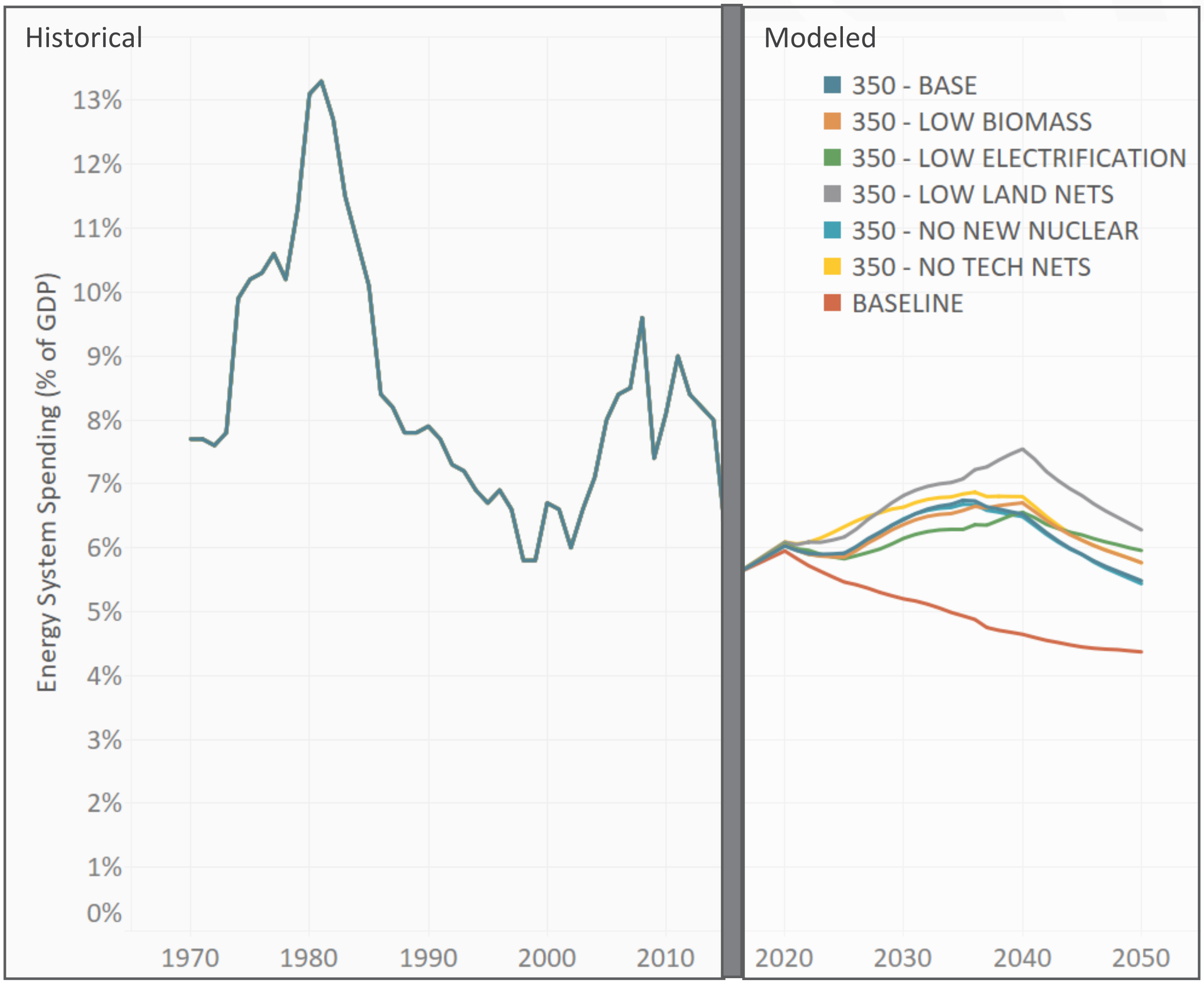


Figure ES5 shows U.S. energy system costs as a share of GDP for the baseline case and six 350 ppm scenarios in comparison to historical energy system costs. While the 350 ppm scenarios have a net cost of 2-3% of GDP more than the business as usual baseline, these costs are not out of line with historical energy costs in the U.S. The highest cost case is the Low Land NETs scenario, which requires a 12% per year reduction in net fossil fuel CO_2 emissions. By comparison, the 6% per year reduction cases are more closely clustered. The lowest increase is the Base scenario, which incorporates all the key decarbonization strategies. These costs do not include any potential economic benefits of avoided climate change or pollution, which could equal or exceed the net costs shown here.

Figure ES5. Total energy system costs as percentage of GDP, modeled (R.) and historical (L.)



A key finding of this study is the potentially important future role of "the circular carbon economy." This refers to the economic complementarity of hydrogen production, direct air capture of CO_2, and fuel synthesis, in combination with an electricity system with very high levels of intermittent renewable generation. If these facilities operate flexibly to take advantage of periods of excess generation, the production of hydrogen and CO_2 feedstocks can provide an economic use for otherwise curtailed energy that is difficult to utilize with electric energy storage technologies of limited duration. These hydrogen and CO_2 feedstocks can be combined as alternatives for gaseous and liquid fuel end-uses that are difficult to electrify directly like freight applications and air travel. While the CO_2 is eventually emitted to the atmosphere, the overall process is carbon neutral as it was extracted from the air and not emitted from fossil reserves. A related finding of this work is that bioenergy with carbon capture and storage (BECCS) for power plants appears uneconomic, while BECCS for bio-refineries appears highly economic and can be used as an alternative source of CO_2 feedstocks in a low-carbon economy.

There are several areas outside the scope of this study that are important to provide a full picture of a low greenhouse gas transition. One important area is better understanding of the potential and cost of land-based NETs, both globally and in the U.S. Another is the potential and cost of reductions in non-CO_2 climate pollutants such as methane, nitrous oxide, and black carbon. Finally, there is the question of the prospects for significant reductions in energy service demand, due to lifestyle choices such as bicycling over cars, structural changes such as increased transit and use of ride-sharing, or the development of less-energy intensive industry, perhaps based on new types of materials.

“Key Actions by Decade” below provides a blueprint for the physical transformation of the energy system. From a policy perspective, this provides a list of the things that policy needs to accomplish, for example the deployment of large amounts of low carbon generation, rapid electrification of vehicles, buildings, and industry, and building extensive carbon capture, biofuel, hydrogen, and synthetic fuel synthesis capacity.

Some of the policy challenges that must be managed include: land use tradeoffs related to carbon storage in ecosystems and siting of low carbon generation and transmission; electricity market designs that maintain natural gas generation capacity for reliability while running it very infrequently; electricity market designs that reward demand side flexibility in high-renewables electricity system and encourage the development of complementary carbon capture and fuel synthesis industries; coordination of planning and policy across sectors that previously had little interaction but will require much more in a low carbon future, such as transportation and electricity; coordination of planning and policy across jurisdictions, both vertically from local to state to federal levels, and horizontally across neighbors and trading partners at the same level;

mobilizing investment for a rapid low carbon transition, while ensuring that new investments in long-lived infrastructure are made with full awareness of what they imply for long-term carbon commitment; and investing in ongoing modeling, analysis, and data collection that informs both public and private decision-making. These topics are discussed in more detail in *Policy Implications of Deep Decarbonization in the United States.*

Key Actions by Decade

This study identifies key actions that are required in each decade from now to mid-century in order to achieve net negative CO_2 emissions by mid-century, at least cost, while delivering the energy services projected in the *Annual Energy Outlook*. Such a list inherently relies on current knowledge and forecasts of unknowable future costs, capabilities, and events, yet a long-term blueprint remains essential because of the long lifetimes of infrastructure in the energy system and the carbon consequences of investment decisions made today. As events unfold, technology improves, energy service projections change, and understanding of climate science evolves, energy system analysis and blueprints of this type must be frequently updated.

2020s

- Begin large-scale electrification in transportation and buildings
- Switch from coal to gas in electricity system dispatch
- Ramp up construction of renewable generation and reinforce transmission
- Allow new natural gas power plants to be built to replace retiring plants
- Start electricity market reforms to prepare for a changing load and resource mix
- Maintain existing nuclear fleet
- Pilot new technologies that will need to be deployed at scale after 2030
- Stop developing new infrastructure to transport fossil fuels
- Begin building carbon capture for large industrial facilities

2030s

- Maximum build-out of renewable generation
- Attain near 100% sales share for key electrified technologies (e.g. EVs)
- Begin large-scale production of bio-diesel and bio-jet fuel
- Large scale carbon capture on industrial facilities
- Build out of electrical energy storage
- Deploy fossil power plants capable of 100% carbon capture if they exist

Maintain existing nuclear fleet

2040s

- Complete electrification process for key technologies, achieve 100% stock penetration
- Deploy circular carbon economy using DAC and hydrogen to produce synthetic fuels
- Use synthetic fuel production to balance and expand renewable generation
- Replace nuclear at the end of existing plant lifetime with new generation technologies
- Fully deploy biofuel production with carbon capture

1. Introduction

This report describes the changes in the U.S. energy system that, in concert with related actions in land use, will be required to reduce U.S. carbon dioxide (CO_2) emissions to a level consistent with returning atmospheric concentrations to 350 parts per million (350 ppm) in 2100, achieving net negative CO_2 emissions by mid-century, and limiting end-of-century global warming to 1°C. This study builds on previous work, *Pathways to Deep Decarbonization in the United States* (Williams et al. 2014) and *Policy Implications of Deep Decarbonization in the United States* (Williams, Haley, and Jones 2015) which examined the requirements for reducing GHG emissions by 80% below 1990 levels by 2050 ("80 x 50").[10]

In the 1980s, with atmospheric CO_2 concentrations climbing rapidly, the U.S. government recognized the need to establish a safe CO_2 target and determine what would be required to reach it. By 1991, at the request of Congress, both the U.S. EPA and the Office of Technology Assessment had issued roadmaps for maintaining CO_2 concentrations near the then-current level of 350 ppm (Lashof and Tirpak 1990; Office of Technology Assessment 1991). Over the last decade, as CO_2 concentrations have risen toward and then passed 400 ppm, the question of what constitutes a "safe" concentration relative to dangerous anthropogenic impacts on the climate system has become increasingly urgent. A recent report by the Intergovernmental Panel on Climate Change evaluated the increased risks of 2°C of warming compared to exceeding 1.5°C, and of 1.5°C of warming compared to present warming, and found that a temperature rise of 1.5°C is "not considered 'safe' for most nations, communities, ecosystems, and sectors and poses significant risks to natural and human systems as compared to current warming of 1°C (*high confidence*)" (Intergovernmental Panel on Climate Change 2018). The U.S. Government's Fourth National Climate Assessment similarly documents an acceleration of climate change impacts already underway (U.S. Global Change Research Program 2017). Studies using global climate models and integrated assessment models (IAMs) indicate that limiting

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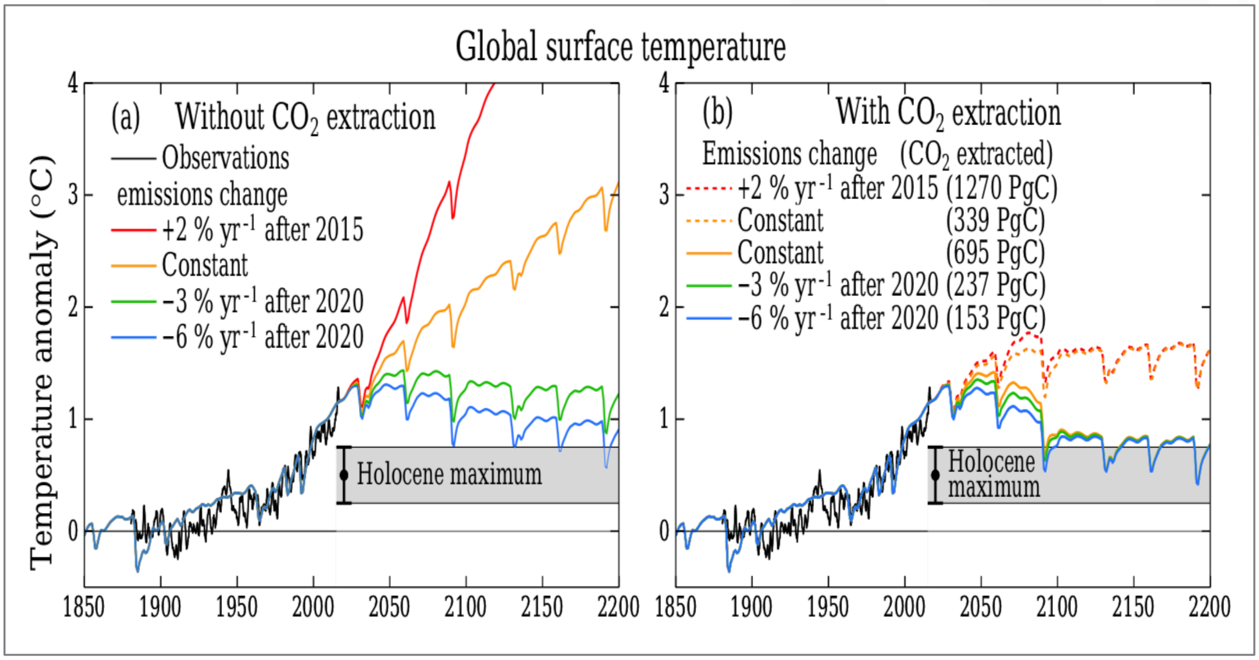
[10] Available at http://usddpp.org/.

warming to a peak of 1.5°C will require reaching net-zero emissions of CO_2 globally by mid-century or earlier (Intergovernmental Panel on Climate Change 2018). Reflecting these findings, a number of jurisdictions around the world have already announced more aggressive emissions targets, for example California's recent executive order calling for the state to achieve economy-wide carbon neutrality by 2045 and negative net emissions thereafter (State of California 2018).

Several well-known climate studies have concluded that the best chance of avoiding the most catastrophic climate change impacts requires CO_2 concentrations to be reduced to 350 ppm or less by the end of the 21st century (Hansen et al. 2008; Veron et al. 2009; Hansen et al. 2013; Hansen et al. 2016; Hansen et al. 2017). The emission trajectories associated with reaching 350 ppm have lower allowable emissions ("emissions budgets") in the 21st century than comparable trajectories that would peak at 2.0 or 1.5°C. These trajectories are intended to minimize the length of time the global temperature increase remains above 1°C to prevent the initiation of irreversible climate feedbacks indicated by paleoclimate evidence. In a recent article, Hansen and colleagues describe several possible trajectories for fossil fuel emission reductions that, in combination with specified levels of atmospheric CO_2 removal, could achieve 350 ppm by 2100 (Hansen et al. 2017).

In this study we have modeled pathways – the sequence of technology and infrastructure changes – for the United States that result in net negative CO_2 emissions before mid-century and that follow a global emissions trajectory consistent with a return to 350 ppm globally by 2100 (Figure 1). The cases modeled are a 6% per year and a 12% per year reduction in net fossil fuel CO_2 emissions after 2020. These equate to a cumulative emissions limit for the U.S. during the 2020 to 2050 period of 74 billion metric tons of CO_2 in the 6% case and 47 billion metric tons in the 12% case. (For comparison, current U.S. CO_2 emissions are about 5 billion metric tons per year.) The emissions reductions in both cases must be accompanied by increased extraction of CO_2 from the atmosphere. The 6% reduction case requires a global removal of 153 Pg.(C) incremental to the current global CO_2 sink from 2020 to 2100, and the 12% reduction case requires an incremental removal of 100 Pg(C) during the same period. In our scenarios, the removal of the 100 Pg(C) or 153 Pg(C) is assumed to be accomplished through land-based negative emissions technologies ("land NETs"). These numbers imply an increase in the current global land sink of about 40% and 60%, respectively (Le Quéré et al. 2018). Additional extraction of atmospheric CO_2 using technological negative emissions technologies ("tech NETs"), meaning direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS), is deployed in some of our cases. DAC is the removal of diffuse CO_2 directly from the air, while BECCS involves capture of concentrated streams of CO_2 from the effluent at industrial facilities that use biofuels; in both cases, the captured CO_2 is stored in geologic structures.

Figure 1 Global surface temperature and CO2 emissions trajectories[11].



The goal of this study is to understand what realistic 350 ppm-compatible cases would mean concretely for changes in the U.S. energy system and industrial fossil fuel use. Our study differs from recent IAM studies of 1.5°C in that it has a tighter emissions budget, concentrates on a single country, and provides a greater level of technical detail on the transformation to a low carbon economy, including sectorally detailed treatment of costs (Rogelj et al. 2015). The principal research questions addressed by this study are the following:

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[11] The solid blue line in (b) illustrates a 350 ppm trajectory based on 6% per year reduction in net fossil fuel CO_2 emissions combined with global extraction of 153 PgC from the atmosphere. Reprinted from Hansen, *ESD*, 2017.

1. Is it technically feasible to achieve a 350 ppm trajectory within the U.S. energy system, given realistic constraints?
2. Is a 350 ppm trajectory robust against the absence of key carbon mitigation technologies, i.e. are there multiple technically feasible pathways?
3. What is the cost of achieving a low-carbon energy system on a 350 ppm trajectory in the U.S?

To answer these questions, we have developed future scenarios using two new models built for this purpose, EnergyPATHWAYS and RIO. These are sophisticated analysis tools with a high level of sectoral, temporal, and geographic granularity. We use these tools to rigorously assess the technical feasibility and cost of rapidly reducing CO_2 emissions through the deployment of low carbon technologies and NETs, year by year from the present out to 2050. Changes in energy mix, technology stocks, emissions, and costs for the 350 ppm scenarios were calculated relative to a high-carbon baseline drawn from the Department of Energy's *Annual Energy Outlook (AEO)*, the U.S. government's official long-term energy forecast.

The first research question above, regarding technical feasibility, was addressed through the development of a scenario called the 350 ppm base case, which uses currently available technologies to decarbonize the energy system while providing all the same energy services needed to support the U.S. economy and daily life forecast in the *AEO*. This scenario draws on objective, nationally recognized studies for both current data and future forecasts of performance and costs for each kind of fuel and technology used, in both energy supply and end use. The analysis in EnergyPATHWAYS and RIO was designed to address all major feasibility concerns, ranging from energy balances at a variety of scales, to the inertia of infrastructure stocks, to the hour-to-hour dynamics of the electricity system, separately in each of fourteen electric grid regions of the U.S.

The second research question is based on the observation that since even the best studies cannot perfectly predict the future decades ahead, it is important to understand what options exist if some key decarbonization technology or strategy does not materialize. This was addressed by the simulation of five additional 350 ppm pathways that remove or limit five key strategies used in the base case, either because in the future they do not meet current expectations for performance or cost, or because they are otherwise unable to be deployed at scale, for example because they do not achieve social acceptance. The five scenarios start with the base case and then apply the following constraints separately: (i) limiting the availability of biomass for energy, (ii) limiting the rate of electrification of end uses, (iii) eliminating new nuclear plant construction, (iv) eliminating tech NETs, and (v) limiting the availability of land NETs.

In order to answer our third question, we calculate the costs of implementing this transition in the United States over the next three decades, with detailed year-by-year modeling of the energy economy. The 350 ppm-consistent scenarios are compared to a high-carbon case based on the *AEO.* This comparison is made "apples-to-apples" by ensuring that the energy services provided in the 350 ppm scenarios are the same as those provided in the *AEO*, and that the cost analysis reflects the differences in capital and operating costs for the low carbon technologies used in the 350 ppm scenarios relative to the business-as-usual technologies in the *AEO.*

The temporal, spatial, and sectoral detail in our modeling provides unique insights into how energy is supplied and used, and how carbon is, managed throughout the U.S. economy on a 350 ppm pathway. It improves current understanding of how energy and carbon removal interact technically, and how fossil fuel emissions, land NETs, and tech NETs trade off economically. Interactions between these different components of the energy-and-emissions system become increasingly important with tighter emissions constraints, so we account for them separately to avoid confusion and double-counting. Each of the scenarios demonstrates a different mode of utilizing infrastructure, balancing the electricity grid, and producing fuels as a single interactive system for least cost energy production. They also demonstrate how a 350 ppm-compatible energy system differs from one designed to achieve 80% reductions in CO_2e below 1990 levels by 2050 ("80 x 50"), such as the pathways previously developed for the U.S. (Williams et al. 2014). 80 x 50 pathways are generally considered to be consistent with emissions scenarios (RCP 2.6) in the IPCC's Fifth Assessment Report that give a 66% chance of not exceeding 2°C.

This study does not model land NETs, instead stipulating the global 100 Pg(C) and 153 Pg(C) cases mentioned above as boundary conditions for our scenarios. Some credible global evaluations indicate that achieving 153 Pg(C) of land-based C sequestration is potentially feasible (Griscom et al. 2017) Achieving this level of sequestration will require changes in current policy and practices that not only improve carbon uptake but address such concerns as indigenous land tenure and competition with food production. Recent assessments of U.S. land-based negative emission potential indicate that a significant share of the required global land NETs, 20 Pg(C) or more of additional land sinks in the 21st century, is possible in the U.S. (Fargione et al. 2018).

For this analysis, an enhanced land sink in the United States on average 50% larger than the current annual sink of approximately 700 million metric tons was assumed.[12] This would require additional sequestration of 25-30 billion metric tons of CO_2 from 2020 to 2100. The present study does not address the cost or technical feasibility of this assumption, but stipulates it as a plausible value for the purpose of calculating an overall CO_2 budget, subject to revision as better information becomes available.

The costs calculated in this study include the net system cost of the transformation in the supply and end use of energy, including tech NETs. They do not include the cost of land NETs or the mitigation of non-CO_2 greenhouse gases. Macroeconomic effects are not explicitly considered. There are a variety of other benefits ("co-benefits") of avoided climate change that are not within the scope of this study, including impacts on human health, ecosystems, and economic productivity. Such co-benefits are addressed in other studies.

The remainder of this report is organized as follows: Chapter 2, Study Design, including descriptions of the EnergyPATHWAYS and RIO modeling platforms, key data sources used, and the scenarios studied; Chapter 3, Results, including emissions, energy supply and demand, infrastructure, bioenergy use, carbon capture, and costs; Chapter 4, Discussion, addressing regional differences, electricity balancing challenges and solutions, cross-sector integration, and the circular carbon economy; and Chapter 5, Conclusions, including key actions by decade. The Appendix describes the scenarios and modeling methodology in detail.

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[12] U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016,* available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016

2. Study Design

2.1. Scenarios

This analysis explores the technical feasibility and cost of achieving a 350 ppm-compatible trajectory in the United States, transforming the energy system and achieving zero net emissions by mid-century. This is accomplished by developing a set of scenarios, subject to a variety of constraints (required outcomes and allowable actions), in the EnergyPATHWAYS and RIO models. In total we developed six 350 ppm- compatible scenarios: a core scenario called the Base Case, which is the least constrained, and five variants on this scenario to address concerns about the robustness of the results against implementation failures in key areas. The variants were designed specifically in response to criticisms of the assumptions made in other deep decarbonization analyses, typically conducted with global integrated assessment models. By doing this, we demonstrate the robustness of the result in a manner similar to “N-1” concept in electricity system planning, in which electricity systems must be designed with redundancy, so that even if the largest generator or transmission line fails, the system remains reliable. The contingencies that could threaten achieving 350 ppm are listed (1-5) below, then the business-as-usual baseline and the six 350 ppm-compatible scenarios are described quantitatively in Table 1.

Constraints

1. Restricted availability of zero-carbon primary biomass resources. This could be a result of inaccurate technical assessments of resource potential, unexpected difficulties in developing a bio-energy economy, or discovery of unintended impacts on other land-uses that lead to restrictions on biomass resource development.

2. Low rates of electrification. Direct electrification of end-uses such as light-duty vehicles and space heating is a key strategy of energy system decarbonization. Slower than expected rates of electrification would challenge a low carbon transition as it would result in higher residual fossil fuel emissions that must be mitigated in other ways.

3. No new nuclear plants. Based on current cost forecasts for advanced (4th generation) nuclear facilities, it is expected that they would play a role in energy system decarbonization, especially in regions with limited renewable resource potential. Restricting new nuclear plant construction means that their role in a low carbon generation portfolio must be accomplished by carbon capture power plants or renewables. In this scenario we assume that nuclear plants already in operation will be operated and retired based on the schedule in the 2017 *AEO*.

4. No technological negative emissions technologies. "Tech NETS" includes biomass facilities (either fuel production or power generation) with carbon capture and sequestration or direct air capture with sequestration. Both of these technologies remove CO_2 from the atmosphere, helping to offset any residual fossil fuel use in the economy. They are heavily relied on in many integrated assessment modeling (IAM) studies of deep decarbonization, which has drawn criticism. This scenario can be interpreted as a contingency test of what happens in the case of technological failure or social refusal of these approaches. While this scenario doesn't employ Tech NETS, it does employ both carbon capture and carbon sequestration in other forms.

5. Low land NETS. Land NETS are strategies that use land-use management practices to increase terrestrial carbon sequestration. In this study we employ estimates of land NETS potential based on the literature to determine the remaining emissions budget for energy and industrial CO_2. This scenario is used to assess whether the necessary energy and industrial CO_2 mitigation can be achieved in the event that changes in land management practices can only produce 100 PgC of carbon sequestration globally by 2100. The changes to land NETS result in a reduced cumulative energy and industrial CO_2 target and a net negative CO_2 emissions target in 2050.

Table 1 Scenario definitions and emissions limits

Scenario	Average annual rate of CO_2 emission reduction	2020-2050 maximum cumulative fossil fuel CO_2 (million metric tons)	Year 2050 maximum net fossil fuel CO_2 (million metric tons)	Year 2050 maximum net CO_2 with 50% increase in U.S. land sink (million metric tons)
Base *Best case, all options available*	6%	73,900	830	-250
Low Biomass *50% reduction in solid biomass feedstocks*	6%	73,900	830	-250
Low Electrification *10-year delay in rates of electrification, all sectors*	6%	73,900	830	-250
No New Nuclear *No new nuclear plants are constructed*	6%	73,900	830	-250
No Tech NETS *No negative emissions from BECCS or DAC*	6%	73,900	830	-250
Low Land NETS *Additional global land sink limited to 100 Pg(C)*	12%	57,000	-200	-450

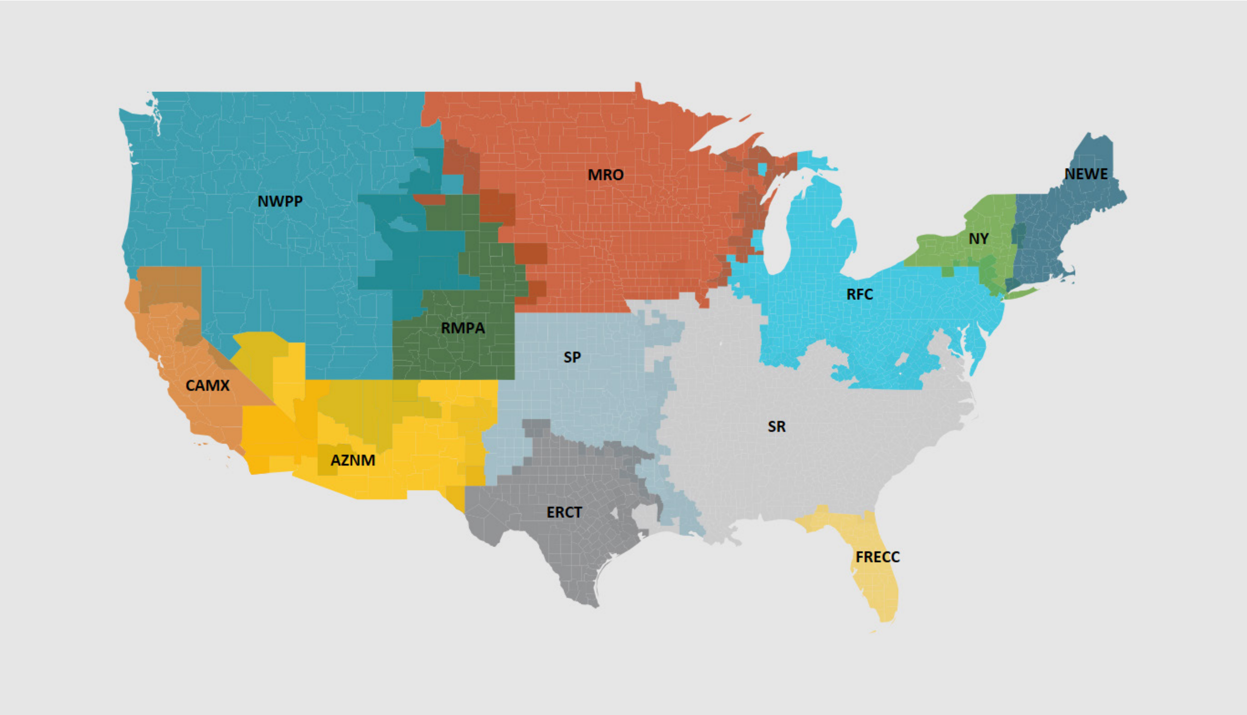
2.2. Modeling Methods and Data Sources

This section summarizes the modeling methods used in this analysis. Further detail on all modeling tools and data sources is available in the Technical Appendix to this report.

2.2.1. EnergyPATHWAYS

EnergyPATHWAYS is a bottom-up energy sector scenario planning tool. It performs a full accounting of all energy, cost, and carbon flows in the economy and can be used to represent both current fossil-based energy systems and transformed, low-carbon energy systems. It includes a granular technology representation with over 380 demand-side technologies and 100 supply-side technologies in order to represent all producing, converting, storing, delivering, and consuming energy infrastructure. It also has very high levels of regional granularity, with detailed representations of existing energy infrastructure (e.g., power plants, refineries, biorefineries, demand-side equipment stocks) and resource potential. The model is geographically flexible, with the ability to perform state-level and even county-level analysis. For this report, the model was run on a customized geography based on an aggregation of the EPA's eGRID (U.S. Environmental Protection Agency 2018) geographies, as shown in Figure 2. The aggregation was done for computational purposes to reduce the total number of zones to a manageable number. EnergyPATHWAYS and its progenitor models have been used to analyze energy system transformations at different levels, starting in California (Williams et al. 2012) then expanding to U.S. wide analysis (Williams et al. 2014; Risky Business Project 2016; Jadun et al. 2017) and other state and regional analyses. The model has also been used internationally in Mexico and Europe. In each context, it has been successful in describing changes in the energy system at a sufficiently granular level to be understood by, and useful to, sectoral experts, decision makers, and policy implementers.

Figure 2 Regional granularity of analysis.



2.2.2. Regional Investment and Operations (RIO) Platform

EnergyPATHWAYS, described in the previous section, focuses on detailed and explicit accounting of energy system decisions. These decisions are made by the user as inputs to the model in developing scenarios. The Regional Investment and Operations (RIO) platform operates differently, finding the set of energy system decisions that are least cost. The rationale for using two models in this study is that energy demand-side decisions (e.g. buying a car) are typically unsuited to least cost optimization, because they are based on many socioeconomic factors that do not necessarily result from optimal decisions and are better examined through scenario analysis. However, RIO's strength is in optimization of supply-side decisions where least cost economic frameworks for decision making are either applied already (e.g., utility integrated resource planning) or are regarded as desirable in the future. RIO is therefore complementary to EnergyPATHWAYS. We use RIO to co-optimize fuel and supply-side infrastructure decisions within each scenario of energy demand and emissions constraints. The resulting supply-side decisions are then input into EnergyPATHWAYS for energy, emissions, and cost accounting of these optimized energy supplies. RIO is the first model we are aware of to integrate the fuels and electricity directly at a highly resolved temporal level, resulting in a co-optimization of infrastructure that is unique and critical for understanding the dynamics of low-carbon energy systems.

RIO works with the same geographic representation as EnergyPATHWAYS. Each zone contains: existing infrastructure; renewable resource potentials and costs; fuel and electricity demand (hourly); current transmission interconnection capacity and specified expansion potential and costs; biomass resource supply curves; and restrictions on construction of new nuclear facilities.

2.2.3. Key References and Data Sources

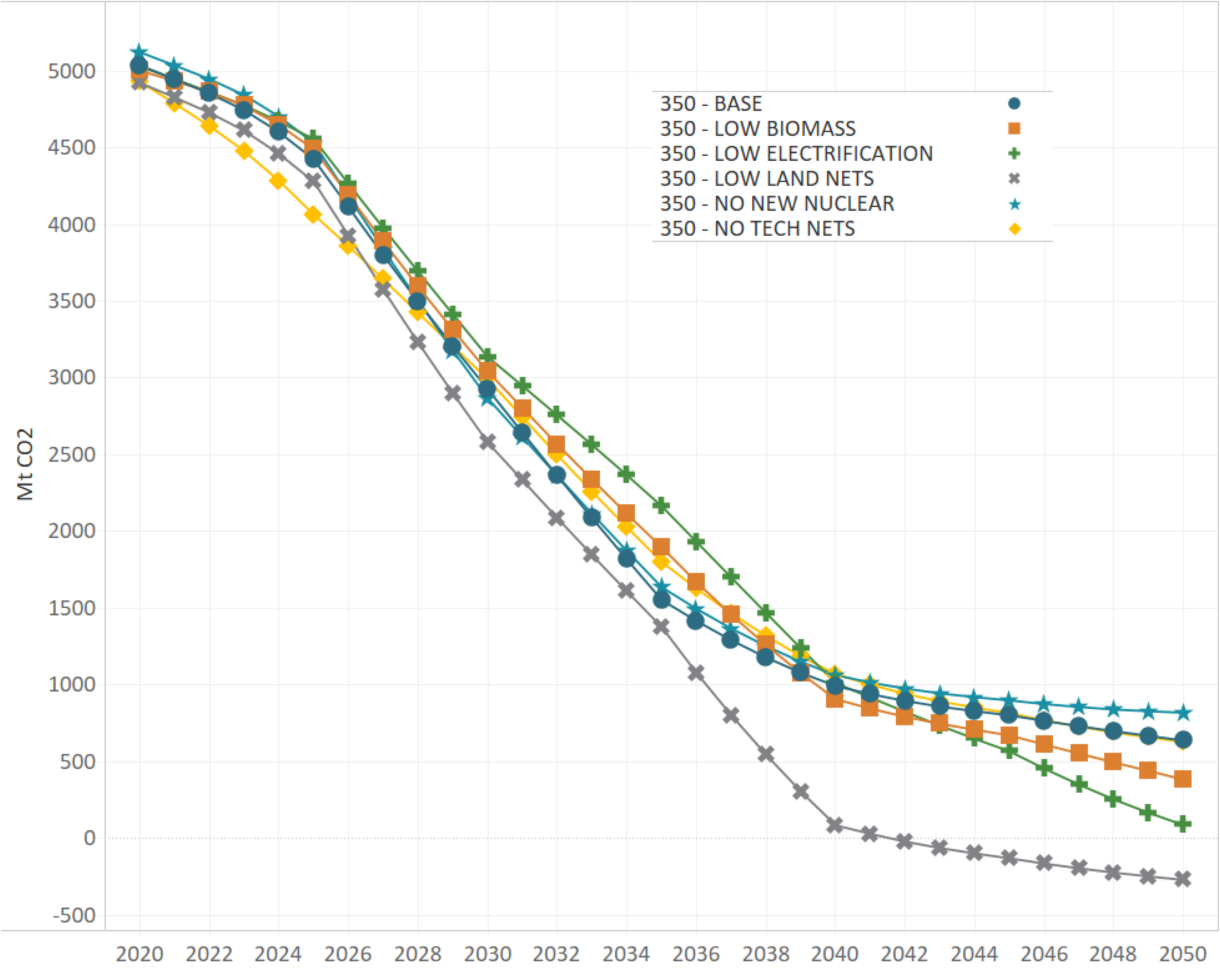
The parameterization of EnergyPATHWAYS and RIO to perform U.S. economy-wide decarbonization analysis requires a wide variety of inputs and data sources. We describe the full breadth of these data sources in the Appendix. There are, however, a few principal sources that are central to understanding and contextualizing our results. First and foremost, we utilized the 2017 *Annual Energy Outlook* (U.S. Energy Information Administration 2017), which includes detailed long-term estimates of economic activity, energy service demand, fuel prices, and technology costs. This allows us to compare our results to the principal energy forecast provided by the United States Government. Renewable costs and resource potentials are derived from National Renewable Energy Laboratory sources including the 2017 Annual Technology Baseline (National Renewable Energy Laboratory 2017) and input files to their ReEDS Model (Eurek et al. 2017). Biomass resource potential and costs are taken from the U.S. Department of Energy's Billion Tons Study Update (Langholtz, Stokes, and Eaton 2016). In all cases we have sought to use thoroughly vetted public sources, which tend to be conservative about cost and performance estimates for low-carbon technologies.

3. Results

3.1. Emissions

Emissions trajectories for energy and industrial CO_2 emissions are shown below for all 350 ppm scenarios. (For net emissions including the negative emissions from Land NETS (enhanced sink), see Table 1). In all scenarios, we find it to be technically feasible, from the standpoint of a reliable energy system that meets all forecast energy service demand, to reach emission levels consistent with the 350 ppm target (Figure 3).

Figure 3 CO2 emissions trajectories



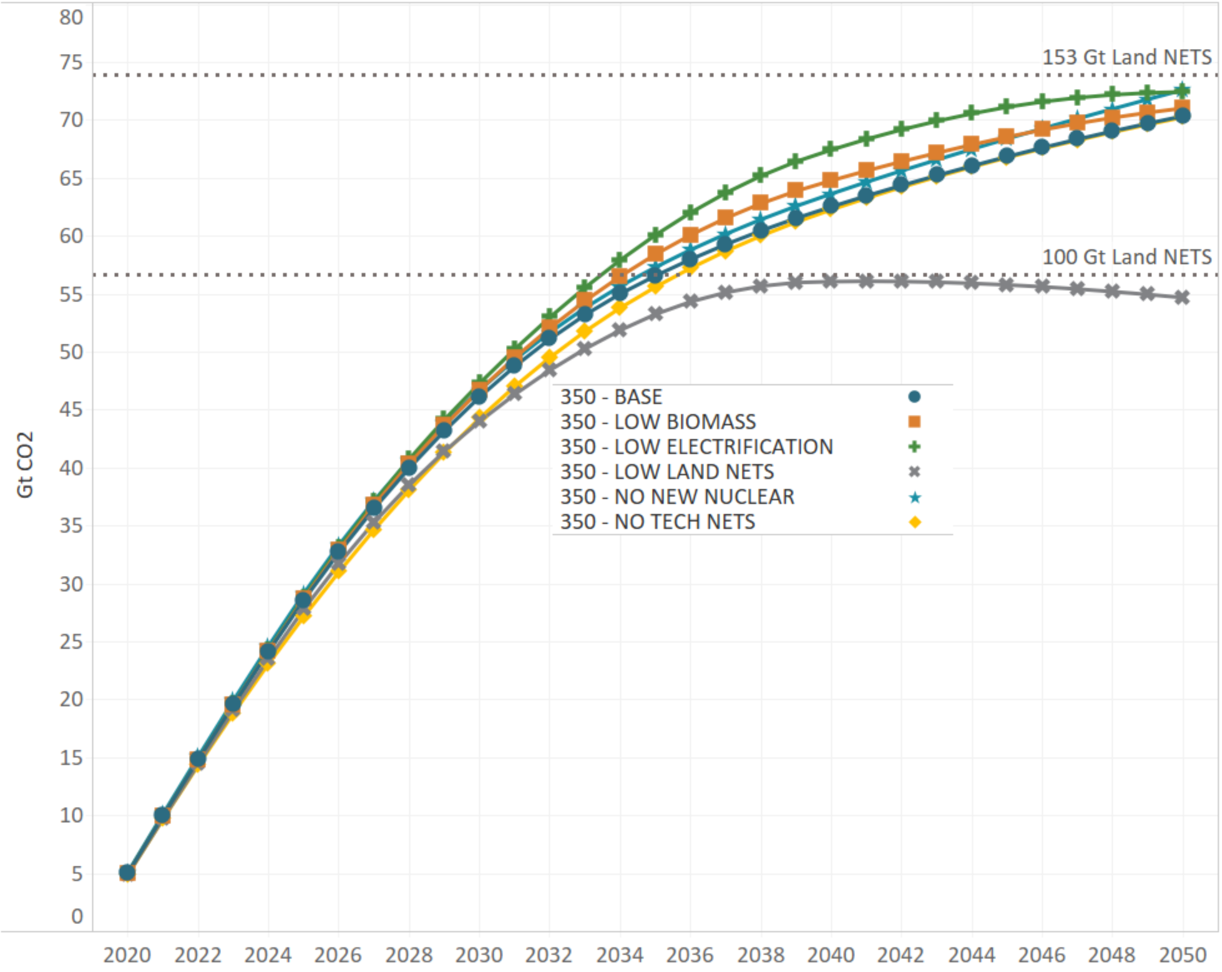
All scenarios show broadly similar emissions trajectories, but they also contain differences in timing and carbon reduction magnitude. Scenarios that reduce the cost-effective mitigation options available before 2035 (i.e., Low Biomass and Low Electrification) show delayed emissions reductions, compensated by deeper reductions in later periods to hit the same cumulative CO_2 budget. Those scenarios that remove options that are critical in the post-2035 time frame (i.e. No New Nuclear and No Tech NETS) show the opposite trend—larger reductions in near term CO_2 reductions to accommodate the higher cost of deeper emissions cuts in the long-term. Scenario-specific findings include:

- The *Low Land NETS* scenario, with a smaller cumulative CO_2 budget by mid-century, requires a steeper and deeper trajectory of emissions reductions from energy and industry than do the other scenarios, and thus requires higher levels of mitigation. This scenario requires that energy and industrial emissions become net negative after 2040, reaching -200 MMT CO_2 per year in 2050, and remaining at that level through the rest of the century in order to meet the cumulative budget for the whole 2020-2100 period.
- The *Low Electrification* scenario shows the slowest rate of emissions reduction through 2035, with few cost-effective options for achieving the rate of transformation seen in the other cases with higher electrification rates. Post-2035, electrification levels catch up and the scenario employs more direct air capture than other scenarios to accelerate the mitigation trajectory.
- The *Low Biomass* scenario also shows a slower rate of emissions decline, as the biomass resources needed to displace fossil fuels directly are not available in sufficient quantity. The alternative strategy of electric fuels does not become cost-effective as a mitigation option until later in the period, when renewable penetrations increase and the electric fuel load can contribute to electricity balancing. The scenario uses direct air capture in the later periods as well, in order to accelerate the mitigation trajectory.
- The *No New Nuclear* scenario sees emissions decline faster than in other scenarios. This is because displacing residual fossil fuel on the electricity system is cheaper than attempting to achieve the same levels of electricity decarbonization in 2050 without the availability of nuclear. This scenario therefore finds a cost-effective route to have a slightly steeper slope but reach a less deep level by 2050.

- The *350 – No Tech NETS* scenario also has a steeper initial trajectory relative to the Base scenario, because without Tech NETS, it becomes more expensive to reduce emissions in the long-term. Thus, the model trades higher near-term emission reductions for additional emissions budget in 2050.

