350 PPM PATHWAYS FOR FLORIDA

October 6, 2020

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ENERGY
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350 PPM Pathways for Florida

Prepared by

Ben Haley, Gabe Kwok, and Ryan Jones

Evolved Energy Research

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Version 1

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Key Terms

100% Renewable Primary Scenario – a scenario that requires all primary energy source be renewable by 2050 (wind, solar, geothermal, hydro, and biomass)

1.0ºC – One degree Celsius (1.8ºF) of global warming over pre-industrial temperatures.

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

2°C – Two degrees Celsius (3.6ºF) 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 commonly used target in the U.S. and other countries for reducing CO_2 emissions, 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.

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

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

Bunkering CO_2 – Offset to gross CO_2 emissions to account for emissions are not considered the responsibility of the U.S. under UNFCC accounting rules (bunkered fuels for international shipping and air travel).

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

FT – Fischer-Tropsch process

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 – the Intergovernmental Panel on Climate Change, is the body of the United Nations that provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation.

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

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

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

MMT – Million metric tonnes

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

Net-negative CO2 - A condition in which human-caused carbon emissions are less than the natural uptake of carbon in land, soils, and oceans such that atmospheric CO_2 concentrations are declining.

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 Regional Transmission (TX) Scenario– A scenario that disallows new inter-regional transmission lines

NWPP – Northwest Power Pool

Oxyfuel - A combustion process where fuel is burned using pure oxygen rather than air, and the resulting flue gas is primarily CO2 appropriate for sequestration

Pg(C) – Peta (10^{15}) grams

ppm – parts per million

Product CO_2 – Offset to gross CO_2 emissions to account for sequestration in products (like plastics)

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

Reference Scenario – 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

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

SNG – Synthetic natural gas

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

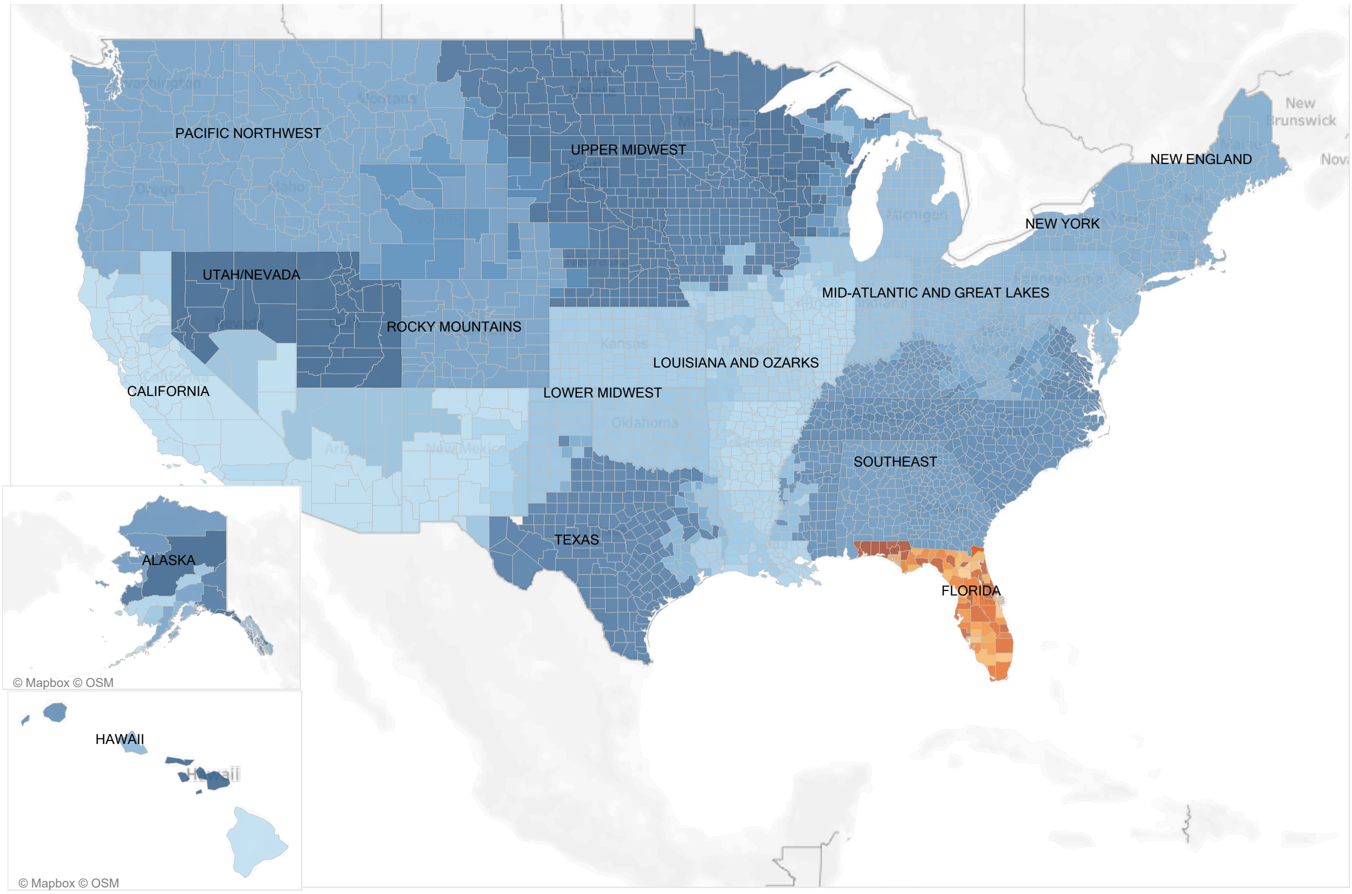
WECC – Western electricity coordinating council

Executive Summary

This study builds off the report issued by Evolved Energy Research and the Sustainability Development Solutions Network (SDSN) on May 8, 2019 titled *350 PPM Pathways for the United States*. The national report described 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) by 2100, achieving net negative CO_2 emissions by mid-century, and limiting end-of-century global warming to 1ºC.

This study focuses on the State of Florida and evaluates new scenarios that strongly affect energy system outcomes for the state. As shown in Figure ES1, the analysis covers all regions of the U.S. in order to maintain consistency with the national report's 350 ppm emissions target and includes key analytical updates made to reflect evolved understandings of technology costs.

Figure ES1 Study Geographies (Florida highlighted here for visual emphasis)



Scenarios

For the Florida-specific analysis, we evaluated five scenarios that represent important and relevant national context for the State's energy system decisions. Brief descriptions of the decarbonization scenarios are included below.

1. **Central**: This is our least-constrained scenario designed to assess an all-options approach to decarbonization.
2. **Low Biomass**: This scenario assesses the robustness of our decarbonization strategy to limited zero-carbon biomass resources with a 50% reduction in the development of new biomass feedstocks.
3. **Low Electrification**: This scenario assesses the robustness of our decarbonization strategy to a twenty-year delay in the adoption of electrified demand-side technologies (electric vehices, heat pumps, etc.)
4. **100% Renewable Primary**: This scenario restricts the use of all non-renewable primary energy sources (fossil and nuclear) to zero by 2050. The economy derives all of its energy from biomass, wind, solar, hydro, and geothermal sources.
5. **No New Regional Transmission (TX)**: This scenario limits new development of inter-regional transmission across the U.S. This restricts the ability of regions to access higher quality renewables.

All of these scenarios remain within the 350ppm carbon budget described above 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, electrification, residual fossil with carbon capture, nuclear energy, and interstate transmission development. The emissions constraints were applied to the U.S. as a whole, given that the ultimate achievement of a U.S. wide reduction pathway is likely to differ substantially by region based on initial energy system conditions, current and future economic structures, and resource endowments. This makes the cumulative emissions trajectory of Florida consistent with 350 PPM target achievement in the U.S. an output of the modeling exercise.

Table ES1 U.S. Emissions Targets

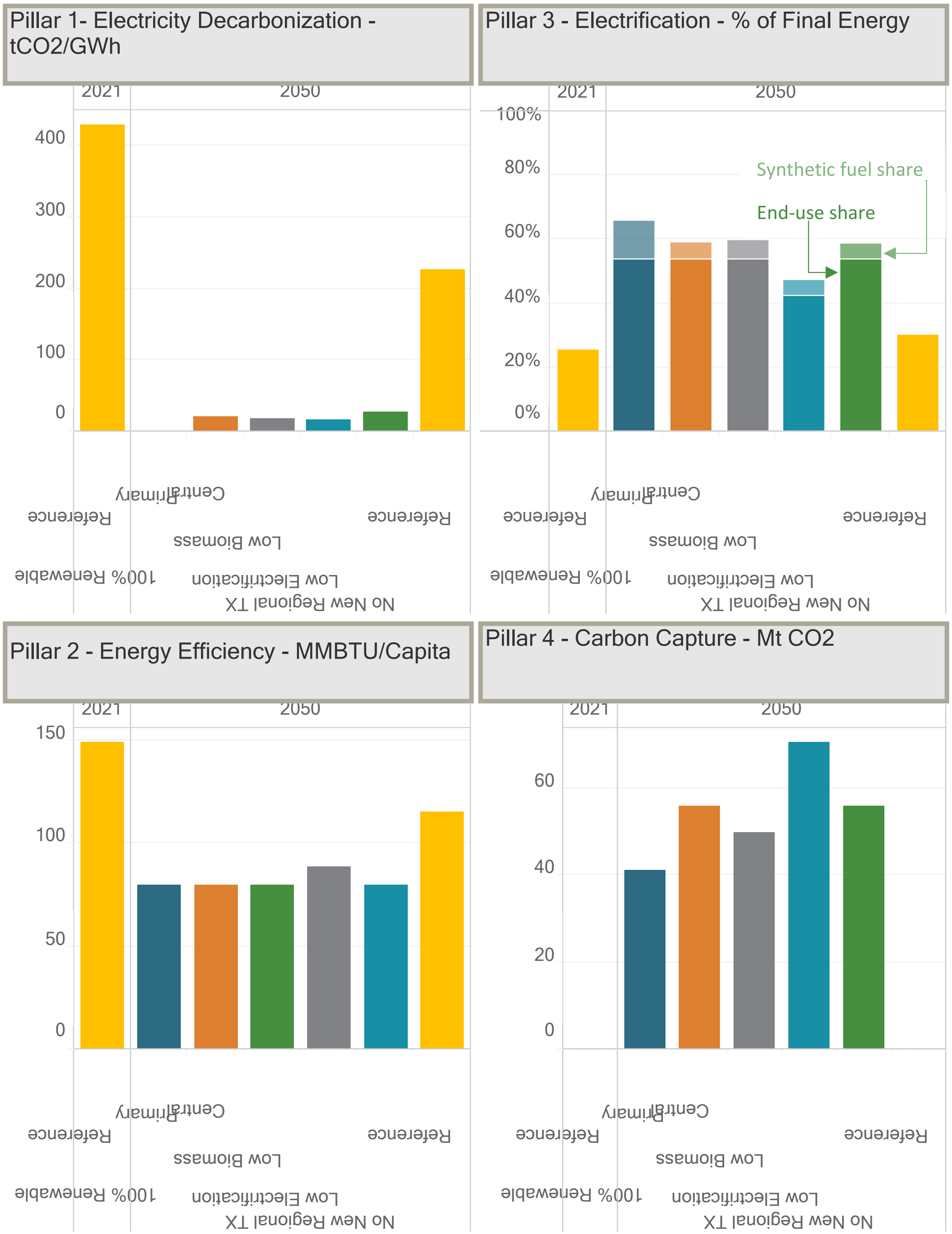
Category	Constraint
2021-2050 Average annual rate of CO_2 emission reduction	6%
2021-2050 maximum cumulative fossil fuel CO_2 (billion metric tonnes)	70.06
2050 Maximum fossil fuel CO_2 (million metric tonnes)	830
2050 Assumed land sink (million metric tonnes)	1080
2050 Maximum net CO_2 (million metric tonnes)	-250

The scenarios were modeled using two analysis tools developed for this purpose, EnergyPATHWAYS and RIO. As 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 factors such as the inertia of infrastructure stocks and the hour-to-hour dynamics of the electricity system, separately in each of sixteen electric grid regions of the U.S. The changes in energy mix, emissions, and costs for the five scenarios were calculated relative to a high-carbon baseline based on the *AEO*.