Figure 4 shows the cumulative 2020 – 2050 emissions path of each mitigation scenario. The shape of cumulative emissions show how critical early action is for achieving 350 ppm goals, even with very aggressive climate mitigation. The first five years, 2020-2025, consumes over one-third (25 MMT) of the Base scenario budget, and the first decade, 2020-2030, consumes almost two-thirds.

Figure 4 Cumulative CO2 emissions trajectories

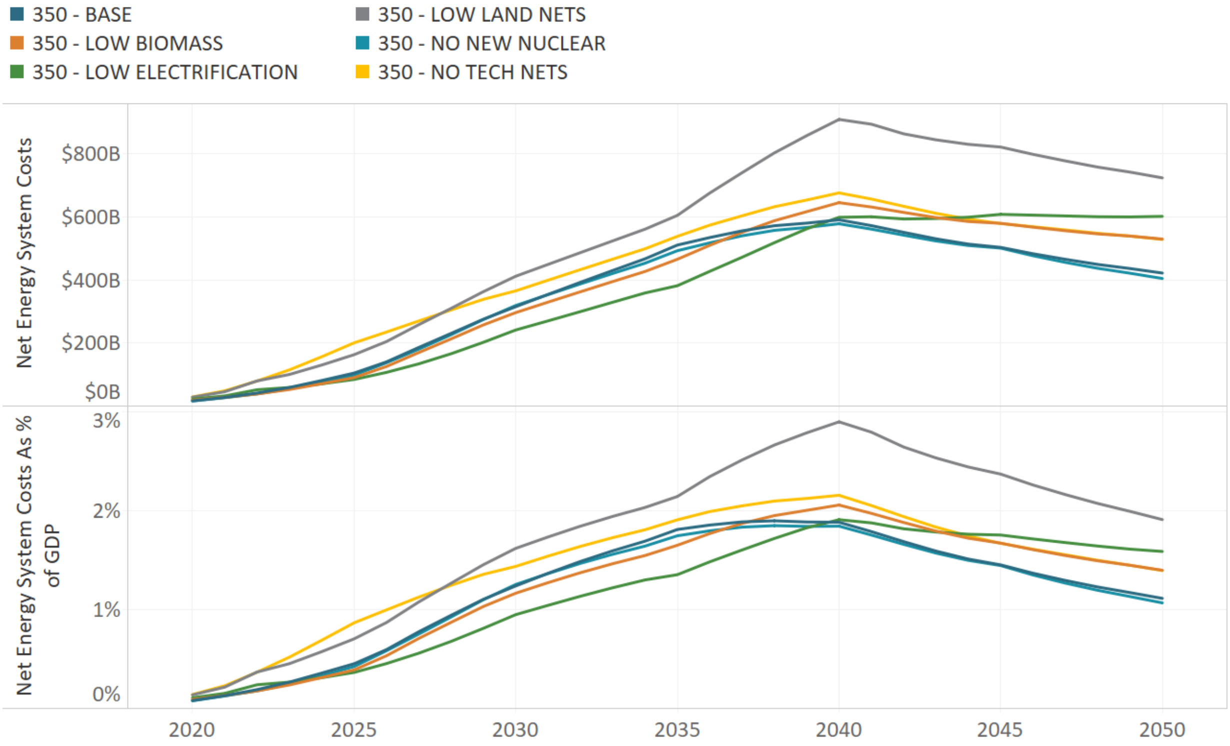


3.2. System Costs

Cost assessment of the 350 ppm scenarios is critical for assessing the potential economic and societal impacts of achieving a 350 ppm-compatible pathway, even if the technical feasibility of the pathway can be demonstrated. We apply a few different cost metrics to assess the economic feasibility of such a transition. First, we find the net cost of decarbonizing energy and industry to be consistent with results from other analyses of this type, using the metrics of incremental costs ($ per year) and incremental costs as a percentage of GDP per year (Figure 5). Incremental costs are calculated by comparing the cost of producing and using energy in each scenario compared to the baseline scenario derived from the *AEO*, which has no carbon constraint. Incremental cost includes the capital and operating costs of all low carbon energy supply infrastructure and demand-side equipment (e.g. electric vehicles and heat pumps) in comparison to the cost of the less efficient or carbon emitting reference technology that it replaces.

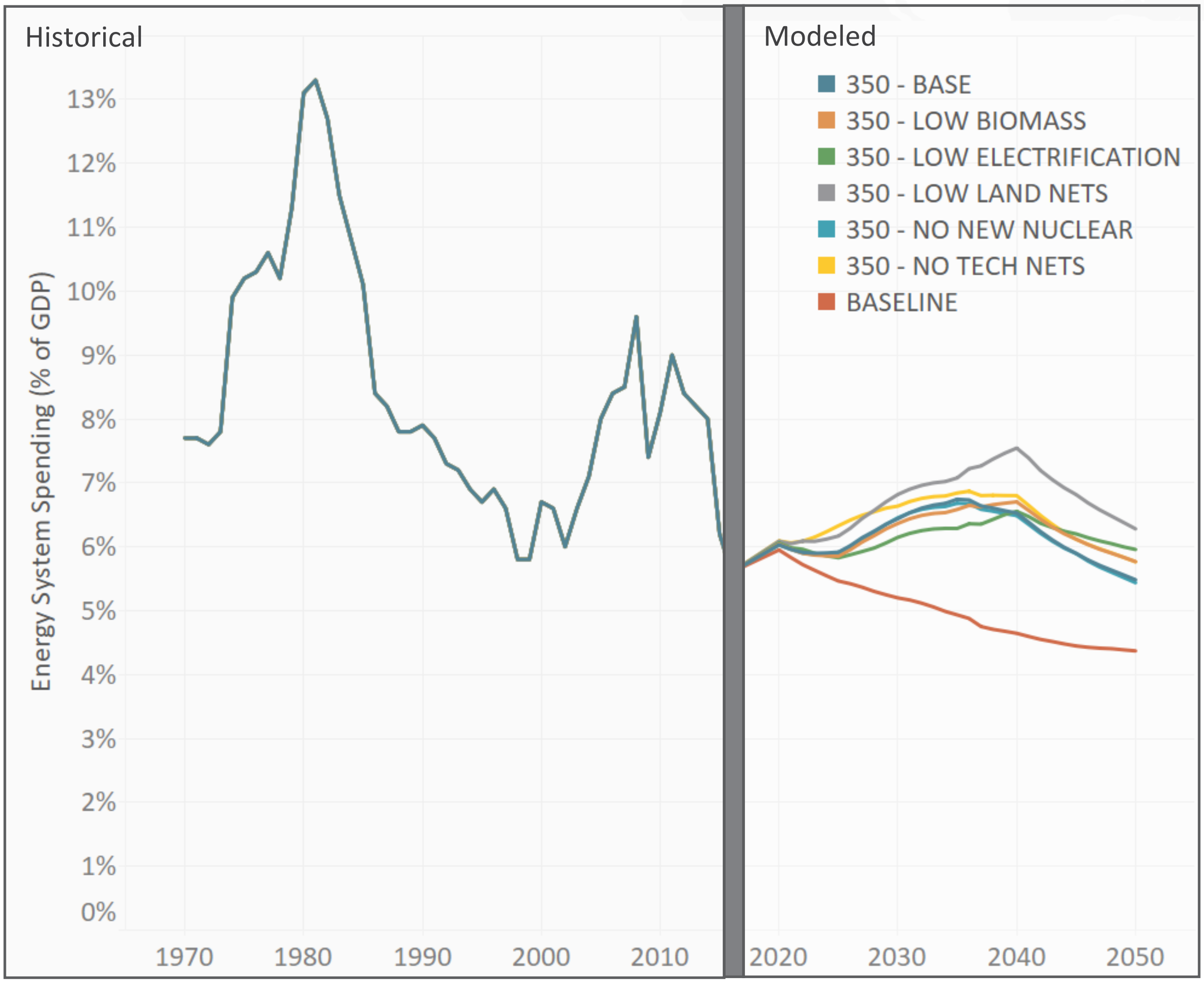
In all but one case these costs peak at less than 2% of the forecast GDP in 2040 (approximately $600B) annually. The Low Land NETS case is the only case that exceeds this value, with a 2040 value approaching 3% of GDP. This result emphasizes the value of negative emissions from land-use in managing the costs of decarbonizing the U.S. energy economy. All cases show the same peak in 2040, with continued cost declines of low-carbon technologies (renewables, electric vehicles, etc.) reducing the incremental cost compared to the fossil fuel baseline by 2050. We make no assessment of the human and environmental co-benefits (including, for example, avoided costs of climate impacts, national security benefits, and health benefits of improved air quality) associated with these emissions reductions, as such an assessment is outside of the scope of this analysis. However, such assessments have been made elsewhere (Risky Business 2015).

Figure 5 Annual net system costs in $2016 and as % of GDP



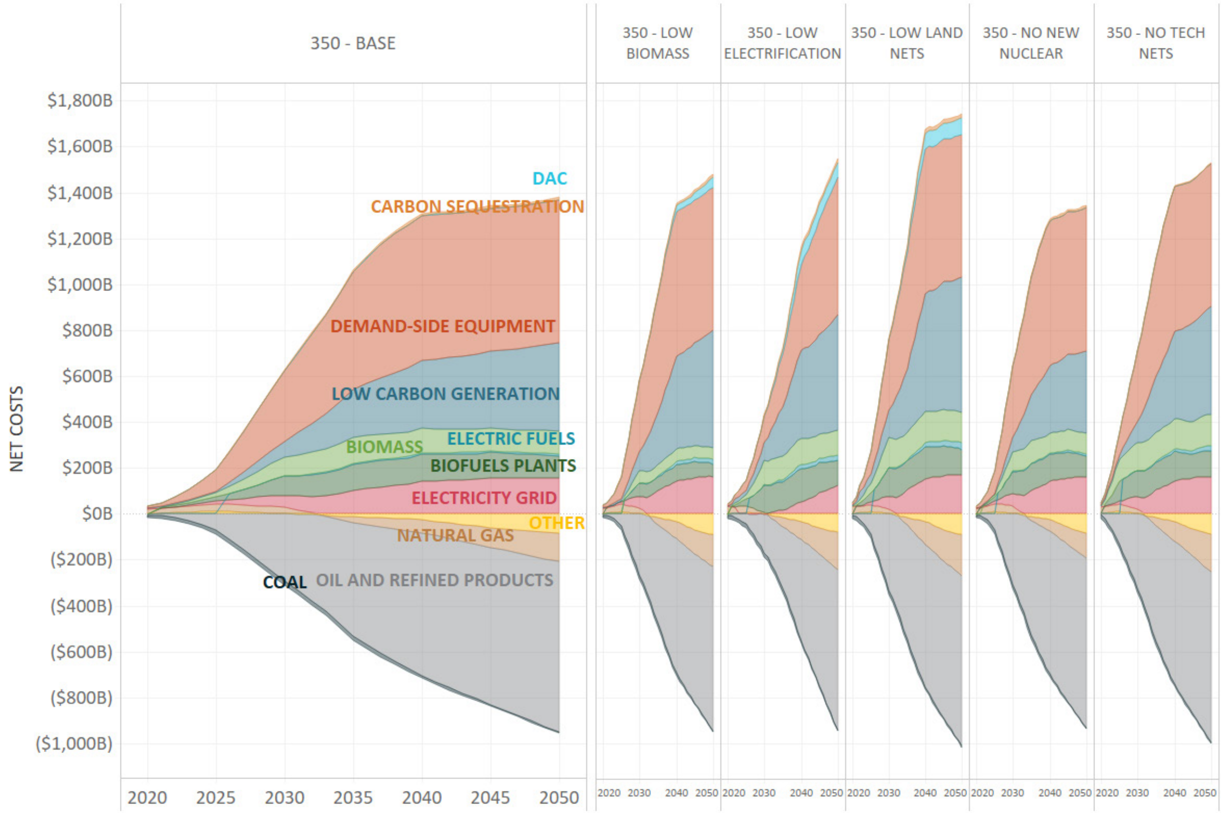
Second, we assess the total spending on the energy system (including carbon capture costs) as a share of GDP and compare that to historical levels of spending on energy. Incremental demand-side costs, such as the cost premium to purchase a high efficiency appliance, are assessed as an energy resource in this context, so that the incremental costs of electrification and efficiency are also treated as spending on energy. Figure 6 shows the results for the six 350 ppm scenarios and the baseline scenario relative to historical U.S. energy spending as a % of GDP going back to 1970. In all cases, the spending on energy in 350 ppm-compatible scenarios is lower than historical peaks. Even in the highest cost case, the peak is only equivalent to 2009 spending levels as a % of GDP. This is a measure of the economic feasibility of energy system transformation, a result arising from cost declines in renewables and electric vehicles (batteries), the continued transition of the U.S. towards a service economy, and the expected continuation of low natural gas prices which helps to manage overall energy system costs even in the 350 ppm-compatible scenarios.

Figure 6 Total energy system costs as % of GDP – modeled and historical



Third, while the overall system costs of 350 ppm pathways are within the range of historical values for the U.S., the way that money flows within the energy economy changes substantially. In the low-carbon economies represented by the 350 scenarios, low-carbon technology investments are substituted for fossil fuels. This transformation is shown in Figure 7 with large new investments in biofuels, demand-side equipment, electric fuels, the electricity grid, and low-carbon generation being offset by dramatically reduced spending on coal, natural gas, and oil, especially the refined oil products gasoline, diesel, and jet fuel.

Figure 7 Components of net energy system costs for all cases



3.3. Energy Transition

Transformation of the U.S. energy system occurs on both the demand and supply side of the system. Final energy consumption rapidly transitions away from direct combustion of fossil fuels towards the use of electricity (e.g. from gasoline powered vehicles to EVs) and other low carbon energy carriers, accompanied by a supply-side transition from primarily fossil sources of energy towards zero-carbon sources such as wind, solar, biomass, or uranium. Figure 8 shows these simultaneous transitions, with the left-hand side showing primary energy supply and the right-hand side showing final energy demand.

Figure 8 Primary and final energy demand for all cases from 2020 – 2050

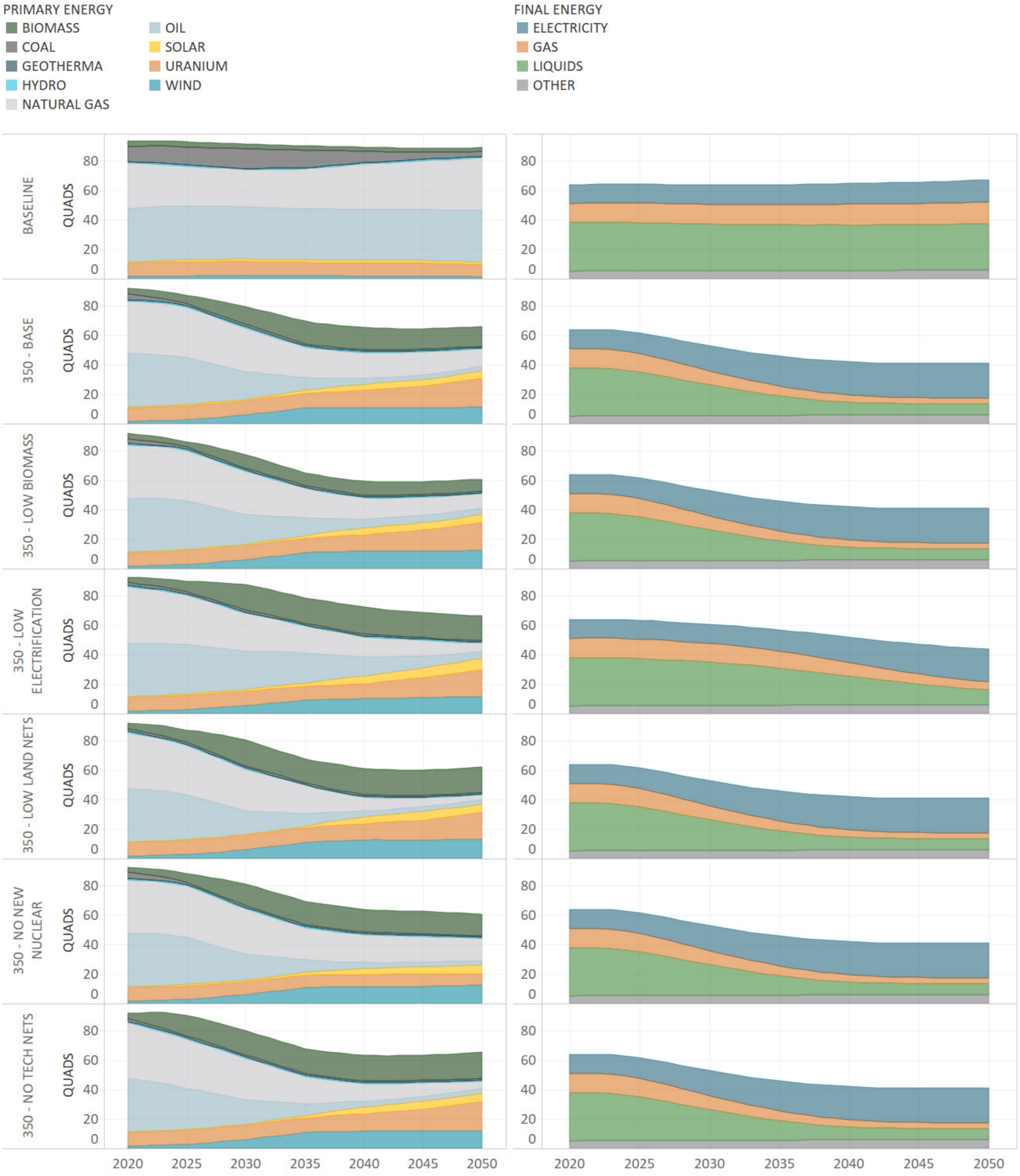
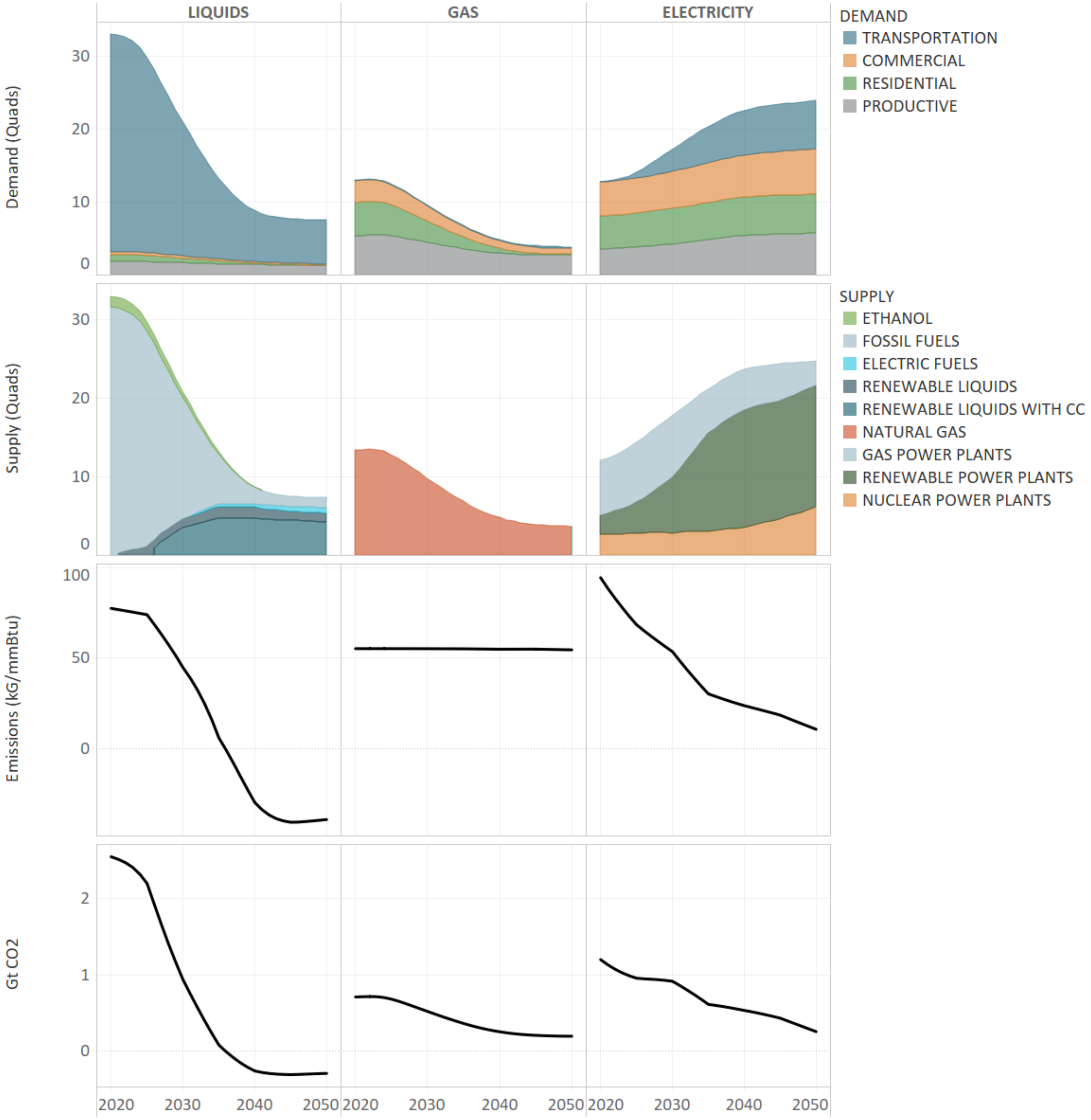


Figure 9 shows the transition of the energy mix over time, as reflected on both the supply and demand sides of the system. The three columns show energy divided into the main energy carrier types (liquids, gases, and electricity). The top row shows the transition in final energy demand over time, broken down by sector. The use of liquids and gases falls dramatically over time as a result of electrification, while electricity use increases for the same reason. The second row shows the evolving mix of energy types used to meet the final demand shown in the first row. The third row shows the average emissions intensity of the energy supply mix in the second row, which declines over time as lower carbon sources are used. The bottom row shows the total emissions over time from each of the main energy carriers, the product of the total amount of each used times its emissions intensity.

Figure 9 Components of emissions reduction for liquids, gas, and electricity in the 350 – Base case



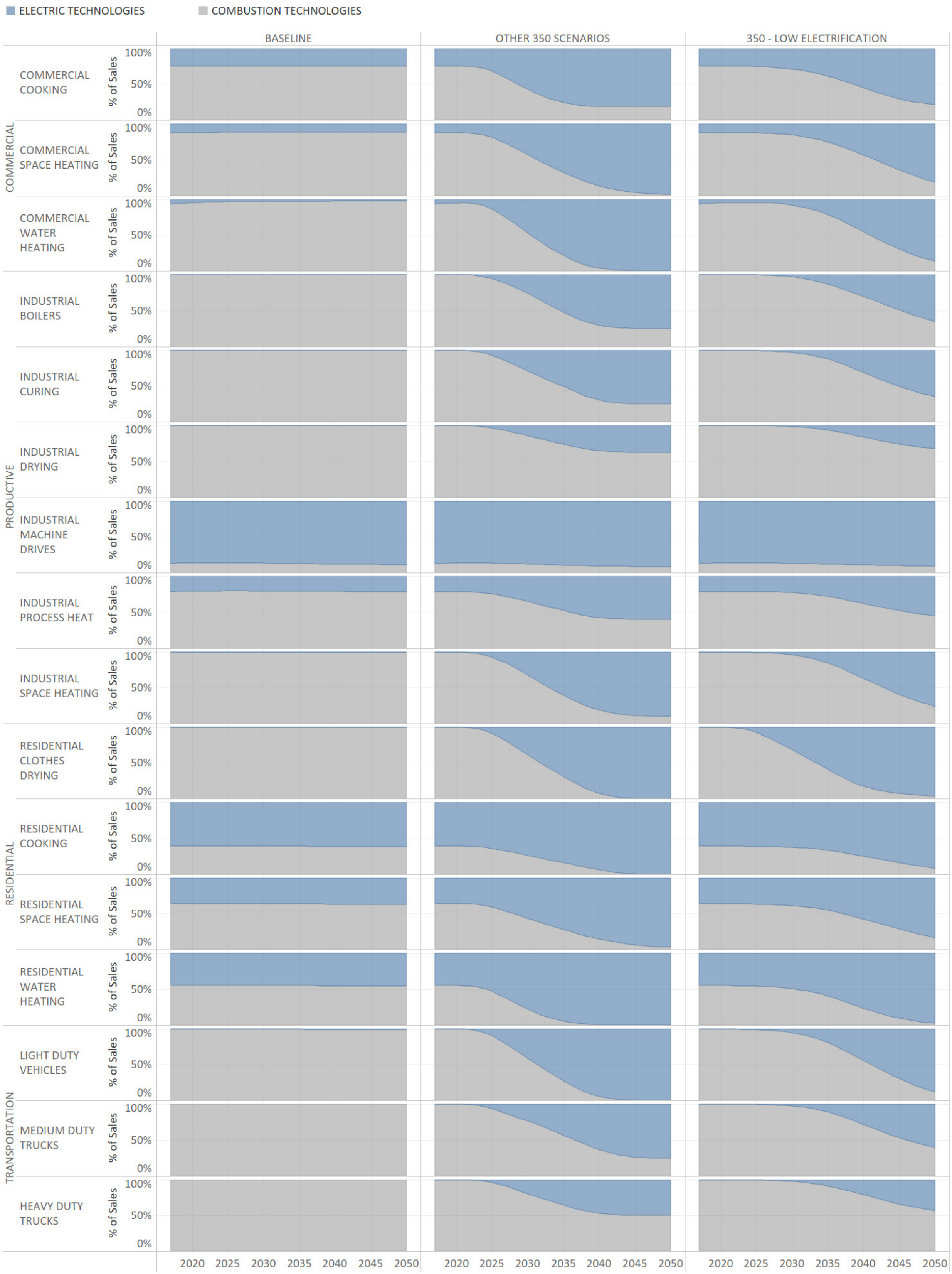
3.4. Infrastructure

Accomplishing the transformation of the energy sector requires significant investments in low-carbon infrastructure and a transition away from the extraction of fossil fuels. We've noted the costs of these investments, and this section details the scale of required infrastructure in the key areas of demand-side equipment, low-carbon electricity generation, biofuels production, electricity storage, electricity transmission, hydrogen electrolysis, and direct-air capture facilities.

3.4.1. Demand-Side Transformation

In addition to employing many efficiency measures, primarily in electric-only end-uses like lighting, ventilation, and household appliances, the demand-side undergoes a large transformation in end-uses where there are direct electric alternatives to fuel combustion. Transitions to electric technologies results in efficiency gains as well as a reduction in the amount of fuels that need to be displaces by bio-based or electric alternatives, reducing the overall cost of achieving emissions reduction goals. Figure 10 shows this transition for a variety of residential, commercial, productive, and transportation end-uses. Transportation electrification is the most critical sector to achieve these electrification goals in due to the volume of liquid fuels that it currently consumes.

Figure 10 Electric Technology Stock Shares



3.4.2. Low-Carbon Generation

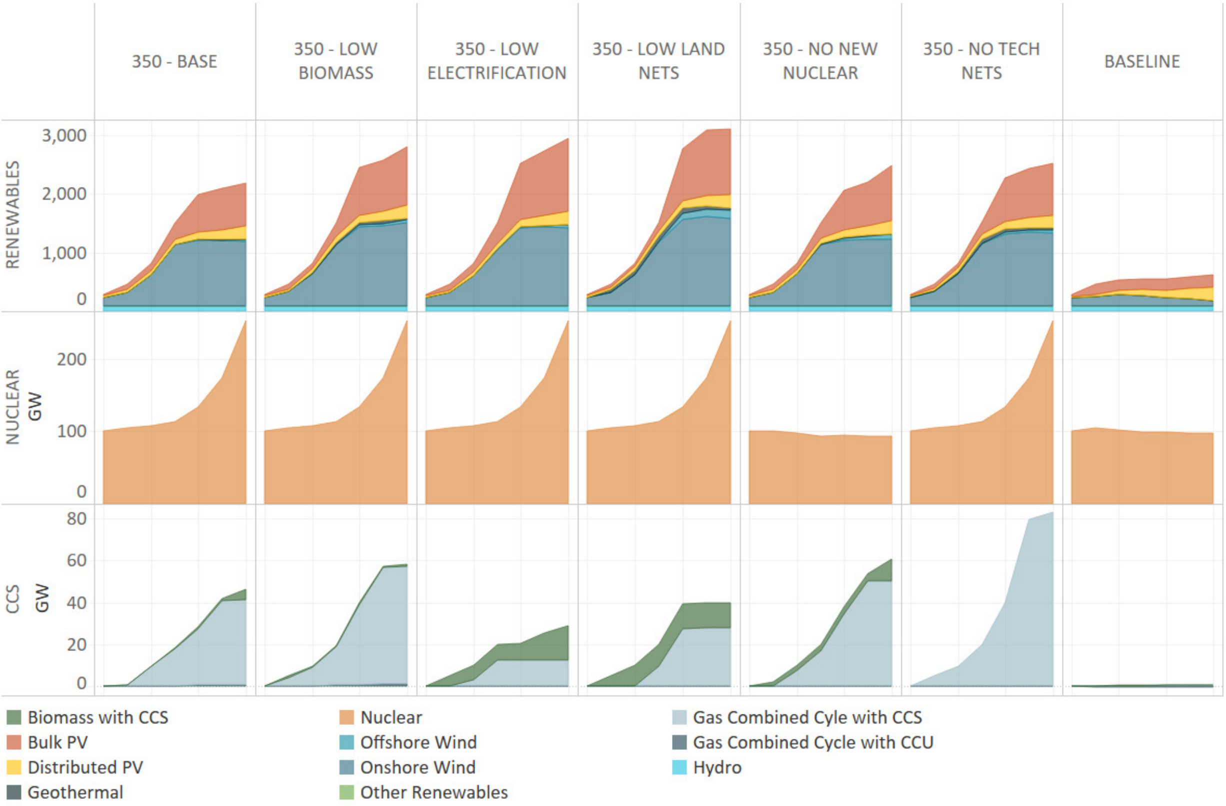
All 350 ppm-compatible scenarios result in the addition of 2000 to 3000 gigawatts of renewable electricity capacity by mid-century – in comparison to total electricity generating capacity of all kinds of about 1000 gigawatts today – because renewables are the lowest-cost zero carbon resource available (Figure 11). This capacity takes the form primarily of new wind resources through 2030, since the majority of U.S. electricity demand (and population) is located in areas with better wind than solar resources, and thus provides better economics for wind. Wind generation is also able to reach higher shares of total generation (renewable penetration) than solar before encountering significant balancing challenges, because the production profile of wind is more evenly distributed throughout the day, in contrast to the concentration of solar generation within a narrow band of hours. Penetrations of solar beyond a certain percentage requires complementary balancing resources, such as energy storage or flexible loads, to avoid curtailment and enable full utilization of the resource.

New renewables built after 2040 are primarily solar PV because: (1) the supply of new low-cost wind resources is exhausted by this point; (2) solar costs continue to decline; and (3) the system’s growing electric fuels production capacity can utilize larger quantities of daytime solar electricity production. Offshore wind is used as a resource in the Low Land NETS and No New Nuclear scenarios, primarily in the Northeast (New York and New England). Higher penetrations of offshore wind would be seen if onshore wind becomes difficult to site, or cost declines for offshore wind turn out to be greater than anticipated.

The scenarios in which new nuclear generation is permitted to be built also see an expansion of nuclear, though the importance of new nuclear is less critical than some of the constraints in other scenarios, as the No New Nuclear scenario shows. A relatively modest increase in the deployment of new renewables above the level in the Base 350 ppm scenario compensates for the constraint imposed by No New Nuclear.

Carbon capture and storage (CCS) is much less important in power generation in all scenarios than it is for capturing the CO_2 streams from biofuel refining and other industrial activities. High penetrations of renewables, which result in frequent surpluses of low marginal-cost energy, mean that CCS generators don't achieve high capacity utilization. This makes CCS an expensive option for limiting emissions from electricity due to its high capital cost spread over a limited number of hours. CCS electricity generation is generally found in regions with restricted new nuclear build and within regions that have limited wind resources where it can provide a consistent source of off-peak power.

Figure 11 Low-Carbon generation capacity growth



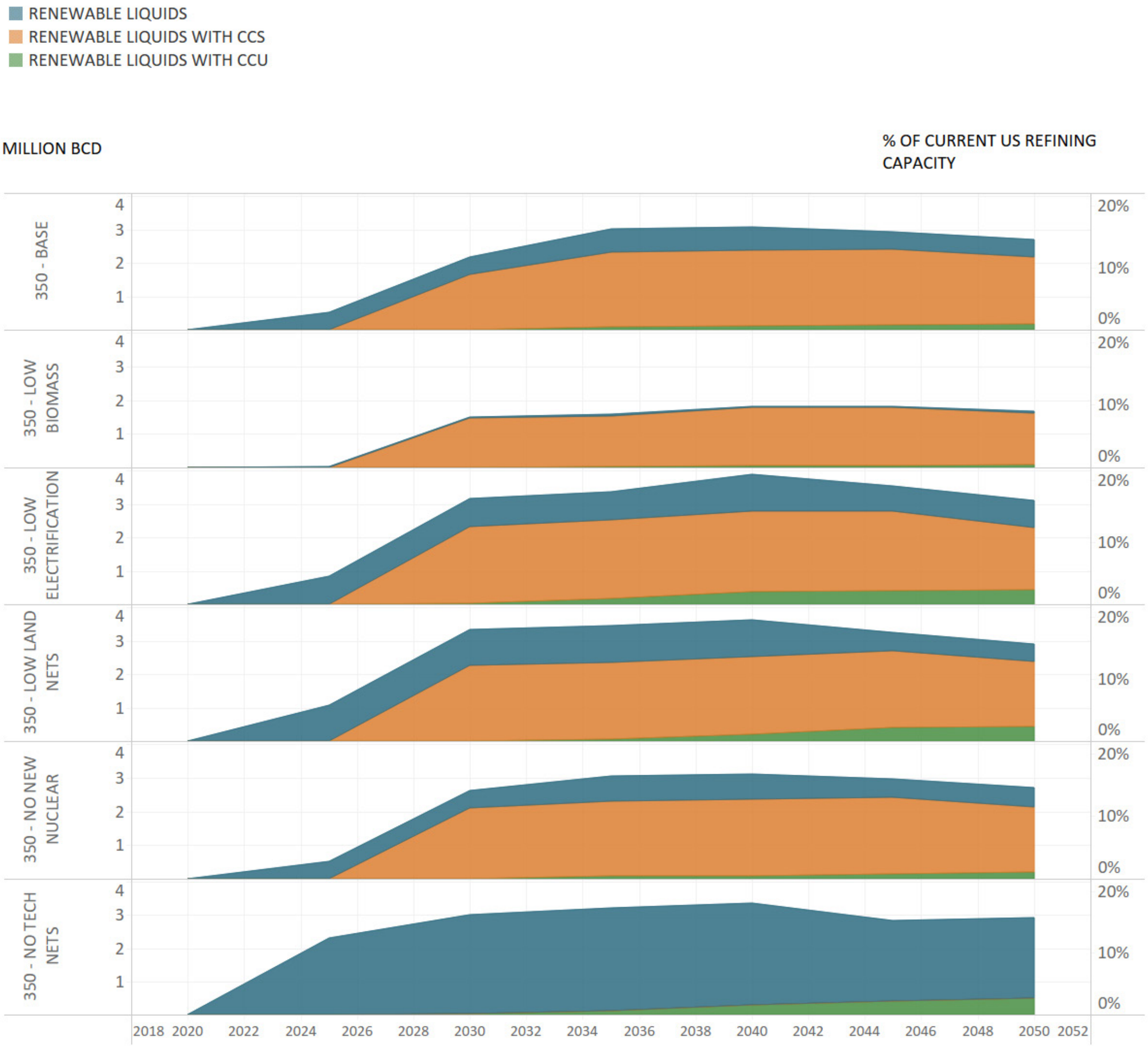
3.4.3. Biofuels Production

3.4.3.1. Liquids

The expansion of biofuels production is a critical strategy for reducing emissions as the economy transitions towards high levels of electrification. Even at the conclusion of the electrification transition, liquid biofuels play an important role in mitigating emissions in hard-to-electrify end-uses such as heavy industry and aviation. The United States already has a biofuels industry of significant size, but it primarily produces corn-derived ethanol, a relatively high carbon form of biofuel over its lifecycle. As light-duty vehicle travel is electrified, the demand for liquid transportation fuels decreases, and this sector is reduced in importance. This analysis did not find cellulosic ethanol to be a critical strategy during the transition from gasoline to electricity due to the high cost of developing cellulosic refining and distribution, and the pace of electrification (the market-size for gasoline alternatives shrinks very quickly). This analysis also finds that the focus of biofuels should be on displacement of liquid fossil fuels, rather than gaseous fuels. This is due to: (a) natural gas has a lower cost per MMBtu than refined liquid fuels; and (2) natural gas CO2 emissions are lower than liquid fossil fuels on an energy basis. Liquid biofuels production is shown Figure 12. While this represents a rapid expansion of production capacity of up to 4 million barrels per day by 2040, it is still only a fraction of the current capacity of U.S. petroleum refineries. In cases where bio-energy carbon capture and storage (BECCS) is allowed, it dominates fuel production, which is understandable given the economic attractiveness of biorefineries for carbon capture, with concentrated CO_2 streams and high utilization factors.

Carbon capture and storage (CCS) is distinct as a strategy from carbon capture and utilization (CCU) in this analysis. In CCU, the captured carbon is used in combination with electrically produced hydrogen to produce methane and other synthetic liquid or gaseous fuels that can be substituted for gasoline and diesel or natural gas, respectively. Bio-energy carbon capture and utilization (BECCU) is used either when the marginal cost of sequestration becomes high or in regions where there are substantial biomass resources but low sequestration potential, for example due to geographic unsuitability. In the No Tech NETS case, BECCS is primarily displaced by biofuels production without capture, but this case also has the highest BECCU production capacity.

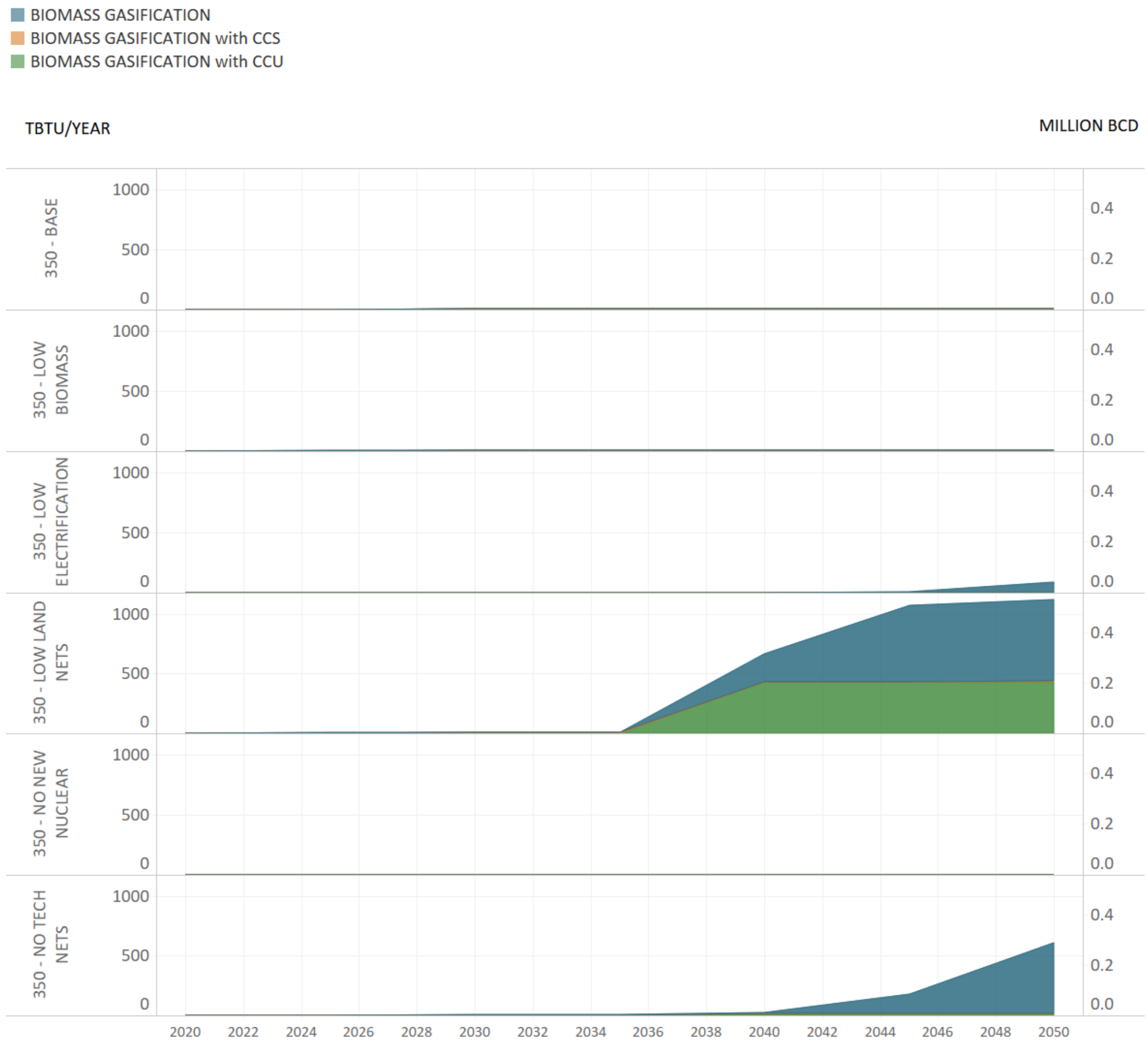
Figure 12 Liquid biofuels production capacity in Million Barrels Per Calendar Day (MBCD) and as a % of current U.S. petroleum refining capacity



3.4.3.2. Gaseous Fuels

The analysis finds that the priority use for biomass feedstocks is liquid fuel production, but in some scenarios, there is also limited production of gaseous biofuels. The Low Land NETS case requires a displacement of almost all fossil fuels, including gas in the pipeline, and so we see deployment of biogas in this case (as well as significant amounts of fuels produced from electricity). This is shown in Figure 13 both in units of TBTU/Year, which is more appropriate for gaseous fuels, and also on the right-hand axis in units of million barrels per calendar day, for purposes of comparison to the scale of liquid biofuels.