Florida Energy System Results

Energy decarbonization in Florida rests on four principal strategies (‘four pillars”) as shown in Figure ES2 for Florida: (1) electricity decarbonization, the reduction in emissions intensity of electricity generation by about 95% 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 50% below today’s level; (3) electrification, converting end-uses like transportation and heating from fossils fuels to low-carbon electricity, so that electricity doubles its share from 25% of current end uses to approximately 50% in 2050; and (4) the use of captured carbon that would otherwise be emitted from power plants and industrial facilities rising from nearly zero today to as much as 70 million metric tonnes in 2050. This captured carbon is either directly sequestered in-state or is a component (along with hydrogen) of synthetic renewable fuels consumed in the State.

Figure ES2 Four pillars of deep decarbonization – Central scenario – Florida[1]



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, 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.

Figure ES3 (Florida) shows that all scenarios achieve the steep reductions in net fossil fuel CO_2 emissions required to reach the cumulative emissions targets. These include four scenarios that are limited in the availability of one key decarbonization strategy. This indicates that the feasibility of reaching the emissions goals is robust due to the availability of alternative strategies. At the same time, the more limited scenarios are, the more difficult and/or costly they are relative to the base scenario with all options available. Severe limits in two or more strategies could make the emissions goals very difficult to achieve in the mid-century time frame, but these combinations were not analyzed here.

Figure ES3 2021-2050 CO_2 emissions for the scenarios in this study – Florida

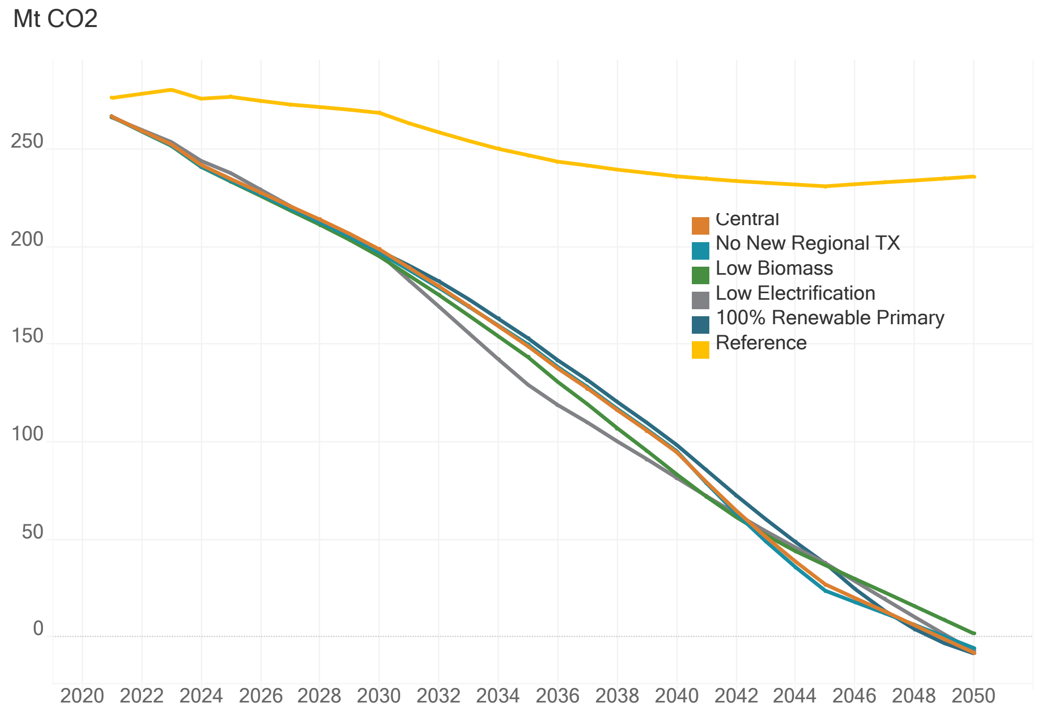
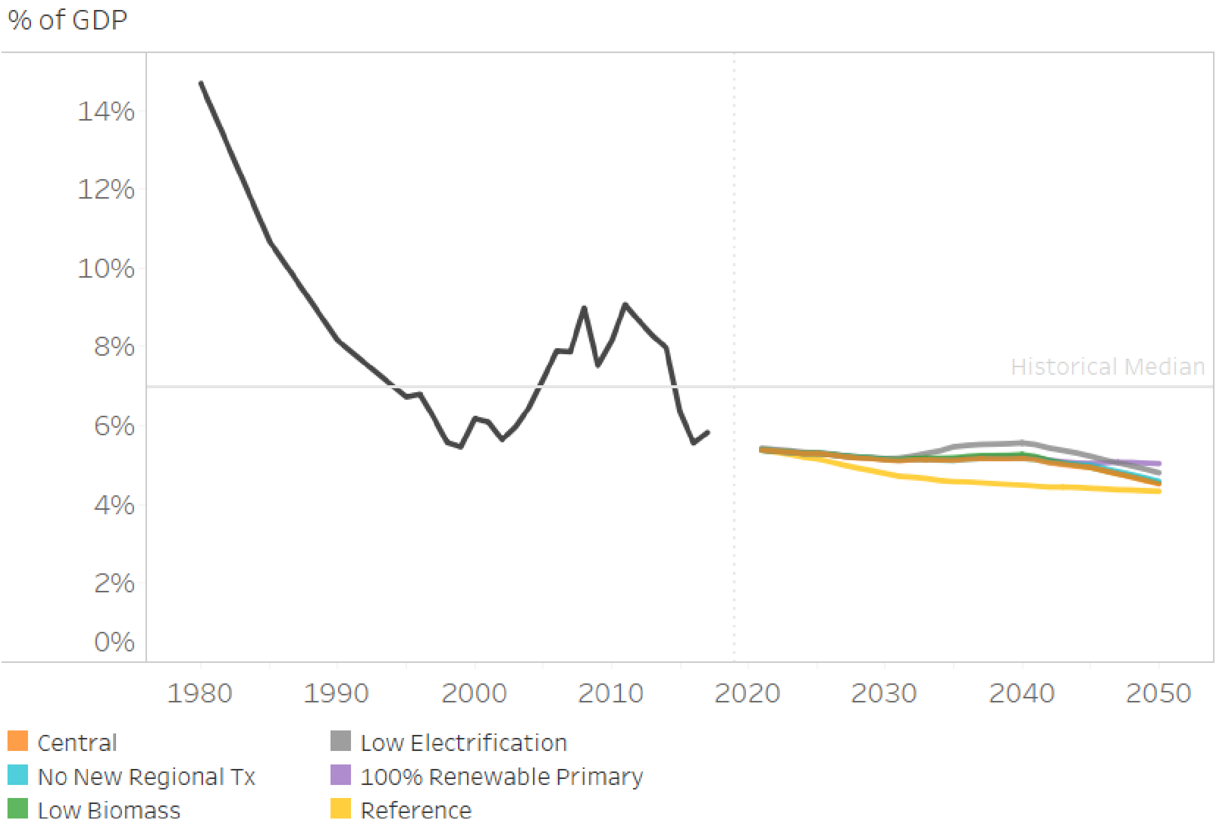