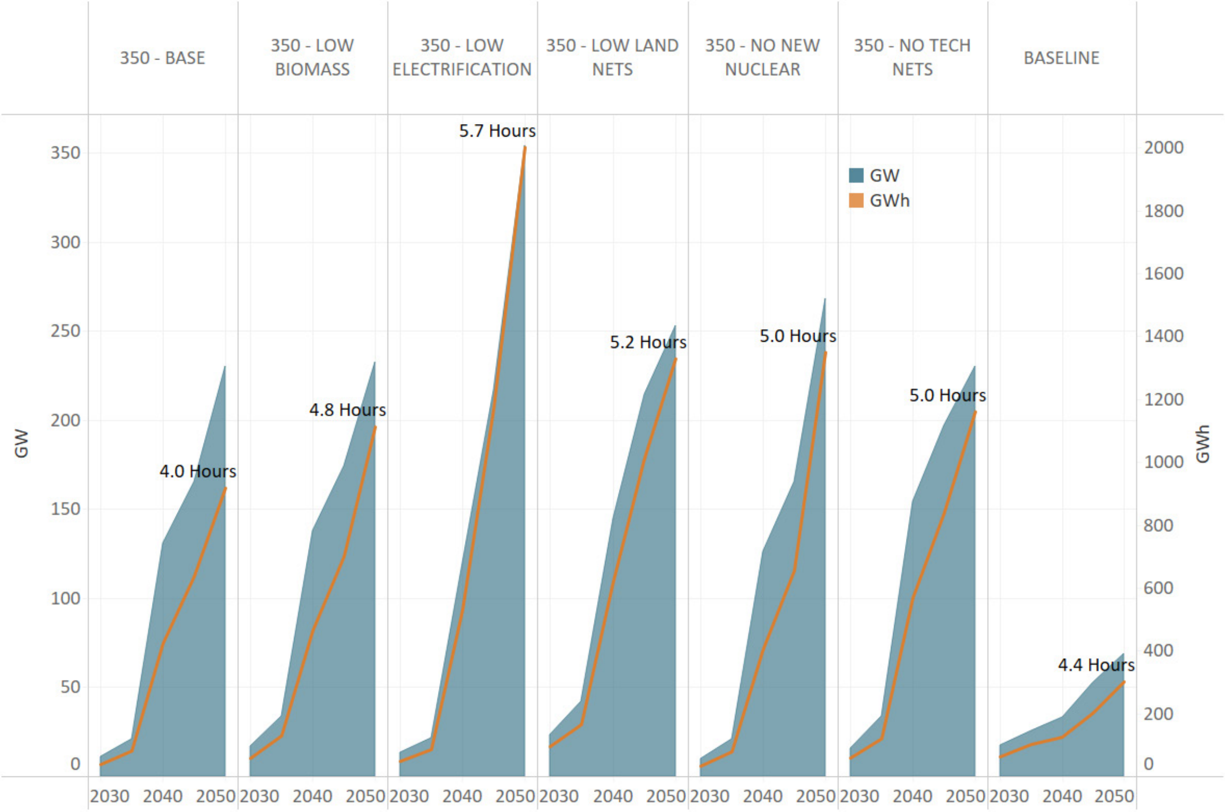
Figure 13 Gaseous biofuels production capacity in TBTU/Year and as a % of current U.S. refining capacity



3.4.4. Electricity Storage

Electricity storage provides capacity to balance the electricity system during times of low renewable energy output. Battery storage is the lowest-cost capacity resource available to address system peaks of limited duration. For this reason, it is deployed on a significant scale even in the Baseline scenario which has no carbon constraints (Figure 14). We find that significant amounts of new electricity storage are needed in all 350 ppm-compatible scenarios starting in 2030, and this storage is deployed with an average duration of four to six hours. Without a significant technological breakthrough, however, the high cost of stored electricity limits its value as a long-duration balancing resource (i.e. on scales from days to months of energy shortfalls from renewables). Thus, it operates primarily as a diurnal resource, using excess solar generation in the middle of the day on a consistent basis to avoid curtailment and to displace thermal generation off-peak (capacity and energy).

Figure 14 Energy storage capacity in gigawatts, gigawatt-hours, and average duration

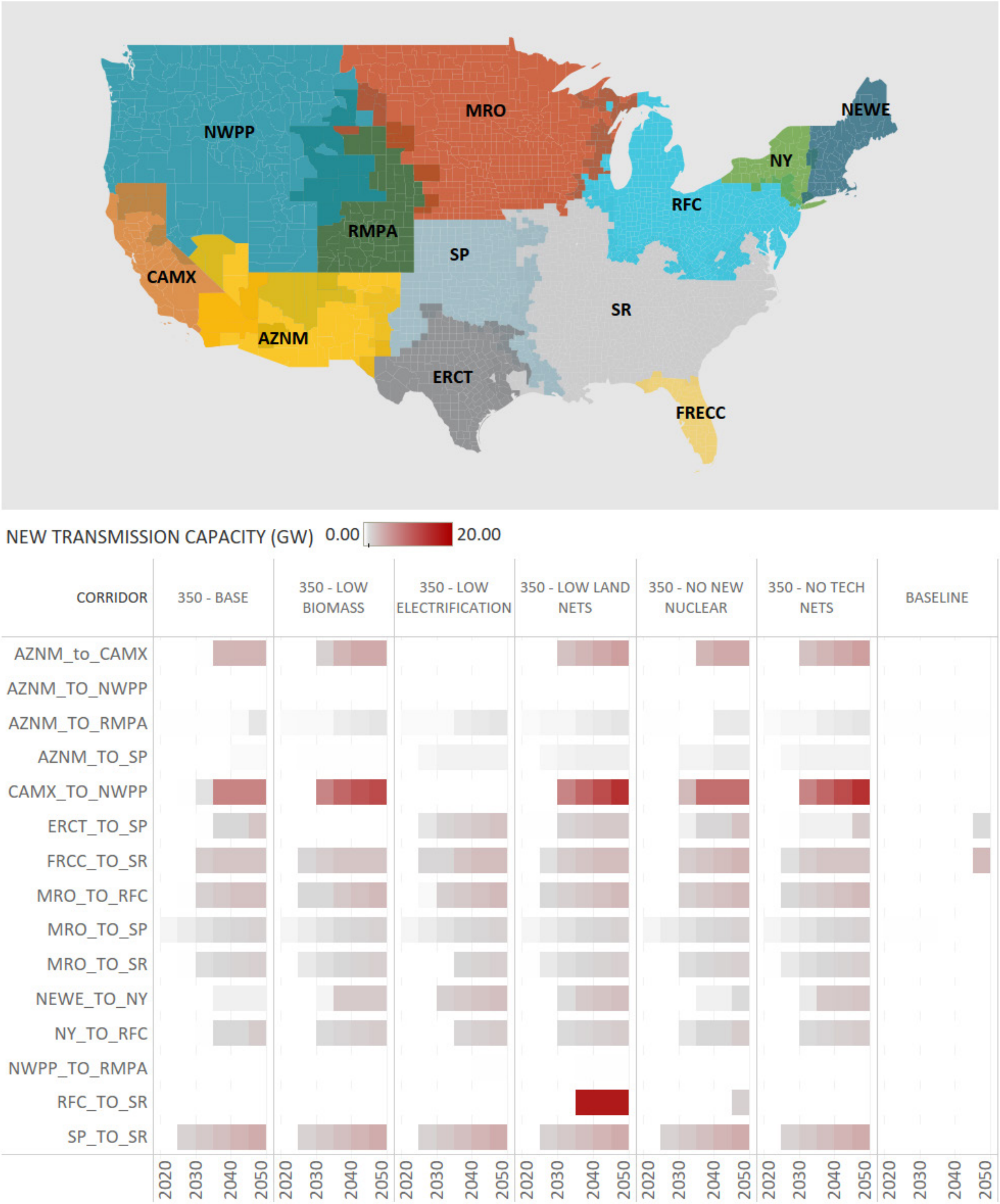


3.4.5. Electricity Transmission

Many deep decarbonization analyses emphasize the importance of transmission to match the supply and demand for renewable electricity spatially across the country. Our findings are consistent with these studies in terms of the value of transmission as a resource. However, transmission has historically proven difficult to permit, site, and build in the U.S., especially in the case of large inter-regional lines. For this reason, in our analysis we have constrained new transmission construction to a doubling of currently existing capacity between regions. This is likely conservative, as some regional interties are quite small at present, not because of being technically or societally difficult but due to a lack of economic justification. However, this admittedly arbitrary limit serves as a useful proxy for barriers to transmission construction, and at any rate is non-binding (does not constrain inter-regional flows) in almost every instance.

Limits on new transmission build may present less of a handicap in our analysis compared to some because our analysis employs other methods to transfer renewable energy between regions, namely through pipelines in the form of fuels produced from electricity (storage of such fuels within regions also provides a form of renewable energy storage). Still, we do see significant new interties between some regions, with almost all regions seeing some new economic transmission build by 2050, in all scenarios. Figure 15 shows all the regional intertie capacity built from 2020 to 2050. The largest such builds are between the CAMX region (California and northern Baja California), which requires imports of wind energy from NWPP (Northwest) and AZNM (Arizona and New Mexico) in all scenarios. There is also major development of transmission capacity between the RFC and SR (Mid-Atlantic and South-Atlantic) regions in the Low Land NETS scenario, related to the higher use of DAC and production of electric fuels in this scenario.

Figure 15 Incremental electric transmission capacity (gigawatts) by corridor

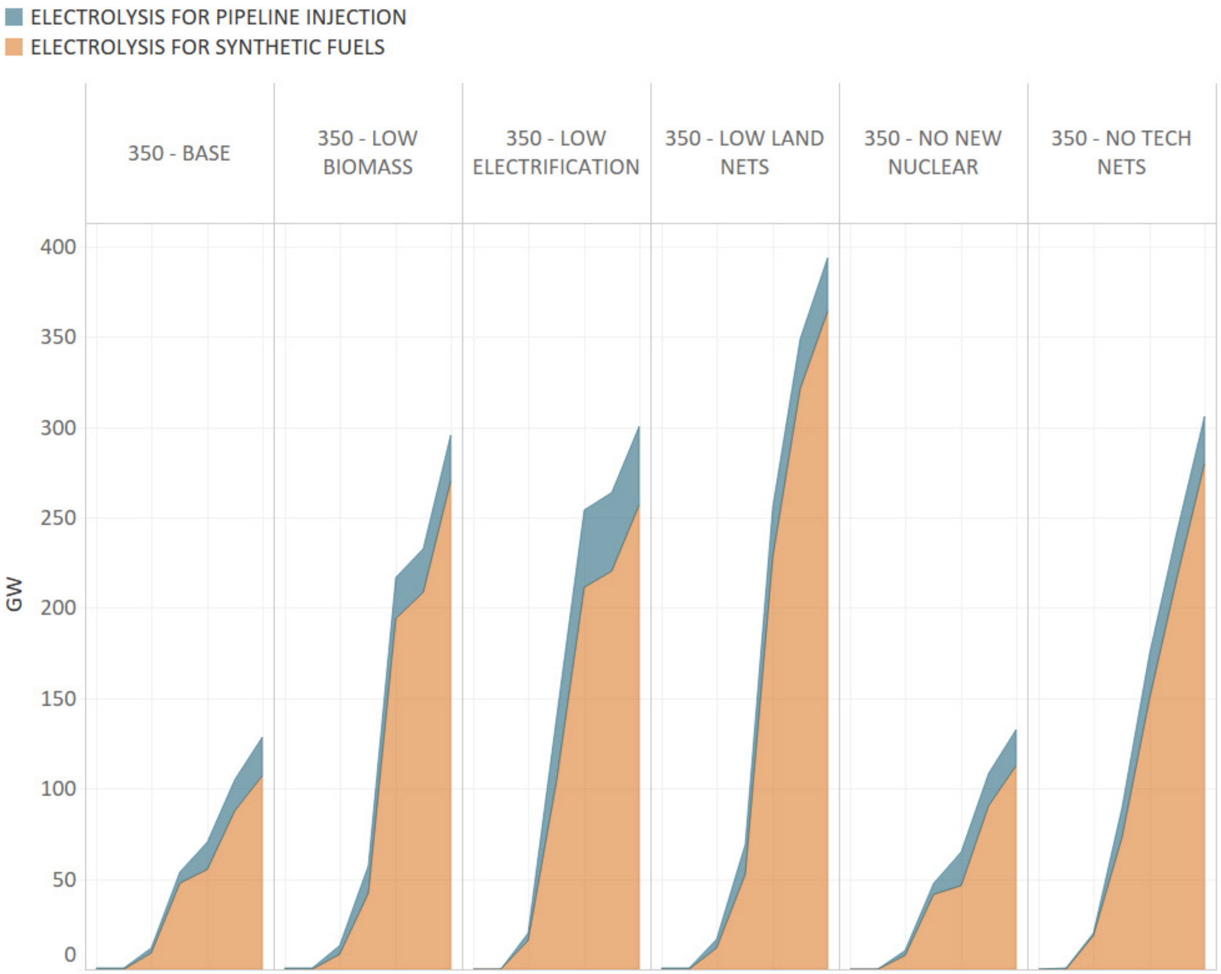


3.4.6. Hydrogen Electrolysis

The use of electricity to produce hydrogen from the electrolysis of water plays a key role in balancing the electricity system during periods of renewable energy overgeneration. The hydrogen produced is then used to create synthetic fuels that can be used in applications that are difficult to electrify. As illustrated in Figure 16, all pathways require more than 100 GW of electrolysis capacity, and the cases that require substantially more electric fuel production – Low Biomass, Low Electrification, Low Land NETS, and No Tech NETS – have up to 400 GW. This situation can be said to constitute a type of “hydrogen economy,” but not the type that has typically been discussed in the literature, in which hydrogen itself becomes a principal energy carrier for end uses. Many of the objections raised regarding that form of hydrogen economy center on the difficulty of developing a delivery infrastructure for this highly flammable fuel. Instead, in our 350 ppm scenarios electrically produced hydrogen is used as a feedstock in the production of renewable liquid and gaseous fuels that already have existing delivery mechanisms. Hydrogen can be combined with captured carbon dioxide to produce methane, the main component of natural gas, and further chemical synthesis using the Fischer-Tropsch process can produce synthetic liquid fuels comparable to (and interchangeable with) refined petroleum products, including diesel, gasoline, and jet fuel. Produced hydrogen can also be injected into a natural gas pipeline directly (limited to 7% by energy, which research has shown can be blended with fossil-based or synthetic natural gas without damaging end use equipment or delivery infrastructure). The hydrogen intended for pipeline injection is represented by the blue wedge in Figure 16. In sum, the “hydrogen economy” used in the 350 ppm scenarios avoids many of the infrastructure challenges typically associated with the use of hydrogen at large scale.

The production of electrolytic hydrogen and synthetic fuels provide the primary method of long-duration energy storage for a system with high penetrations of renewable generation. When peak electricity generation exceeds demand, the extra electricity is used to synthesize these fuels. These fuels can be used directly to meet demand for liquid and gaseous fuels and—to a limited extent— also be used to produce electricity at times of fallow renewable production. However, unlike previous hydrogen economy conceptions, in the 350 ppm scenarios the principal mechanism by which electric fuels balance the electricity system is not round-trip electricity storage (production and storage, then burning in a power plant to produce more electricity), but instead by enabling the economically efficient over-building of renewable resources, in which curtailment (wasted energy) is minimized because the energy is used to produce fuels used elsewhere.

Figure 16 Capacity of hydrogen electrolysis for pipeline injection and synthetic fuels

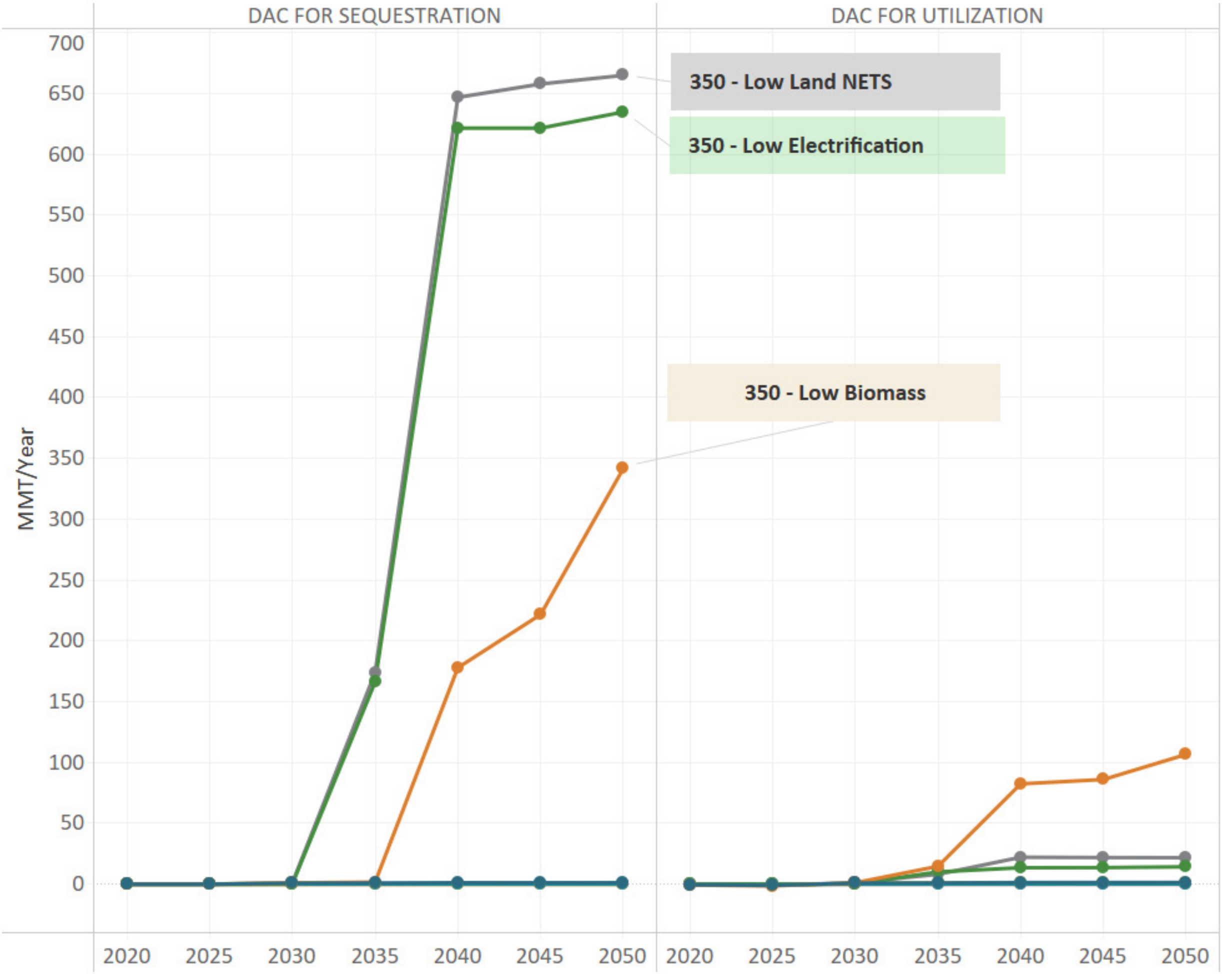


3.4.7. Direct Air Capture

Direct air capture (DAC) is the removal of CO_2 directly from ambient air. It has traditionally been imagined as a post-2050 technology, as 2°C scenarios called for achieving net-zero and net-negative emissions levels in the 2070 time frame. This analysis, however, demonstrates a role for DAC even before a net-zero economy is reached (Figure 17). In scenarios where there are insufficient biomass-based alternatives to replace fossil fuels (Low Electrification and Low

Biomass), DAC plays a role in accelerating the transition necessitated by the cumulative emissions cap, either by creating a carbon feedstock used for electric fuel production (DAC for utilization) or through geological carbon sequestration. We find that a heightened emphasis on the early commercialization of DAC is warranted due to its role as an accelerator of the overall transformation, as well as its obvious role as a technological backstop in the event of such contingencies as slower electrification or limited biomass deployment.

Figure 17 Direct air capture capacity for sequestration and utilization (MMT/Year)



Historically there has been reticence to treat DAC as a legitimate portfolio technology for achieving deep emissions reductions, not necessarily for reasons of technological maturity or acceptance but because of "moral hazard": the not unwarranted concern that the presence of this technology could be used to justify continued unabated combustion of fossil fuels. Our analysis, however, shows that there is clearly a place for DAC in the rapid transition to low-carbon energy systems, not as an alternative to decarbonization but as a complementary technology to hasten energy decarbonization and increase sequestration. Our analysis also shows that DAC pairs best economically with low-cost zero carbon resources such as wind and solar, because DAC (like hydrogen electrolysis) is a large industrial load that has high variable costs relative to fixed costs, and can therefore operate flexibly at less than full utilization, taking advantage of periods of renewable overgeneration. Alternative carbon capture scenarios in which grid electricity continues to be provided by fossil thermal generation do not offer the same economic opportunities.

4. Discussion

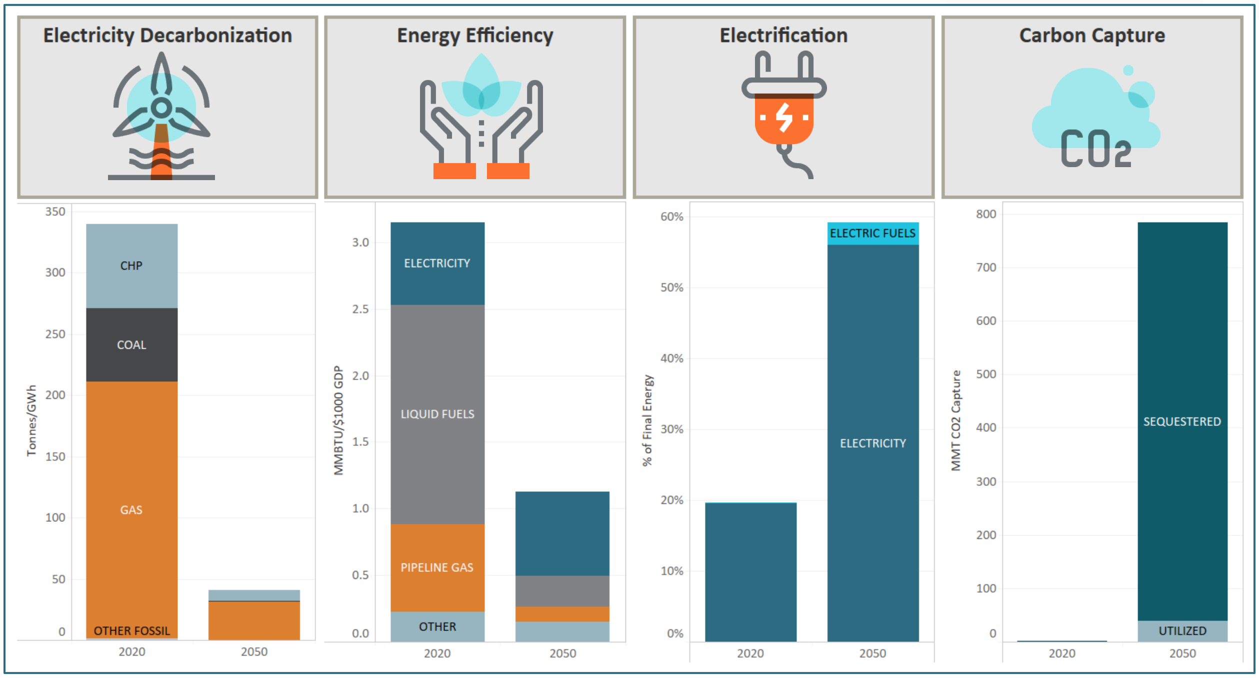
In addition to high-level summary results presented above, this discussion details additional features and components of low-carbon energy systems that can achieve 350 ppm trajectories in the U.S.

4.1. Four Pillars

Deep decarbonization analyses have relied on three primary strategies for achieving emissions targets: (1) electricity decarbonization, the reduction in the emissions intensity of electricity generation; (2) energy efficiency, the reduction in units of energy needed to provide energy service demands; and (3) electrification, the conversion of end-uses from fuel to electricity. These have been referred to as the "three pillars" and the use of these strategies to achieve deep decarbonization is a robust finding across many jurisdictions both domestically and internationally. Under our scenarios, which assume EIA projections for economic growth and increased consumption of "energy services", achieving 350 ppm requires the inclusion of a fourth pillar, carbon capture, which includes the capture of otherwise emitted CO_2 from power plants, industrial facilities, and biorefineries. It also includes the use of direct-air capture facilities to capture carbon from the atmosphere. Once captured, this CO_2 can either be utilized in the production of synthesized electric fuels or it can be sequestered. Both strategies are used extensively in the scenarios analyzed here.

Figure 18 below shows the four pillars of decarbonization employed in the Base scenario. The emissions intensity of electricity has declined to less than 50 tonnes/GWh in 2050 from 350 tonnes/GWh in 2020, which is itself less than the current U.S. average of 424 tonnes/GWh in 2016 (U.S. Energy Information Administration 2018). One of the principal strategies employed in the early years is a change in the *merit order dispatch* (the prioritization used by system operators to determine the order in which electric generation is employed to meet demand) so that electricity generation from gas plants is prioritized over generation from coal plants. This accounts for the difference between 2020 Electricity Decarbonization in Figure 18 and 2016 historical. Energy consumption per dollar GDP, one metric for energy efficiency, decreases substantially from 3.2 in 2020 to 1.2 in 2050. This is due to significant same-fuel energy efficiency, economic transition towards services, and direct electrification of end-uses, which contributes efficiency gains over fuel alternatives. Electricity, used either directly (e.g. in electric vehicle) or as an electrically produced fuel represents almost 60% of final energy demand by 2050. Carbon capture contributes 800 MMT of emissions reductions by 2050, either when directly sequestered or when utilized for making synthetic electric fuel.

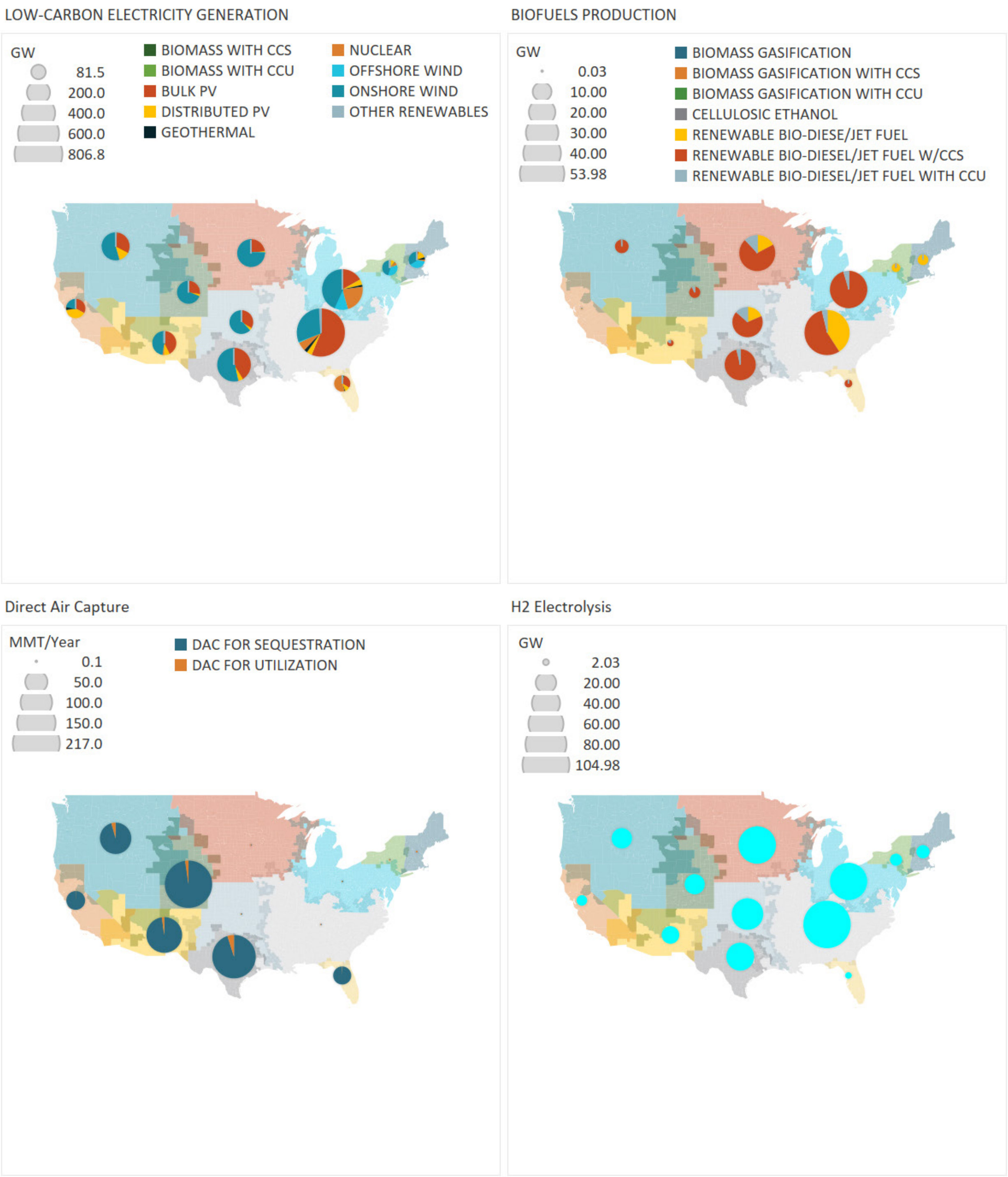
Figure 18 Four pillars of deep decarbonization in the 350 – Base case



4.2. Regional Focus

Our current energy economy exhibits significant regional variation in terms of energy demand, energy supply, and overall energy costs. The future energy economy will exhibit these same regional variations and it is worth identifying geographic regions that may be at the center of the new energy economy. While all regions require significant investment in generation resources to decarbonize their sources of supply, some regions, due to particular resource endowments, will see additional investment as they become both the center of the fuel production and direct air capture sectors. These regional dynamics are illustrated in Figure 19 for the Low Land NETS case, which requires the most significant infrastructure investments of all the cases and therefore shows the regional dynamics most clearly.

Figure 19 Regional infrastructure needs in the 350 – Low Land NETS case



Zero-carbon generation follows a predictable pattern of resource endowments, with regions that have access to the wind-belt extending from Texas up through Wyoming developing wind-heavy portfolios. The Southwest and Southeast have solar-heavy portfolios. The Northeast relies primarily on wind, both onshore and offshore. The Southeast and Midwest also rely on nuclear energy in this case.

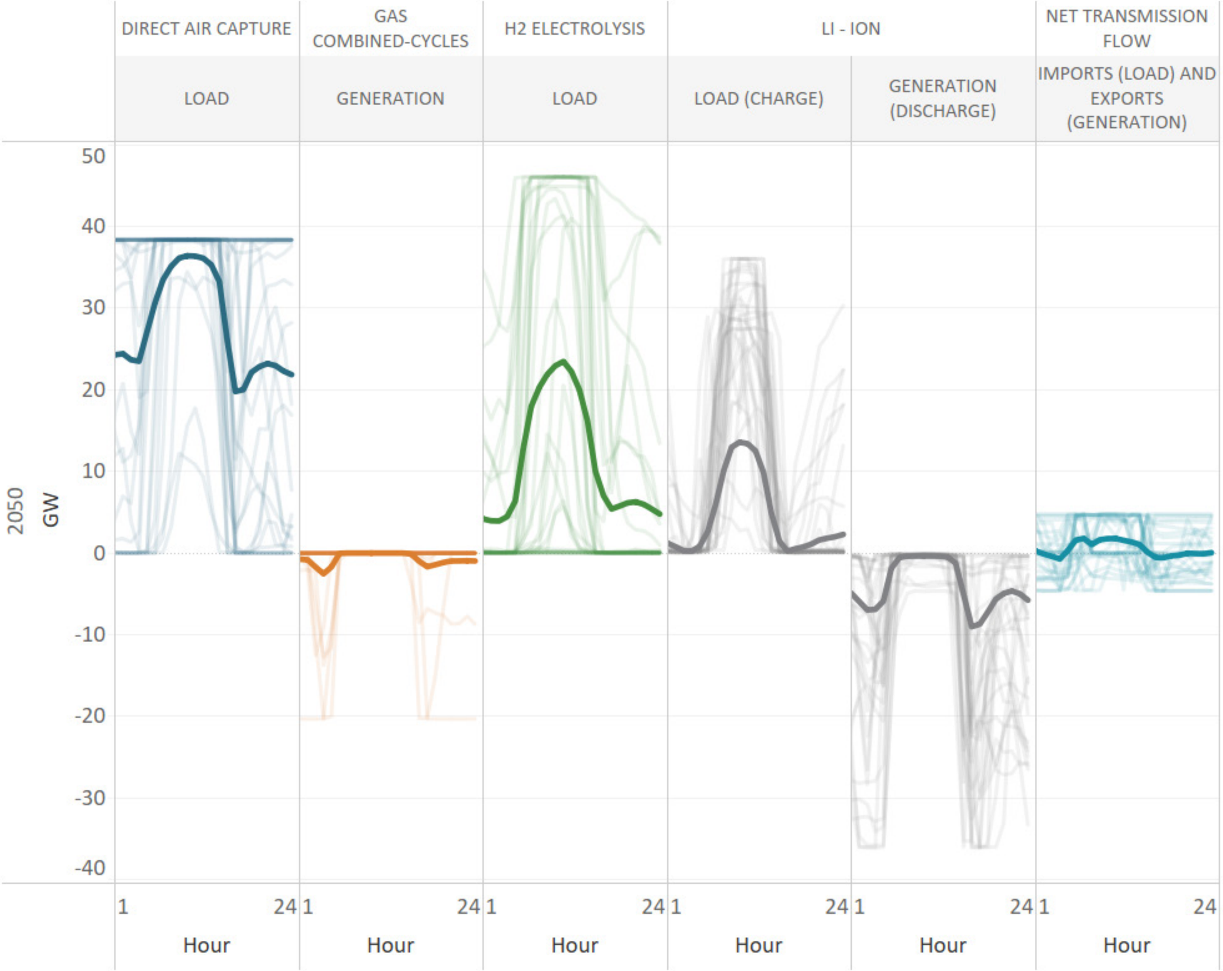
Biofuels production will be concentrated in areas with significant biomass resources, primarily the Midwest and the Southeast. In addition, biofuels production is best located in areas with available saline aquifers in which captured CO_2 can be stored. Electric fuels production will be determined by availability of CO_2 as well as grid conditions that support low-cost electrolysis. These conditions include either low-cost solar or wind generation, which explains the high concentration of electrolysis in the desert southwest, as well as in the wind-belt. One additional consideration not modeled explicitly here is the availability of water, which may affect siting of electrolysis facilities as well. Direct air capture facilities will depend similarly on low-cost renewables as well as the availability of saline aquifers for sequestration or hydrogen for synthetic electric fuels production.

4.3. Electricity Balancing

Electricity balancing, which is the matching of electricity supply and demand at all time-scales is one of the principal technical and economic challenges of decarbonization. The systems modeled here have a large percentage of non-dispatchable generation resources. On important characteristic is that variable costs for these resources are low and curtailing production represents lost economic value. In many studies of low-carbon electricity systems, the principal resource used to balance these types of systems is electricity storage (batteries, pumped hydro, etc.). However, this is an incomplete toolkit, specifically when dealing with imbalances that can persist over days and weeks. This analysis expands the portfolio of options available to address the balancing challenge, employing solutions such as flexible electric fuel production, dual-fuel boilers systems (i.e. gas and electric), and direct air capture in addition to traditional solutions such as batteries, thermal generation, and transmission expansion. Figure 20 shows balancing behavior in the ERCOT (Texas) dispatch region in 2050 in the Low Land NETS case.

The range of daily system balancing operations are shown by the set of transparent lines, while the daily average behavior shown by the thicker opaque lines. It can be seen, in this scenario, the lion's share of balancing needed is provided by direct air capture and electrolysis loads. Thermal generation is needed infrequently but must be maintained on the system for purposes of reliability. Storage exhibits a diurnal pattern, common across all resources, of increased load in the middle of the day responding to regular solar overgeneration conditions. Due to limited physical interties between ERCOT and other regions, transmission plays a relatively minor role here.

Figure 20 Electricity balancing from key technologies in ERCOT in 2050 in the 350 – Low Land NETS case



One can see the relative economics of building each type of capacity to balance load by looking at the average operations of each resource compared to the maximum operations in any single period. This average operation represents the utilization factor of each resource (this is referred to as a “capacity factor” for generation resources). More expensive capacity such as direct air capture facilities operate at a much higher utilization factor than do cheaper forms of capacity such as electrolysis or batteries.

All these solutions contribute to addressing the balancing challenges posed by large amounts of non-dispatchable resources. Figure 21 shows the overall contribution by resource type, case, and year. How a resource contributes to electricity balancing is a function of its unique characteristics. Thermal generation and hydro contribute to balancing the system by generating during periods of some combination of low renewable output and high load; storage moves energy from overgeneration periods to hours where thermal generation would otherwise be needed; flexible fuel production and direct air capture balance the system by soaking up overgeneration and turning it either into electric fuels or sequestering carbon directly; finally, renewable curtailment balances the system by reducing overgeneration when there is no economic case for utilizing it.

The relative contributions are unique to each case and resource build, but there are commonalities. First, the scale of balancing needs in 2050 compared to 2020 is drastically different. That’s because the net-load signal that the system is trying to balance is significantly more volatile, as renewables make up a larger portion of generation.

In all cases, thermal generation provides most of the balancing through 2030 before the significant renewable penetration that ramps up post-2030. Flexible electric loads (Ex. fuel production and duel fuel boilers) play a role in all cases and become the dominant resource in cases where they are needed to displace fossil fuels. Storage plays a key role but not a solitary one, as its primary use is to operate diurnally and balance out solar overgeneration. Renewable curtailment is present in all cases.

Figure 21 Balancing contribution by resource (TWh)

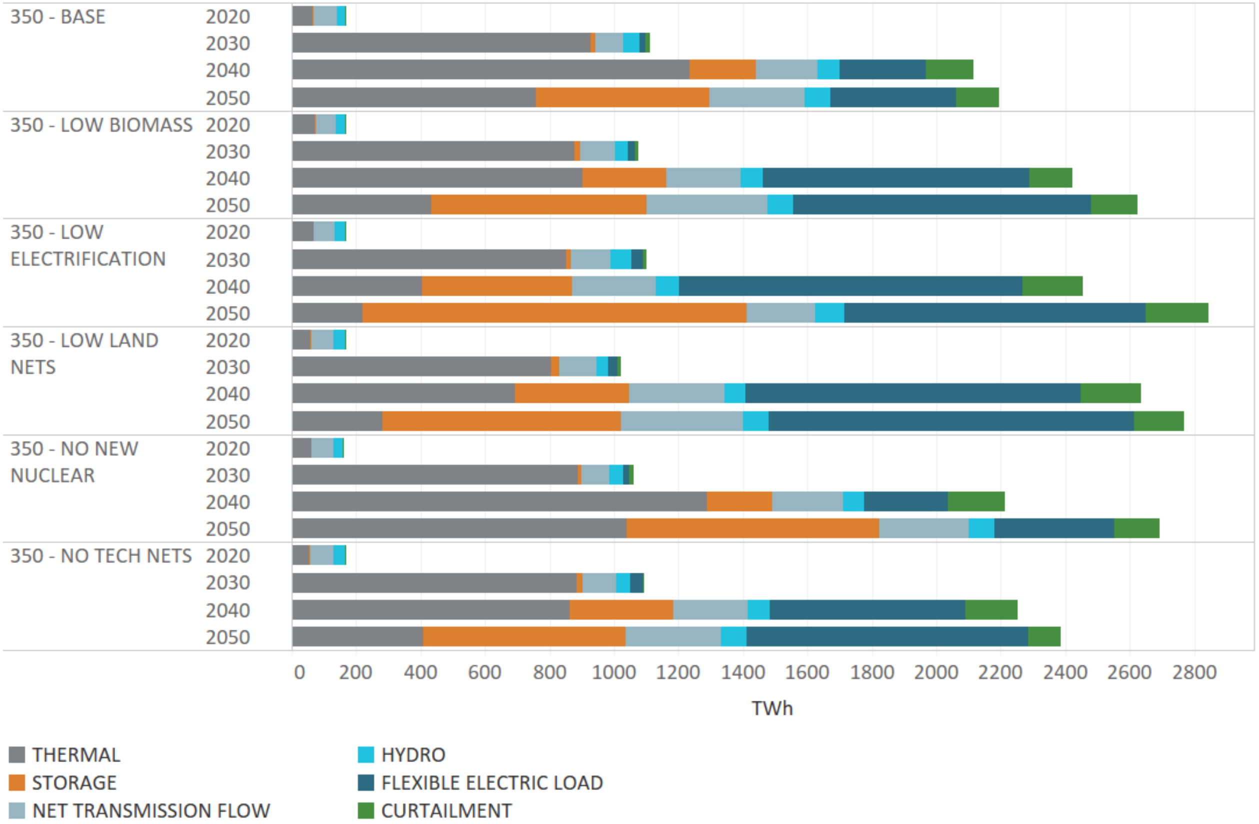
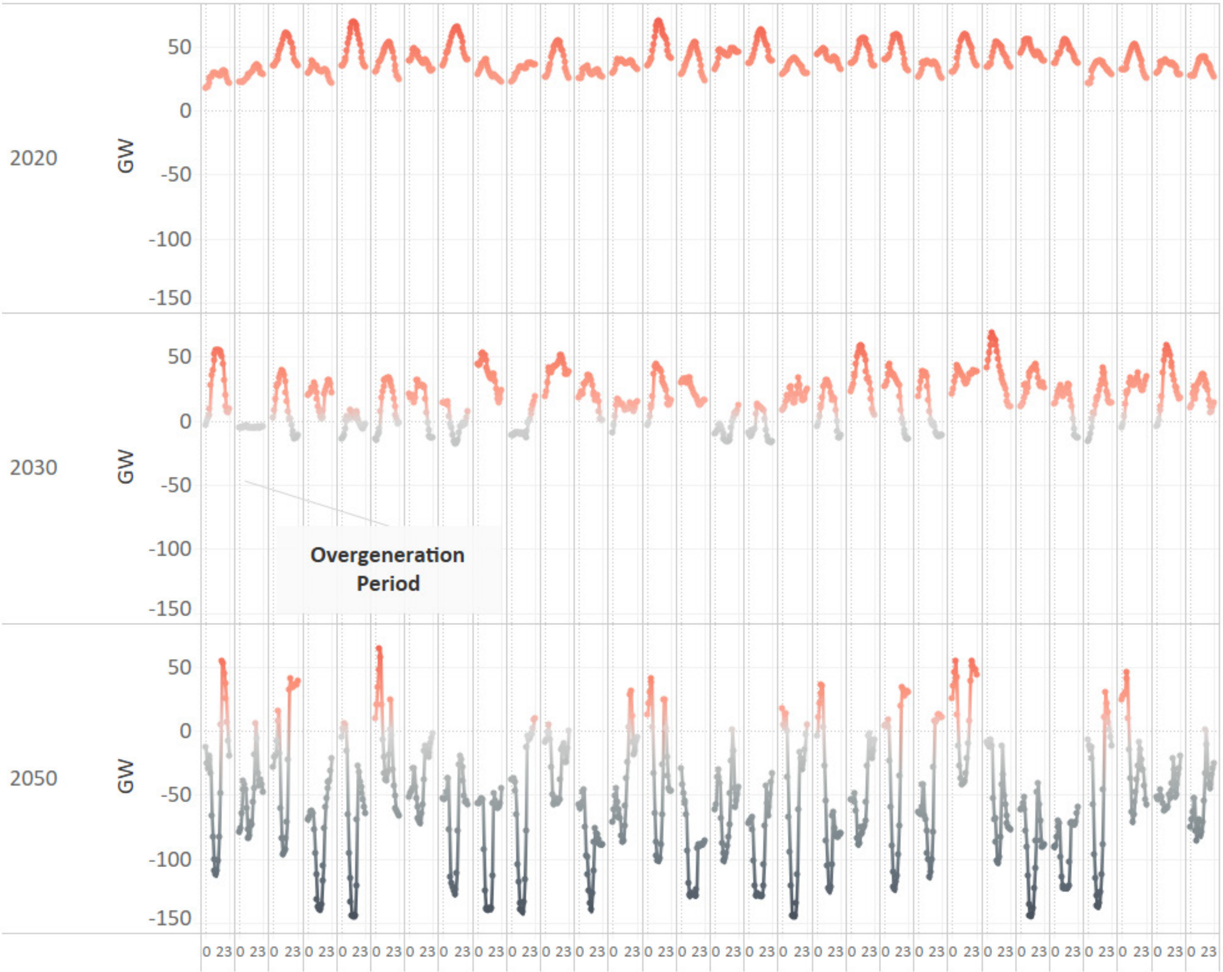


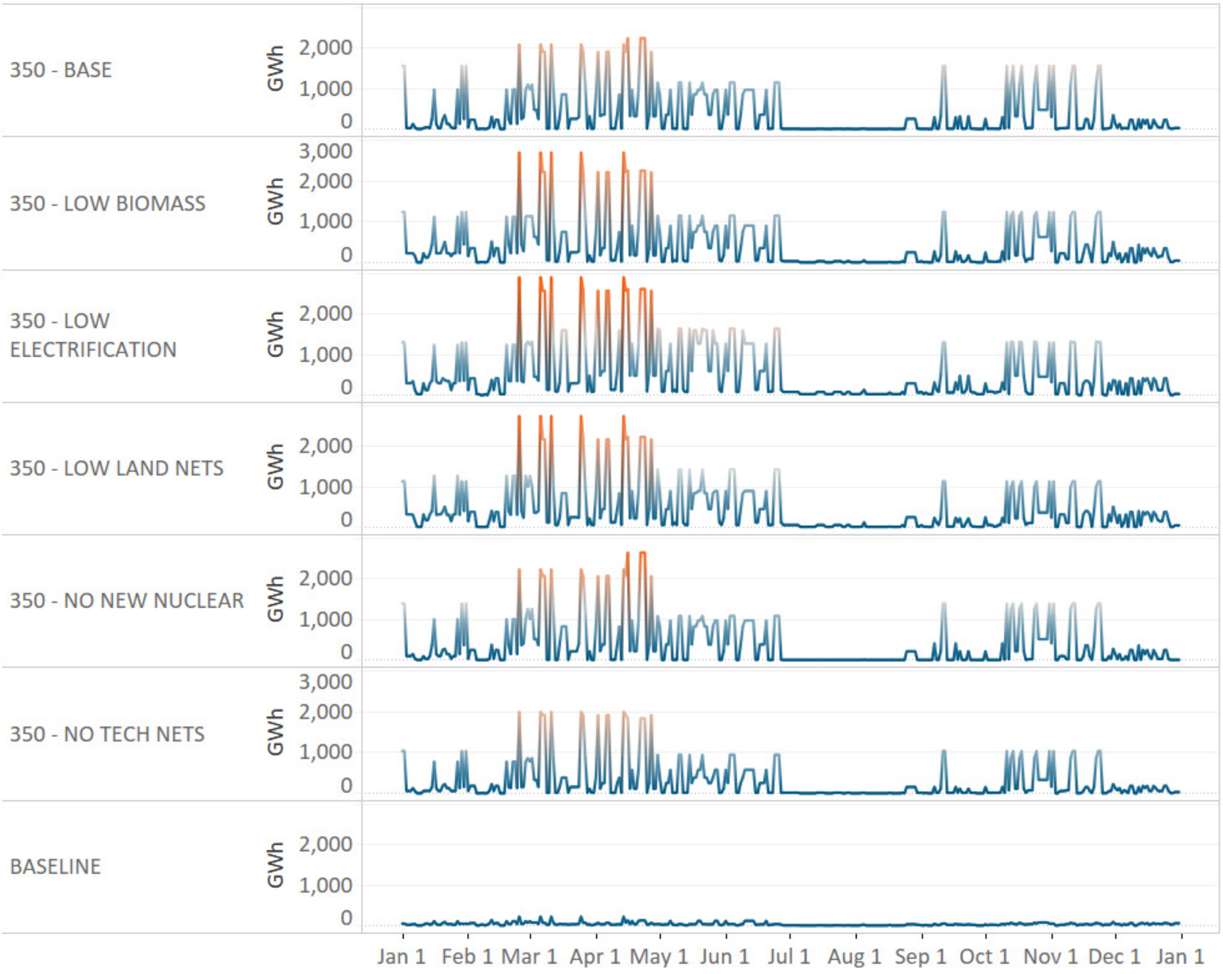
Figure 22 shows the initial net-load signal for ERCOT across sample days in 2020, 2030, and 2050. In 2020, variation is primarily a result of the electricity demand shape. By 2030 and certainly by 2050, that load variation is swamped by variability in renewable output, with average daily swings in the net load of almost 100 GW.