Figure ES4 shows historical and projected energy system costs as a share of State GDP. Decarbonized energy system costs are not out of line with historical energy costs in Florida in any scenario and even with decarbonization, energy system costs are anticipated to decline as a share of GDP. The highest cost scenario is the 100% Renewable Primary pathway due to the emphasis on displacing instead of offsetting (through geologic sequestration) even the lowest-cost fossil in 2050. The lowest cost scenario is in the Central scenario, which allows for the most flexibility in terms of key decarbonization strategies. These costs exclude any potential economic benefits of avoided climate change or pollution, energy price predictability, or energy security which could equal or exceed the net costs shown here. In addition, the analysis does not incorporate any behavioral changes or energy service demand reductions (e.g., lower vehicle miles traveled or modal shifting), but these would contribute to lower costs, lower infrastructure needs and could improve quality of life in ways not quantified by this analysis.

Figure ES4. Total energy system costs as percentage of GDP, historical and projected for Florida



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 (the Central scenario), while delivering the same level of energy services projected in the U.S. Department of Energy *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.

From a policy perspective, this provides a list of goals 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 rate designs that reward demand side flexibility in high-renewable electricity systems 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.*

The key actions listed below apply for the U.S., and, although specific to the Central scenario, they are generally applicable to all 350 ppm-compatible scenarios barring the specific implementation challenges assumed in each scenario. For the State of Florida, decarbonizing its energy system consistent with the U.S.'s pathway is also feasible. The State's relative position as an energy consumer and producer doesn't dictate serious deviations away from the Country's overall pathway, and we have provided additional detail specific to Florida below.

2020s

- Begin large-scale electrification in transportation and buildings
- Switch from coal to gas in electricity system priority dispatch and retire coal assets
- Ramp up construction of renewable generation and reinforce transmission
- Allow strategic replacement of natural gas power plants to support rapid deployment of low-carbon generation. These plants must be built with the understanding that they will run very infrequently to provide capacity, not as they are operated today.
- Maintain existing nuclear fleet
- Pilot new technologies that will need to be deployed at scale after 2030
- Stop developing new infrastructure to transport and process 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) in technology and building heating
- Begin large-scale production of biodiesel and bio-jet fuel
- Large scale carbon capture on industrial facilities
- Build out electrical energy storage
- Deploy fossil power plants capable of 100% carbon capture if they exist
- Maintain existing nuclear fleet
- Continue to reduce generation from gas-fired power plants

2040s

- Complete electrification process for key technologies, achieve 100% stock penetration
- Produce large volumes of hydrogen for use in freight trucks and fuel production
- Use synthetic fuel production to balance and expand renewable generation
- Fully deploy biofuel production with carbon capture
- Further limit gas generation to infrequent periods when needed for system reliability

1. Introduction

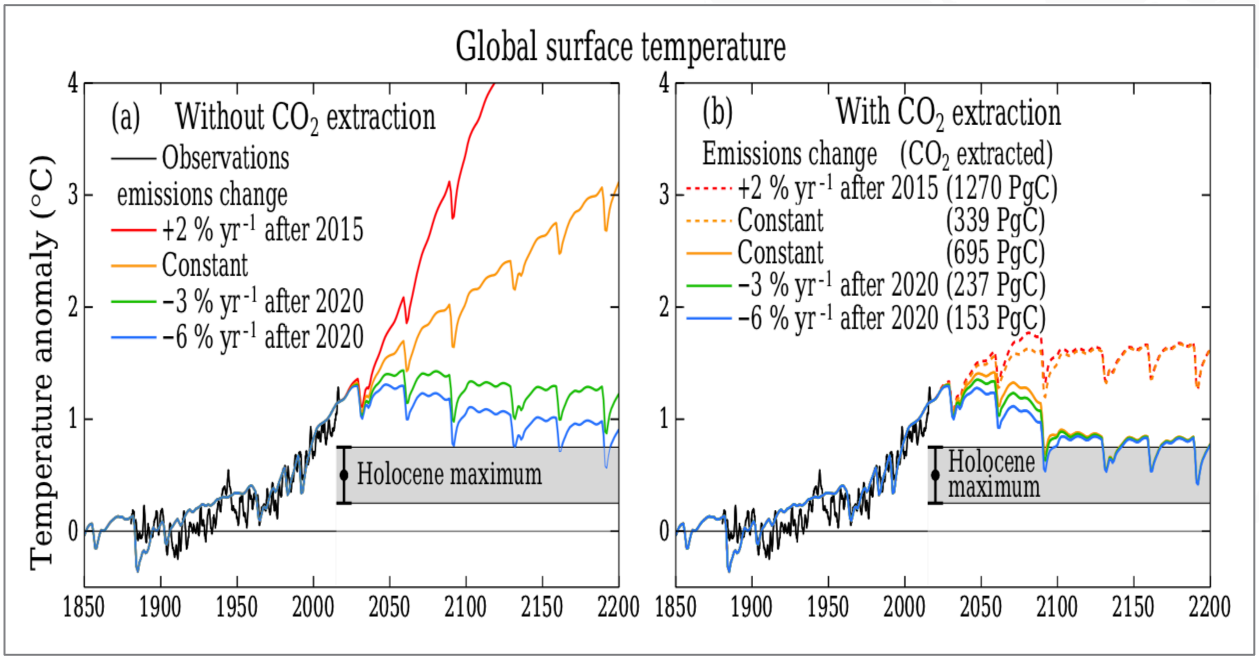
This report builds on previous analytical work in *350 ppm Pathways for the United* States (Haley et al. 2019) that described the changes in the U.S. energy system that, in concert with related actions in land use, will be required to reduce U.S. carbon dioxide (CO_2) emissions to a level consistent with returning atmospheric concentrations to 350 parts per million (350 ppm) by 2100, achieving net negative CO_2 emissions by mid-century, and limiting end-of-century global warming to 1°C. This study focuses on the State of Florida within that national context and identifies concrete actions needed to contribute to this nationwide decarbonization strategy. The study also builds on the previous work - *Pathways to Deep Decarbonization in the United States* (J. Williams et al. 2014) and *Policy Implications of Deep Decarbonization in the United States* (James H. Williams, Benjamin Haley, and Ryan Jones 2015) - which examined the requirements for reducing GHG emissions by 80% below 1990 levels by 2050 (“80 x 50”).