Figure 22 Net Load in 2050 in ERCOT in the 350 – Low Land NETS case



Even with the magnitude of the different balancing solutions employed in the 350 ppm scenarios, there is in all cases still some level of renewable curtailment that is economically efficient. That is, during periods of significant or sustained overgeneration, the capacity that would be needed to be built to fully utilize that renewable energy generation is not economic. Economic curtailment exhibits a distinctly seasonal pattern, with much of it occurring in the spring and fall, shown in Figure 23. This is due to either generally high renewable production (wind, in particular, has a strongly seasonal shape), generally low-load conditions (i.e. no heating or air conditioning load), or a combination of the two. In regions with significant hydro resources, seasonal release requirements can contribute to spring overgeneration conditions as well. The baseline scenario has very low curtailment because without carbon constraints, the impetus to push renewable penetrations to levels that result in curtailment is diminished.

Figure 23. Renewable resource curtailment patterns in 2050

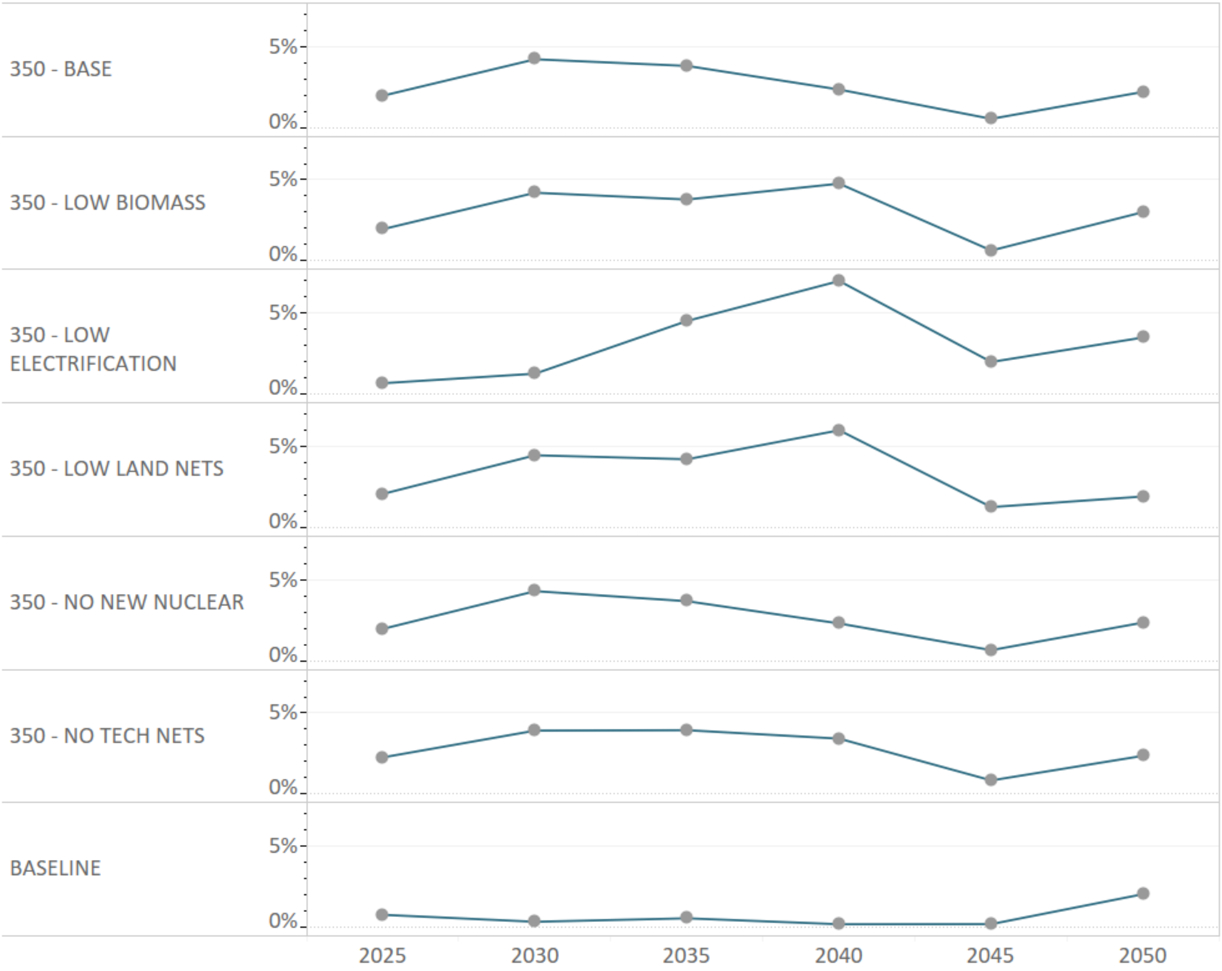


4.4. Sector Integration

The 350 ppm-compatible scenarios demonstrate the need for sectoral integration in deeply decarbonized economies. The lines between traditionally distinct sectors become blurred when decisions and their effect are so tightly linked across sectors. For example, the need for electric fuels to replace fossil liquid or gaseous fuels has a huge impact on renewable resource needs in the electricity sector, as well as on the need for supplementary balancing resources such as electric storage. Electric fuel production even competes with the need for transmission, as energy can instead be transferred between high renewable production zones either as gaseous or liquid fuels.

The demand-side transformation, especially rapid electrification in buildings, transportation, and industry, will also require sectorally integrated planning both to ensure that new generation resources are developed to meet the growing demand, and also to plan distribution system upgrades and charging infrastructure, and to leverage the ability of new electric loads (specifically, space heating, water heating, and vehicle charging) to operate flexibly. Figure 24 shows the rate of load growth in each of our cases, with rates exceeding 4% in some cases during the 2030 to 2040 timeframe.

Figure 24 Electric load growth by year (%)



Allocation of limited biomass resources is another area in which cross-sector integration is critical. Some jurisdictions have undertaken policies that emphasize 100% renewable electricity. The ambition of these types of targets is consistent with the challenge of deep emissions reductions targets, but 100% renewable or zero-carbon electricity can be regarded *de facto* as a biofuels allocation policy—achieving a zero emissions target requires some portion of biomass to be burned in electric generators rather than used as liquid biofuels. Allocation of biomass towards liquids, however, might be lower cost and provide the same overall emissions reduction, illustrating the fungibility of emissions reductions between sectors.

4.5. Circular Carbon Economy

The circular carbon economy, or CCE, is a term for an energy economy that uses CO_2 embodied in biomass feedstocks or through direct air capture to produce electric fuels. Given existing energy service delivery mechanisms, both fuel delivery and fuel consumption infrastructure, large portions of energy demand in 2050 is still met as it is today, with liquid and gaseous fuels. These fuels can no longer be fossil-based and so require drop-in, non-fossil-based alternatives.

These fuels begin as electrolyzed hydrogen before they are catalyzed with captured CO_2. Critical sources of carbon for utilization in this analysis are biorefineries and direct air capture facilities. Biorefineries that are located in areas with limited sequestration potential are specifically good candidates as they can run at high utilization factors and have extremely concentrated sources of CO_2 emissions for low-cost capture. DAC facilities with utilization are also employed to a lesser extent as seen in Figure 17. This is a critical strategy in the long-term, even before net-zero emissions economies have been achieved.

5. Conclusions

Based on the analyses described in this report, we conclude that achieving U.S. emissions consistent with 350 ppm globally is technically feasible. This result is robust against five key strategies not materializing at the scale expected in the base case – biomass deployment, electrification, new nuclear deployment, technological NETS deployment, and land NETS implementation. While feasible, achieving the outcomes modeled here requires ambitious early action in order to maintain reasonable trajectories towards mid-century. Without this ambitious early action, it will require the achievement of net-negative emissions energy economies before mid-century and then sustain them at these low-levels through the end of the century.

These scenarios are intended to answer the question of whether the U.S. and its anticipated growth in consumption of energy services can develop an energy system that is consistent with 350 ppm in the atmosphere and we conclude that it can. We do not assert the necessity of, nor model the effects of, behavioral changes and energy service demand reductions (i.e. lower VMTs, lower temperature setpoints, lower consumption of material goods) though all would contribute to lower system costs, lower material requirements, lower infrastructure needs, and could improve quality of life in ways not measured by this analysis. There are co-benefits aside from CO_2 including improved air quality, energy price predictability, job creation and energy security that are not modeled here.

We observe large shifts in energy spending away from fossil fuels towards fixed infrastructure, both demand-side (electric vehicles, heat pumps, etc.) and supply-side (low-carbon generation, hydrogen electrolysis, electric storage, etc.). That said, the overall net costs of decarbonization found here are well within the range that a major industrial economy can manage, and indeed that the U.S. has managed historically. Based on this analysis, achieving 350 ppm-compatible pathways would maintain energy system costs within the low-range of historical values.

5.1. Key Actions by Decade

In conclusion, "Key Actions by Decade" below describes the sequence of actions needed to achieve a 350 ppm trajectory in the U.S. The list is by no means comprehensive, but it does highlight the most important physical transformations required and when each needs to occur. These actions make up a general blueprint for the U.S.—regional differences in resource endowment, existing infrastructure, and societal preferences will mean that not every step is universally relevant. In some cases, these actions need to build on one another, so that later actions are path dependent on earlier successes.

This and previous research have indicated that many pathways to decarbonize the energy system exist. The list below represents our current best understanding of how to achieve mid-century carbon targets at lowest cost while delivering the energy services projected in the 2017 *AEO*. Inherently this blueprint relies on projections of cost and performance that are unknowable. Despite this, a long-term blueprint is essential because of the long lifetimes of infrastructure in the energy system—making decisions that have long-term consequences using imperfect information is an enduring challenge. Uncertainty means an energy system plan is never static. Thus, we expect future work to revise this plan as decisions get made, technology improves, energy service projections change, and as our understanding of the climate science evolves.

From a policy perspective, this provides a list of the things that policy needs to accomplish, for example the deployment of large amounts of low carbon generation, rapid electrification of vehicles, buildings, and industry, and building extensive carbon capture, biofuel, hydrogen, and synthetic fuel synthesis capacity. Some of the policy challenges and opportunities that must be managed include: land use tradeoffs related to carbon storage in ecosystems and siting of low carbon generation and transmission; electricity market designs that maintain natural gas generation capacity for reliability while running it very infrequently; electricity market designs that reward demand side flexibility in high-renewables electricity system and encourage the development of complementary carbon capture and fuel synthesis industries; coordination of planning and policy across sectors that previously had little interaction but will require much more in a low carbon future, such as transportation and electricity; coordination of planning and policy across jurisdictions, both vertically from local to state to federal levels, and horizontally across neighbors and trading partners at the same level; mobilizing investment for a rapid low carbon transition, while ensuring that new investments in long-lived infrastructure are made with full awareness of what they imply for long-term carbon commitment; and investing in ongoing modeling, analysis, and data collection that informs both public and private decision-making. These topics are discussed in more detail in *Policy Implications of Deep Decarbonization in the United States* (Williams et al. 2015).

2020s

- **Begin electrification** – Electrification of buildings, transportation, and industry is necessary for affordable decarbonization. The initial focus should be on making new buildings all electric and building markets to electrify vehicles of all types. The transportation electrification goal is not near-term carbon emissions reductions but instead transformation of an industry to eliminate carbon emissions in the long term as the carbon intensity of electricity drops. Replacing air conditioners or furnaces with heat pumps in existing buildings is also a priority, pushing a technology that has improved markedly in recent years to further maturation. Steps towards electrification also involve removing systemic bias preventing electrotechnology adoption that are often good intentioned around energy efficiency goals but self-defeating in the long term. Examples include providing incentives on high-efficiency gas furnaces but no such incentives on heat-pumps or policies that discourage electric utility load growth of any type.
- **Switch from coal to gas in electricity system dispatch** – Dispatching gas in preference to coal is one of the most impactful and cost-effective ways to curtail carbon emissions in the near-term. Natural gas has approximately half the carbon intensity of coal but costs only slightly more on an energy basis at time of writing and is generally burned more efficiently than coal. Coal to gas switching in dispatch is distinct from retiring all coal, which will happen more gradually due to considerations on reliability and speed at which replacement generation can be built. Natural gas plants also are better complementary generation in the medium-term as renewable generation is deployed.
- **Build renewables and reinforce TX where possible** – Due to their abundance and based on current cost projections, wind and solar will form the backbone of a future low carbon energy system. Meeting 2050 goals requires a truly enormous quantity of renewable deployment, which must accelerate. Complementarity between wind and solar profiles means both get built wherever possible, but regional specialization will

occur depending on resource quality. Offshore wind should be emphasized in places, like the Northeast, where this resource holds promise as a vital part of the electricity system long-term. Transmission that connects renewable resources to loads takes time to permit and build and thus planning must start early for this critical infrastructure.

- **Allow gas build to replace retiring plants** – Even in a future electricity system with 80%+ energy coming from renewables, difficult long-duration (seasonal) electricity balancing challenges mean that dispatchable thermal capacity that can be dispatched during fallow periods of renewable production will be a part of a low-cost energy system. Our modeling shows that an optimized pathway to deep decarbonization shows little change to gas capacity relative to today over the next 30 years but eventual retirement of all other fossil electricity generation.
- **Start electricity market reforms to prepare for a changing load & resource mix** – Future electricity systems must accommodate rapid load growth from electrification, increasingly flexible demand, and increasingly inflexible supply resources. Fossil generation in the future without carbon capture will operate for far fewer hours than today making capacity markets more and more attractive. In those capacity markets the need to distinguish resources that can offer capacity over long durations will become important. Future energy markets must also compensate balancing services, with full symmetry between supply and demand side balancing**.**
- **Maintain nuclear** – Nuclear is an important source of low-cost carbon free electricity and when possible to do safely, the lowest cost path to decarbonization involves maintaining these resources. Retiring nuclear to 'make room' for renewable resources is ultimately self-defeating. Reducing climate change should be the priority when weighed against nuclear accidents given relative risk and consequence except where specific circumstances dictate otherwise (E.x. reactors in active seismic zones). This is not an assertion of the safety of generation III nuclear but rather a recognition of the urgency of the latest climate science.
- **Pilot new technologies that will be deployed at scale after 2030** – Among these are carbon capture of many varieties including direct air capture, carbon storage and utilization including creating drop-in replacement fuels through methanation, and generation IV nuclear technologies.
- **No new infrastructure to transport fossil fuels** – Consumption of every fossil fuel declines in a pathway to 350 ppm. Thus, new infrastructure to transport fossil fuels run a high risk of either becoming stranded or locking in a higher emission pathway. Some infrastructure built for a 20th century energy system is still useful in the 21st century such as natural gas storage and transmission pipelines and should be maintained.
- **Start building carbon capture on industrial facilities** – Carbon capture on industrial processes should be prioritized because many processes result in higher CO_2 concentrations than post-combustion capture on electricity generation and operate at

higher utilization factors, reducing cost, and because some industrial processes offer no ready alternatives making this type of carbon capture a necessary long-term strategy.

2030s

- **Large renewables push** – The 2030s is when the bulk of new renewable generation is built. Renewable curtailment is a necessary if sometimes transient balancing solution while transmission is expanded, market rules with high variable generation mature, and other balancing solutions get built.
- **Reach near 100% sales on key electric technologies** – All new vehicle sales must become electric or zero carbon compatible, for example fuel cells or biodiesel for heavy equipment. Similar transitions must occur in buildings for heating and cooking equipment. In industry electric or dual-fuel equipment should be installed for process heating and steam production which can be called upon based on electric system conditions (i.e. they can utilize overgeneration).
- **Start significant biofuel production in diesel & jet fuel** – Diesel and jet fuel are two of the largest residual fuels after high electrification. Bio-fuels used as drop-in replacements for fossil are a major strategy for reducing emissions. In the 2030s both are beginning to be produced in significant quantities, often with carbon capture on the biorefineries.
- **Large scale carbon capture on industrial facilities** – This completes the carbon capture on industry begun in the 2020s. By the late 2030s the marginal carbon abatement cost exceeds the capture cost for most industrial processes making this a cost-effective measure to pursue. The main challenge becomes geographic mismatch between where industry is located and where CO_2 is sequestered or used.
- **Electrical energy storage for capacity** – As fossil capacity retires, electric energy storage technologies are deployed at a modest scale for reliability and to assist with diurnal balancing between electricity supply and demand. The phrase 'modest' is used because energy storage technologies cannot cost effectively replace all types of other dispatchable generation without a major cost breakthrough in long duration storage. Just like in the 2020s, some new gas power plant capacity is needed. When the duration of need for dispatchable capacity is less than 8 hours, energy storage will most likely be the most cost-effective option, for anything longer than 8 hours, gas turbines are the cheapest option for the system.
- **Fossil power plants with 100% capture** – If competitive with renewables and nuclear, fossil power plants with pre-capture or oxy technologies should start to be deployed. It's possible that CCS technologies in electricity are unable to compete with a combination of renewables and energy storage, in which case most carbon capture stays focused on industry and refining.

- **Maintain nuclear** – As in the previous decade, continue to maintain nuclear where safe to do so.

2040s

- **Reach near 100% stock penetration on electric technologies** – The key building heating and transportation technologies that approached 100% new technology adoption in the 2030s have lifetimes of 10-15 years; and therefore, stock shares of these technologies should approach 100% in the 2040s based on natural replacement.
- **Deploy circular carbon economy** – In the 2040s synthetic fuel production & direct air capture (DAC) become important strategies to further reduce emissions and to balance a system with high renewables. The degree to which each are needed is dependent on many factors including: how much sustainable biomass can be produced, how much electrification is achieved, how cheap and efficient can DAC become, how much annual sequestration potential is there and at what cost, and how cheap are renewables and competing balancing strategies?
- **Maintain/grow renewables together with new flexible loads** – As synthetic fuel industrial loads grow it gives a new tool for balancing a grid composed of large amounts of variable generation. This, in turn, allows for further increases in renewables at low cost. Distributed fuel production also avoids the need for some new transmission.
- **Replace nuclear at the end of its lifetime** – As generation three nuclear retires, it should be replaced with fourth generation nuclear technologies if possible. By the 2040s renewables make up most of all electricity generation. Because of high marginal balancing costs when installing further wind and solar, dispatchable zero-carbon technologies such a nuclear are highly competitive.
- **Fully deploy biofuels including bio-energy with carbon capture** – Biofuel production and deployment reaches its limit in the 2040s. Biofuels find only marginal application in electricity because of higher value uses in transport and industry. Those industrial applications that can also deploy carbon capture allow opportunities of negative life-cycle emissions. Carbon capture on biofuel refining becomes an important technology.

Bibliography

Ashe, Mary, Dan Chwastyk, Caroline de Monasterio, Mahima Gupta, and Mika Pegors. 2012. “2010 U.S. Lighting Market Characterization.” U.S. Department of Energy; Office of Energy Efficiency and Renewable Energy; Building Technologies Program; Solid-State Lighting Program. https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf.

Boer, Eelco den, Sanne Aarnink, Florian Kleiner, and Johannes Pagenkopf. 2013. “Zero Emissions Trucks: An Overview of State-of-the-Art Technologies and Their Potential.” CE Delft. https://www.theicct.org/sites/default/files/publications/CE_Delft_4841_Zero_emissions_trucks_Def.pdf.

Brooker, Aaron, Jeffrey Gonder, Sean Lopp, and Jacob Ward. 2015. “ADOPT: A Historically Validated Light Duty Vehicle Consumer Choice Model.” In . https://doi.org/10.4271/2015-01-0974.

Capros, P., E. Dimopoulou, S. Evangelopoulou, T. Fotiou, M. Kannavou, P. Siskos, and G. Zazias. 2018. “Technology Pathways in Decarbonisation Scenarios.” Advanced System Studies for Energy Transition. https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf.

Congress of the U.S., Office of Technology Assessment. 1991. *Changing by Degrees: Steps to Reduce Greenhouse Gases*. Congress of the U.S., Office of Technology Assessment.

Dentz, Jordan, David Podorson, and Kapil Varshney. 2014. “Mini-Split Heat Pumps Multifamily Retrofit Feasibility Study.” U.S. Department of Energy; Office of Energy Efficiency and Renewable Energy. https://www.nrel.gov/docs/fy14osti/61620.pdf.

Eurek, Kelly, Wesley Cole, David Bielen, Nate Blair, Stuart Cohen, Bethany Frew, Jonathan Ho, et al. 2017. “Regional Energy Deployment System (ReEDS) Model Documentation: Version 2016.” NREL/TP-6A20-67067. Golden, Colorado: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/67067.pdf.

Fargione, Joseph E., Steven Bassett, Timothy Boucher, Scott D. Bridgham, Richard T. Conant, Susan C. Cook-Patton, Peter W. Ellis, et al. 2018. “Natural Climate Solutions for the United States.” *Science Advances* 4 (11): eaat1869. https://doi.org/10.1126/sciadv.aat1869.

Fulton, Lew, and Marshall Miller. 2015. “Strategies for Transitioning to Low-Emissions Trucks.” Davis, California: UC Davis Institute of Transportation Studies. https://steps.ucdavis.edu/files/06-11-2015-STEPS-NCST-Low-carbon-Trucks-in-US-06-10-2015.pdf.

G. del Alamo, J. Sandquist, B.J. Vreugdenhil, G. Aranda Almansa, and M. Carbo. 2015. “Implementation of Bio-CCS in Biofuels Production.” IEA Bioenergy Task 33 Special Project ISBN 978-1-910154-44-1. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2018/08/Implementation-of-bio-CCS-in-biofuels-production_final.pdf.

Griscom, Bronson W., Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, et al. 2017. “Natural Climate Solutions.” *Proceedings of the National Academy of Sciences* 114 (44): 11645–50. https://doi.org/10.1073/pnas.1710465114.

Hansen, James et al. 2008. "Target Atmospheric CO2: Where Should Humanity Aim?" *Open Atmos. Sci. J.* vol. 2, pp. 217-231 arXiv:0804.1126v3

Hansen, James, Pushker Kharecha, Makiko Sato, Valerie Masson-Delmotte, Frank Ackerman, David J. Beerling, Paul J. Hearty, et al. 2013. “Assessing ‘Dangerous Climate Change’: Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature.” *PLOS ONE* 8 (12): e81648. https://doi.org/10.1371/journal.pone.0081648.

Hansen, James, et al. "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 C global warming could be dangerous." *Atmospheric Chemistry and Physics*16.6 (2016): 3761-3812.

Hansen, James, Makiko Sato, Pushker Kharecha, Karina Von Schuckmann, David J. Beerling, Junji Cao, Shaun Marcott, Valerie Masson-Delmotte, Michael J. Prather, and Eelco J. Rohling. 2017. “Young People’s Burden: Requirement of Negative CO2 Emissions.” *Earth Syst. Dynam.,* ***8****, 577-616, doi:10.5194/esd-8-577-2017.*

Intergovernmental Panel on Climate Change. 2018. “Global Warming of 1.5C.” IPCC Special Report. United Nations. https://www.ipcc.ch/pdf/special-reports/sr15/sr15_draft.pdf.

International Energy Agency GHG Programme. 2017. “Techno - Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS.” International Energy Agency. https://ieaghg.org/exco_docs/2017-02.pdf.

Jadun, Paige, Colin McMillan, Matteo Muratori, Laura Vimmerstedt, and Trieu Mai. 2017. “Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050.” NREL/TP-6A20-70485. Golden, Colorado: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/70485.pdf.

Johnson, Timothy L., Joseph F. DeCarolis, Carol L. Shay, Daniel H. Loughlin, Cynthia L. Gage, and Samudra Vijay. 2006. “MARKAL Scenario Analyses of Technology Options for the Electric Sector: The Impact on Air Quality.” EPA/600/R-06/114. Washington D.C.: United States Environmental Protection Agency Office of Research and Development. https://nepis.epa.gov/Exe/ZyPDF.cgi/P10089YQ.PDF?Dockey=P10089YQ.PDF.

Keith, David W., Geoffrey Holmes, David St. Angelo, and Kenton Heidel. 2018. “A Process for Capturing CO2 from the Atmosphere.” *Joule* 2 (8): 1573–94. https://doi.org/10.1016/j.joule.2018.05.006.

Kuramochi, Takeshi, Andrea Ramírez, Wim Turkenburg, and André Faaij. 2012. “Comparative Assessment of CO2 Capture Technologies for Carbon-Intensive Industrial Processes.” *Progress in Energy and Combustion Science* 38 (1): 87–112. https://doi.org/10.1016/j.pecs.2011.05.001.

Langholtz, M. H., B. J. Stokes, and L. M. Eaton. 2016. “2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy.” DOE/EE-1440, ORNL/TM-2016/160, 1271651. https://doi.org/10.2172/1271651.

Lashof, Daniel, and Dennis A. Tirpak. 1990. “Policy Options for Stabilizing Global Climate.” U.S Environmental Protection Agency EPA--21P-2003.1. http://inis.iaea.org/Search/search.aspx?orig_q=RN:23016941.

Le Quéré, Corinne, Robbie M. Andrew, Pierre Friedlingstein, Stephen Sitch, Julia Pongratz, Andrew C. Manning, Jan Ivar Korsbakken, et al. 2018. “Global Carbon Budget 2017.” *Earth System Science Data* 10 (1): 405–48. https://doi.org/10.5194/essd-10-405-2018.

National Renewable Energy Laboratory. 2017. “Annual Technology Baseline.” 2017. https://atb.nrel.gov/electricity/2017/.

Navigant. 2014. “Updated Buildings Sector Appliance and Equipment Costs and Efficiencies.” U.S. Energy Information Administration. https://www.eia.gov/analysis/studies/buildings/equipcosts/archive/2015/pdf/full.pdf.

Risky Business Project. 2016. “From Risk To Return: Investing in a Clean Energy Economy.” https://riskybusiness.org/site/assets/uploads/sites/5/2016/10/RiskyBusiness_FromRiskToReturn.pdf.

Rogelj, J., G. Luderer, R. C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey, and K. Riahi. 2015. “Energy System Transformations for Limiting End-of-Century Warming to below 1.5 °C.” *Nature Climate Change* 5 (June): 519–27. https://doi.org/Rogelj J <http://pure.iiasa.ac.at/view/iiasa/254.html>, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V <http://pure.iiasa.ac.at/view/iiasa/166.html>, & Riahi K <http://pure.iiasa.ac.at/view/iiasa/250.html> (2015). Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nature Climate Change 5 (6): 519-527. DOI:10.1038/nclimate2572 <https://doi.org/10.1038/nclimate2572>.

State of California. 2018. “Exxecutive Order B-55-18 to Achieve Carbon Neutrality.” https://www.gov.ca.gov/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf.

TA Engineering Inc. 2012. “TRUCK5.1: Heavy Vehicle Market Penetration Model Documentation.” National Petroleum Council. https://www.npc.org/reports/HDV/TRUCK5.1_Model_Documentation-final.pdf.

U.S. Department of Energy: National Energy Technology Laboratory. 2017. “FE/NETL CO2 Saline Storage Cost Model.” U.S. Department of Energy: National Energy Technology Laboratory. https://edx.netl.doe.gov/dataset/fe-netl-co2-saline-storage-cost-model-2017/resource/154e5905-e84b-4f80-8e6e-89e0228f28c5.

U.S. Energy Information Administration. 2012. “Commercial Building Energy Consumption Survey.” Commercial Building Energy Consumption Survey. 2012. https://www.eia.gov/consumption/commercial/.

———. 2013. “Residential Energy Consumption Survey (RECS) 2009 Technical Documentation-Summary.” Washington D.C.: U.S. Energy Information Administration. https://www.eia.gov/consumption/residential/methodology/2009/pdf/techdoc-summary010413.pdf.

———. 2015. “Annual Energy Outlook 2015.” U.S. Energy Information Administration. https://www.eia.gov/outlooks/aeo/pdf/0383(2015).pdf.

———. 2017. “Annual Energy Outlook 2017.” U.S. Energy Information Administration. https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf.

———. 2018. “State Electricity Profiles.” https://www.eia.gov/electricity/state/.

U.S. Environmental Protection Agency. 2018. “Emissions & Generation Resource Integrated Database (EGRID).” February 5, 2018. https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid.

U.S. Global Change Research Program. 2017. “Fourth National Climate Assessment.” Climate Science Special Report. U.S. Global Change Research Program. https://science2017.globalchange.gov/.

Veron, J. E. N., et al. "The coral reef crisis: the critical importance of< 350 ppm CO2." *Marine pollution bulletin* 58.10 (2009): 1428-1436.

Williams, James H., Andrew DeBenedictis, Rebecca Ghanadan, Amber Mahone, Jack Moore, William R. Morrow, Snuller Price, and Margaret S. Torn. 2012. “The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity.” *Science* 335 (6064): 53–59. https://doi.org/10.1126/science.1208365.

Williams, James H., Benjamin Haley, Fritz Kahrl, Jack Moore, Andrew D. Jones, Margaret S. Torn, Haewon McJeon. 2014. Pathways to deep decarbonization in the United States. Energy and Environmental Economics, Inc. and the Deep Decarbonization Pathways Project. Revision with technical supplement, Nov 16, 2015. http://usddpp.org/usddpp-reports/

Williams, James H., Benjamin Haley, and Ryan Jones. 2015. Policy Implications of Deep Decarbonization in the United States. Energy and Environmental Economics, Inc. and the Deep Decarbonization Pathways Project. http://usddpp.org/usddpp-reports/

Technical Supplement

Figure 25 350 - Low Biomass Emissions Reductions Breakdown

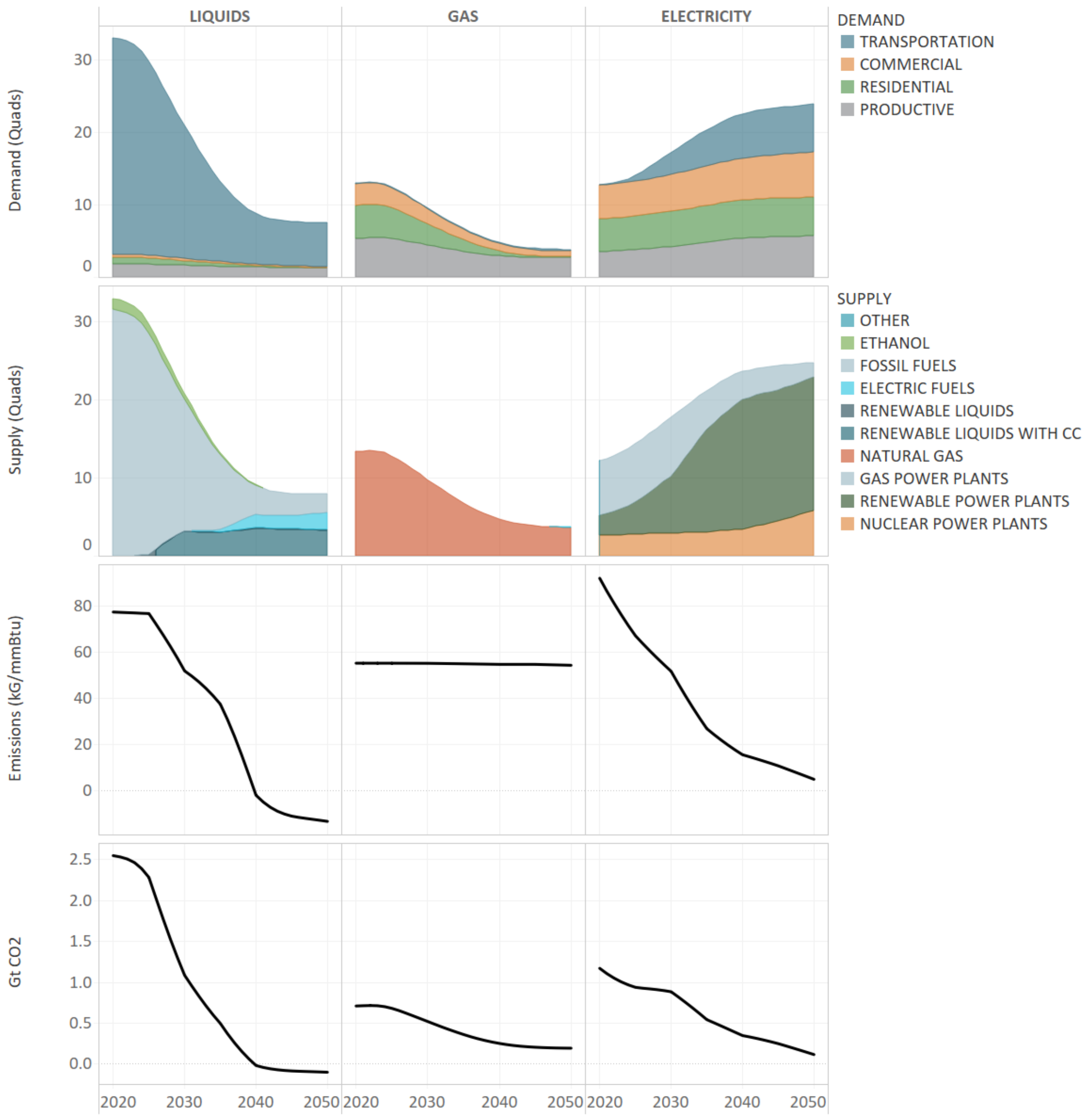


Figure 26 350 - Low Electrification Emissions Reductions Breakdown

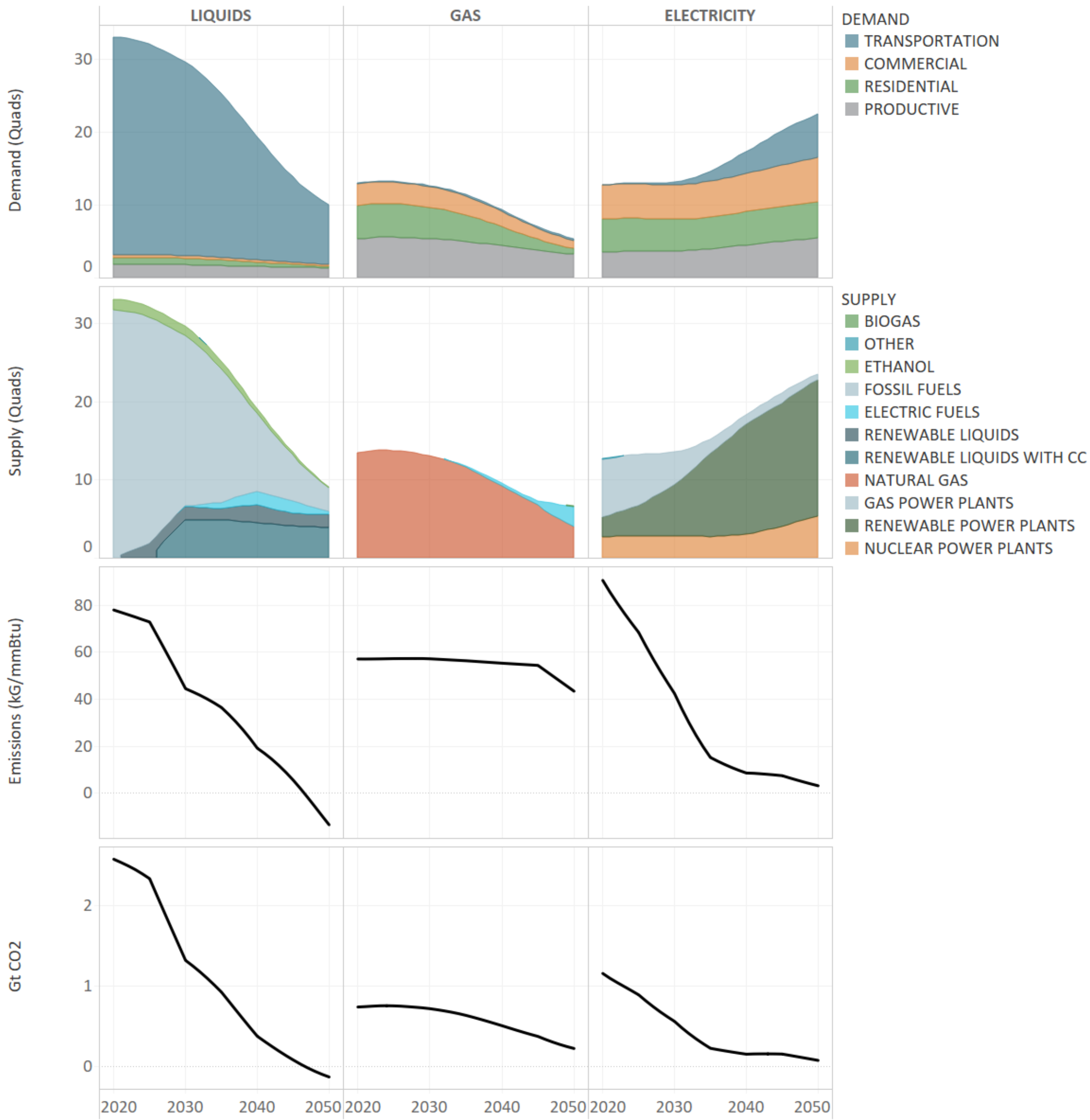


Figure 27 350 - Low Land NETS Emissions Reductions Breakdown

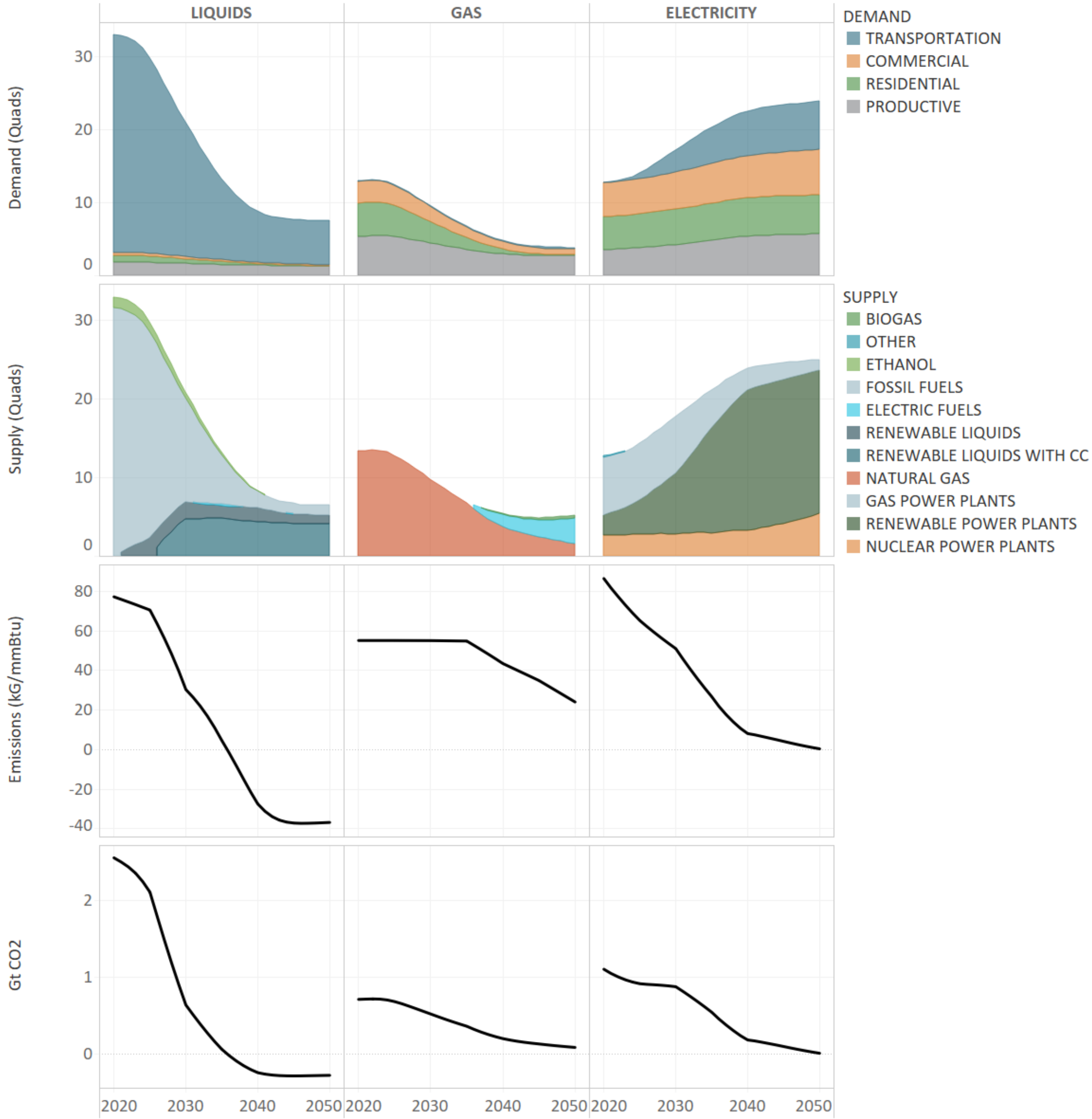


Figure 28 350 - No New Nuclear Emissions Reductions Breakdown

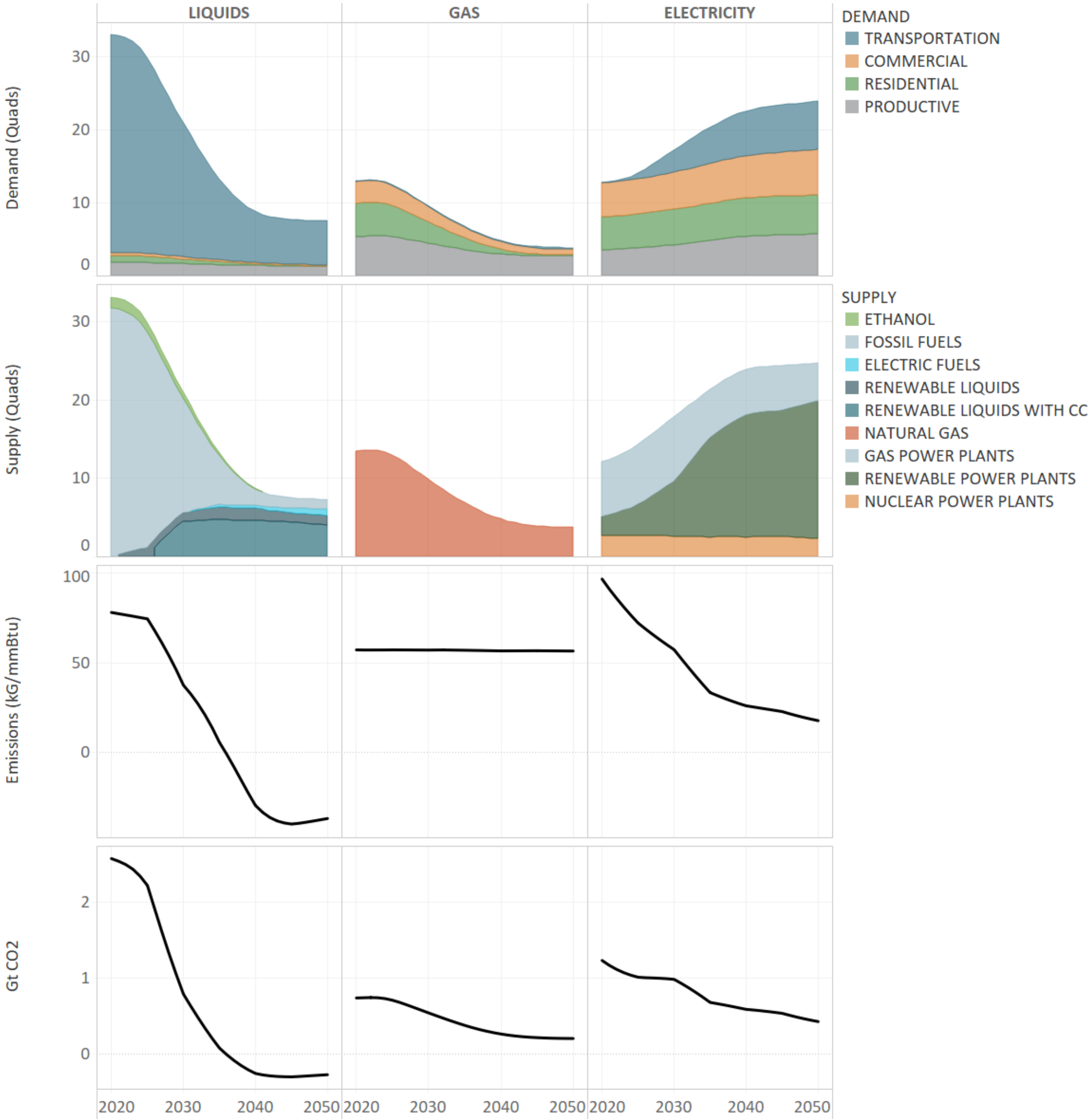


Figure 29 350 - No Tech NETS Emissions Reductions Breakdown

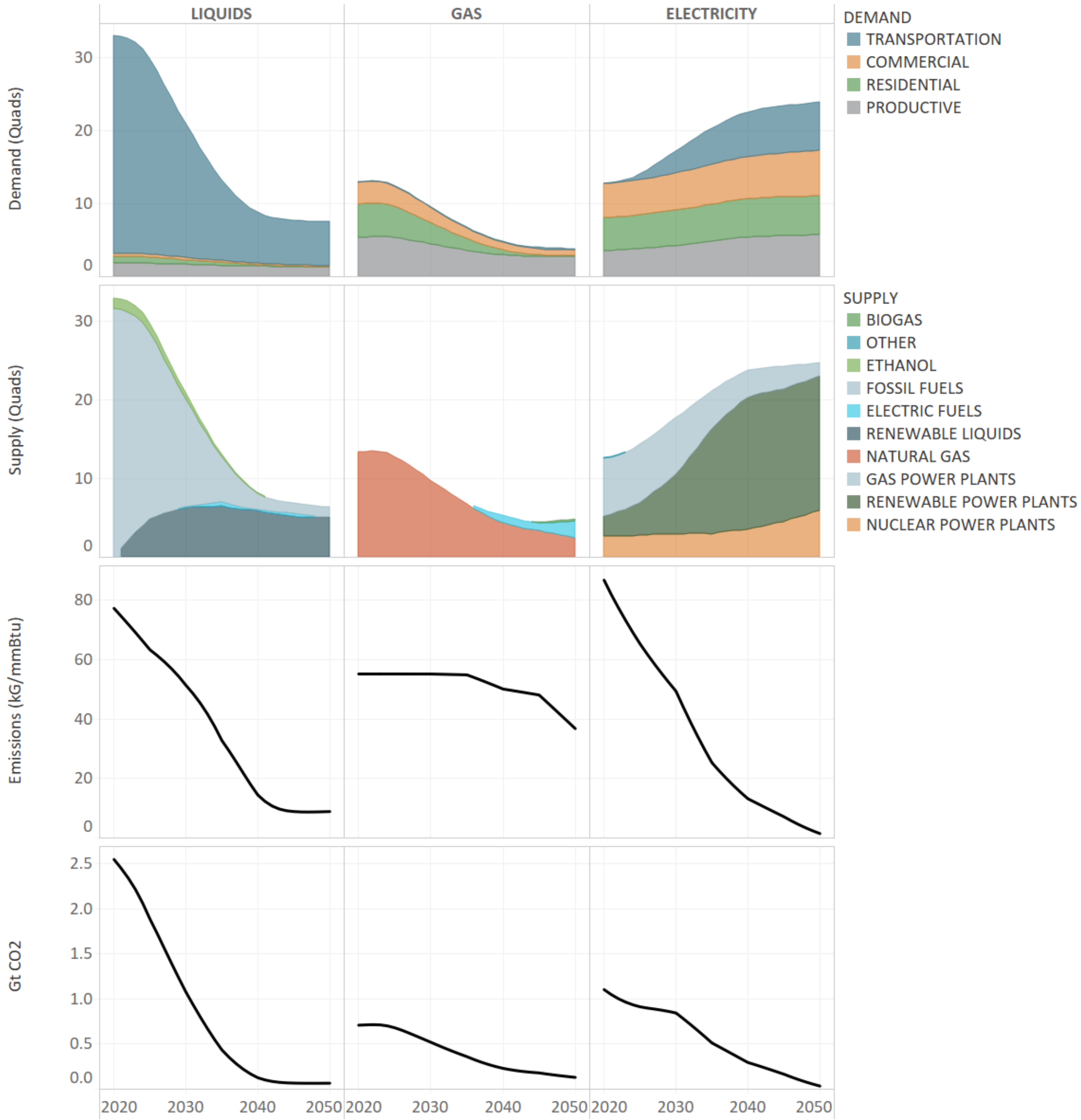


Figure 30 Net Costs by Sector

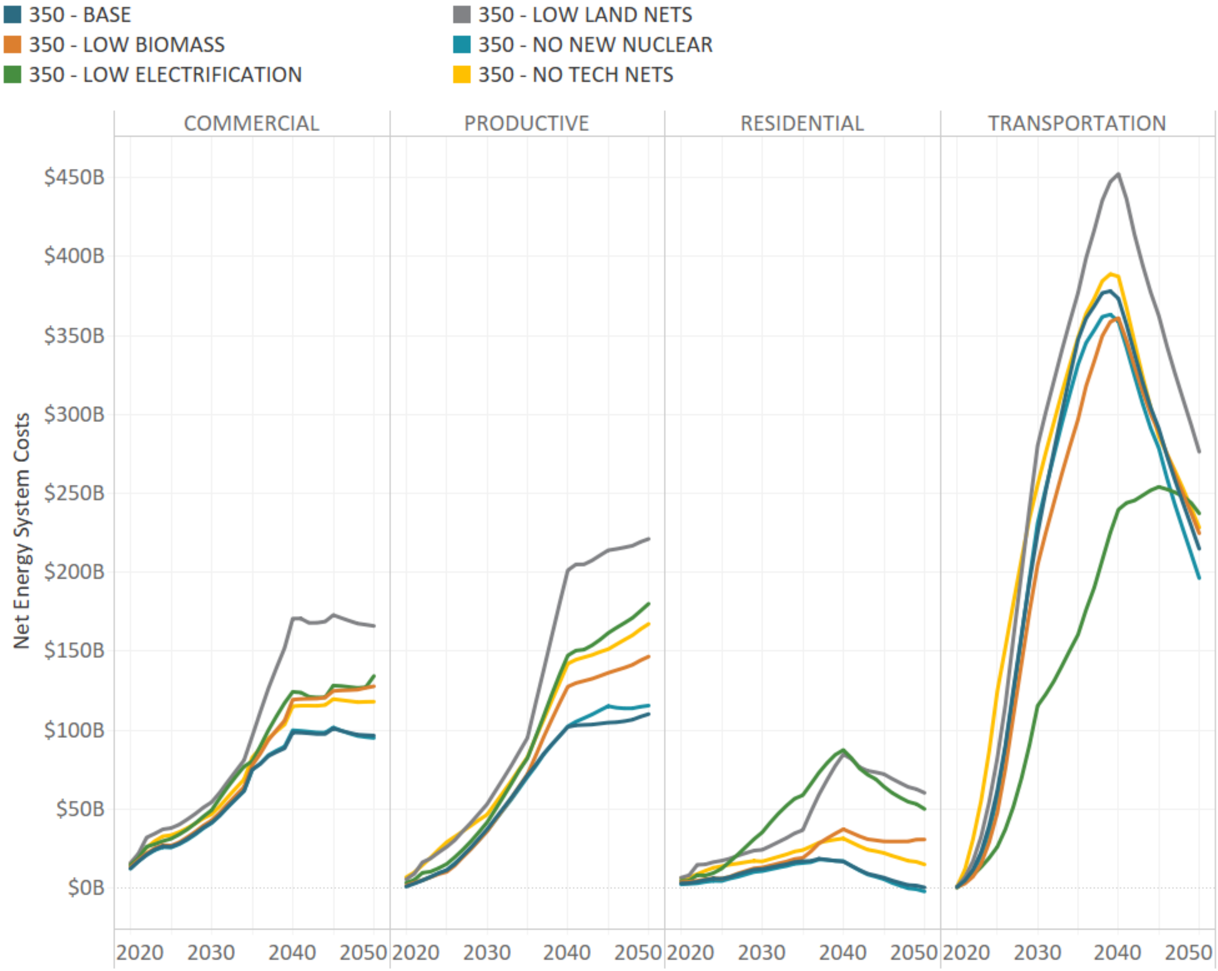
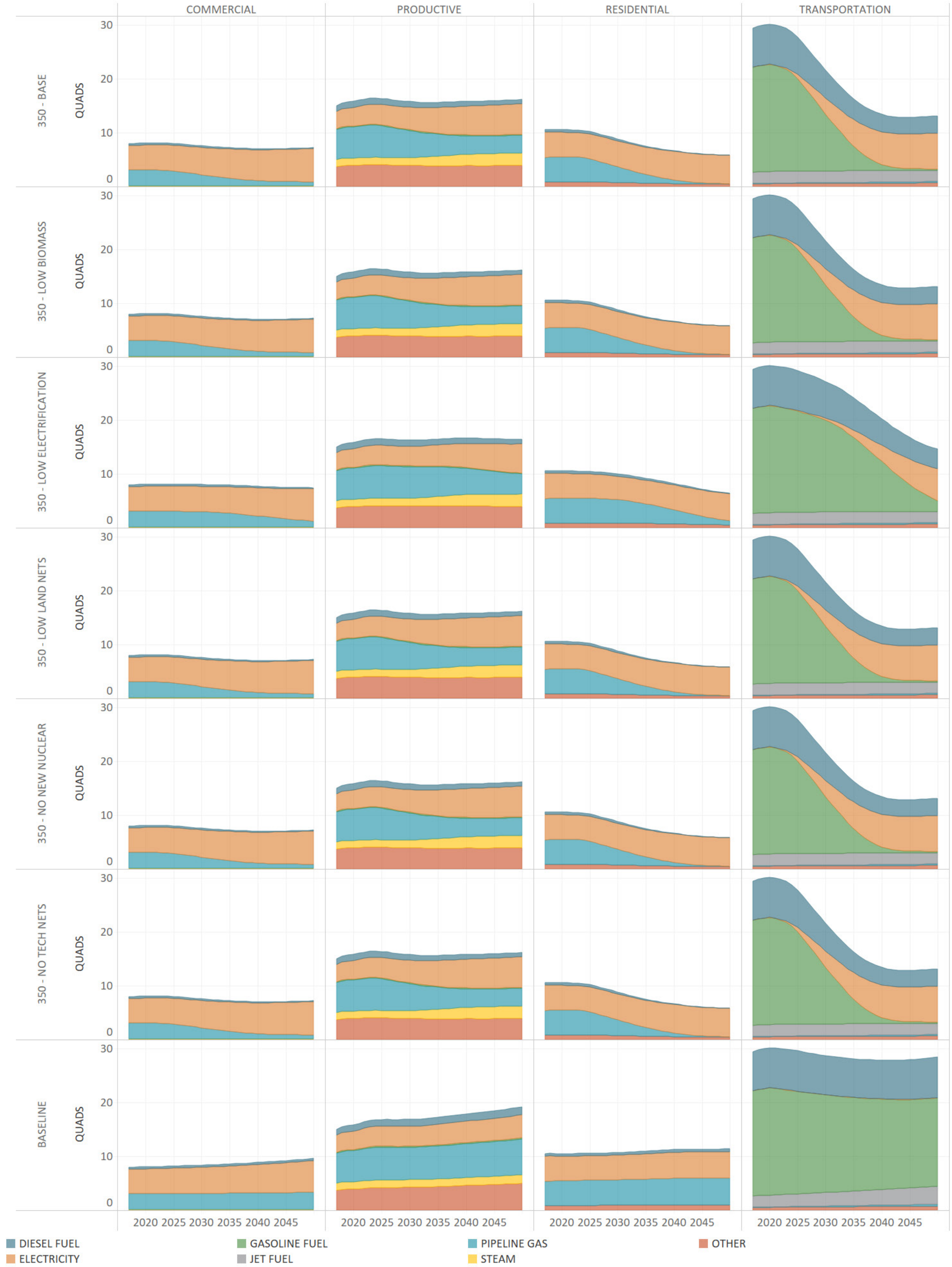


Figure 31 Four Pillars

Figure 32 Final Energy Demand



Appendix

1. Scenario Descriptions

EnergyPATHWAYS scenarios consist of combinations of energy demand scenarios as well as emissions targets and other constraints applied to the entire energy economy. In this framework, we have three energy demand scenarios – Baseline, Base 350, and Low Electrification 350 – that are used for our seven energy economy scenarios. These relationships are described in the below table.

Table 2 Energy demand and energy economy scenarios

Energy Demand Scenarios	Energy Economy Scenarios
Baseline	Baseline
Base 350	Base 350
Base 350	No New Nuclear
Base 350	Limited Biomass
Base 350	No Tech NETS
Base 350	Low Land NETS
Low Electrification 350	Low Electrification

1.1 Energy Demand Scenario Descriptions

1.1.1 Baseline

This represents an assumption of stasis in terms of technology adoption. For example, gas storage water heaters in the residential sector are replaced with newer gas storage water heaters. These new technology vintages have changing parameters of cost and efficiency but represent the same technology type and class (i.e. they use the same fuel and represent the same level of relative efficiency in the market).

1.1.2 Base 350

This scenario assumes rapid adoption of electrification technologies and high efficiency technologies where the end-use is already electric (i.e. refrigeration) or where complete electrification is infeasible. Adoption rates of these technologies accelerates through 2030, with the stock of these technologies lagging but making steady progress through 2050.

1.1.3 Low Electrification 350

This scenario assumes difficulty in inducing electrification of end-uses. Instead of adoption rates peaking by 2030, the adoption of these technologies is much slower, with peak adoption rates not being achieved until the 2050 timeframe. This slower rate of adoption leaves much more fuel combustion in intermediate years and also represents an incomplete electrification process by 2050, as much of the existing fuel combustion stock is still in service.

1.2 Demand-Side Mitigation Measures

1.2.1 Stock Rollover

The tables below show the stock shares (Table 3) and sales shares (Table 4) for three demand technology groups (Electrified Techs; HE Techs; Other Techs).[13] The demand-side consists of over 380 technologies across all subsectors or end-uses, but we aggregate here for presentation purposes to show broader trends in our input values. The stock shares shown are determined by stock rollover assumptions specified in the measure for each technology as well as the lifetimes of the infrastructure and the methodology described in section 4.2.1.2.

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[13] Electrified Techs == Technologies that use electricity for end-uses where other fuels are competitors (i.e. water heating but not lighting); HE Techs == High efficiency technologies; Other Techs == Technologies not categorized as Electrified Techs or HE Techs.

Table 3 Stock shares

Sector	Subsector	Scenario	Technology Group	2020	2030	2040	2050
COMMERCIAL	COMMERCIAL AIR CONDITIONING	BASE 350	HE TECHS	11%	47%	84%	93%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	BASE 350	OTHER TECHS	89%	53%	16%	7%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	BASELINE	HE TECHS	11%	9%	9%	10%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	BASELINE	OTHER TECHS	89%	91%	91%	90%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	LOW ELECTRIFICATION 350	HE TECHS	11%	40%	79%	92%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	LOW ELECTRIFICATION 350	OTHER TECHS	89%	60%	21%	8%
COMMERCIAL	COMMERCIAL COOKING	BASE 350	ELECTRIFIED TECHS	25%	57%	81%	81%
COMMERCIAL	COMMERCIAL COOKING	BASE 350	OTHER TECHS	75%	43%	19%	19%
COMMERCIAL	COMMERCIAL COOKING	BASELINE	ELECTRIFIED TECHS	25%	25%	25%	25%
COMMERCIAL	COMMERCIAL COOKING	BASELINE	OTHER TECHS	75%	75%	75%	75%
COMMERCIAL	COMMERCIAL COOKING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	25%	29%	55%	78%
COMMERCIAL	COMMERCIAL COOKING	LOW ELECTRIFICATION 350	OTHER TECHS	75%	71%	45%	22%
COMMERCIAL	COMMERCIAL LIGHTING	BASE 350	HE TECHS	39%	78%	81%	81%
COMMERCIAL	COMMERCIAL LIGHTING	BASE 350	OTHER TECHS	61%	22%	19%	19%
COMMERCIAL	COMMERCIAL LIGHTING	BASELINE	HE TECHS	43%	72%	75%	75%
COMMERCIAL	COMMERCIAL LIGHTING	BASELINE	OTHER TECHS	57%	28%	25%	25%
COMMERCIAL	COMMERCIAL LIGHTING	LOW ELECTRIFICATION 350	HE TECHS	39%	78%	81%	81%
COMMERCIAL	COMMERCIAL LIGHTING	LOW ELECTRIFICATION 350	OTHER TECHS	61%	22%	19%	19%
COMMERCIAL	COMMERCIAL REFRIGERATION	BASE 350	HE TECHS	10%	55%	96%	100%
COMMERCIAL	COMMERCIAL REFRIGERATION	BASE 350	OTHER TECHS	90%	45%	4%	0%
COMMERCIAL	COMMERCIAL REFRIGERATION	BASELINE	HE TECHS	10%	11%	14%	17%
COMMERCIAL	COMMERCIAL REFRIGERATION	BASELINE	OTHER TECHS	90%	89%	86%	83%
COMMERCIAL	COMMERCIAL REFRIGERATION	LOW ELECTRIFICATION 350	HE TECHS	10%	55%	96%	100%
COMMERCIAL	COMMERCIAL REFRIGERATION	LOW ELECTRIFICATION 350	OTHER TECHS	90%	45%	4%	0%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASE 350	ELECTRIFIED TECHS	13%	43%	86%	98%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASE 350	HE TECHS	1%	1%	1%	1%

COMMERCIAL	COMMERCIAL SPACE HEATING	BASE 350	OTHER TECHS	86%	56%	12%	1%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASELINE	ELECTRIFIED TECHS	13%	12%	12%	12%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASELINE	HE TECHS	1%	1%	1%	1%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASELINE	OTHER TECHS	86%	86%	87%	87%
COMMERCIAL	COMMERCIAL SPACE HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	13%	16%	44%	82%
COMMERCIAL	COMMERCIAL SPACE HEATING	LOW ELECTRIFICATION 350	HE TECHS	1%	1%	1%	1%
COMMERCIAL	COMMERCIAL SPACE HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	86%	83%	55%	17%
COMMERCIAL	COMMERCIAL VENTILATION	BASE 350	HE TECHS	11%	41%	80%	99%
COMMERCIAL	COMMERCIAL VENTILATION	BASE 350	OTHER TECHS	89%	59%	20%	1%
COMMERCIAL	COMMERCIAL VENTILATION	BASELINE	HE TECHS	11%	13%	11%	10%
COMMERCIAL	COMMERCIAL VENTILATION	BASELINE	OTHER TECHS	89%	87%	89%	90%
COMMERCIAL	COMMERCIAL VENTILATION	LOW ELECTRIFICATION 350	HE TECHS	11%	41%	80%	99%
COMMERCIAL	COMMERCIAL VENTILATION	LOW ELECTRIFICATION 350	OTHER TECHS	89%	59%	20%	1%
COMMERCIAL	COMMERCIAL WATER HEATING	BASE 350	ELECTRIFIED TECHS	5%	47%	96%	100%
COMMERCIAL	COMMERCIAL WATER HEATING	BASE 350	HE TECHS	31%	28%	2%	0%
COMMERCIAL	COMMERCIAL WATER HEATING	BASE 350	OTHER TECHS	64%	25%	2%	0%
COMMERCIAL	COMMERCIAL WATER HEATING	BASELINE	ELECTRIFIED TECHS	5%	3%	3%	2%
COMMERCIAL	COMMERCIAL WATER HEATING	BASELINE	HE TECHS	31%	51%	54%	55%
COMMERCIAL	COMMERCIAL WATER HEATING	BASELINE	OTHER TECHS	64%	45%	44%	43%
COMMERCIAL	COMMERCIAL WATER HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	5%	8%	45%	86%
COMMERCIAL	COMMERCIAL WATER HEATING	LOW ELECTRIFICATION 350	HE TECHS	31%	49%	29%	6%
COMMERCIAL	COMMERCIAL WATER HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	64%	43%	26%	8%
PRODUCTIVE	INDUSTRIAL BOILERS	BASE 350	ELECTRIFIED TECHS	0%	26%	70%	75%
PRODUCTIVE	INDUSTRIAL BOILERS	BASE 350	OTHER TECHS	100%	74%	30%	25%
PRODUCTIVE	INDUSTRIAL BOILERS	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL BOILERS	BASELINE	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL BOILERS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	3%	31%	65%
PRODUCTIVE	INDUSTRIAL BOILERS	LOW ELECTRIFICATION 350	OTHER TECHS	100%	97%	69%	35%

PRODUCTIVE	INDUSTRIAL CURING	BASE 350	ELECTRIFIED TECHS	0%	29%	70%	75%
PRODUCTIVE	INDUSTRIAL CURING	BASE 350	OTHER TECHS	100%	71%	30%	25%
PRODUCTIVE	INDUSTRIAL CURING	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL CURING	BASELINE	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL CURING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	3%	31%	65%
PRODUCTIVE	INDUSTRIAL CURING	LOW ELECTRIFICATION 350	OTHER TECHS	100%	97%	69%	35%
PRODUCTIVE	INDUSTRIAL DRYING	BASE 350	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL DRYING	BASE 350	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL DRYING	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL DRYING	BASELINE	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL DRYING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL DRYING	LOW ELECTRIFICATION 350	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	BASE 350	ELECTRIFIED TECHS	87%	88%	91%	92%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	BASE 350	OTHER TECHS	13%	12%	9%	8%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	BASELINE	ELECTRIFIED TECHS	87%	87%	88%	89%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	BASELINE	OTHER TECHS	13%	13%	12%	11%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	87%	87%	89%	91%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	LOW ELECTRIFICATION 350	OTHER TECHS	13%	13%	11%	9%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	BASE 350	ELECTRIFIED TECHS	21%	35%	57%	60%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	BASE 350	OTHER TECHS	79%	65%	43%	40%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	BASELINE	ELECTRIFIED TECHS	21%	21%	21%	22%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	BASELINE	OTHER TECHS	79%	79%	79%	78%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	21%	23%	38%	55%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	LOW ELECTRIFICATION 350	OTHER TECHS	79%	77%	62%	45%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	BASE 350	ELECTRIFIED TECHS	0%	32%	81%	90%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	BASE 350	OTHER TECHS	100%	68%	19%	10%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	BASELINE	OTHER TECHS	100%	100%	100%	100%

PRODUCTIVE	INDUSTRIAL SPACE HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	4%	37%	76%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	100%	96%	63%	24%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	BASE 350	HE TECHS	11%	50%	93%	100%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	BASE 350	OTHER TECHS	89%	50%	7%	0%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	BASELINE	HE TECHS	10%	11%	10%	11%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	BASELINE	OTHER TECHS	90%	89%	90%	89%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	LOW ELECTRIFICATION 350	HE TECHS	11%	46%	92%	100%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	LOW ELECTRIFICATION 350	OTHER TECHS	89%	54%	8%	0%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	BASE 350	HE TECHS	0%	16%	38%	55%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	BASE 350	OTHER TECHS	100%	84%	62%	45%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	LOW ELECTRIFICATION 350	HE TECHS	0%	16%	38%	55%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	LOW ELECTRIFICATION 350	OTHER TECHS	100%	84%	62%	45%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	BASE 350	ELECTRIFIED TECHS	80%	88%	99%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	BASE 350	OTHER TECHS	20%	12%	1%	0%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	BASELINE	ELECTRIFIED TECHS	80%	80%	80%	80%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	BASELINE	OTHER TECHS	20%	20%	20%	20%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	80%	81%	88%	97%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	LOW ELECTRIFICATION 350	OTHER TECHS	20%	19%	12%	3%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	BASE 350	HE TECHS	0%	41%	96%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	BASE 350	OTHER TECHS	100%	59%	4%	0%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	BASELINE	HE TECHS	0%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	LOW ELECTRIFICATION 350	HE TECHS	0%	41%	96%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	LOW ELECTRIFICATION 350	OTHER TECHS	100%	59%	4%	0%
RESIDENTIAL	RESIDENTIAL COOKING	BASE 350	ELECTRIFIED TECHS	61%	74%	94%	100%
RESIDENTIAL	RESIDENTIAL COOKING	BASE 350	OTHER TECHS	39%	26%	6%	0%
RESIDENTIAL	RESIDENTIAL COOKING	BASELINE	ELECTRIFIED TECHS	61%	61%	61%	62%

RESIDENTIAL	RESIDENTIAL COOKING	BASELINE	OTHER TECHS	39%	39%	39%	38%
RESIDENTIAL	RESIDENTIAL COOKING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	61%	63%	75%	92%
RESIDENTIAL	RESIDENTIAL COOKING	LOW ELECTRIFICATION 350	OTHER TECHS	39%	37%	25%	8%
RESIDENTIAL	RESIDENTIAL DISHWASHING	BASE 350	HE TECHS	0%	41%	96%	100%
RESIDENTIAL	RESIDENTIAL DISHWASHING	BASE 350	OTHER TECHS	100%	59%	4%	0%
RESIDENTIAL	RESIDENTIAL DISHWASHING	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL DISHWASHING	LOW ELECTRIFICATION 350	HE TECHS	0%	41%	96%	100%
RESIDENTIAL	RESIDENTIAL DISHWASHING	LOW ELECTRIFICATION 350	OTHER TECHS	100%	59%	4%	0%
RESIDENTIAL	RESIDENTIAL FREEZING	BASE 350	HE TECHS	0%	30%	73%	98%
RESIDENTIAL	RESIDENTIAL FREEZING	BASE 350	OTHER TECHS	100%	70%	27%	2%
RESIDENTIAL	RESIDENTIAL FREEZING	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL FREEZING	LOW ELECTRIFICATION 350	HE TECHS	0%	30%	73%	98%
RESIDENTIAL	RESIDENTIAL FREEZING	LOW ELECTRIFICATION 350	OTHER TECHS	100%	70%	27%	2%
RESIDENTIAL	RESIDENTIAL LIGHTING	BASE 350	HE TECHS	4%	31%	77%	94%
RESIDENTIAL	RESIDENTIAL LIGHTING	BASE 350	OTHER TECHS	96%	69%	23%	6%
RESIDENTIAL	RESIDENTIAL LIGHTING	BASELINE	HE TECHS	4%	3%	3%	2%
RESIDENTIAL	RESIDENTIAL LIGHTING	BASELINE	OTHER TECHS	96%	97%	97%	98%
RESIDENTIAL	RESIDENTIAL LIGHTING	LOW ELECTRIFICATION 350	HE TECHS	4%	31%	77%	94%
RESIDENTIAL	RESIDENTIAL LIGHTING	LOW ELECTRIFICATION 350	OTHER TECHS	96%	69%	23%	6%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	BASE 350	HE TECHS	0%	37%	86%	100%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	BASE 350	OTHER TECHS	100%	63%	14%	0%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	BASELINE	HE TECHS	0%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	LOW ELECTRIFICATION 350	HE TECHS	0%	37%	86%	100%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	LOW ELECTRIFICATION 350	OTHER TECHS	100%	63%	14%	0%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	BASE 350	ELECTRIFIED TECHS	36%	57%	86%	97%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	BASE 350	OTHER TECHS	64%	43%	14%	3%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	BASELINE	ELECTRIFIED TECHS	36%	36%	37%	37%

RESIDENTIAL	RESIDENTIAL SPACE HEATING	BASELINE	OTHER TECHS	64%	64%	63%	63%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	36%	39%	58%	84%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	64%	61%	42%	16%
RESIDENTIAL	RESIDENTIAL WATER HEATING	BASE 350	ELECTRIFIED TECHS	44%	77%	98%	99%
RESIDENTIAL	RESIDENTIAL WATER HEATING	BASE 350	OTHER TECHS	56%	23%	2%	1%
RESIDENTIAL	RESIDENTIAL WATER HEATING	BASELINE	ELECTRIFIED TECHS	44%	44%	44%	44%
RESIDENTIAL	RESIDENTIAL WATER HEATING	BASELINE	OTHER TECHS	56%	56%	56%	56%
RESIDENTIAL	RESIDENTIAL WATER HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	44%	48%	75%	96%
RESIDENTIAL	RESIDENTIAL WATER HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	56%	52%	25%	4%
TRANSPORTATION	HEAVY DUTY TRUCKS	BASE 350	ELECTRIFIED TECHS	0%	20%	47%	50%
TRANSPORTATION	HEAVY DUTY TRUCKS	BASE 350	HE TECHS	0%	20%	47%	50%
TRANSPORTATION	HEAVY DUTY TRUCKS	BASE 350	OTHER TECHS	100%	60%	6%	0%
TRANSPORTATION	HEAVY DUTY TRUCKS	BASELINE	OTHER TECHS	100%	100%	100%	100%
TRANSPORTATION	HEAVY DUTY TRUCKS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	2%	21%	44%
TRANSPORTATION	HEAVY DUTY TRUCKS	LOW ELECTRIFICATION 350	HE TECHS	0%	2%	21%	44%
TRANSPORTATION	HEAVY DUTY TRUCKS	LOW ELECTRIFICATION 350	OTHER TECHS	100%	95%	58%	13%
TRANSPORTATION	LIGHT DUTY AUTOS	BASE 350	ELECTRIFIED TECHS	1%	44%	94%	100%
TRANSPORTATION	LIGHT DUTY AUTOS	BASE 350	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY AUTOS	BASE 350	OTHER TECHS	99%	56%	6%	0%
TRANSPORTATION	LIGHT DUTY AUTOS	BASELINE	ELECTRIFIED TECHS	1%	1%	2%	3%
TRANSPORTATION	LIGHT DUTY AUTOS	BASELINE	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY AUTOS	BASELINE	OTHER TECHS	99%	99%	97%	97%
TRANSPORTATION	LIGHT DUTY AUTOS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	1%	6%	44%	89%
TRANSPORTATION	LIGHT DUTY AUTOS	LOW ELECTRIFICATION 350	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY AUTOS	LOW ELECTRIFICATION 350	OTHER TECHS	99%	93%	55%	11%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASE 350	ELECTRIFIED TECHS	0%	39%	95%	100%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASE 350	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASE 350	OTHER TECHS	99%	60%	5%	0%

TRANSPORTATION	LIGHT DUTY TRUCKS	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASELINE	HE TECHS	0%	1%	1%	1%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASELINE	OTHER TECHS	100%	99%	99%	99%
TRANSPORTATION	LIGHT DUTY TRUCKS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	5%	44%	88%
TRANSPORTATION	LIGHT DUTY TRUCKS	LOW ELECTRIFICATION 350	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY TRUCKS	LOW ELECTRIFICATION 350	OTHER TECHS	99%	94%	56%	12%
TRANSPORTATION	MEDIUM DUTY TRUCKS	BASE 350	ELECTRIFIED TECHS	0%	24%	63%	75%
TRANSPORTATION	MEDIUM DUTY TRUCKS	BASE 350	HE TECHS	0%	8%	21%	25%
TRANSPORTATION	MEDIUM DUTY TRUCKS	BASE 350	OTHER TECHS	100%	68%	16%	0%
TRANSPORTATION	MEDIUM DUTY TRUCKS	BASELINE	OTHER TECHS	100%	100%	100%	100%
TRANSPORTATION	MEDIUM DUTY TRUCKS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	3%	28%	61%
TRANSPORTATION	MEDIUM DUTY TRUCKS	LOW ELECTRIFICATION 350	HE TECHS	0%	1%	9%	20%
TRANSPORTATION	MEDIUM DUTY TRUCKS	LOW ELECTRIFICATION 350	OTHER TECHS	100%	96%	62%	19%
TRANSPORTATION	TRANSIT BUSES	BASE 350	ELECTRIFIED TECHS	0%	58%	100%	100%
TRANSPORTATION	TRANSIT BUSES	BASE 350	HE TECHS	17%	7%	0%	0%
TRANSPORTATION	TRANSIT BUSES	BASE 350	OTHER TECHS	82%	35%	0%	0%
TRANSPORTATION	TRANSIT BUSES	BASELINE	HE TECHS	17%	17%	17%	17%
TRANSPORTATION	TRANSIT BUSES	BASELINE	OTHER TECHS	83%	83%	83%	83%
TRANSPORTATION	TRANSIT BUSES	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	7%	55%	95%
TRANSPORTATION	TRANSIT BUSES	LOW ELECTRIFICATION 350	HE TECHS	17%	16%	8%	1%
TRANSPORTATION	TRANSIT BUSES	LOW ELECTRIFICATION 350	OTHER TECHS	83%	77%	37%	4%

Table 4 Sales shares

Sector	**Subsector**	**Scenario**	**Technology Group**	**2020**	**2030**	**2040**	**2050**
COMMERCIAL	COMMERCIAL AIR CONDITIONING	BASE 350	HE TECHS	10%	96%	95%	94%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	BASE 350	OTHER TECHS	90%	4%	5%	6%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	BASELINE	HE TECHS	7%	9%	11%	13%

COMMERCIAL	COMMERCIAL AIR CONDITIONING	BASELINE	OTHER TECHS	93%	91%	89%	87%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	LOW ELECTRIFICATION 350	HE TECHS	9%	94%	95%	94%
COMMERCIAL	COMMERCIAL AIR CONDITIONING	LOW ELECTRIFICATION 350	OTHER TECHS	91%	6%	5%	6%
COMMERCIAL	COMMERCIAL COOKING	BASE 350	ELECTRIFIED TECHS	26%	81%	81%	81%
COMMERCIAL	COMMERCIAL COOKING	BASE 350	OTHER TECHS	74%	19%	19%	19%
COMMERCIAL	COMMERCIAL COOKING	BASELINE	ELECTRIFIED TECHS	25%	25%	25%	25%
COMMERCIAL	COMMERCIAL COOKING	BASELINE	OTHER TECHS	75%	75%	75%	75%
COMMERCIAL	COMMERCIAL COOKING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	25%	36%	73%	81%
COMMERCIAL	COMMERCIAL COOKING	LOW ELECTRIFICATION 350	OTHER TECHS	75%	64%	27%	19%
COMMERCIAL	COMMERCIAL LIGHTING	BASE 350	HE TECHS	26%	82%	83%	83%
COMMERCIAL	COMMERCIAL LIGHTING	BASE 350	OTHER TECHS	74%	18%	17%	17%
COMMERCIAL	COMMERCIAL LIGHTING	BASELINE	HE TECHS	38%	70%	72%	72%
COMMERCIAL	COMMERCIAL LIGHTING	BASELINE	OTHER TECHS	62%	30%	28%	28%
COMMERCIAL	COMMERCIAL LIGHTING	LOW ELECTRIFICATION 350	HE TECHS	26%	82%	83%	83%
COMMERCIAL	COMMERCIAL LIGHTING	LOW ELECTRIFICATION 350	OTHER TECHS	74%	18%	17%	17%
COMMERCIAL	COMMERCIAL REFRIGERATION	BASE 350	HE TECHS	12%	99%	100%	100%
COMMERCIAL	COMMERCIAL REFRIGERATION	BASE 350	OTHER TECHS	88%	1%	0%	0%
COMMERCIAL	COMMERCIAL REFRIGERATION	BASELINE	HE TECHS	10%	12%	15%	17%
COMMERCIAL	COMMERCIAL REFRIGERATION	BASELINE	OTHER TECHS	90%	88%	85%	83%
COMMERCIAL	COMMERCIAL REFRIGERATION	LOW ELECTRIFICATION 350	HE TECHS	12%	99%	100%	100%
COMMERCIAL	COMMERCIAL REFRIGERATION	LOW ELECTRIFICATION 350	OTHER TECHS	88%	1%	0%	0%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASE 350	ELECTRIFIED TECHS	13%	98%	99%	99%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASE 350	HE TECHS	1%	1%	1%	1%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASE 350	OTHER TECHS	86%	1%	0%	0%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASELINE	ELECTRIFIED TECHS	12%	12%	12%	12%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASELINE	HE TECHS	1%	1%	1%	1%
COMMERCIAL	COMMERCIAL SPACE HEATING	BASELINE	OTHER TECHS	87%	87%	87%	87%
COMMERCIAL	COMMERCIAL SPACE HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	13%	28%	86%	98%