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 an urgent focus of the scientific community. A recent report by the Intergovernmental Panel on Climate Change emphasizes the potential risks associated with allowing 1.5°C warming above pre-industrial temperatures: “warming of 1.5°C is not considered ‘safe’ for most nations, communities, 28 ecosystems and sectors and poses significant risks to natural and human systems” (Intergovernmental Panel on Climate Change 2018). The U.S. Government’s Fourth National Climate Assessment documents an acceleration of climate change impacts already underway with 1.0°C warming above pre-industrial temperatures (U.S. Global Change Research Program 2017). Studies using global climate models and integrated assessment models (IAMs) indicate that limiting warming to a short-term 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 carbon neutrality by 2045 and negative net emissions thereafter (State of California 2018).

Climate studies have concluded that the best chance of avoiding the most catastrophic and irreversible climate change impacts requires CO_2 concentrations to be reduced to 350 ppm or less by the end of the 21st century (Veron et al. 2009; Hansen et al. 2013; 2016a). 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 in order 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, thereby restoring the energy imbalance of the Earth (Hansen et al. 2016b).

In this study we 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 scenarios modeled are a 6% 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 2021 to 2050 period of 70.06 billion metric tonnes of CO_2. (For comparison, current U.S. CO_2 emissions exceed 5 billion metric tonnes per year.) The emissions reductions in both scenarios must be accompanied by global increased extraction of CO_2 from the atmosphere of 153 Pg(C) above and beyond the current global CO_2 sink from 2020 to 2100. In our scenarios, the removal of 153 Pg(C) is assumed to be accomplished through land-based negative emissions technologies ("land NETs") (Griscom et al. 2017). These numbers imply an increase in the current global land sink of about 60% (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 scenarios. 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. The captured CO_2 is stored in geologic structures and/or used as a carbon feedstock for electric fuel production.

Figure 1 Global surface temperature and CO2 emissions trajectories[2]*.*



Our study differs from recent IAM studies of 1.5°C in that it has a tighter emissions budget, concentrates on concrete actions at a regional and State level, and provides a greater level of technical detail on the transformation to a low carbon economy, including detailed treatment of costs by sector (Rogelj et al. 2015).

The goal of this study is to understand how realistic 350 ppm-compatible scenarios would concretely change Florida' energy system and industrial fossil fuel use. In addition to continuing to develop our understanding of the 350 ppm target for the U.S., the principal additional research questions addressed by this study are the following:

1. What concrete actions are necessitated in the State of Florida to achieve emissions reductions consistent with national 350 ppm pathway achievement?

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[2] 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.

2. What are the key national conditions (electrification levels, biomass availability, restriction on the use of fossil and nuclear primary energy, and limited ability to construct new inter-regional transmission) that may influence decisions in Florida?

3. What are the costs to Florida of achieving 350 ppm-comaptible pathways?

To answer these questions, we developed five deep decarbonization scenarios using two 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.[3] 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 concrete actions necessitated in Florida are an output of our modeling tools. Their richness, both in terms of the granularity referenced above as well as their technological detail provide the basis of a concrete blueprint for the region to achieve deep levels of decarbonization of their economy.

The second research question reflects the reality that many of the decisions Florida will have to make in decarbonizing their energy system will be informed and affected by a broader national context. Achievable levels of electrification and biomass deployment are likely to be influenced by national decisions; restrictions on the use of fossil fuels as a primary energy source is also likely to be influenced by national policy; and the ability to construct large inter-regional transmission corridors is a multi-region question. Therefore, we investigate these questions as variations off of our Central scenario.

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[3] Evolved has worked with the state of New Jersey and is currently working with the states of Massachusetts and Washington to analyze plans for decarbonization.

In order to answer our third question, we calculate the costs of implementing this transition in the United States as a whole and for the State of Florida 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 scenario 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.

This study does not model land NETs, instead stipulating the global 100 Pg(C) and 153 Pg(C) scenarios 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 tonnes was assumed.[4] This would require additional sequestration of 25-30 billion metric tonnes 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 we 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, the built environment, and economic productivity. Such co-benefits are addressed in other studies[5].

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, costs, and sector-specific results; and Chapter 4, Conclusions, including key actions by decade. The Appendix describes the scenarios and modeling methodology in detail.