COMMERCIAL	COMMERCIAL SPACE HEATING	LOW ELECTRIFICATION 350	HE TECHS	1%	1%	1%	1%
COMMERCIAL	COMMERCIAL SPACE HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	86%	71%	13%	1%
COMMERCIAL	COMMERCIAL VENTILATION	BASE 350	HE TECHS	11%	99%	100%	100%
COMMERCIAL	COMMERCIAL VENTILATION	BASE 350	OTHER TECHS	89%	1%	0%	0%
COMMERCIAL	COMMERCIAL VENTILATION	BASELINE	HE TECHS	10%	10%	10%	10%
COMMERCIAL	COMMERCIAL VENTILATION	BASELINE	OTHER TECHS	90%	90%	90%	90%
COMMERCIAL	COMMERCIAL VENTILATION	LOW ELECTRIFICATION 350	HE TECHS	11%	99%	100%	100%
COMMERCIAL	COMMERCIAL VENTILATION	LOW ELECTRIFICATION 350	OTHER TECHS	89%	1%	0%	0%
COMMERCIAL	COMMERCIAL WATER HEATING	BASE 350	ELECTRIFIED TECHS	7%	99%	100%	100%
COMMERCIAL	COMMERCIAL WATER HEATING	BASE 350	HE TECHS	49%	0%	0%	0%
COMMERCIAL	COMMERCIAL WATER HEATING	BASE 350	OTHER TECHS	43%	0%	0%	0%
COMMERCIAL	COMMERCIAL WATER HEATING	BASELINE	ELECTRIFIED TECHS	6%	5%	4%	4%
COMMERCIAL	COMMERCIAL WATER HEATING	BASELINE	HE TECHS	50%	52%	53%	55%
COMMERCIAL	COMMERCIAL WATER HEATING	BASELINE	OTHER TECHS	44%	43%	42%	41%
COMMERCIAL	COMMERCIAL WATER HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	7%	22%	83%	96%
COMMERCIAL	COMMERCIAL WATER HEATING	LOW ELECTRIFICATION 350	HE TECHS	50%	42%	8%	0%
COMMERCIAL	COMMERCIAL WATER HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	44%	36%	9%	4%
PRODUCTIVE	INDUSTRIAL BOILERS	BASE 350	ELECTRIFIED TECHS	1%	74%	75%	75%
PRODUCTIVE	INDUSTRIAL BOILERS	BASE 350	OTHER TECHS	99%	26%	25%	25%
PRODUCTIVE	INDUSTRIAL BOILERS	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL BOILERS	BASELINE	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL BOILERS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	1%	14%	64%	74%
PRODUCTIVE	INDUSTRIAL BOILERS	LOW ELECTRIFICATION 350	OTHER TECHS	99%	86%	36%	26%
PRODUCTIVE	INDUSTRIAL CURING	BASE 350	ELECTRIFIED TECHS	1%	74%	75%	75%
PRODUCTIVE	INDUSTRIAL CURING	BASE 350	OTHER TECHS	99%	26%	25%	25%
PRODUCTIVE	INDUSTRIAL CURING	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL CURING	BASELINE	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL CURING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	1%	14%	64%	74%

PRODUCTIVE	INDUSTRIAL CURING	LOW ELECTRIFICATION 350	OTHER TECHS	99%	86%	36%	26%
PRODUCTIVE	INDUSTRIAL DRYING	BASE 350	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL DRYING	BASE 350	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL DRYING	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL DRYING	BASELINE	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL DRYING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL DRYING	LOW ELECTRIFICATION 350	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	BASE 350	ELECTRIFIED TECHS	88%	91%	92%	92%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	BASE 350	OTHER TECHS	12%	9%	8%	8%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	BASELINE	ELECTRIFIED TECHS	88%	87%	89%	89%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	BASELINE	OTHER TECHS	12%	13%	11%	11%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	88%	88%	91%	91%
PRODUCTIVE	INDUSTRIAL MACHINE DRIVES	LOW ELECTRIFICATION 350	OTHER TECHS	12%	12%	9%	9%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	BASE 350	ELECTRIFIED TECHS	23%	60%	60%	61%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	BASE 350	OTHER TECHS	77%	40%	40%	39%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	BASELINE	ELECTRIFIED TECHS	23%	20%	22%	22%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	BASELINE	OTHER TECHS	77%	80%	78%	78%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	23%	29%	55%	60%
PRODUCTIVE	INDUSTRIAL PROCESS HEAT	LOW ELECTRIFICATION 350	OTHER TECHS	77%	71%	45%	40%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	BASE 350	ELECTRIFIED TECHS	1%	89%	90%	90%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	BASE 350	OTHER TECHS	99%	11%	10%	10%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	BASELINE	OTHER TECHS	100%	100%	100%	100%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	1%	17%	77%	89%
PRODUCTIVE	INDUSTRIAL SPACE HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	99%	83%	23%	11%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	BASE 350	HE TECHS	13%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	BASE 350	OTHER TECHS	87%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	BASELINE	HE TECHS	10%	11%	10%	11%

RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	BASELINE	OTHER TECHS	90%	89%	90%	89%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	LOW ELECTRIFICATION 350	HE TECHS	12%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL AIR CONDITIONING	LOW ELECTRIFICATION 350	OTHER TECHS	88%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	BASE 350	HE TECHS	9%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	BASE 350	OTHER TECHS	91%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	LOW ELECTRIFICATION 350	HE TECHS	9%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL BUILDING SHELL	LOW ELECTRIFICATION 350	OTHER TECHS	91%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	BASE 350	ELECTRIFIED TECHS	81%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	BASE 350	OTHER TECHS	19%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	BASELINE	ELECTRIFIED TECHS	80%	80%	80%	81%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	BASELINE	OTHER TECHS	20%	20%	20%	19%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	80%	84%	97%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES DRYING	LOW ELECTRIFICATION 350	OTHER TECHS	20%	16%	3%	0%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	BASE 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	BASE 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	BASELINE	HE TECHS	0%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	LOW ELECTRIFICATION 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL CLOTHES WASHING	LOW ELECTRIFICATION 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL COOKING	BASE 350	ELECTRIFIED TECHS	62%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL COOKING	BASE 350	OTHER TECHS	38%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL COOKING	BASELINE	ELECTRIFIED TECHS	61%	61%	61%	62%
RESIDENTIAL	RESIDENTIAL COOKING	BASELINE	OTHER TECHS	39%	39%	39%	38%
RESIDENTIAL	RESIDENTIAL COOKING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	62%	69%	94%	100%
RESIDENTIAL	RESIDENTIAL COOKING	LOW ELECTRIFICATION 350	OTHER TECHS	38%	31%	6%	0%
RESIDENTIAL	RESIDENTIAL DISHWASHING	BASE 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL DISHWASHING	BASE 350	OTHER TECHS	98%	1%	0%	0%

RESIDENTIAL	RESIDENTIAL DISHWASHING	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL DISHWASHING	LOW ELECTRIFICATION 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL DISHWASHING	LOW ELECTRIFICATION 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL FREEZING	BASE 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL FREEZING	BASE 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL FREEZING	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL FREEZING	LOW ELECTRIFICATION 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL FREEZING	LOW ELECTRIFICATION 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL LIGHTING	BASE 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL LIGHTING	BASE 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL LIGHTING	BASELINE	HE TECHS	0%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL LIGHTING	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL LIGHTING	LOW ELECTRIFICATION 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL LIGHTING	LOW ELECTRIFICATION 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	BASE 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	BASE 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	BASELINE	HE TECHS	0%	0%	0%	0%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	BASELINE	OTHER TECHS	100%	100%	100%	100%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	LOW ELECTRIFICATION 350	HE TECHS	2%	99%	100%	100%
RESIDENTIAL	RESIDENTIAL REFRIGERATION	LOW ELECTRIFICATION 350	OTHER TECHS	98%	1%	0%	0%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	BASE 350	ELECTRIFIED TECHS	36%	97%	98%	98%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	BASE 350	OTHER TECHS	64%	3%	2%	2%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	BASELINE	ELECTRIFIED TECHS	35%	35%	36%	36%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	BASELINE	OTHER TECHS	65%	65%	64%	64%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	36%	47%	89%	98%
RESIDENTIAL	RESIDENTIAL SPACE HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	64%	53%	11%	2%
RESIDENTIAL	RESIDENTIAL WATER HEATING	BASE 350	ELECTRIFIED TECHS	37%	99%	99%	99%
RESIDENTIAL	RESIDENTIAL WATER HEATING	BASE 350	OTHER TECHS	63%	1%	1%	1%

RESIDENTIAL	RESIDENTIAL WATER HEATING	BASELINE	ELECTRIFIED TECHS	36%	36%	36%	36%
RESIDENTIAL	RESIDENTIAL WATER HEATING	BASELINE	OTHER TECHS	64%	64%	64%	64%
RESIDENTIAL	RESIDENTIAL WATER HEATING	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	36%	48%	90%	99%
RESIDENTIAL	RESIDENTIAL WATER HEATING	LOW ELECTRIFICATION 350	OTHER TECHS	64%	52%	10%	1%
TRANSPORTATION	HEAVY DUTY TRUCKS	BASE 350	ELECTRIFIED TECHS	1%	50%	50%	50%
TRANSPORTATION	HEAVY DUTY TRUCKS	BASE 350	HE TECHS	1%	50%	50%	50%
TRANSPORTATION	HEAVY DUTY TRUCKS	BASE 350	OTHER TECHS	98%	1%	0%	0%
TRANSPORTATION	HEAVY DUTY TRUCKS	BASELINE	OTHER TECHS	100%	100%	100%	100%
TRANSPORTATION	HEAVY DUTY TRUCKS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	0%	9%	43%	50%
TRANSPORTATION	HEAVY DUTY TRUCKS	LOW ELECTRIFICATION 350	HE TECHS	0%	9%	43%	50%
TRANSPORTATION	HEAVY DUTY TRUCKS	LOW ELECTRIFICATION 350	OTHER TECHS	99%	81%	15%	1%
TRANSPORTATION	LIGHT DUTY AUTOS	BASE 350	ELECTRIFIED TECHS	3%	99%	100%	100%
TRANSPORTATION	LIGHT DUTY AUTOS	BASE 350	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY AUTOS	BASE 350	OTHER TECHS	97%	1%	0%	0%
TRANSPORTATION	LIGHT DUTY AUTOS	BASELINE	ELECTRIFIED TECHS	1%	2%	3%	3%
TRANSPORTATION	LIGHT DUTY AUTOS	BASELINE	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY AUTOS	BASELINE	OTHER TECHS	99%	97%	97%	97%
TRANSPORTATION	LIGHT DUTY AUTOS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	2%	22%	87%	99%
TRANSPORTATION	LIGHT DUTY AUTOS	LOW ELECTRIFICATION 350	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY AUTOS	LOW ELECTRIFICATION 350	OTHER TECHS	98%	78%	13%	1%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASE 350	ELECTRIFIED TECHS	2%	99%	100%	100%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASE 350	HE TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASE 350	OTHER TECHS	98%	1%	0%	0%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASELINE	ELECTRIFIED TECHS	0%	0%	0%	0%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASELINE	HE TECHS	0%	1%	1%	1%
TRANSPORTATION	LIGHT DUTY TRUCKS	BASELINE	OTHER TECHS	100%	99%	99%	99%
TRANSPORTATION	LIGHT DUTY TRUCKS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	1%	21%	87%	99%
TRANSPORTATION	LIGHT DUTY TRUCKS	LOW ELECTRIFICATION 350	HE TECHS	0%	1%	0%	0%

TRANSPORTATION	LIGHT DUTY TRUCKS	LOW ELECTRIFICATION 350	OTHER TECHS	98%	79%	13%	1%
TRANSPORTATION	MEDIUM DUTY TRUCKS	BASE 350	ELECTRIFIED TECHS	1%	74%	75%	75%
TRANSPORTATION	MEDIUM DUTY TRUCKS	BASE 350	HE TECHS	0%	25%	25%	25%
TRANSPORTATION	MEDIUM DUTY TRUCKS	BASE 350	OTHER TECHS	98%	1%	0%	0%
TRANSPORTATION	MEDIUM DUTY TRUCKS	BASELINE	OTHER TECHS	100%	100%	100%	100%
TRANSPORTATION	MEDIUM DUTY TRUCKS	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	1%	14%	64%	74%
TRANSPORTATION	MEDIUM DUTY TRUCKS	LOW ELECTRIFICATION 350	HE TECHS	0%	5%	21%	25%
TRANSPORTATION	MEDIUM DUTY TRUCKS	LOW ELECTRIFICATION 350	OTHER TECHS	99%	81%	15%	1%
TRANSPORTATION	TRANSIT BUSES	BASE 350	ELECTRIFIED TECHS	2%	99%	100%	100%
TRANSPORTATION	TRANSIT BUSES	BASE 350	HE TECHS	17%	0%	0%	0%
TRANSPORTATION	TRANSIT BUSES	BASE 350	OTHER TECHS	81%	1%	0%	0%
TRANSPORTATION	TRANSIT BUSES	BASELINE	HE TECHS	17%	17%	17%	17%
TRANSPORTATION	TRANSIT BUSES	BASELINE	OTHER TECHS	83%	83%	83%	83%
TRANSPORTATION	TRANSIT BUSES	LOW ELECTRIFICATION 350	ELECTRIFIED TECHS	1%	19%	85%	99%
TRANSPORTATION	TRANSIT BUSES	LOW ELECTRIFICATION 350	HE TECHS	17%	14%	3%	0%
TRANSPORTATION	TRANSIT BUSES	LOW ELECTRIFICATION 350	OTHER TECHS	82%	67%	12%	1%

1.2.2 Energy Efficiency and Fuel Switching

The outputs of the stock rollover, when combined with the projections of service demand that the technology stocks must meet, contributes to the majority of final energy demand projections in our model. In subsectors where we do not have technology-level detail, we also employ subsector-level estimates of energy efficiency and fuel switching. Energy efficiency is a reduction in the same-fuel efficiency of providing an energy service. Fuel switching, which can also contribute to end-use efficiency, is a measure that changes the share of delivered energy service that is satisfied with a specific energy carrier.

Table 5

Sector	Subsector	Description	BASELINE	BASE 350	LOW ELECTRIFICATION 350
COMMERCIAL	OTHER	Reduction of 20% of all final energy demand by 2050. Levelized cost of efficiency for all fuel types assessed at $20/MMBTU.		X	X
TRANSPORTATION	AVIATION	Reduction of 48% of jet-fuel demand by 2050. Levelized cost of efficiency for all fuel types assessed at $20/MMBTU		X	X
PRODUCTIVE	various[14]	Reduction of 32% of all final energy-demand by 2050. Levelized cost of efficiency for all fuel types assessed at $20/MMBTU		X	X

Sector	Subsector	Description	BASELINE	BASE 350	LOW ELECTRIFICATION 350
PRODUCTIVE	AGRICULTURE - CROPS	90% of pipeline gas and diesel energy demand for irrigation is converted to electricity.		X	
PRODUCTIVE	AGRICULTURE - CROPS	60% of pipeline gas and diesel energy demand for irrigation is converted to electricity.			X

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[14] AGRICULTURE – CROPS; AGRICULTURE-OTHER; ALUMINUM; BALANCE of MANUFACTURING – OTHER; COMPUTER AND ELECTRONIC PRODUCTS; CONSTRUCTION; ELECTRICAL EQUIP., APPLIANCES, and COMPONENTS; FABRICATED METAL PRODUCTS; FOOD AND KINDRED PRODUCTS; GLASS AND GLASS PRODUCTS; MACHINERY; METAL AND OTHER NON-METALLIC MINING; PAPER AND ALLIED PRODUCTS; PLASTIC AND RUBBER PRODUCTS; TRANSPORTATION EQUIPMENT; WOOD PRODUCTS

RESIDENTIAL	SECONDARY HEATING	90% of fuel demand for pipeline gas and 100% of fuel demand for LPG and diesel fuel is converted to electricity.		X	
RESIDENTIAL	SECONDARY HEATING	60% of fuel demand for pipeline gas and 66% of fuel demand for LPG and diesel fuel is converted to electricity.			X

1.3 Final Energy Demand

The combination of stock rollover, fuel switching, and energy efficiency measures results in different final energy demand trajectories across our energy demand scenarios. Final energy demand by sector and energy carrier are shown for each of our demand scenarios below.

Table 6 Final energy demand by sector and energy carrier for each scenario

Sector	Scenario	Final Energy	2020	2030	2040	2050
COMMERCIAL	BASE 350	DIESEL FUEL	0.38	0.31	0.21	0.15
COMMERCIAL	BASE 350	ELECTRICITY	4.64	5.09	5.75	6.19
COMMERCIAL	BASE 350	PIPELINE GAS	2.96	2.08	0.97	0.74
COMMERCIAL	BASE 350	SOLAR	0	0	0	0
COMMERCIAL	BASE 350	STEAM	0.1	0.11	0.12	0.13
COMMERCIAL	BASELINE	DIESEL FUEL	0.38	0.4	0.41	0.41
COMMERCIAL	BASELINE	ELECTRICITY	4.61	4.86	5.26	5.92
COMMERCIAL	BASELINE	PIPELINE GAS	2.97	3.01	3.09	3.17
COMMERCIAL	BASELINE	SOLAR	0	0	0	0
COMMERCIAL	BASELINE	STEAM	0.1	0.11	0.12	0.13
COMMERCIAL	LOW ELECTRIFICATION 350	DIESEL FUEL	0.38	0.38	0.31	0.21

COMMERCIAL	LOW ELECTRIFICATION 350	ELECTRICITY	4.64	4.71	5.21	6.01
COMMERCIAL	LOW ELECTRIFICATION 350	PIPELINE GAS	2.97	2.86	2.08	1.09
COMMERCIAL	LOW ELECTRIFICATION 350	SOLAR	0	0	0	0
COMMERCIAL	LOW ELECTRIFICATION 350	STEAM	0.1	0.11	0.12	0.13
PRODUCTIVE	BASE 350	ASPHALT	0.88	0.89	0.99	1.06
PRODUCTIVE	BASE 350	BIOMASS - WOOD	0.13	0.14	0.13	0.15
PRODUCTIVE	BASE 350	COAL	0.37	0.34	0.3	0.32
PRODUCTIVE	BASE 350	COKING COAL	0.55	0.55	0.53	0.45
PRODUCTIVE	BASE 350	DIESEL FUEL	1.16	1.06	0.9	0.8
PRODUCTIVE	BASE 350	ELECTRICITY	3.44	4.2	5.35	5.7
PRODUCTIVE	BASE 350	GASOLINE FUEL	0.17	0.16	0.14	0.13
PRODUCTIVE	BASE 350	LPG FEEDSTOCKS	0.51	0.6	0.65	0.68
PRODUCTIVE	BASE 350	LPG FUEL	0.34	0.32	0.3	0.29
PRODUCTIVE	BASE 350	MUNICIPAL SOLID WASTE	0.11	0.1	0.09	0.08
PRODUCTIVE	BASE 350	NATURAL GAS FEEDSTOCKS	0.49	0.54	0.56	0.56
PRODUCTIVE	BASE 350	OTHER PETROLEUM	0.35	0.3	0.26	0.25
PRODUCTIVE	BASE 350	PETROCHEMICAL FEEDSTOCKS	0.34	0.42	0.46	0.49
PRODUCTIVE	BASE 350	PETROLEUM COKE	0.24	0.19	0.13	0.13
PRODUCTIVE	BASE 350	PIPELINE GAS	5.3	4.46	2.93	2.78
PRODUCTIVE	BASE 350	RESIDUAL FUEL OIL	0.1	0.09	0.04	0.04
PRODUCTIVE	BASE 350	STEAM	1.37	1.46	2.09	2.3
PRODUCTIVE	BASELINE	ASPHALT	0.88	1	1.25	1.56
PRODUCTIVE	BASELINE	BIOMASS - WOOD	0.13	0.15	0.15	0.17
PRODUCTIVE	BASELINE	COAL	0.36	0.37	0.39	0.43
PRODUCTIVE	BASELINE	COKING COAL	0.55	0.55	0.53	0.45
PRODUCTIVE	BASELINE	DIESEL FUEL	1.16	1.29	1.37	1.49
PRODUCTIVE	BASELINE	ELECTRICITY	3.43	3.73	3.98	4.32
PRODUCTIVE	BASELINE	GASOLINE FUEL	0.17	0.18	0.18	0.19

PRODUCTIVE	BASELINE	LPG FEEDSTOCKS	0.51	0.6	0.65	0.68
PRODUCTIVE	BASELINE	LPG FUEL	0.34	0.35	0.37	0.39
PRODUCTIVE	BASELINE	MUNICIPAL SOLID WASTE	0.11	0.11	0.11	0.12
PRODUCTIVE	BASELINE	NATURAL GAS FEEDSTOCKS	0.49	0.54	0.56	0.56
PRODUCTIVE	BASELINE	OTHER PETROLEUM	0.35	0.35	0.35	0.37
PRODUCTIVE	BASELINE	PETROCHEMICAL FEEDSTOCKS	0.34	0.42	0.46	0.49
PRODUCTIVE	BASELINE	PETROLEUM COKE	0.25	0.25	0.23	0.24
PRODUCTIVE	BASELINE	PIPELINE GAS	5.3	5.51	5.76	6.1
PRODUCTIVE	BASELINE	RESIDUAL FUEL OIL	0.11	0.12	0.1	0.11
PRODUCTIVE	BASELINE	STEAM	1.36	1.39	1.46	1.6
PRODUCTIVE	LOW ELECTRIFICATION 350	ASPHALT	0.88	0.89	0.99	1.06
PRODUCTIVE	LOW ELECTRIFICATION 350	BIOMASS - WOOD	0.13	0.15	0.15	0.15
PRODUCTIVE	LOW ELECTRIFICATION 350	COAL	0.37	0.37	0.35	0.34
PRODUCTIVE	LOW ELECTRIFICATION 350	COKING COAL	0.55	0.55	0.53	0.45
PRODUCTIVE	LOW ELECTRIFICATION 350	DIESEL FUEL	1.16	1.17	1.01	0.88
PRODUCTIVE	LOW ELECTRIFICATION 350	ELECTRICITY	3.44	3.65	4.46	5.44
PRODUCTIVE	LOW ELECTRIFICATION 350	GASOLINE FUEL	0.17	0.16	0.14	0.13
PRODUCTIVE	LOW ELECTRIFICATION 350	LPG FEEDSTOCKS	0.51	0.6	0.65	0.68
PRODUCTIVE	LOW ELECTRIFICATION 350	LPG FUEL	0.34	0.32	0.3	0.29
PRODUCTIVE	LOW ELECTRIFICATION 350	MUNICIPAL SOLID WASTE	0.11	0.1	0.09	0.08
PRODUCTIVE	LOW ELECTRIFICATION 350	NATURAL GAS FEEDSTOCKS	0.49	0.54	0.56	0.56
PRODUCTIVE	LOW ELECTRIFICATION 350	OTHER PETROLEUM	0.35	0.32	0.28	0.25
PRODUCTIVE	LOW ELECTRIFICATION 350	PETROCHEMICAL FEEDSTOCKS	0.34	0.42	0.46	0.49
PRODUCTIVE	LOW ELECTRIFICATION 350	PETROLEUM COKE	0.24	0.23	0.18	0.14
PRODUCTIVE	LOW ELECTRIFICATION 350	PIPELINE GAS	5.3	5.32	4.36	3.2
PRODUCTIVE	LOW ELECTRIFICATION 350	RESIDUAL FUEL OIL	0.1	0.11	0.07	0.04
PRODUCTIVE	LOW ELECTRIFICATION 350	STEAM	1.37	1.46	2.09	2.3
RESIDENTIAL	BASE 350	BIOMASS - WOOD	0.43	0.43	0.44	0.43

RESIDENTIAL	BASE 350	COAL	0	0	0	0
RESIDENTIAL	BASE 350	DIESEL FUEL	0.49	0.34	0.13	0.01
RESIDENTIAL	BASE 350	ELECTRICITY	4.6	4.84	5.27	5.32
RESIDENTIAL	BASE 350	KEROSENE FUEL	0.02	0.01	0.01	0
RESIDENTIAL	BASE 350	LPG FUEL	0.43	0.28	0.08	0
RESIDENTIAL	BASE 350	PIPELINE GAS	4.61	2.9	0.72	0.05
RESIDENTIAL	BASE 350	SOLAR	0.01	0.01	0.01	0.01
RESIDENTIAL	BASELINE	BIOMASS - WOOD	0.43	0.43	0.45	0.44
RESIDENTIAL	BASELINE	COAL	0	0	0	0
RESIDENTIAL	BASELINE	DIESEL FUEL	0.48	0.49	0.54	0.53
RESIDENTIAL	BASELINE	ELECTRICITY	4.55	4.59	4.85	4.97
RESIDENTIAL	BASELINE	KEROSENE FUEL	0.02	0.02	0.02	0.02
RESIDENTIAL	BASELINE	LPG FUEL	0.43	0.44	0.47	0.47
RESIDENTIAL	BASELINE	PIPELINE GAS	4.59	4.75	4.97	4.96
RESIDENTIAL	BASELINE	SOLAR	0.01	0.01	0.01	0.01
RESIDENTIAL	LOW ELECTRIFICATION 350	BIOMASS - WOOD	0.43	0.42	0.42	0.4
RESIDENTIAL	LOW ELECTRIFICATION 350	COAL	0	0	0	0
RESIDENTIAL	LOW ELECTRIFICATION 350	DIESEL FUEL	0.49	0.46	0.32	0.12
RESIDENTIAL	LOW ELECTRIFICATION 350	ELECTRICITY	4.6	4.35	4.58	4.99
RESIDENTIAL	LOW ELECTRIFICATION 350	KEROSENE FUEL	0.02	0.02	0.01	0.01
RESIDENTIAL	LOW ELECTRIFICATION 350	LPG FUEL	0.43	0.42	0.27	0.09
RESIDENTIAL	LOW ELECTRIFICATION 350	PIPELINE GAS	4.61	4.32	2.65	0.77
RESIDENTIAL	LOW ELECTRIFICATION 350	SOLAR	0.01	0.01	0.01	0.01
TRANSPORTATION	BASE 350	COMPRESSED PIPELINE GAS	0.07	0.04	0.01	0
TRANSPORTATION	BASE 350	DIESEL FUEL	7.42	5.15	3.24	3.21
TRANSPORTATION	BASE 350	ELECTRICITY	0.05	2.99	6.1	6.65
TRANSPORTATION	BASE 350	GASOLINE FUEL	19.9	10.6	1.11	0.29
TRANSPORTATION	BASE 350	JET FUEL	2.17	2.2	2.17	2.05

TRANSPORTATION	BASE 350	LIQUEFIED PIPELINE GAS	0.01	0.08	0.17	0.25
TRANSPORTATION	BASE 350	LIQUID HYDROGEN	0	0	0	0
TRANSPORTATION	BASE 350	LPG FUEL	0.05	0.03	0	0
TRANSPORTATION	BASE 350	LUBRICANTS	0.14	0.14	0.14	0.14
TRANSPORTATION	BASE 350	RESIDUAL FUEL OIL	0.35	0.41	0.48	0.54
TRANSPORTATION	BASELINE	COMPRESSED PIPELINE GAS	0.07	0.07	0.07	0.07
TRANSPORTATION	BASELINE	DIESEL FUEL	7.44	7.29	7.17	7.65
TRANSPORTATION	BASELINE	ELECTRICITY	0.03	0.04	0.05	0.06
TRANSPORTATION	BASELINE	GASOLINE FUEL	19.93	18.11	16.79	16.39
TRANSPORTATION	BASELINE	JET FUEL	2.17	2.53	2.92	3.34
TRANSPORTATION	BASELINE	LIQUEFIED PIPELINE GAS	0.01	0.09	0.18	0.26
TRANSPORTATION	BASELINE	LIQUID HYDROGEN	0	0	0	0
TRANSPORTATION	BASELINE	LPG FUEL	0.05	0.06	0.06	0.07
TRANSPORTATION	BASELINE	LUBRICANTS	0.14	0.14	0.14	0.14
TRANSPORTATION	BASELINE	RESIDUAL FUEL OIL	0.35	0.41	0.48	0.54
TRANSPORTATION	LOW ELECTRIFICATION 350	COMPRESSED PIPELINE GAS	0.07	0.07	0.04	0.01
TRANSPORTATION	LOW ELECTRIFICATION 350	DIESEL FUEL	7.43	7.02	5.07	3.62
TRANSPORTATION	LOW ELECTRIFICATION 350	ELECTRICITY	0.04	0.4	3.01	5.95
TRANSPORTATION	LOW ELECTRIFICATION 350	GASOLINE FUEL	19.91	17.19	9.48	2.1
TRANSPORTATION	LOW ELECTRIFICATION 350	JET FUEL	2.17	2.2	2.17	2.05
TRANSPORTATION	LOW ELECTRIFICATION 350	LIQUEFIED PIPELINE GAS	0.01	0.09	0.18	0.25
TRANSPORTATION	LOW ELECTRIFICATION 350	LIQUID HYDROGEN	0	0	0	0
TRANSPORTATION	LOW ELECTRIFICATION 350	LPG FUEL	0.05	0.05	0.03	0.01
TRANSPORTATION	LOW ELECTRIFICATION 350	LUBRICANTS	0.14	0.14	0.14	0.14
TRANSPORTATION	LOW ELECTRIFICATION 350	RESIDUAL FUEL OIL	0.35	0.41	0.48	0.54

2. Energy Supply Scenario Descriptions

Energy supply portfolios are selected using the RIO optimization based on the economy-wide emissions constraint employed. The tables below show the cumulative and annual emissions constraint employed on energy and industrial process CO2 in this analysis. This also includes any contribution from direct air capture. The cumulative emissions caps from 2020 through 2050 for the **Base 350, No New Nuclear 350, Limited Biomass 350, No Tech NETS 350, and Low Electrification 350** represent a cumulation of Hansen's CO2 trajectories from 2020 through 2050. The annual target in 2050 of 828 MMT ensures that we are on the required low-emissions trajectory for post-2050 emissions. The **Low Land NETS 350** case requires a different methodology, as achievement of this emissions target encourages net-negative emissions by 2050. Given this, we use the entire 2020 through 2100 emissions budget and additionally assume that at least the negative emissions achieved in 2050 persist through 2100. This results in a cumulative emissions target of 57 MMT (47 MMT represents the 2020-2100 emissions budget plus 10 MMT which represents 50 years of -200 MMT per year of emissions). The **Baseline** scenario is only required to maintain the 2020 emissions cap through 2050. This is not binding.

Table 7 Emissions targets for each scenario

Energy Economy Scenarios	Cumulative Emissions Target (2020-2050)	Annual Emissions Target - 2050
Baseline	N/A	5300
Base 350	75 MMT	828
No New Nuclear 350	75 MMT	828
Limited Biomass 350	75 MMT	828
No Tech NETS 350	75 MMT	828
Low Land NETS 350	57 MMT	-200
Low Electrification 350	75 MMT	828

In addition to differing targets, the energy economy scenarios employ different constraints on potential energy supply options. Specifically, the scenarios constrain the availability of technological NETS (**No Tech NETS 350**), primary biomass resources (**Limited Biomass 350)**, and advanced nuclear plants (**No New Nuclear 350)**. These constraints are shown in the table below.

Table 8 Additional scenario constraints

Energy Economy Scenarios	**Additional Constraint**
No New Nuclear	No additional nuclear resources are allowed to be built.
Limited Biomass	Supply of herbaceous and woody biomass is reduced by 50% in 2050.
No Tech NETS	No biomass with CCS or direct air capture with sequestration technologies are allowed to be built.

3. Model Overview

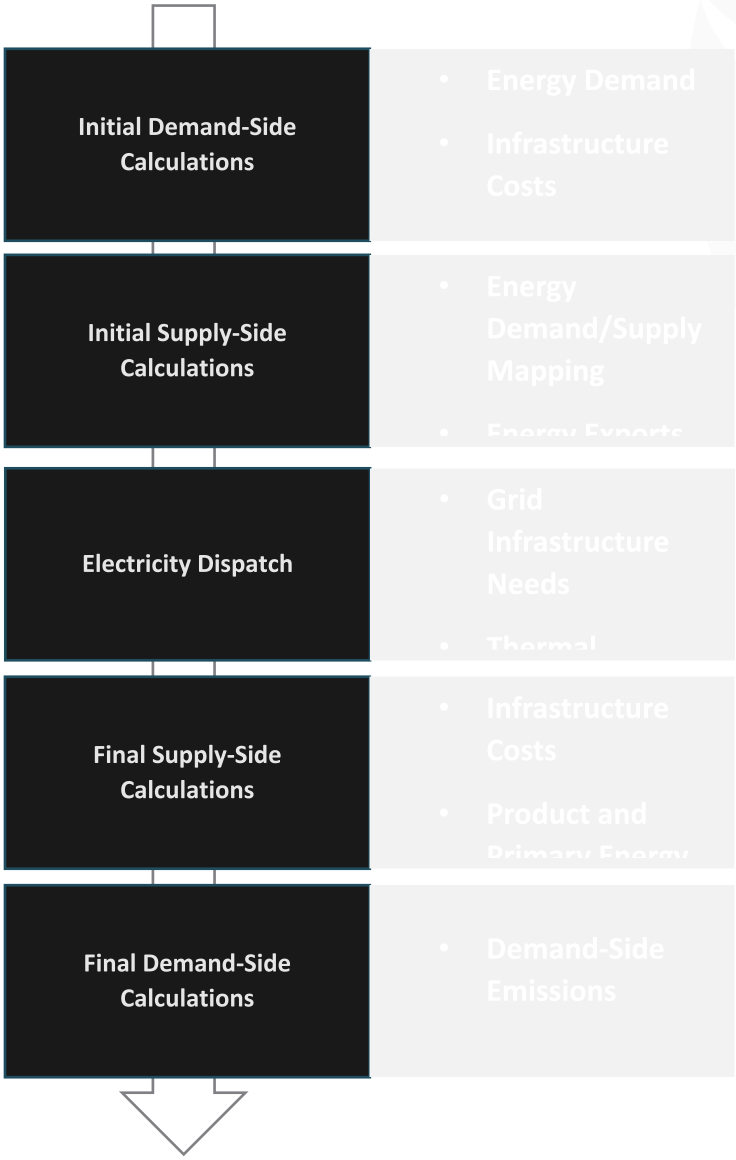
The EnergyPATHWAYS model is a comprehensive energy accounting and analysis frameworks specifically designed to examine the large-scale energy system transformations. It accounts for the costs and emissions associated with producing, transforming, delivering, and consuming energy in an economy. It has strengths in infrastructure accounting and electricity operations hat separate it from models of similar types. It is used, as it has been in this analysis, to calculate the impacts of energy system decisions out into the future in terms of infrastructure; emissions, and cost impacts to energy consumers and the economy more broadly.

The model works using decision-making "stasis" as a baseline. This means, for example, that when projecting energy demand for residential space heating, EnergyPATHWAYS implicitly assume that consumers will replace their water heater with a water heater of a similar type. This baseline does, however, include efficiency gains and technology development either required by codes and standards or reasonably anticipated based on techno-economic projections. If there are deviations from the current system in terms of technology deployment, these are made explicit in our scenario with the application of measures, which represent explicit user-defined changes to the baseline. These can take the form of adjustments of sales shares measures - changes in the relative penetration of technology adoption in a defined year; or stock measures, changes to the amount of technology deployment by a defined year. A further description of measures is found in the Scenario section of the technical documentation.

4. Model Structure

EnergyPATHWAYS projects energy demand and costs in subsectors based on explicit user-decisions about technology adoption (I.e. electric vehicle adoption) and activity levels (I.e. reduced VMTs). These projections of energy demand across energy carriers are then sent to the supply-side of the model, which calculates upstream energy flows, primary energy usage, infrastructure requirements, emissions, and costs of supplying energy. These supply-side outputs are then combined with the demand-side outputs to calculate the total energy flows, emissions, and costs of the modeled energy system. Figure 33 shows the basic calculation steps for EnergyPATHWAYS as well as the outputs from each step.

Figure 33 EnergyPATHWAYS calculation steps



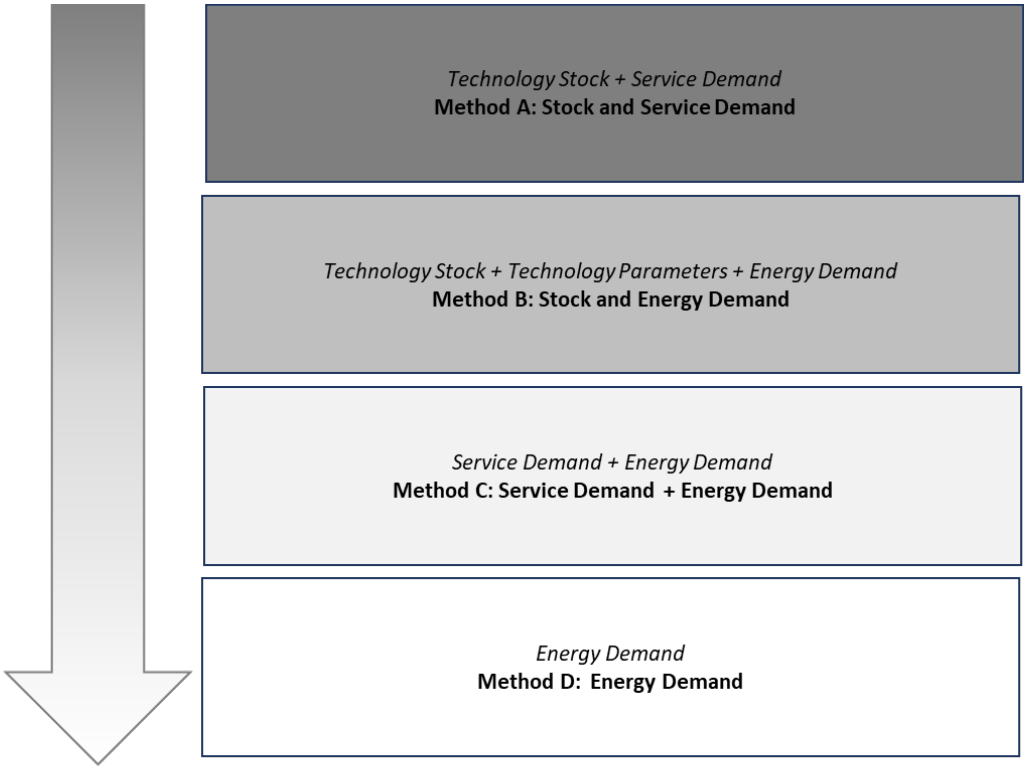
In the following section EnergyPATHWAYS separately detail the demand-side and supply-side of this calculation framework.

4.1 Subsectors

Subsectors represent separately modeled units of demand for energy services. These are often referred to as end-uses in other modeling frameworks. EnergyPATHWAYS is flexible in the configuration of these subsectors and the choices in the subsector detail rendered depends heavily on data availability. The high level of detail in subsectors in the US EnergyPATHWAYS database represents the availability of numerous high-quality data sources for the US energy economy, which allows us to represent demand for energy services on a highly detailed, granular basis. We will describe the calculations for individual subsectors on the demand-side in this document, but assessing the total demand is simply the summation of these calculations for all subsectors.

4.2 Energy Demand Projection

Data availability informs subsector granularity and informs the methods used in each subsector. The flow diagram below represents the decision matrix used to determine the potential methods used to detail an individual energy demand subsector. The arrow downward indicates a progression from most-preferred to least-preferred methodology for detailing a subsector. More preferred methods allow for more explicit interventions of measures and better accounting for costs and energy impacts of concrete actions. Each method for projecting energy demand is described below.



4.2.1 Method A: Stock and Service Demand

This method is the most explicit representation of energy demand possible in the EnergyPATHWAYS framework. It has a high data requirement, however, as many end-uses are not homogenous enough to represent with technology stocks and others do not have measurements of energy service demand. When they do EnergyPATHWAYS use the following formula to calculate energy demand from the subsector.

Equation 1

$$E_{ycr} = \sum_{v \in V} \sum_{t=T} U_{yvtcr} * f_{vtc} * \ d_{yr} * (1 - \ R_{yrc})$$

Where

E = Energy demand in year y of energy carrier c in region r

U_{yvtcr} = Normalized share of service demand in year y of vintage v of technology t for energy carrier c in region r

f_{vtc} = Efficiency (energy/service) of vintage v of technology t using energy carrier c

d_{yr} = Total service demand input aggregated for year y in region r

R_{yrc} = Unitized service demand reductions for year y in region r for energy carrier c. Service demand reductions are calculated from input service demand measures, which change the baseline energy service demand levels.

4.2.1.1 Service Demand Share (U)

The normalized share of service demand is calculated as a function of the technology stock (S), service demand modifiers (M), and energy carrier utility factors (C). Below is the decomposition of *U* into its component parts of *S* and *M and C.*

Equation 2

$$U_{yvtr} = \frac{S_{yvtr} * M_{yvtr} * C_{tc}}{\sum_{v \in V} \sum_{t \in T} S_{yvtr} * M_{yvtr}}$$

Where

S_{yvtr} = Technology stock in year y of vintage v of technology t in region r

M_{yvtr} = Service demand modifier in year y for vintage v for vintage t in region r

C_{tc} = Utility factor for energy carrier c for technology t

The calculation of these are detailed in the sections below

4.2.1.2 Technology Stock (S)

The composition of the technology stock is governed by technology stock rollover mechanics in the model, technology inputs (lifetime parameters, technology decay parameters), initial technology stock states, and the application of sales share or stock measures. The section below describes the ways in which these model variables can affect the eventual calculation of technology share.

4.2.1.2.1 Initial Stock

The model uses an initial representation of the technology stock to project forward. This usually represents a single-year stock representation based on customer survey data (I.e. U.S. Commercial Building Energy Consumption Survey data informs 2012 technology stock estimates) but can also be "specified" into the future, where the composition of the stock is determined exogenously. At the end of this initial stock specification, the model uses technology parameters and rollover mechanics to determine stock compositions by year.

4.2.1.2.2 Stock Decay and Replacement

EnergyPATHWAYS allows for technology stocks to decay using linear representations or Weibull distributions, which are typical functions used to represent technology reliability and failure rates. These parameters are governed by a combination of technology lifetime parameters. Technology lifetimes can be entered as minimum and maximum lifetimes or as an average lifetime with a variance.

After the conclusion of the initial stock specification period, the model decays existing stock based on the age of the stock, technology lifetimes, and specified decay functions. This stock decay in a year (y) must be replaced with technologies of vintage (v) $v = y$. The share of replacements in vintage v is equal to the share of replacements unless this default is overridden with exogenously specified sales share or stock measures. This share of sales is also used to inform the share of technologies deployed to meet any stock growth.

4.2.1.2.3 Sales Share Measures

Sales share measures override the pattern of technologies replacing themselves in the stock rollover.

An example of a sales share measure is shown below for two technologies – A and B - that are represented equally in the initial stock and have the same decay parameters. EnergyPATHWAYS apply a sales share measure in the year 2020 that requires 80% of new sales in 2020 to be technology A and 20% to be technology B. The first equation shows the calculation in the absence of this sales share measure. The second shows the stock rollover governed with the new sales share measure.

S = Stock

D = Stock decay

G = Year on year stock growth

R = Stock decay replacement

N = New Sales

a = Technology A

b = Technology B

Before Measure (i.e. Baseline)

S_{2019} = 100

S_{a2019} = 50

S_{b2019} = 50

D_{2020} = 10

D_{a2020} = 5

D_{b2020} = 5

S_{2020} = 110

$G_{2020} = S_{2020} - S_{2019} = 110 - 100 = 10$

R_{a2020} = D_{a2020} = 5

R_{b2020} = D_{b2020} = 5

G_{a2020} = $\frac{D_{a2020}}{D_{2020}} * G_{2020}$ = 5/10 * 10 =5

$G_{b2020} = \frac{D_{b2020}}{D_{2020}} * G_{2020}$ = 5/10 * 10 = 5

$N_{a2020} = R_{a2020} + G_{a2020}$ = 5 + 5 = 10

$N_{b2020} = R_{b2020} + G_{b2020}$ = 5 + 5 = 10

$S_{a2020} = S_{a2019} + D_{a2020} + N_{a2020}$ = 50 – 5 + 10 = 55

$S_{b2020} = S_{b2019} + D_{b2020} + N_{b2020}$ = 50 – 5 + 10 = 55

After Sales Share Measure

S_{2019} = 100

S_{a2019} = 50

S_{b2019} = 50

D_{2020} = 10

D_{a2020} = 5

D_{b2020} = 5

S_{2020} = 110

$G_{2020} = S_{2020} - S_{2019} = 110 - 100 = 10$

$R_{a2020} = D_{2020} * H_{a2020}$ = 10 * .8 = 8

$R_{b2020} = D_{2020} * H_{b2020}$ = 10 * .2 = 2

$G_{a2020} = G_{2020} * H_{a2020}$ = 10 * .8 = 8

$G_{b2020} = G_{2020} * H_{b2020}$ = 10 * .2 = 2

$N_{a2020} = R_{a2020} + G_{a2020}$ = 8 + 8 = 16

$N_{b2020} = R_{b2020} + G_{b2020}$ = 2 + 2 = 4

$S_{a2020} = S_{a2019} + D_{a2020} + N_{a2020}$ = 50 – 5 + 16 = 61

$S_{b2020} = S_{b2019} + D_{b2020} + N_{b2020}$ = 50 – 5 + 4 = 49

This shows a very basic example of the role that sales share measures play to influence the stock of technology. In the context of energy demand, these technologies can use different energy carriers (i.e. gasoline internal combustion engine vehicles to electric vehicles) and/or have different efficiency characteristic.

Though not shown in the above example, the stock is tracked on a vintaged basis, so decay of technology A in 2020 in the above example would be decay in 2020 of all vintages before 2020. In the years immediately succeeding the deployment of vintage cohort, there is very little technology retirement given the shape of the decay functions. As a vintage approaches the end of their anticipated useful life, however, retirement accelerates.

4.2.1.2.4 Stock Specification Measures

EnergyPATHWAYS also allows for stock specification measures, which create exogenous specification of technology stocks along the year index (i.e. existing stock in a year), as opposed to sales share measures which operate along the vintage index (i.e. sales in a year). They both interact with the same basic stock rollover mechanics in the model but are interpreted differently by the model.

In the example below, EnergyPATHWAYS replicate the stock in 2020 of our previous sales share example where Technology A is 61 units in 2020 and Technology B is 49 Units.

<u>After Stock Specification Measure</u>

$S_{2019} = 100$

$S_{a2019} = 50$

$S_{b2019} = 50$

$D_{2020} = 10$

$D_{a2020} = 5$

$D_{b2020} = 5$

$S_{2020} = 110$

$G_{2020} = S_{2020} - S_{2019} = 110 - 100 = 10$

$N_{a2020} = S_{a2020} - S_{a2019} + D_{a2020} = 61 – 50 + 5 = 16$

$S_{b2020} = S_{2020} - S_{a2020} = 110 – 61 = 49$

N_{b2020} = $S_{b2020} - S_{b2019} + D_{b2020}$ = 49 – 50 + 5 = 4

$H_{a2020} = \frac{N_{a2020}}{N_{2020}}$ = .8

$H_{b2020} = \frac{N_{b2020}}{N_{2020}}$ = .2

R_{a2020} = $D_{2020} * H_{a2020}$ = 10 * .8 = 8

R_{b2020} = $D_{2020} * H_{b2020}$ = 10 * .2 = 2

G_{a2020} = $G_{2020} * H_{a2020}$ = 10 * .8 = 8

G_{b2020} = $G_{2020} * H_{b2020}$ = 10 * .2 = 2

The model uses the stock specifications to produce sales shares that result in the specified stock. Where a stock specification measure requires more new sales than are available through natural rollover decay and stock growth, the model early-retires infrastructure to increase the pool of available sales based on the probability of retirement for given combination of vintage and technology. The model separately tracks physical and financial lifetimes, so even though technologies may be taken out of service, they are still paid for. Further discussion of this accounting can be found in 4.2.2.1.

4.2.1.3 Service Demand Modifier (M)

Many energy models use stock technology share as a proxy for service demand share. This makes the implicit assumption that all technologies of all vintage in a stock are used equally. This assumption obfuscates some key dynamics that influence the pace and nature of energy system transformation. For example, new heavy-duty vehicles are used heavily at the beginning of their useful life but are sold to owners who operate them for reduced duty-cycles later in their lifecycles. This means that electrification of this fleet would accelerate the rollover of electrified miles faster than it would accelerate the rollover of the trucks themselves. Similar dynamics are at play in other vehicle subsectors. In subsectors like residential space heating, the distribution of current technology stock is correlated with its utilization. Even within the same region, with the same climactic conditions, the choice of heating technology informs its usage. Homes that have baseboard electric heating, for example, are often seasonal homes with limited heating loads.

EnergyPATHWAYS has two methods for determining the discrepancy between stock shares and service demand shares. First, technologies can have the input of a *service demand modifier*. This is used an adjustment between stock share and service demand share.

Using the example stock of Technology, A and B, the formula below shows the impact of service demand modifier on the service demand share.[15]

$$S_{2019} = 100$$

$$S_{a2019} = 50$$

$$S_{a2020} = 50$$

$$x_{a2019} = \frac{S_{a2019}}{S_{2019}} = \frac{50}{100} = .5$$

$$x_{b2019} = \frac{S_{b2019}}{S_{2019}} = \frac{50}{100} = .5$$

$$M_{a2019} = 2$$

$$M_{b2019} = 1$$

$$U_{a2019} = \frac{S_{a2019} * M_{a2019}}{\sum_{t=a..b} S_{t2019} * M_{t2019}} = \frac{50*2}{150} = .667$$

$$U_{b2019} = \frac{S_{b2019} * M_{b2019}}{\sum_{t=T} S_{t2019} * M_{t2019}} = \frac{50*1}{150} = .333$$

When service demand modifiers aren't entered for individual technologies, they can potentially still be calculated using input data. For example, if the service demand input data is entered with the index of t, the model calculates service demand modifiers by dividing stock and service demand inputs.

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[15] EnergyPATHWAYS again ignore the index of vintage (v) for simplicity, but this is an important index to reflect technology utilization determined by age.

Equation 3

$$M_{tyr} = \frac{s_{tyr}}{d_{tyr}}$$

Where

$M_{ty} =$ Service demand modifier for technology t in year y in region r

$s_{tyr} =$ Stock input data for technology t in year y in region r

$d_{tyr} =$ Energy demand input data for technology t in year y in region r

4.2.1.3.1 Energy Carrier Utility Factors (C)

Energy carrier utility factors are technology inputs that allocates a share of the technology's service demand to energy carriers. The model currently supports up to two energy carriers per technology. This allows EnergyPATHWAYS to support analysis of dual-fuel technologies, like plug-in-hybrid electric vehicles. The input structure is defined as a primary energy carrier with a utility factor (0 – 1) and a secondary energy carrier that has a utility factor of 1 – the primary utility factor.

4.2.1.4 Method B: Stock and Energy Demand

Method B is like Method A in almost all its components except for the calculation of the service demand term. In Method A, service demand is an input. In Method B, the energy demand of a subsector is input as a substitute. From this input, EnergyPATHWAYS must take the additional step of deriving service demand, based on stock and technology inputs.

Equation 4

$$E_{ycr} = \sum_{v \in V} \sum_{t=T} U_{yvtcr} * f_{vtc} * \ D_{yr} * (1 - R_{yrc})$$

Where

E = Energy demand in year y of energy carrier c in region r

U = Normalized share of service demand in year y of vintage v of technology t for energy carrier c in region r

f = Efficiency (energy/service) of vintage v of technology t using energy carrier c

D = Total service demand calculated for year y in region r

R_{yrc} = Unitized service demand reductions for year y in region r for energy carrier c

4.2.1.4.1 Total Service Demand (D)

Total service demand is calculated using stock shares, technology efficiency inputs, and energy demand inputs. The intent of this step is to derive a service demand term (D) that allows us to use the same calculation framework as Method A.

Equation 5

$$D_{yr} = \sum_{v\in V}\sum_{c\in C}\sum_{t=T} U_{yvtcr} * f_{vtc} * \ e_{ycr}$$

Where

D_{yr} = Total service demand in year y in region r

f_{vtc} = Efficiency (energy/service) of vintage v of technology t using energy carrier c

e_{ycr} = Input energy data in year y of carrier c in region r

4.2.1.5 Method C: Service and Service Efficiency

Method C is used when EnergyPATHWAYS do not have sufficient input data, either at the technology level or the stock level, to parameterize a stock rollover. Instead EnergyPATHWAYS replace the stock terms in the energy demand calculation with a service efficiency term (j). This is an exogenous input that substitutes for the stock rollover dynamics and outputs in the model.

Equation 6

$$E_{ycr} = \ j_{ycr} * \ d_{yr} * \ R_{yrc} - O_{yrc}$$

where

E_{ycr} = Energy demand in year y for energy carrier c in region r

j_{ycr} = Service efficiency (energy/service) of subsector in year y for energy carrier c in region r

d_{yr} = Input service demand for year y in region r

R_{yrc} = Unitized service demand multiplier for year y in region r for energy carrier c

O_{yrc} = Energy efficiency savings in year y in region r for energy carrier c

4.2.1.5.1 Energy Efficiency Savings (O)

Energy efficiency savings are a result of specified energy efficiency measures in the model. These take the form of prescribed levels of energy savings measures that are netted off the baseline projection of energy usage.

4.2.1.6 Method D: Energy Demand

The final method is simply the use of an exogenous specification of energy demand. This is used for subsectors where there is neither the data necessary to populate a stock rollover nor any data available to decompose energy use from its underlying service demand.

Equation 7

$$E_{ycr} = e_{ycr} - O_{yrc}$$

Where

E_{ycr} = Energy demand in year y for energy carrier c in region r

e_{ycr} = Input baseline energy demand in year y for energy carrier c in region r

O_{yrc} = Energy efficiency savings in year y in region r for energy carrier c

4.2.2 Demand-Side Costs

Cost calculations for the demand-side are separable into technology stock costs and measure costs (energy efficiency and service demand measures).

4.2.2.1 Technology Stock Costs

EnergyPATHWAYS uses vintaged technology cost characteristics as well as the calculated stock rollover to calculate the total costs associated with technology used to provide energy services.[16]

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[16] Levelized costs are the principal cost metric reported, but the model also calculates annual costs (i.e. the cost in 2020 of all technology sold).

$$C_{yr}^{stk} = C_{yr}^{cap} + C_{yr}^{ins} + C_{yr}^{fs} + C_{yr}^{fom}$$

Where

C_{yr}^{stk} = Total levelized stock costs in year y in region r

C_{yr}^{cap} = Total levelized capital costs in year y in region r

C_{yr}^{ins} = Total levelized installation costs in year y in region r

C_{yr}^{fs} = Total levelized fuel switching costs in year y in region r

C_{yr}^{fom} = Total fixed operations and maintenance costs in year y in region r

4.2.2.1.1 Technology Stock Capital Costs

The model uses information from the physical stock rollover used to project energy demand, with a few modifications. First, the model uses a different estimate of technology life. The financial equivalent of the physical "decay" of the technology stock is the depreciation of the asset. EnergyPATHWAYS uses a linear function with a maximum and minimum life of the mean technology life, meaning that all financial decay takes place in one year (i.e. the asset comes off of the financial books). This is referred to as the "book life" of the asset.

To provide a concrete example of this, a 2020 technology vintage with a book life of 15 years is maintained in the financial stock in its entirety for the 15 years before it is financially "retired" in 2035. This financial stock estimate, in addition to being used in the capital costs calculation, is used for calculating installation costs and fuel switching costs.

Equation 8

$$C_{yr}^{cap} = \sum_{v \in V} \sum_{t \in T} S_{tvyr}^{fin} * W_{tvr}^{cap}$$

Where

C_{yr}^{cap} = Total levelized technology costs in year y in region r

W_{tvr}^{cap} = Levelized capital costs for technology t for vintage v in region r

S_{tvyr}^{fin} = Financial stock of technology t and vintage v in year y in region r

EnergyPATHWAYS primarily use this separate financial accounting so that EnergyPATHWAYS accurately account for the costs of early-retirement of technology. There is no way to financially early-retire an asset, so physical early retirement increases overall costs (by increasing the overall financial stock).

4.2.2.1.2 Levelized Capital Costs (W)

EnergyPATHWAYS levelized technology costs over the mean of their projected useful lives (referred to as book life). This is either the input mean lifetime parameter of the arithmetic mean of the technology's max and min lifetimes. EnergyPATHWAYS additionally assess a cost of capital on this levelization of the technology's upfront costs. While this may seem an unsuitable assumption for technologies that could be considered "out-of-pocket" purchases, EnergyPATHWAYS assume that all consumer purchases are made using backstop financing options. This is the implicit assumption that if "out-of-pocket" purchases were reduced, the amount needed to be financed on larger purchases like vehicles and homes could be reduced in-kind.

$$W_{tvr}^{cap} = \frac{d_t * z_{tvr}^{cap} * (1 + d_t)^{l_t^{book}}}{(1 + d_t)^{l^{book}} - 1}$$

Where

W_{tvr}^{cap} = Levelized capital costs for technology t for vintage v in region r

d_t = Discount rate of technology t

z_{tvr}^{cap} = Capital costs of technology t in vintage v in region r

l_t^{book}= Book life of technology t

4.2.2.2 Technology Stock Installation Costs

Installation costs represent costs incurred when putting a technology into service. The methodology for calculating these is the same as that used to calculate capital costs. These are levelized in a similar manner.

4.2.2.3 Technology Stock Fuel Switching Costs

Fuel switching costs represent costs incurred for a technology only when switching from a technology with a different primary energy carrier. This input is used for technologies like gas furnaces that may need additional gas piping if they are being placed in service in a household that had a diesel furnace. Calculating these costs requires the additional step of determining the number of equipment sales in a given year associated with switching fuels.

$$C_{yr}^{fs} = \sum_{v \in V} \sum_{t \in T} S_{tvyr}^{fs} * W_{tvr}^{fs}$$

Where

S_{tvyr}^{fs} = Financial stock associated with fuel-switched equipment installations

W_{tvr}^{fs} = Levelized fuel-switching costs for technology t for vintage v in region r

d_t = Discount rate of technology t

z_{tvr}^{fs} = Fuel switching costs for technology t in vintage v in region r

4.2.2.4 Technology Stock Fixed Operations and Maintenance Costs

Fixed operations and maintenance (O&M) costs are the only stock costs that utilize physical and not financial representations of technology stock. This is because O&M costs are assessed annually and are only incurred on technologies that remain in service. If equipment has been retired, then it no longer has ongoing O&M costs.

$$C_{yr}^{fom} = \sum_{v \in V} \sum_{t \in T} S_{tyvr} * W_{tvr}^{fom}$$

Where

S_{tyvr}= Technology stock of technology t in year y of vintage v in region r

W_{tvr}^{fom} = Fixed O&M costs for technology t for vintage v in region r

4.2.3 Measure Costs

Measure costs are assessed for interventions either at the service demand (service demand measures) or energy demand levels (energy efficiency measures). While these measures are abstracted from technology-level inputs, EnergyPATHWAYS uses a similar methodology for these measures as EnergyPATHWAYS do for technology stock costs. EnergyPATHWAYS use measure savings to create “stocks” of energy efficiency or service demand savings. These measure stocks are vintaged like technology stocks and EnergyPATHWAYS use analogous inputs like capital costs and useful lives to calculate measure costs.

4.2.3.1 Service Demand Measure Costs

Service demand measure costs are costs associated with achieving service demand reductions. In many cases, no costs are assessed for these activities as they represent conservation or improved land-use planning that occurs at zero or negative-costs.

Equation 9

$$C_{yr}^{sd} = \sum_{v \in V} \sum_{m \in M} S_{mvyr}^{sd} * W_{mvr}^{sd}$$

Where

C_{yr}^{sd} = Total service demand measure costs

S_{mvyr}^{sd} = Financial stock of service demand reductions from measure m of vintage v in year y in region r

W_{mvr}^{sd} = Levelized per-unit service demand reduction costs

4.2.3.2 Energy Efficiency Measure Costs

Energy efficiency costs are costs associated the reduction of energy demand. These are representative of incremental equipment costs or costs associated with non-technology interventions like behavioral energy efficiency.

Equation 10

$$C_{yr}^{ee} = \sum_{v \in V} \sum_{m \in M} S_{mvyr}^{ee} * W_{mvr}^{ee}$$

Where

C_{yr}^{ee} = Total energy efficiency measure costs

S_{mvyr}^{sd} = Financial stock of energy demand reductions from measure m of vintage v in year y in region r

W_{mvr}^{ee} = Levelized per-unit energy efficiency costs

5. Supply

5.1 Supply Nodes

Supply nodes represent the fundamental unit of analysis on the supply-side and are analogous to subsectors on the demand-side. We will primarily describe the calculations for individual supply nodes in this document, but assessing the total costs and emissions from the supply-side is just the summation of all supply nodes for a year and region.

5.2 I/O Matrix

There is one principal difference between supply nodes and subsectors that explains the divergent approaches taken for calculating them; energy flows through supply nodes must be solved concurrently due to a number of dependencies between nodes. As an example, it is not possible to know the flows through the gas transmission pipeline node without knowing the energy flow through gas power plant nodes. This tenet requires a fundamentally different supply-side structure. To solve the supply-side, EnergyPATHWAYS leverages techniques from economic modeling by arranging supply nodes in an input-output matrix, where coefficients of a node represent units of other supply nodes required to produce the output product of that node.

Consider a simplified representation of upstream energy supply with four supply nodes:

a. Electric Grid
b. Gas Power Plant
c. Gas Transmission Pipeline
d. Primary Natural Gas

This is a system that only delivers final energy to the demand-side in the form of electricity from the electric grid. It also has the following characteristics:

1. The gas transmission pipeline has a loss factor of 2% from leakage. It also uses grid electricity to power compressor stations and requires .05 units of grid electricity for every unit of delivered gas.
2. The gas power plant has a heat rate of 8530 Btu/kWh, which means that it requires 2.5 (8530 Btu/kWh/3412 Btu/kWh) units of gas from the transmission pipeline for every unit of electricity generation.

3. The electricity grid has a loss factor of 5%, so it needs 1.05 units of electricity generation to deliver 1 unit of electricity to its terminus.

The I/O matrix for this system is shown below in tabular form Table 9 as well as in matrix form below

Table 9 Tabular I/O Matrix

	Natural Gas	Gas Transmission Pipeline	Gas Power Plant	Electric Grid
Natural Gas		**1.02**		
Gas Transmission Pipeline			**2.5**	
Gas Power Plant				**1.05**
Electric Grid		**.05**		

Equation 11

$$A = \begin{pmatrix} & 1.05 & & \\ & & 2.5 & \\ & & & 1.05 \\ & .05 & & \end{pmatrix}$$

With this I/O matrix, if we know the demand for energy from a node (supplied from the demand-side of the EnergyPATHWAYS model), we can calculate energy flows through every upstream supply node. To continue the example, if 100 units of electricity are demanded:

$$d = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 100 \end{pmatrix}$$

We can calculate the energy flow through each node using the equation, which represents the inverted matrix multiplied the demand term.

$$x = (I - A)^{-1} * d$$

This gives us the following result:

$$x = \begin{pmatrix} 308 \\ 302 \\ 121 \\ 115 \end{pmatrix}$$

We use the I/O structure in much more complicated ways, and most of the supply-side calculations are focused on populating I/O coefficients and solving throughput through each node, which allows us to calculate infrastructure needs, costs, resource usage, and greenhouse gas emissions associated with energy supply

There are six distinct types of nodes that represent different components of the energy supply system. These will be examined individually in all of the supply-side calculation descriptions. The list below details some of their basic functionality

1. **Conversion Nodes –** Conversion nodes represent units of infrastructure specified at the technology level (i.e. gas combined cycle power plant) that have a primary purpose of converting the outputs of one supply node to the inputs of another supply node. Gas power plants in the above example are a conversion node, converting the output of the gas transmission pipeline to the inputs of the electric grid.

2. **Delivery Nodes –** Delivery nodes represent infrastructure specified at a non-technology level. The gas transmission pipeline is an example of a delivery node. A transmission pipeline system is the aggregation of miles of pipeline, hundreds of compressor stations, and storage facilities. We represent it as an aggregation of these components. The role of delivery nodes is to deliver the outputs of one supply node to a different physical location in the system required so that they can be used as inputs to another supply node. In the above example, gas transmission pipelines deliver natural gas from gas fields to gas power plants, which are not co-located with the resource.

3. **Primary Nodes –** Primary nodes are used for energy accounting, but they generally represent the terminus of the energy supply chain. That is, absent some exceptions, their coefficients are generally zero.

4. **Product Nodes –** Product nodes are used to represent energy products where it is not possible to endogenously build up the costs and emissions through to their primary energy source. For example, we represent refined fuels as product nodes, generally, so that the price of these refined fuels can be divorced from the price of their primary oil inputs.

5. **Blend Nodes –** Blend nodes are non-physical control nodes in the energy supply chain. These are the locations in the energy system that we apply measures to change the relative inputs to other supply nodes. There are no blend nodes in the simplified example above, but an alternative energy supply system may add a biogas product node and place a blend node between the gas transmission pipeline and the primary natural gas node. This blend node would be used to control the relative inputs to the gas transmission pipeline (between natural gas and biogas).

6. **Electric Storage Nodes –** Electric storage nodes are nodes that provide a unique role in the electricity dispatch functionality of EnergyPATHWAYS.

5.3 Energy Flows

5.3.1 Coefficient Determination (A – Matrix)

The determination of coefficients is unique to supply-node types. For primary, product, and delivery nodes, these efficiencies are exogenously specified by year and region.

5.3.1.1 Conversion Nodes

Conversion node efficiencies are calculated as the weighted averages of the online technology stocks. We use both stock and capacity factor terms because we want the energy-weighted efficiency, not capacity-weighted.

Equation 12

$$X_{ynr} = \sum_{t \in T} \sum_{v \in V} \frac{S_{tvyr} * u_{tvyr}}{\sum_{t \in T} \sum_{v \in V} S_{tvyr} * u_{tvyr}} * f_{tvnr}$$

Where

X_{ynr} = Input coefficients in year y of node n in region r

S_{tvyr} = Technology stock of technology t in year of vintage v in year y in region r

U_{tvyr} = Utilization rate, or capacity factor, of technology t of vintage v in year y in region r

f_{vntr} = Input requirements (efficiency) of technology t of vintage v using node n in region r

5.3.1.2 Blend Nodes

Blend node coefficients are user-determined. Blend measures determine the coefficients in each blend node in every year y and region r. Where measures haven't been specified, or are incomplete (i.e. coefficients don't sum to at least 1 as required) blend nodes have a user-specified "residual" supply node that supplies the remainder.

There are two blend nodes in the model that are treated differently than other blend nodes and both are related to the electricity dispatch functionality in EnergyPATHWAYS which will be described in further detail in the following sections. The primary purpose of the electricity dispatch functionality is to develop coefficients for the Electricity Blend Node and Thermal Dispatch Node.

5.3.1.2.1 Bulk Electricity Blend Node

The coefficients of the bulk electricity blend node, before EnergyPATHWAYS calculates an electricity dispatch, are user-determined. For example, a user may specify that they would like 50% of the bulk electricity energy to come from solar power plants and 50% of the energy to come from wind power plants. The electricity dispatch is used to calculate the feasibility of these selections given the hourly electricity profiles of the generation as well as the online balancing resources like energy storage, hydro, flexible electric fuel production (hydrogen electrolysis and power-to-gas), and flexible end-use loads. If sufficient balancing resources are available to balance the 50% wind and 50% solar system, in this case, then the coefficients of the node remain the same. If the dispatch finds, however, that residual thermal resources are required to supply electricity (i.e. the wind and solar generation cannot be completely balanced against demand) then the model calculates the need for residual energy supply from the Thermal Dispatch Node (which always functions as the residual node of the Bulk Electricity Blend Node). This results in a situation where the coefficients of the Bulk Electricity Blend Node are greater than 1 (.5 wind; .5 solar; >0 Thermal Dispatch). Coefficients greater than 1 in this case represent the curtailment of the unbalanced wind and solar generation.

5.3.1.2.2 Thermal Dispatch Node

Energy requirements of the Thermal Dispatch Node are determined in the electricity dispatch process briefly described above. The coefficients of the Thermal Dispatch Node are determined in the thermal dispatch, which occurs after all other electricity dispatch processes and functions as the residual to the electricity dispatch. In this process, the share of the Thermal Dispatch Node output that come from different thermal resources like gas combined-cycle generators, gas combustion turbines, and coal power plants is determined using an economic dispatch stack model. Given the resource stack online in a year y, the model determines the share of generation that comes from each input node to the Thermal Dispatch Node and also determines the capacity factor of every vintage v and technology t combination in that supply node. The thermal dispatch process, therefore, influences both the overall flow through each node as well as the capacity factor term (U) in the efficiency determination.

5.3.2 Energy Demands

5.3.2.1 Demand Mapping

To help develop the (d) term in the matrix calculations described in section 5.2, EnergyPATHWAYS must map the demand for energy carriers calculated on the demand-side to specific supply-nodes. In the simplified energy system example, electricity as a final energy carrier, for example, maps to the Electric Grid supply node.

5.3.2.2 Energy Export Specifications

In addition to demand-side energy requirements, the energy supply system must also meet export demands, that is demand for energy products that aren't used to satisfy endogenous energy service demands. These products aren't ultimately consumed in the model, but their upstream impacts must still be accounted for.

5.3.2.3 Total Demand

Total demand is therefore the sum of endogenous energy demands from the demand-side of EnergyPATHWAYS as well as any specified energy exports.

Equation 13

$$D_{yrn} = D_{yrn}^{end} + D_{yrn}^{exp}$$

Where

D_{yrn} = Total energy demand in year y in region r for supply node n

D_{yrn}^{end} = Endogenous energy demand in year y in region r for supply node n

D_{yrn}^{exp} = Export energy demand in year y in region r for supply node n

This total demand term is then multiplied by the inverted coefficient matrix to determine energy flows through each node.

5.4 Infrastructure Requirements

Infrastructure is represented only in delivery and conversion supply nodes. In delivery nodes, this infrastructure is represented at the aggregate node-level. In conversion nodes, infrastructure is represented in technology stocks similarly to stocks on the demand-side. The sections below detail the basic calculations used to determine the infrastructure capacity needs associated with energy flows through the supply node.

5.4.1 Delivery Nodes

The infrastructure capacity required is determined by Equation 14 below:

Equation 14

$$I_{yr} = \frac{E_{yr}}{u_{yr} * 8760}$$

Where

u_{yr}[17] = Utilization (capacity) factor in year y in region r

E_{yr} = Energy flow through node in year y in region r

h = Hours in a year, or 8760

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[17] Capacity factors of delivery nodes are endogenous inputs to the model except in the special cases of the Electricity Transmission Grid Node and the Electricity Distribution Grid node, where capacity factors are determined in the electricity dispatch.

5.4.2 Conversion Nodes

Conversion nodes are specified on a technology-basis, and a conversion node can contain multiple technologies to produce the energy flow required by the supply system. The operations of these nodes are analogous to the demand-side in terms of stock rollover mechanics, with sales shares and specified stock measures determining the makeup of the total stock. The only difference is that the size of the total stock is determined by the demand for energy production for the supply node, which is different than on the demand-side, where the size of the total stock is an exogenous input.

The formula to determine the size of the total stock remains the essentially the same as the one used to determine the size of the total delivery stock. However, the average cap factor of the node is a calculated term determined by the weighted average capacity factor of the stock in the previous year:

Equation 15

$$U_{yr} = \frac{\sum_{t\in T}\sum_{v\in V} S_{tvy-1r} * u_{tvyr}}{\sum_{t\in T}\sum_{v\in V} S_{tvy-1r}}$$

Where

U_{yr} = Utilization (capacity) factor in year y in region r

S_{tvy-1r} = Technology stock of technology t in year of vintage v in year y-1 in region r

u_{tvyr} = Utilization rate, or capacity factor, of technology t of vintage v in year y in region r

5.5 Emissions

There are two categories of greenhouse gas emissions in the model. First, there are physical emissions. These are traditional emissions associated with the combustion of fuels, and they represent the greenhouse gas emissions embodied in a unit of energy. For example, natural gas has an emissions rate of 53.06 kG/MMBTU of consumption while coal has an emissions rate of 95.52 kG/MMBTU. Physical emissions are accounted for on the supply-side in the supply nodes where fuels are consumed, which can occur in primary, product, delivery, and conversion nodes. Emissions, or consumption, coefficients, that is the units of fuel consumed can be a subset of energy coefficients. While the gas transmission pipeline may require 1.03 units of natural gas, it only consumes .03 units. Gas power plants, however, consume all 2.5 units of gas required. Equation 16 shows the calculation of physical emissions in a node:

Equation 16

$$G_{yr}^{phy} = \sum_{n \in N} X_{yrn}^{con} * E_{yr} * B_{yrn}^{phy}$$

Where

G_{yr}^{phy} = Physical greenhouse gas emissions in year y in region r

X_{yrn}^{con} = Consumption coefficients in year y in region r of node n

E_{yr}= Energy flow through node in year y in region r

B_{yrn}^{phy} = Emissions rates (emissions/energy) in year y in region r of input nodes n.

Emissions rates are either a function of a direct connection in the I/O matrix to a node with an emissions coefficient or they are "passed through" delivery nodes, which don't consume them. Gas powerplants in the supplied example take the emission rates from the Natural Gas Node, despite being linked in the I/O matrix only through the delivery node of Gas Transmission Pipeline.

The second type of emissions are accounting emissions. These are not associated with the consumption of energy products elsewhere in the energy system. Instead, these are a function of energy production in a node[18]. Accounting emissions rates are commonly associated with carbon capture and sequestration supply nodes or with biomass. Accounting emissions are calculated using:

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[18] For example, biomass may have a positive physical emissions rate, but if the biomass is considered to be zero-carbon, it would offset that with a negative accounting emissions rate. For accounting purposes, this would result in the Biomass Node showing negative greenhouse gas emissions and the supply nodes that use biomass, for example Biomass Power Plants, recording positive greenhouse gas emissions.

Equation 17

$$G_{yr}^{acc} = E_{yr} * B_{yrn}^{acc}$$

Where

G_{yr}^{acc} = Accounting greenhouse gas emissions in the node in year y in region r

E_{yr} = Energy flow through the node in year y in region r

B_{yr}^{acc} = Node accounting emissions rate

For primary, product, and delivery nodes, the accounting emissions rate in year y in region r is exogenously specified. For conversion nodes, this is an energy-weighted stock average.

$$B_{yr}^{acc} = \frac{\sum_{t \in T} \sum_{v \in V} S_{tvyr} * b_{tvyr}^{acc}}{\sum_{t \in T} \sum_{v \in V} S_{tvyr}}$$

Where

B_{yr}^{acc} = Energy weighted average of node accounting emissions factor in year y in region r

S_{tvyr} = Stock of technology t of vintage v in year y in region r

b_{tvyr}^{acc} = Exogenous inputs of accounting emissions rate for technology t of vintage v in year y in region r

5.6 Costs

Costs are calculated using different methodologies for those nodes with infrastructure (delivery, conversion, and electric storage) and those without represented infrastructure (primary and product).

5.6.1 Primary and Product Nodes

Primary and product nodes are calculated as the multiplication of the energy flow through a node and an exogenously specified cost for that energy.

$$C_{yr} = E_{yr} * w_{yr}$$

Where

C_{yr} = total costs of supplying energy from node in year y in region r

E_{yr}= Energy flow through node in year y in region r

w_{yr}= Exogenous cost input for node in year y in region r

5.6.2 Delivery Nodes

Delivery node cost inputs are entered as per-energy unit tariffs. We use and adjust for any changes for the ratio of on-the-books capital assets and node throughput. This is done to account for dramatic changes in the utilization rate of capital assets in these nodes. This allows EnergyPATHWAYS to calculate and demonstrate potential death spirals for energy delivery systems, whereas the demand for energy from a node declines faster than the capital assets can depreciate. This pegs the tariff of the delivery node to the existing utilization rates of capital assets and increases them when that relationship diverges.

Equation 18

$$C_{yr} = \left(\frac{\frac{S_{yr}}{S_{yr}^{fin}}}{\sum_{y\in 1}\frac{S_{yr}}{S_{yr}^{fin}}} * \frac{\sum_{y\in 1} u_{yr}}{u_{yr}} * q * w_{yr} + (1-q) * w_{yr} \right) * E_{yr}$$

Where

C_{yr} = Total costs of delivery node in year y in region r

S_{yr}= Physical stock of delivery node in year y in region r

S_{yr}^{fin} = Financial stock of delivery node in year y in region r

u_{yr} = Exogenously specified utilization rate of delivery node in year y in region r

q = Share of tariff related to throughput-related capital assets, which are the only share of the tariff subjected to this adjustment.

w_{yr} = Exogenous tariff input for delivery node in year y in region r

E_{yr} = Energy flow through node in year y in region r

5.6.3 Conversion Nodes

Conversion node cost accounting is similar to the cost accounting of stocks on the demand-side with terms for capital, installation, and fixed O&M cost components. Instead of fuel switching costs, however the equation substitutes a variable O&M term.

Equation 19

$$C_{yr}^{stk} = C_{yr}^{cap} + C_{yr}^{ins} + C_{yr}^{fom} + C_{yr}^{vom}$$

Where

C_{yr}^{stk} = Total levelized stock costs in year y in region r

C_{yr}^{cap} = Total levelized capital costs in year y in region r

C_{yr}^{ins} = Total levelized installation costs in year y in region r

C_{yr}^{fom} = Total fixed operations and maintenance costs in year y in region r

C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r

There is no difference in the calculation of the capital, installation, and fixed O&M terms from the demand-side, so reference calculation for calculating those components of technology stocks in section 4.2.2.1.

5.6.3.1 Variable O&M Costs

Variable O&M costs are calculated as the energy weighted average of technology stock variable O&M costs.

$$C_{yr}^{vom} = \sum_{t \in T} \sum_{v \in V} \frac{S_{tvyr} * u_{tvyr}}{\sum_{t \in T} \sum_{v \in V} S_{tvyr} * u_{tvyr}} * w_{tvry}^{vom} * E_{yr}$$

Where

C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r

S_{tvyr} = Technology stock of technology t in year of vintage v in year y in region r

U_{tvyr} = Utilization rate, or capacity factor, of technology t of vintage v in year y in region r

w_{tvry}^{vom} = Exogenous input of variable operations and maintenance costs for technology t of vintage v in region r in year y

E_{yr} = Energy flow through node in year y in region r

5.6.4 Electric Storage Nodes

Electric storage nodes are a special case of node used in the electricity dispatch. They add an additional term, which is a capital energy cost, to the equation used to calculate the costs for conversion nodes. This is the cost for the storage energy capacity, which is additive with the storage power capacity.

$$C_{yr}^{stk} = C_{yr}^{cap} + C_{yr}^{ecap}\ C_{yr}^{ins} + C_{yr}^{fom} + C_{yr}^{vom}$$

Where

C_{yr}^{stk} = Total levelized stock costs in year y in region r

C_{yr}^{cap} = Total levelized capital costs in year y in region r

C_{yr}^{ecap} = Total levelized energy capital costs in year y in region r

C_{yr}^{ins} = Total levelized installation costs in year y in region r

C_{yr}^{fom} = Total fixed operations and maintenance costs in year y in region r

C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r

5.6.4.1 Energy Capacity Costs

Energy storage nodes have specified durations, defined as the ability to discharge at maximum power capacity over a specified period of time, and also have an input of energy capital costs, which are levelized like all capital investments.

Equation 20

$$C_{yr}^{ecap} = \sum_{v \in V} \sum_{t \in T} S_{tvyr}^{fin} * d_t * W_{tvr}^{ecap}$$

Where

C_{yr}^{ecap} = Total levelized energy capacity capital costs in year y in region r

W_{tvr}^{ecap} = Levelized energy capacity capital costs for technology t for vintage v in region r

d_t = Exogenously specified discharge duration of technology t

S_{tvyr}^{fin} = Financial stock of technology t and vintage v in year y in region r

6. Regional Investment and Operations Platform and EnergyPATHWAYS integration

EnergyPATHWAYS is a scenario analysis tool, with a focus on detailed and explicit accounting of energy system decisions. There are advantages, however, in employing optimization approaches for a more limited subset of energy system decisions. The Regional Investment and Operations (RIO) platform is a complementary optimization approach where we develop a subset of decisions on the energy supply-side that benefit from linear optimization techniques to develop a co-optimization of fuel and supply-side infrastructure decisions under different scenarios of energy demand and emissions constraints. RIO is utilized to inform two types of EnergyPATHWAYS measures:

- **Stock Measures**

RIO can be used to optimize capacity decisions in electricity generation (e.g. wind, solar, etc.), electricity storage, and fuel conversion processes.

- **Blend Measures**

RIO can also be used to optimize blend ratios for fuel. This allows for optimal determinations of bio-based, fossil-based, or electrically produced fuels (i.e. hydrogen, or power-to-gas synthetic natural gas).

RIO is also used as the tool for assessing the reliability of the electricity system, with hourly dispatch representations for all zones and resources including thermal, electricity storage, fixed output (i.e. renewables), and flexible loads (fuel production, direct air capture, etc.)

6.1 EnergyPATHWAYS/RIO Integration

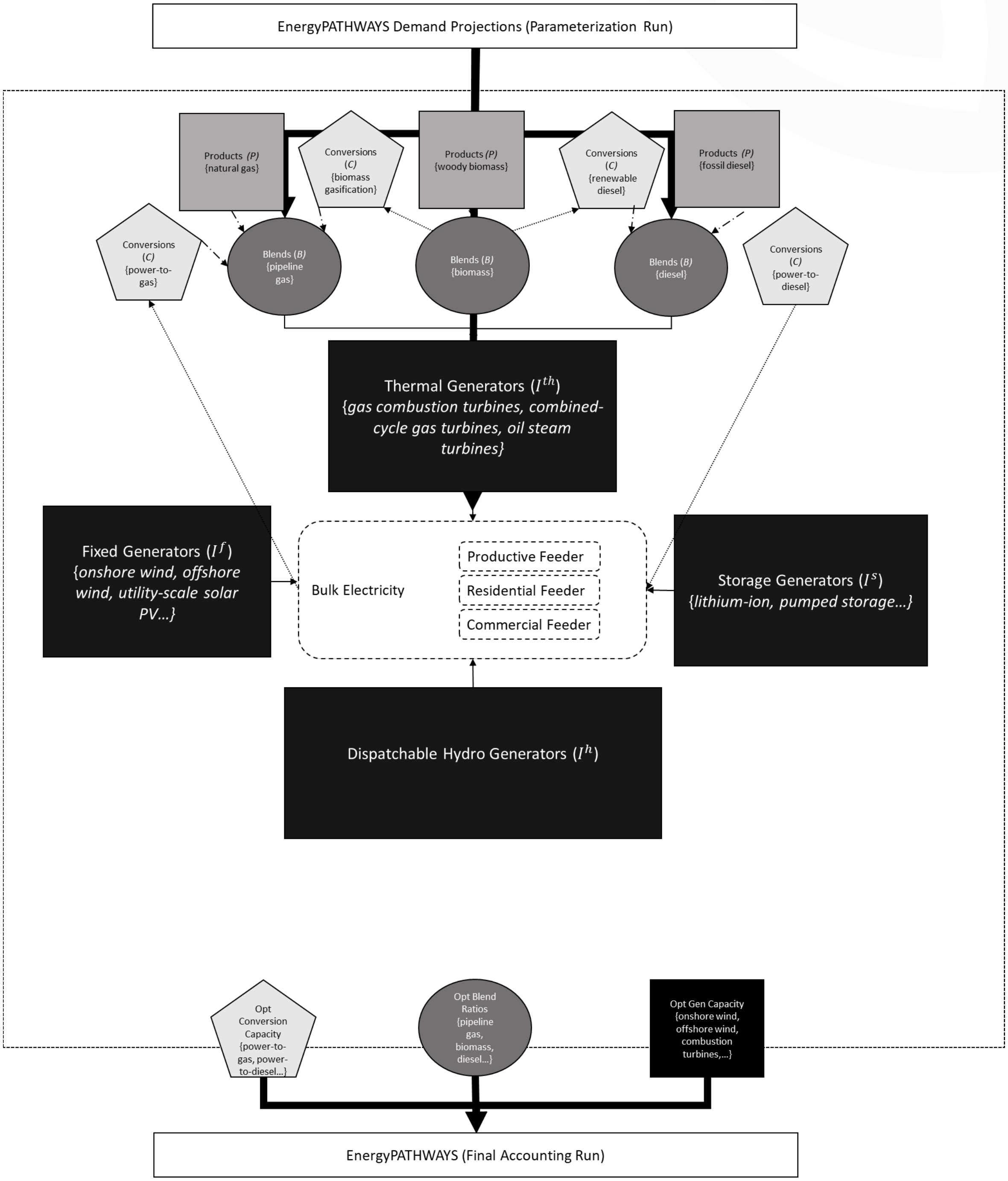
The EnergyPATHWAYS/RIO integration is a multi-step process where:

- EnergyPATHWAYS is used to define energy demand scenarios as parameterizations for RIO optimizations.
- RIO is used to optimize investments in EnergyPATHWAYS conversion supply nodes and determine optimal blends of fuel components.
- Optimized energy decisions are returned to EnergyPATHWAYS where they are input into the EnergyPATHWAYS accounting framework as stock measures or blend measures. This allows us to validate and represent the optimal scenario with the comprehensive accounting detail of EnergyPATHWAYS.

6.2 RIO Features

The following sections will detail the specific features of the RIO optimization framework. The model is designed with a focus on electricity system operations and reliability. It also integrates fuels module that optimizes fuel production capacity expansion, storage, and use under emissions constraints.