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[4] 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

[5] Union of Concerned Scientists, *Underwater: Rising Seas, Chronic Floods, and the Implications for U.S. Coastal Real Estate*, available at https://www.ucsusa.org/sites/default/files/attach/2018/06/underwater-analysis-full-report.pdf

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 significant CO_2 emissions reductions by mid-century. All scenarios hit the same cumulative and annual emissions constraints, which are described in Table 1 below:

Table 1 Scenario definitions and emissions limits

Category	Constraint
2021-2050 Average annual rate of CO_2 emission reduction	6%
2021-2050 maximum cumulative fossil fuel CO_2 (billion metric tonnes)	70.06
2050 Maximum fossil fuel CO_2 (million metric tonnes)	830
2050 Assumed land sink (million metric tonnes)	1080
2050 Maximum net CO_2 (million metric tonnes)	-250

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 five 350 ppm-compatible scenarios: a core scenario called the Central scenario, which is the least constrained, and four variants on this scenario to address potential alternatives for the State of Florida depending on differing national and local concerns. The decarbonization scenarios are described below.

1. Central: This is our least-constrained scenario designed to assess an all-options approach to decarbonization.
2. Low Biomass: This scenario assesses the robustness of our decarbonization strategy to limited zero-carbon biomass resources with a 50% reduction in the development of new biomass feedstocks.

3. Low Electrification: This scenario assesses the robustness of our decarbonization strategy to a twenty-year delay in the adoption of electrified demand-side technologies (electric vehicles, heat pumps, etc.)
4. 100% Renewable Primary: This scenario restricts the use of all non-renewable primary energy sources (fossil and nuclear) to zero by 2050. The economy derives all of its energy from biomass, wind, solar, hydro, and geothermal sources.
5. No New Regional Transmission (TX): This scenario limits new development of inter-regional transmission across the U.S. This restricts the ability of regions to access higher quality renewables.

Although the modeling tools, approach and a subset of the scenarios are the same or similar to the May 2019 report, there are key analytical differences between this study and the May 2019 report that are described in the table below.

Key Updates Between April 2020 and May 2019 Analyses

Category	Description	Impact
End-use electrification	Continued and anticipated progress in battery costs has lowered the costs of end-use electrification, which has a significant impact on estimates of overall net costs.	Reduced costs of transportation electrification and reduced overall costs of decarbonization.
Hydrogen for end-use demand	Previous analysis relied on hydrogen exclusively as a feedstock for synthetic fuels. Subsequent research and analyses have identified high value direct hydrogen applications in freight applications (on-road and off-road) and process heating. Additionally, we have decomposed the need for hydrogen from chemical feedstocks demand values the AEO, allowing for substitution of green hydrogen.	Lower demand for liquid fossil substitutes reduces overall demand for biomass as a feedstock as well as reducing dependence on DAC in Low Biomass and Low Electrification scenarios.

Geographic granularity	Increased number of regions, including: (a) separating the northwest into the pacific northwest and Utah/Nevada; (b) separating the Midwest into two regions; (c) separating the Southeast; and (d) including Alaska and Hawaii separately.	Renewable resource endowments are more accurately reflected. Specifically, limited deployment of onshore wind in the Southeast, with a higher reliance on offshore wind.
Wind performance	Current analysis relies on NREL's Annual Technology Baseline 2019, which assumes wind technology cost reductions and improved performance (i.e., capacity factor) projections that are more optimistic than its predecessor.	Onshore wind is economical in more locations than it previously was, and offshore wind plays a large role particularly beginning in the 2040s. This has outcompeted nuclear economically in regions where our scenarios allow it to be built. These results are sensitive to availability of onshore wind resources as well as modeled costs of new wind vs. new nuclear and so should be interpreted as indicative of future resource competition but not declarative.
Expanded conversion technology options	More comprehensive bio and synthetic fuel representations allow for displacement of liquefied petroleum gas; residual fuel oil; petroleum coke; coal; and other petroleum with zero-carbon alternatives.	Allows for the modeling of 100% renewable energy economy, without fossil or nuclear primary energy.

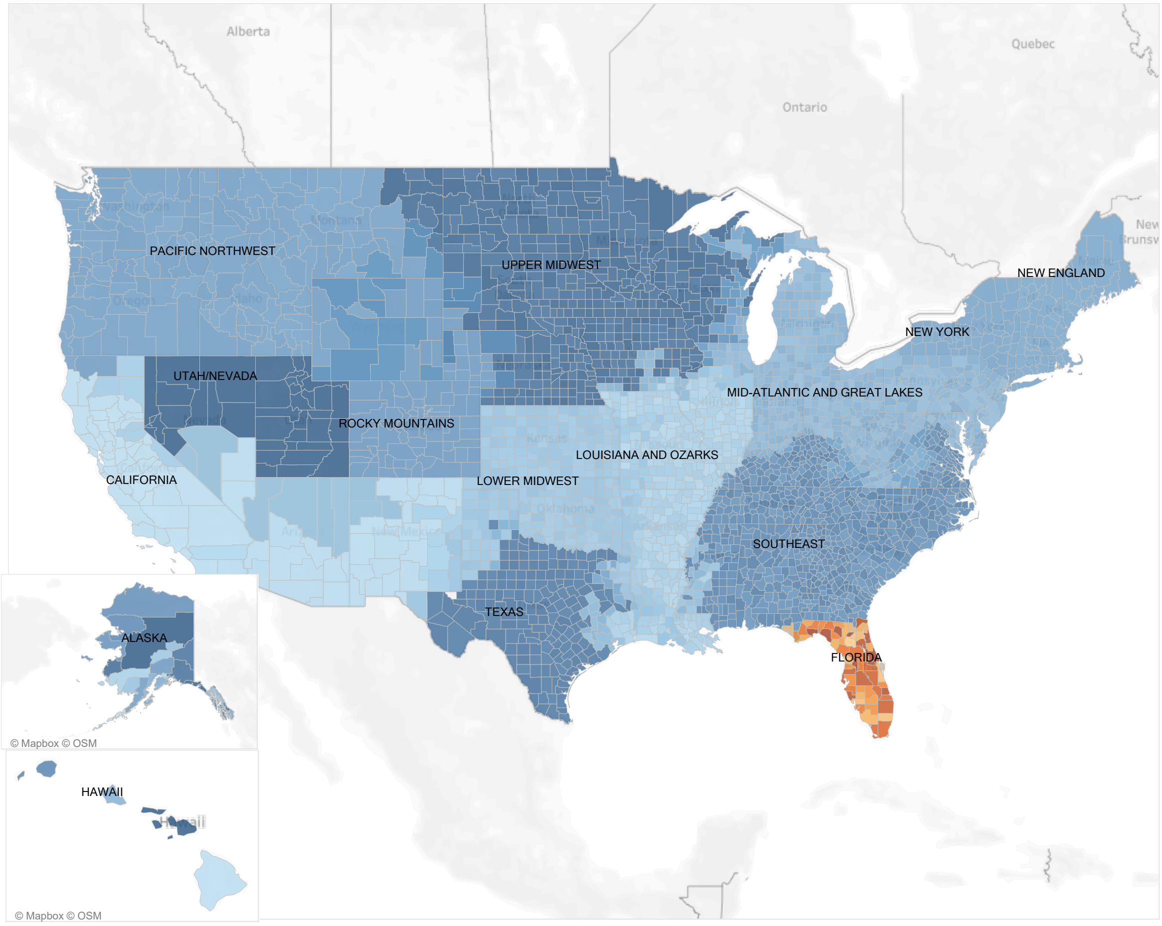
2.2. Modeling Methods and Data Sources

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 300 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 (J. H. Williams et al. 2012) then expanding to U.S. wide analysis (J. H. Williams et al. 2012; Risky Business Project 2016; Jadun et al. 2017) and other state analyses conducted for governments (New Jersey, Massachusetts (ongoing), Washington (ongoing)). 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

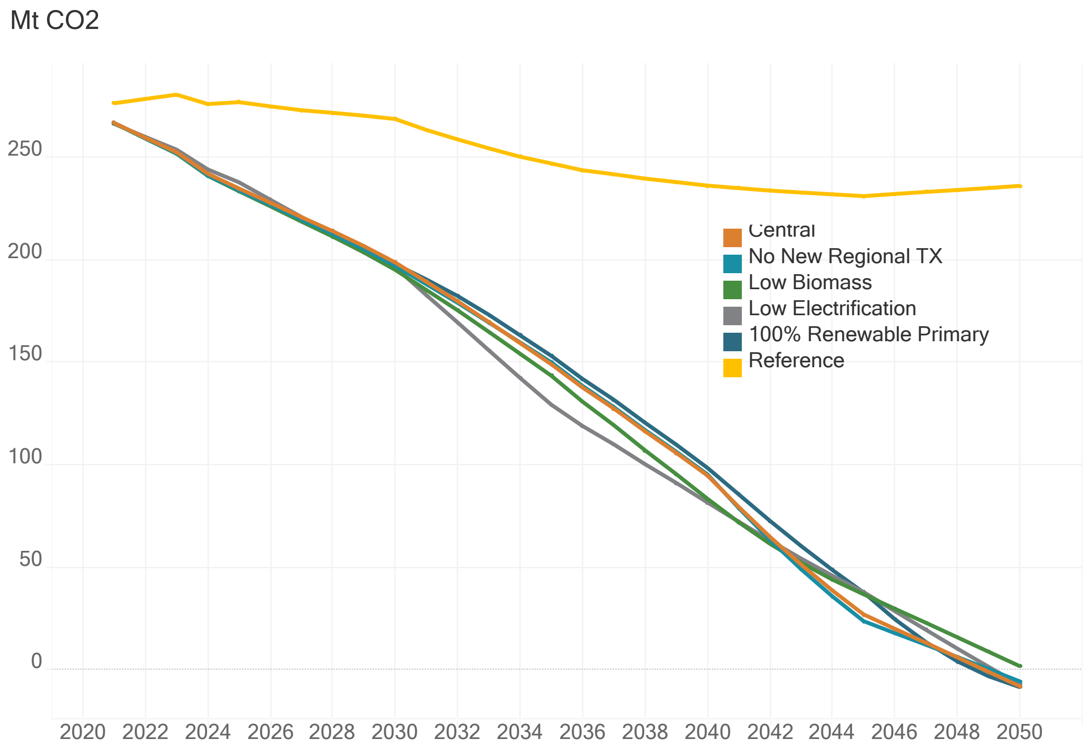
The parameterization of EnergyPATHWAYS and RIO to perform U.S. economy-wide decarbonization analysis requires a wide variety of inputs and data sources. We describe the full breadth of these data sources in the Appendix. There are, however, a few principal sources that are central to understanding and contextualizing our results. First and foremost, we utilized the 2019 *Annual Energy Outlook* (U.S. Energy Information Administration 2019), 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. We derive renewable costs and resource potentials from National Renewable Energy Laboratory sources including the 2019 Annual Technology Baseline (National Renewable Energy Laboratory 2019) and input files to their ReEDS Model (Eurek et al. 2017). We take biomass resource potential and costs the U.S. Department of Energy's Billion Tons Study Update (Langholtz, Stokes, and Eaton 2016). In all scenarios 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 (E&I) CO_2 emissions in Florida are shown below for the 350 ppm scenarios. Instead of relying on a Florida-specific emissions target, the emissions reductions in Florida are a result of a U.S.-wide optimization for a 350 ppm pathway. Florida's emissions[6] must follow a similar trajectory to those of the United States as a whole. Net E&I emissions approach zero by 2050 in all scenarios, with the 100% Renewable Primary scenario having negative E&I emissions by 2050.

Figure 3 CO2 Emissions Trajectories – Florida



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[6] Emissions are accounted for on a consumption basis. This means that upstream emissions associated with fuels refining and out-of-State electricity generation (imports) are allocated to Florida.