Figure 34 EnergyPATHWAYS/RIO Integration Schematic

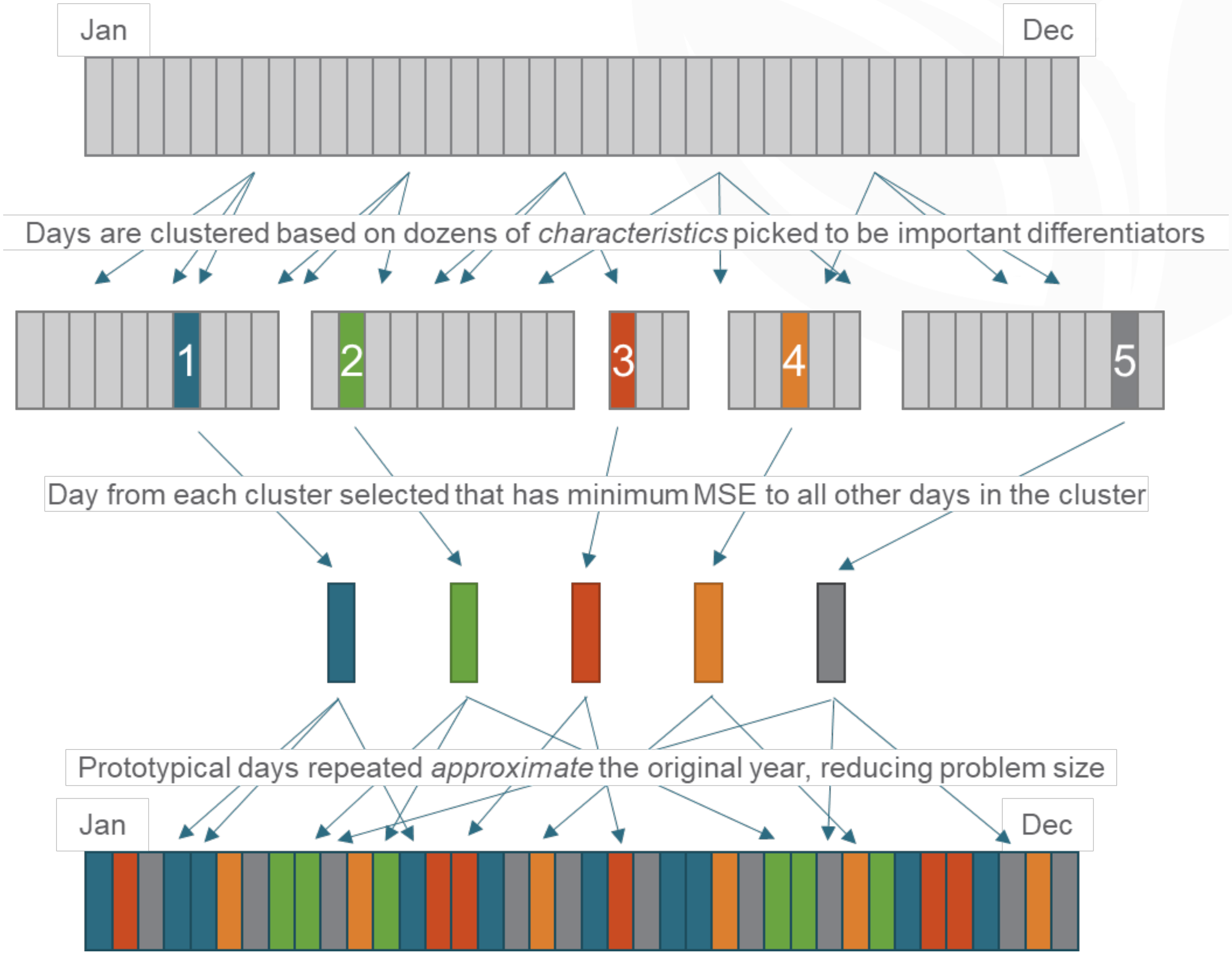


6.2.1 Operations days selection

RIO utilizes the 8760 hourly profiles for electricity demand and generation from EnergyPATHWAYS and optimizes operations for a subset of representative days (sample days) and maps them to the rest of the year. Operations are performed over sequential hourly timesteps. To ensure that the sample days can reasonably represent the full set of days over the year, RIO uses clustering algorithms on the initial 8760 data sets. The clustering process is designed to identify days that represent a diverse set of potential system conditions, including different fixed generation profiles and load shapes. The number of sample days impacts the total runtime of the model. A balance is struck in the day selection process between representation of system conditions through number of sample days, and model runtime. Clustering and sample day selection occurs for each model year in the time horizon. This process is shown in *Figure 35* below. The starting dataset is the EnergyPATHWAYS load and generation shapes, scaled to system conditions for the model year being sampled and mapped. Load shapes come directly from EnergyPATWHAYS accounting runs. The coincidence of fixed generation profiles (i.e. renewables) and load determine when important events for investment decision making occur during the year. For example, annual peak load and low load events may be the coincident occurrence of relatively high loads and relatively low renewables, and the inverse, respectively. However, renewable build is determined by RIO decision making. To ensure that the sample days in each model year are representative of the events that define investment decisions, renewable scaling happens for expected levels of renewables in future years as well as a range of renewables proportional builds (for example, predominantly wind, predominantly solar). The sample days are then selected to be representative of system conditions under all possible renewable build decisions by RIO.

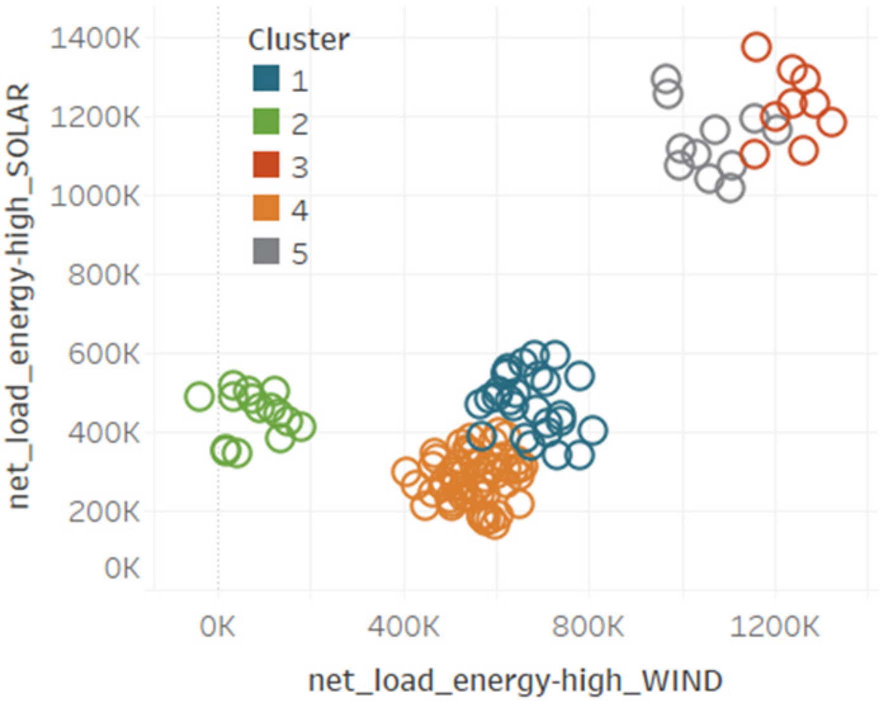
As *Figure 35* shows, the scaled historical days are clustered based on a number of characteristics. These include different metrics describing every day in the data set. Examples include peak daily load, peak daily net load, lowest daily solar output, largest daily ramping event etc. The result is a set of clusters of days with similar characteristics. One day within each cluster is selected to represent the rest by minimizing mean square error (MSE). As described in the previous section, RIO determines short-term operations for each of these representative days. For long-term operations, each representative day is mapped back to the chronological historical data series, with the representative day in place of every other day from its cluster.

Figure 35 Conceptual diagram of sampling and day matching process



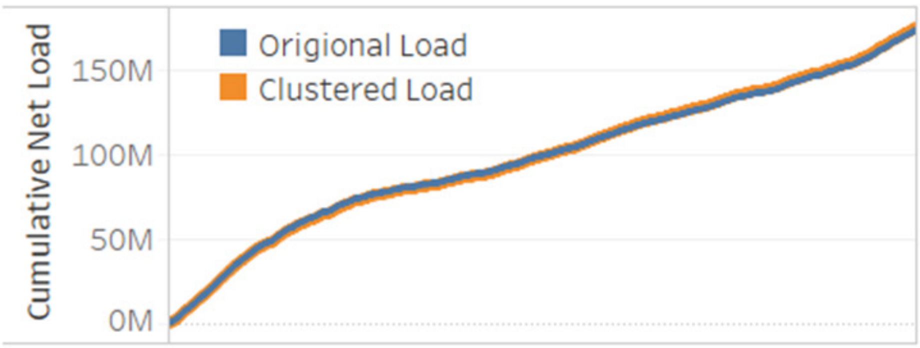
The clustering process depends on many characteristics of the coincident load and renewable shapes and uses statistical clustering algorithms to determine the best set of sample days. *Figure 36* shows a simple, two characteristic, example of clustering. In this case the two characteristics are net load with high proportional solar build and net load with high proportional wind build. It is important to select sample days that both represent the full spectrum of potential net load, as well as be representative for both the solar and the wind case. The clustering algorithm has identified 5 clusters (a low number, but appropriate for the conceptual example) that ensure the sample days will represent the full range of net load differences among days and remain representative regardless of whether RIO chooses to build a high solar system or a high wind system.

Figure 36 Simple, two characteristic, example of clustering



Mapping the clustered days back to the chronological historical dataset, the newly created year of sample days can be validated by checking that metrics describing the original historical dataset match those of the new set. Cumulative net load in Figure 37 is one example. These are related to the characteristics used to select the sample days in the clustering process such as peak load, largest ramp etc. and the distribution of these over the whole year.

Figure 37 Comparison of original and clustered load



6.2.2 Operations

Time sequential operations are an important component of determining value of a portfolio of resources[19]. All resources have a set of attributes they can contribute to the grid, including, for example, energy, capacity, ancillary services, and flexibility. They work in complimentary fashion to serve the needs of the system. Whether a portfolio of resources is optimal or not depends on whether it can maintain system reliability, and whether it is cheaper than other portfolios. RIO determines the least cost dispatch for each one of the sample days to determine the least cost investments to make.

Operations are split into short-term and long-term operations in RIO. This is a division between those resources that do not have any multiday constraints on their operations, i.e. they can operate in the same way regardless of system conditions, and those resources that will operate differently depending on system condition trends that last longer than a day. An example of the former is a gas generator that can produce the same output regardless of system conditions over time, and an example of the latter is a long-duration storage system whose state of charge is drawn down over time when there is not enough energy to charge it. The long-term category includes all long-term storage mediums.

Operational decisions determine the value of one investment over another, so it is important to capture the detailed contributions and interactions of the many different types of resource that RIO can build.

Important factors captures in operations are:

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[19] Though typically an hour, the timestep of time sequential operations can be set to any length of time. For example, investment decisions in some systems may be insensitive to whether the time step is 1 hour or 2 hours. Having the option of setting timestep length for operations is another way of reducing model computation while preserving detail around important model components.

- Maximum operating levels – how many resources are needed to meet peak load conditions?
- Planning reserves – are there enough resources to meet planning reserve margins?
- Energy – what resources are required to ensure total daily energy budgets are met?

RIO can constrain operations based on constraints that are similar to those used in production simulation. These include:

- Resource minimum and maximum generation levels
- Resource efficiency at different set points
- Thermal generator linearized commitment constraints
- Start up and shut down costs
- Resource must run schedules
- Resource contribution to reserves
- Storage charge and discharge constraints
- Storage efficiency constraints
- Energy budgets and operational constraints for hydro resources

Figure 38 below shows a conceptual daily dispatch. Thermal generation minimum generation level is constrained by Pmin and must run. RIO trades off the cost of starting up and shutting down generation, the available generator headroom for reserves, and the efficiency of operating the generators at sub optimal set points to find the best thermal generator dispatch. The short-term storage reservation is also optimally dispatched. These operational decisions drive concurrent capacity build decisions by determining the relative value of different potential resources.[20]

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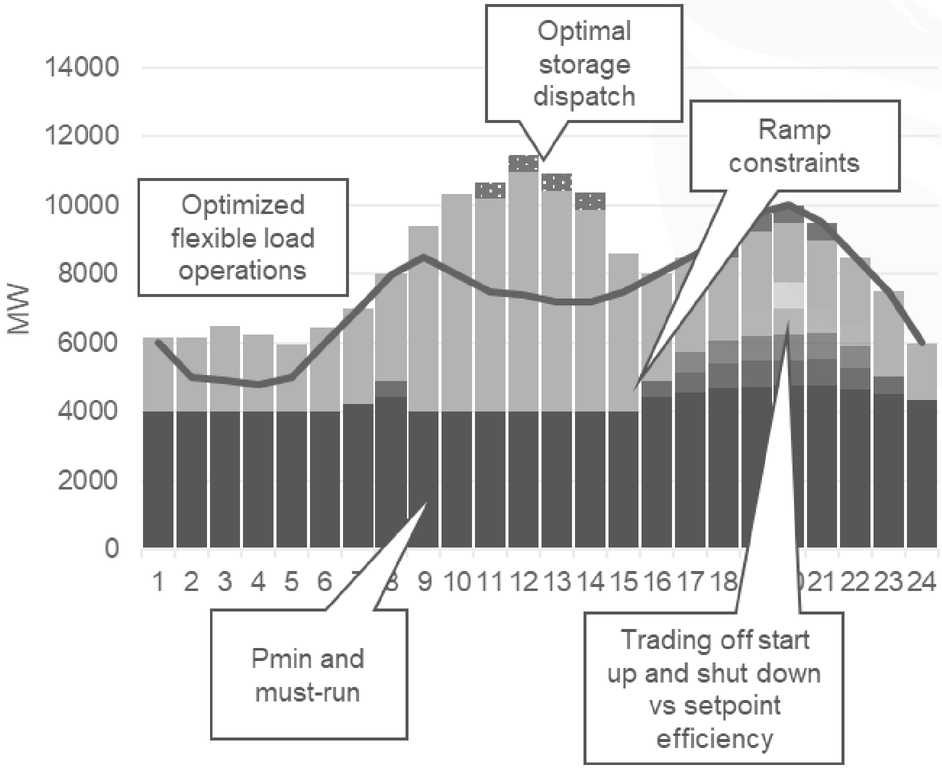
[20] In this integration with EnergyPATHWAYS, RIO is configured to run without enforcing constraints on thermal operating states. This means that constraints for minimum generation

Figure 38 Example RIO daily dispatch



6.2.2.1 Thermal Generator Operations

To reduce runtimes, generators are aggregated in RIO by common operating and cost attributes. These are by technology and vintage when the operating costs and characteristics vary significantly by installation year. Each modeled aggregation of generators contains a set of identical generators.

6.2.2.2 Hydro Operating Constraints

Hydro behavior is constrained by historical data on how fast the hydro system can ramp[21], the minimum and maximum discharge by hour, and the degree to which hydro energy can be shifted from one period to another. Summed daily hydro output over user defined periods of

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levels; startup and shutdown costs; efficiency penalties for deviation from optimal generator setpoints; and operating reserves are not included.

[21] Hydro ramp constraints not enforced in this integration

the year must fall within a cumulative energy envelope. For example, the energy envelope could be defined by 4 seasons: spring, summer, autumn, and winter. In this case, the cumulative energy envelope would have 4 sets of upper and lower bounds that constrain energy release in each period.

6.2.2.3 Storage Operating Constraints

Storage is constrained by maximum discharge rates dependent on built capacity. In addition, the model tracks storage state of charge hour to hour, including losses into and out of the storage medium. Storage, like all technologies, is dispatched with perfect foresight. Storage can operate through both short term and long term operations. In short term operations, storage is dispatched on an hourly basis within each sample day, as with all other dispatchable technology types. Short term storage dispatch shifts energy stored within a sample day and discharges it within the same sample day, such that the short term storage device is energy neutral across the day. In long term operations, storage can charge energy on one day and discharge it into another. This allows for optimal use of storage to address longer cycle reliability needs, such as providing energy on low renewable generation days, and participation in longer cycle energy arbitrage opportunities.

6.2.3 Planning reserve

Planning reserve is defined for each zone. A planning demand is specified for every hour that is equal to the demand in that hour net of the dependable contribution by local resources and flexible loads. The planning demand has to be met or exceeded by the contribution from system level resources that are also adjusted for dependability. Dependability is defined as the fraction of nameplate capacity of each resource that can be relied upon during peak load events. In this integration, we do not assume additional dependability derates on renewables past the coincidence of their generation profiles. For thermal resources, we assume derates equal to their forced outage rates.

6.2.4 Resource build decisions

Concurrently with optimal operational decisions, the model makes resource build decisions that together produce the lowest total system cost. There are three modes for resource build decisions, specified by aggregate generator. In all modes, the addition of new capacity is limited by the rate at which capacity can be constructed year on year, and the total quantity of capacity that can be constructed by a future year. The model builds resources when needed and those resources remain through the end of their useful life when they are retired. Resources are not economically retired early, repowered, or extended. Generators using this mode are built on top of a predefined MW schedule of existing resources in every year.

6.2.5 Transmission constraints

Transmission flows are constrained by the capacity of the line. If optimal transmission build by RIO is selected as an option, transmission additions are equal in flow capacity in both directions of the line. However, existing transmission does not have to have equally sized paths in each direction. Transmission additions are capped by a maximum addition by path and year.

The user specifies a schedule of transmission path flow capacities for every model year in the future. RIO can run with fixed transmission schedules or the user can select optimal transmission expansion.

6.2.6 Local Transmission and Distribution Capacity

RIO can incorporate local distribution feeders that are representative of the distribution system as a whole. These can be specified in different ways, for example representative urban and rural, or set of feeders representing different customer classes could be used. The constraints on local capacity track the local loads on the feeder. These net local generation from the local load shape and determine whether transmission capacity additions are needed to serve local load. Upgrade costs are determined as a penalty function for additional MW of local capacity.

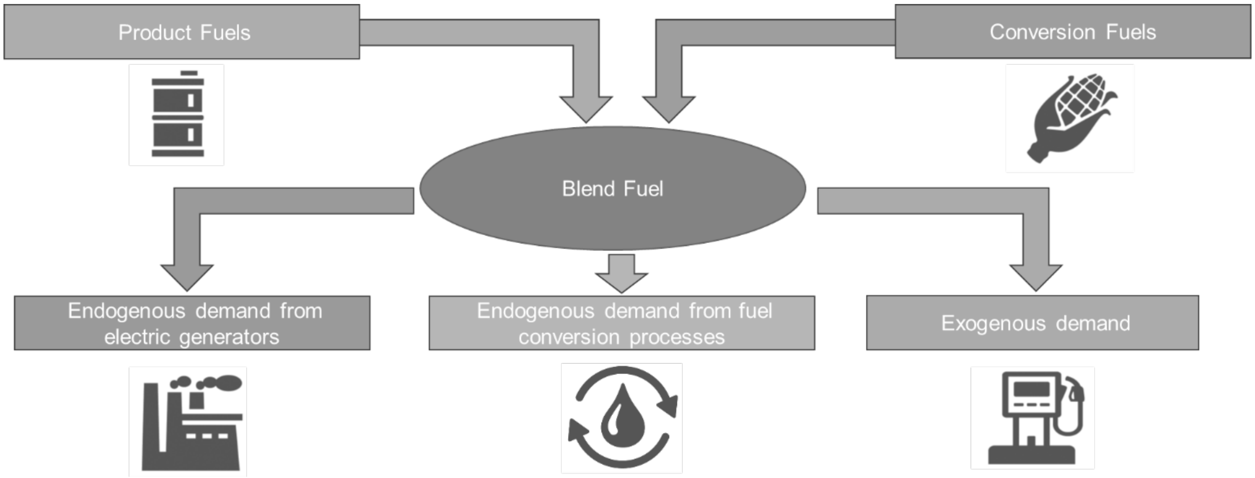
6.2.7 Emissions cap/Emissions cost

As options, the user can include an emissions cap or an emissions cost to simulate future policy. Emissions accounting works through the fuel consumed by generators rather than the generators themselves. The total emissions are therefore the emissions factor per MMBTU of each fuel multiplied by the total consumption of that fuel, respectively.

6.2.8 Fuels

In addition to generator operating decisions, RIO also optimizes the fuel blend that a generator is eligible to receive, while also allowing fuels produced by electricity to contribute to fuel stocks. This functionality is what allows RIO to extend beyond the electricity sector and optimize the entire energy supply side. Fuels can come from conventional fuel products (product fuels) or through converting something else into fuel using electricity (conversion fuels). By fueling generation with eligible blends, created from fuels that each have their own cost trajectory over time, or conversion infrastructure capacity costs, RIO can optimize the fuels burned as well as the generator investments and operations to burn them. One use of this is the realistic transition to clean fuels where fuel blends begin to include biofuels, and generation investments and operational decisions are driven by the changing costs of the blend over a generator's lifetime.

Figure 39 RIO fuels schematic



7. United States EnergyPATHWAYS Database

The database of the United States energy economy used in this analysis has high geographical resolution on technology stocks; technology cost and performance; built infrastructure and resource potential as well as high temporal resolution on electricity loads by end-use as well as renewable generation profiles. EnergyPATHWAYS leverages many of the same input files used to populate the National Energy Modeling System (NEMS) used by the United States Energy Information Administration (EIA) to forecast their Annual Energy Outlook.

The model of the U.S. energy economy is separated into 65 energy-using demand subsectors. Subsectors, like residential space heating, represent energy-use associated with the performance of an energy-service. A description of the methods EnergyPATHWAYS use to project energy-service demands, energy demands, and ultimately cost and emissions associated with the performance of that service is found in Demand. On the supply-side, the model is separated into interconnected nodes, which are associated with the production, transformation, and delivery of energy to demand subsectors. A description of how the data described in this section is used in the model calculations is found in the above sections.

7.1 Demand – Side Data Description

Table 10 lists all the subsectors in the US Database grouped by demand sector. It also specifies the methodology used to calculate energy demand in each subsector.

Table 10 Sectors, subsectors, and method of demand energy projection

Sector	Subsector	Method
residential	residential water heating	B
residential	residential furnace fans	D
residential	residential clothes drying	A
residential	residential dishwashing	A
residential	residential refrigeration	A
residential	residential freezing	A
residential	residential cooking	B
residential	residential secondary heating	D
residential	residential other appliances	D
residential	residential clothes washing	A
residential	residential lighting	A
residential	residential other - electric	D
residential	residential air conditioning	B
residential	residential space heating	B
commercial	commercial water heating	A
commercial	commercial ventilation	A

commercial	office equipment (p.c.)	D
commercial	office equipment (non-p.c.)	D
commercial	commercial space heating	A
commercial	commercial air conditioning	A
commercial	commercial lighting	A
commercial	district services	D
commercial	commercial refrigeration	A
commercial	commercial cooking	A
commercial	commercial other	D
transportation	heavy duty trucks	A
transportation	international shipping	D
transportation	recreational boats	D
transportation	transit buses	A
transportation	military use	D
transportation	lubricants	D
transportation	medium duty trucks	A
transportation	aviation	C
transportation	motorcycles	D
transportation	domestic shipping	D
transportation	passenger rail	C
transportation	school and intercity buses	A
transportation	freight rail	C
transportation	light duty trucks	A
transportation	light duty autos	A
industry	metal and other non-metallic mining	D
industry	aluminum industry	D

industry	balance of manufacturing other	D
industry	plastic and rubber products	D
industry	wood products	D
industry	bulk chemicals	D
industry	glass and glass products	D
industry	cement	D
industry	industrial space heating	B
industry	agriculture-other	D
industry	industrial drying	B
industry	industrial curing	B
industry	industrial machine drives	B
industry	agriculture-crops	D
industry	fabricated metal products	D
industry	machinery	D
industry	computer and electronic products	D
industry	transportation equipment	D
industry	construction	D
industry	iron and steel	D
industry	food and kindred products	D
industry	paper and allied products	D
industry	industrial boilers	B
industry	electrical equip., appliances, and components	D
industry	industrial process heat	B

The methods for representing demand-side subsectors are described in section 107. *Table 11* describes the input data used to populate stock representations in the subsectors that employ Method A. and *Table 13* describes the energy service demand inputs.

Table 11 Demand stock data

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Source
Residential Lighting	Bulbs per housing unit	No	Total square footage	US	2012	(U.S. Energy Information Administration 2017)
Residential Clothes Washing	Clothes washer	No	Households	Census division	2009	(U.S. Energy Information Administration 2013)
Residential Clothes Drying	Clothes dryer	No	Households	Census division	2009	(U.S. Energy Information Administration 2013)
Residential Dishwashing	Dishwashers per household	No	Households	Census division	2009	(U.S. Energy Information Administration 2013)
Residential Refrigeration	Cubic feet	No	Households	Census division	2009	(U.S. Energy Information Administration 2013)
Residential Freezing	Cubic feet	No	Households	Census division	2009	(U.S. Energy Information Administration 2013)
Commercial Water Heating	Capacity factor	No	Com square feet	Census division	2012	(U.S. Energy Information Administration 2012)
Commercial Space Heating	Capacity factor	No	Com square feet	Census division	2012-2013	(U.S. Energy Information Administration 2012)
Commercial Air Conditioning	Capacity factor	No	Com square feet	Census division	2012	(U.S. Energy Information Administration 2012)
Commercial Lighting	Capacity factor	No	n/a	Census division	2012	(U.S. Energy Information Administration 2012)
Commercial Refrigeration	Capacity factor	No	Com square feet	Census division	2012	(U.S. Energy Information Administration 2012)
Commercial Cooking	Capacity factor	No	Com square feet	Census division	2012	(U.S. Energy Information Administration 2012)
Commercial Ventilation	Capacity factor	No	Com square feet	Census division	2012	(U.S. Energy Information Administration 2012)

Light Duty Autos	Car per mile travelled	Yes	n/a	US	2012; 2020; 2030; 2040	(U.S. Energy Information Administration 2015)
Light Duty Trucks	Truck per mile travelled	Yes	n/a	US	2012; 2020; 2030; 2040	(U.S. Energy Information Administration 2015)
Medium Duty Trucks	Truck	Yes	n/a	US	2015	(TA Engineering Inc. 2012)
Heavy Duty Trucks	Truck	Yes	n/a	US	2011	(TA Engineering Inc. 2012)
Transit Buses	Bus	Yes	n/a	US	2014	(Brooker et al. 2015)

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Source
Residential Lighting	klm-hr per housing unit	No	Total square feet	US	2012	(Ashe et al. 2012)
Residential Clothes Washing	Cu. Ft. Cycle	Yes	n/a	Census division	2009	(U.S. Energy Information Administration 2013)
Residential Clothes Drying	Pound	Yes	n/a	Census division	2009	(U.S. Energy Information Administration 2013)
Residential Dishwashing	Cycle	Yes	n/a	Census division	2009	(U.S. Energy Information Administration 2013)
Residential Refrigeration	Cu. Ft.	Yes	n/a	Census division	2009	(U.S. Energy Information Administration 2013)
Residential Freezing	Cu. Ft.	Yes	n/a	Census division	2009	(U.S. Energy Information Administration 2013)
Commercial Water Heating	Terabtu	No	Com square feet	Census division	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Space Heating	Terabtu	No	Com square feet	Census division	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Air Conditioning	Terabtu	No	Com square feet	Census division	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Lighting	gigalumen_year	No	Com square feet	Census division	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Refrigeration	Terabtu	No	Com square feet	Census division	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Cooking	Terabtu	No	Com square feet	Census division	2012 - 2050	(U.S. Energy Information Administration 2017)

Commercial Ventilation	gigacubic_foot	No	Com square feet	Census division	2012 - 2050	(U.S. Energy Information Administration 2017)
Light Duty Autos	Gigamile	No	n/a	US	2007; 2015-2050	(U.S. Energy Information Administration 2017)
Light Duty Trucks	Gigamile	No		US	2012-2050	(U.S. Energy Information Administration 2017)
Medium Duty Trucks	Mile	No		US	2015-2050	(U.S. Energy Information Administration 2017)
Heavy Duty Trucks	Mile	No	N/A	US	2015-2050	(U.S. Energy Information Administration 2017)
Transit Buses	Mile	No	Population	Census division	1995-2008	(U.S. Energy Information Administration 2017)

Demand subsectors with technology stock also require technology-specific parameters for cost and performance. These input sources by subsector and technology-type are show below in *Table 12*.

Table 12 Demand technology inputs

Subsector	Technologies	Source
Residential Space Heating and Air Conditioning	Air source heat pump (ducted)	Cost: (Jadun et al. 2017) Efficiency: NREL building simulations in support of (Jadun et al. 2017)
	Ductless mini-split heat pump	Cost: (Dentz, Podorson, and Varshney 2014) Efficiency: NREL building simulations in support of (Jadun et al. 2017)
	Remainder	(Navigant 2014)
Residential Water Heating	Heat pump water heater	(Jadun et al. 2017)
	Remainder	(Navigant 2014)
Residential Remaining Subsectors	All	(Navigant 2014)
Commercial Space Heating and Air Conditioning	Air source heat pump	(Jadun et al. 2017)
	Remainder	(Navigant 2014)
Commercial Water Heating	Heat pump water heater	(Jadun et al. 2017)

	Remainder	(Navigant 2014)
Commercial Lighting	All	(U.S. Energy Information Administration 2017)
Commercial Building Shell	All	(U.S. Energy Information Administration 2017)
Light-duty Vehicles	Battery electric vehicle and plug-in hybrid electric vehicle	(Jadun et al. 2017)
	Hydrogen fuel cell vehicle	(TA Engineering Inc. 2012)
	Remainder	Efficiency: (Navigant 2014) Cost: (TA Engineering Inc. 2012)
Medium Duty Vehicles	Battery electric	(Jadun et al. 2017)
	Hydrogen fuel cell	(den Boer et al. 2013)
	Remainder (CNG, diesel, etc.)	(TA Engineering Inc. 2012)
Heavy Duty Vehicles	Battery electric	(Jadun et al. 2017)
	Hydrogen fuel cell	(Fulton and Miller 2015)
	Reference diesel, gasoline and propane	(TA Engineering Inc. 2012)
	Diesel hybrid and liquefied pipeline gas	(TA Engineering Inc. 2012)
Transit Buses	All	(Jadun et al. 2017; Brooker et al. 2015)
Industrial Space Heating	Air source heat pump	(Jadun et al. 2017)
	Furnace	(Navigant 2014))
Industrial Boilers	All	(Jadun et al. 2017)
Industrial Process Heat	All	(Jadun et al. 2017)
Industrial Curing	All	(Jadun et al. 2017)
Industrial Drying	All	(Jadun et al. 2017)
Industrial Machine Drives	All	(Jadun et al. 2017)

Table 13 Service demand inputs

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Downscaling method	Input Data: Year(s)	Source
Residential Lighting	klm-hr per housing unit	No	Total sq ft	US	Households 2010	2012	(Ashe et al. 2012)
Residential Clothes Washing	Cu. Ft. Cycle	Yes	n/a	Census division	Stock	2009	(U.S. Energy Information Administration 2013)
Residential Clothes Drying	Pound	Yes	n/a	Census division	Stock	2009	(U.S. Energy Information Administration 2013)
Residential Dishwashing	Cycle	Yes	n/a	Census division	Stock	2009	(U.S. Energy Information Administration 2013)
Residential Refrigeration	Cu. Ft.	Yes	n/a	Census division	Stock	2009	(U.S. Energy Information Administration 2013)
Residential Freezing	Cu. Ft.	Yes	n/a	Census division	Stock	2009	(U.S. Energy Information Administration 2013)
Commercial Water Heating	Terabtu	No	Com square feet	Census division	Employment in all industries (NAICS, no code) 2007	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Space Heating	Terabtu	No	Com square feet	Census division	HDD x com_sq_ft	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Air Conditioning	Terabtu	No	Com square feet	Census division	CDD x com_sq_ft	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Lighting	gigalumen_year	No	Com square feet	Census division	Employment in all industries (NAICS, no code) 2007	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Refrigeration	Terabtu	No	Com square feet	Census division	Employment in all industries (NAICS, no	2012 - 2050	(U.S. Energy Information Administration

					code) 2007		2017)
Commercial Cooking	Terabtu	No	Com square feet	Census division	Employment in all industries (NAICS, no code) 2007	2012 - 2050	(U.S. Energy Information Administration 2017)
Commercial Ventilation	gigacubic_foot	No	Com square feet	Census division	Employment in all industries (NAICS, no code) 2007	2012 - 2050	(U.S. Energy Information Administration 2017)
Light Duty Autos	Gigamile	No	MD + HD VMT Historical	US	LDV VMT Share	2007; 2015-2050	(U.S. Energy Information Administration 2017)
Light Duty Trucks	Gigamile	No	MD + HD VMT Historical	US	LDV VMT Share	2012-2050	(U.S. Energy Information Administration 2017)
Medium Duty Trucks	Mile	No	gasoline sales volumes	US	MDV VMT Share	2015-2050	(U.S. Energy Information Administration 2017)
Heavy Duty Trucks	Mile	No		US	HDV VMT Share	2015-2050	(U.S. Energy Information Administration 2017)
Transit Buses	Mile	No	Population	Census division	Square miles	1995-2008	(U.S. Energy Information Administration 2017)

Table 14 describes stock input data sources for subsectors that uses Method B (0). *Table 15* describes energy demand input sources.

Table 14 Equipment stock data sources for Method B subsectors

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Downscaling method	Input Data: Year(s)	Source
Residential Water Heating	Water heater	No	Households	Census division	Households 2010	2009	(U.S. Energy Information Administration 2013)
Residential Space Heating	Space heater	No	Households	Census division	Households 2010	2009-2015	(U.S. Energy Information Administration 2017)

Residential Air Conditioning	Air conditioner	No	Households	Census division	Households 2010	2009	(U.S. Energy Information Administration 2013)
Residential Cooking	Cooktop	No	Households	Census division	Households 2010	2009	(U.S. Energy Information Administration 2013)
Industrial Boilers	Capacity factor[22]	Yes	n/a	US	Value of Shipments	2015	By Assumption
Industrial Process Heat	Capacity factor	Yes	n/a	US	Value of Shipments	2015	By Assumption
Industrial Space Heating	Capacity factor	Yes	n/a	US	Value of Shipments	2015	By Assumption
Industrial Machine Drives	Capacity factor	Yes	n/a	US	Value of Shipments	2015	By Assumption
Industrial Curing	Capacity factor	No	n/a	US	Value of Shipments	2015	By Assumption
Industrial Drying	Capacity factor	No	n/a	US	Value of Shipments	2015	By Assumption

Table 15 Energy demand data sources for Method B subsectors

Subsector	Unit	Driver	Input Data: Geography	Downscaling method	Input Data: Year(s)	Source
Residential Water Heating	MMBTU	Households	Census division	Households 2010	2009	(U.S. Energy Information Administration 2013)
Residential Space Heating	MMBTU	HDD; occupied square feet	Census division	HDD x residential square footage	2009-2015	(U.S. Energy Information Administration 2017)
Residential Air Conditioning	MMBTU	CDD	Census division	CDD x residential square footage	2009	(U.S. Energy Information Administration 2013)

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[22] The model uses an assumed capacity factor to translate energy service demand into equipment stocks in units of service demand/hour.

Residential Cooking	MMBTU	Households	Census division	Households 2010	2009	(U.S. Energy Information Administration 2013)
Industrial Boilers	USD	Value of shipments	Census region	Earnings in manufacturing (NAICS 31-33) 2007	2011-2050	(U.S. Energy Information Administration 2017)
Industrial Process Heat	USD	Value of shipments	Census region	Earnings in manufacturing (NAICS 31-33) 2007	2011-2050	(U.S. Energy Information Administration 2017)
Industrial Space Heating	USD	Value of shipments	Census region	Earnings in manufacturing (NAICS 31-33) 2007	2011-2050	(U.S. Energy Information Administration 2017)
Industrial Machine Drives	USD	Value of shipments	Census region	Earnings in manufacturing (NAICS 31-33) 2007	2011-2050	(U.S. Energy Information Administration 2017)
Industrial Curing	USD	Value of shipments	Census region	Earnings in manufacturing (NAICS 31-33) 2007	2011-2050	(U.S. Energy Information Administration 2017)
Industrial Drying	USD	Value of shipments	Census region	Earnings in manufacturing (NAICS 31-33) 2007	2011-2050	(U.S. Energy Information Administration 2017)

Table 16 includes the service demand projections for subsectors represented with Method C (4.2.1.5). *Table 17* includes the service efficiency for Method C subsectors.

Table 16 Service demand data sources for Method C subsectors

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Source
Iron and Steel CO2 Capture	Tonnes of BOF Steel Production	No	Subsector value of output	Census region	2011-2050	(U.S. Energy Information Administration 2017)
Cement CO2 Capture	Tonnes of Clinker Production	No	Subsector value of output	Census region	2011-2050	(U.S. Energy Information Administration 2017)

Table 17 Service efficiency data sources

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Source
Iron and Steel CO2 Capture	MMBTU/Tonne of CO2	No		US	2018	(Kuramochi et al. 2012)
Cement CO2 Capture	MMBTU/Tonne of CO2	No		US	2018	(Kuramochi et al. 2012)

Table 18 shows baseline energy demand projection input data sources for subsectors employing Method D (4.2.1.6).

Table 18 Energy demand data sources for Method D subsectors

Subsector	Unit	Driver	Input Data: Geography	Downscaling method	Input Data: Year(s)	Source
Residential computers and related	MMBTU	Households	Census division	Households 2010	2009-2050	(U.S. Energy Information Administration 2017)
Residential televisions and related	MMBTU	Households	Census division	Households 2010	2009-2050	(U.S. Energy Information Administration 2017)
Residential Secondary Heating	MMBTU per household	Households; HDD	Census division	Households 2010	2010	(U.S. Energy Information Administration 2017)
Residential other uses	MMBTU	Households	Census division	Households 2010	2009-2050	(U.S. Energy Information Administration 2017)
Residential Furnace Fans	MMBTU	Households	Census division	Households 2010	2009	(U.S. Energy Information Administration 2013)
Office Equipment (P.C.)	Quads	Office space	US	Employment in all industries (NAICS, no code) 2007	2015-2050	(U.S. Energy Information Administration 2017)
Office Equipment (Non-	Quads	Office space	US	Employment in all industries (NAICS,	2015-	(U.S. Energy Information

P.C.)				no code) 2007	2050	Administration 2017)
Commercial Other	Quads	Commercial square footage	US	Employment in all industries (NAICS, no code) 2007	2015-2050	(U.S. Energy Information Administration 2017)
Non-CHP District Services	kilobtu per square feet	Commercial square footage	Census division	Households 2010	2012	(U.S. Energy Information Administration 2017)
CHP District Services	Terabtu	Commercial square footage	US	Households 2010	2015-2050	(U.S. Energy Information Administration 2017)
Domestic Shipping	Terabtu	n/a	US	Marine Fuel Use	2015-2050	(U.S. Energy Information Administration 2017)
Military Use	Terabtu	n/a	US	Households 2010	2015-2050	(U.S. Energy Information Administration 2017)
Motorcycles	Terabtu	Population	US	Households 2010	2012-2050	(U.S. Energy Information Administration 2017)
Lubricants	Terabtu	Population	US	Households 2010	2015-2050	(U.S. Energy Information Administration 2017)
International Shipping	Terabtu	n/a	US	Marine Fuel Use	2015-2050	(U.S. Energy Information Administration 2017)
Recreational Boats	Terabtu	n/a	US	Households 2010	2015-2050	(U.S. Energy Information Administration 2017)
School and intercity buses	Terabtu	Passenger miles, population	US	BUSES VMT Share	2015-2050	(U.S. Energy Information Administration 2017)
Passenger rail	Terabtu	Rail passenger miles	Census division	Rail Fuel Use	2015-2050	(U.S. Energy Information Administration 2017)

Freight rail	Terabtu	Gigaton mile service demand	Census division	Rail Fuel Use	2015-2050	(U.S. Energy Information Administration 2017)
Aviation	Terabtu	Seat miles, population	US	Aviation Fuel Use	2015-2050	(U.S. Energy Information Administration 2017)
Various Industrial Subsectors [1]	Terabtu	Subsector value of output	Census region	Value of shipments	2011-2050	(U.S. Energy Information Administration 2017)

8. Supply – Side Data Description

Table 19 Supply-side data sources

Data Category	Data Description	Supply Node	Source
Resource Potential	Binned resource potential (GWh) by state with associated resource performance (capacity factors) and transmission costs to reach load	Transmission – sited Solar PV; Onshore Wind; Offshore Wind; Geothermal	(Eurek et al. 2017)
Resource Potential	Binned resource potential of biomass resources by state with associated costs	Biomass Primary – Herbaceous; Biomass Primary – Wood; Biomass Primary – Waste; Biomass Primary – Corn	(Langholtz, Stokes, and Eaton 2016)
Resource Potential	Binned annual carbon sequestration injection potential by state with associated costs	Carbon Sequestration	(U.S. Department of Energy: National Energy Technology Laboratory 2017)
Resource Potential	Domestic production potential of natural gas	Natural Gas Primary – Domestic	(U.S. Energy Information Administration 2017)
Resource Potential	Domestic production potential of oil	Oil Primary – Domestic	(U.S. Energy Information Administration 2017)
Product Costs	Commodity cost of natural gas at Henry Hub	Natural Gas Primary – Domestic	(U.S. Energy Information Administration 2017)

Product Costs	Undelivered costs of refined fossil products	Refined Fossil Diesel; Refined Fossil Jet Fuel; Refined Fossil Kerosene; Refined Fossil Gasoline; Refined Fossil LPG	(U.S. Energy Information Administration 2017)
Product Costs	Commodity cost of Brent oil	Oil Primary – Domestic; Oil Primary - International	(U.S. Energy Information Administration 2017)
Delivery Infrastructure Costs	AEO transmission and delivery costs by EMM region	Electricity Transmission Grid; Electricity Distribution Grid	(U.S. Energy Information Administration 2017)
Delivery Infrastructure Costs	AEO transmission and delivery costs by census division and sector	Gas Transmission Pipeline; Gas Distribution Pipeline	(U.S. Energy Information Administration 2017)
Delivery Infrastructure	AEO delivery costs by fuel product	Gasoline Delivery; Diesel Delivery; Jet Fuel; LPG Fuel Delivery; Kerosene Delivery	(U.S. Energy Information Administration 2017)
Technology Cost and Performance	Renewable and conventional electric technology installed cost projections	Nuclear Power Plants; Onshore Wind Power Plants; Offshore Wind Power Plants; Transmission – Sited Solar PV Power Plants; Distribution – Sited Solar PV Power Plants; Rooftop PV Solar Power Plants; Combined – Cycle Gas Turbines; Coal Power Plants; Combined – Cycle Gas Power Plants with CCS; Coal Power Plants with CCS; Gas Combustion Turbines	(National Renewable Energy Laboratory 2017)
Technology Cost and Performance	Electric fuel cost projections including electrolysis and fuel synthesis facilities	Central Hydrogen Grid Electrolysis; Power – To – Diesel; Power – To – Jet Fuel; Power – To – Gas Production Facilities	(Capros et al. 2018)
Technology Cost and Performance	Hydrogen Gas Reformation costs with and without carbon capture	H2 Natural Gas Reformation; H2 Natural Gas Reformation w/CCS	(International Energy Agency GHG Programme 2017)
Technology Cost and Performance	Nth plant Direct air capture costs for sequestration and utilization	Direct Air Capture with Sequestration; Direct Air Capture with Utilization	(Keith et al. 2018)
Technology Cost and Performance	Gasification cost and efficiency of conversion including gas upgrading.	Biomass Gasification; Biomass Gasification with CCS	(G. del Alamo et al. 2015)
Technology Cost and	Cost and efficiency of renewable Fischer-Tropsch diesel	Renewable Diesel; Renewable Diesel with CCS	(G. del Alamo et al. 2015)

Performance	production.		
Technology Cost and Performance	Cost and efficiency of industrial boilers	Electric Boilers; Other Boilers	(Capros et al. 2018)
Technology Cost and Performance	Cost and efficiency of other, existing power plant types	Fossil Steam Turbines; Coal Power Plants	(Johnson et al. 2006)

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