In all other scenarios, some gross fossil emissions are offset by geologic and product sequestration. 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 4 CO2 Emissions by Final Energy/Emissions Category – Florida

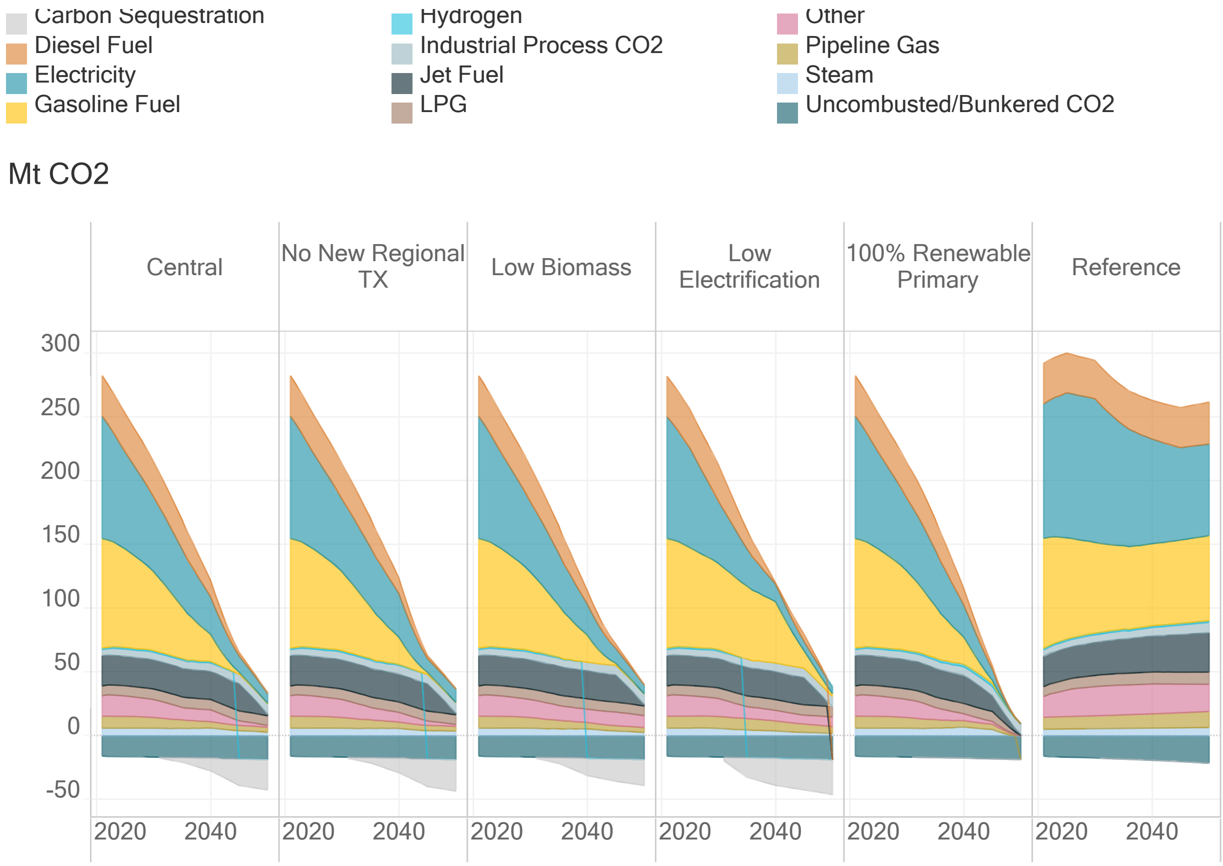
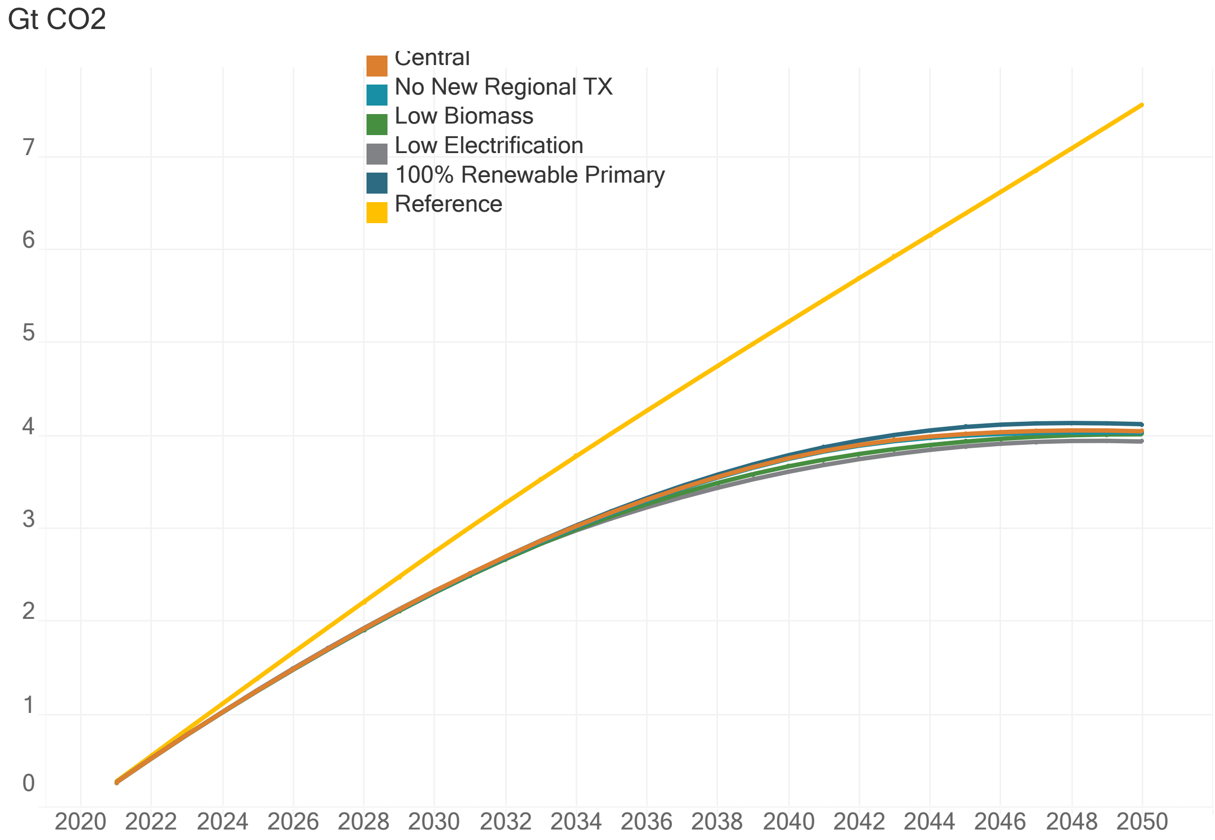


Figure 5 Cumulative CO2 emissions trajectories – Florida



3.2. System Transformation

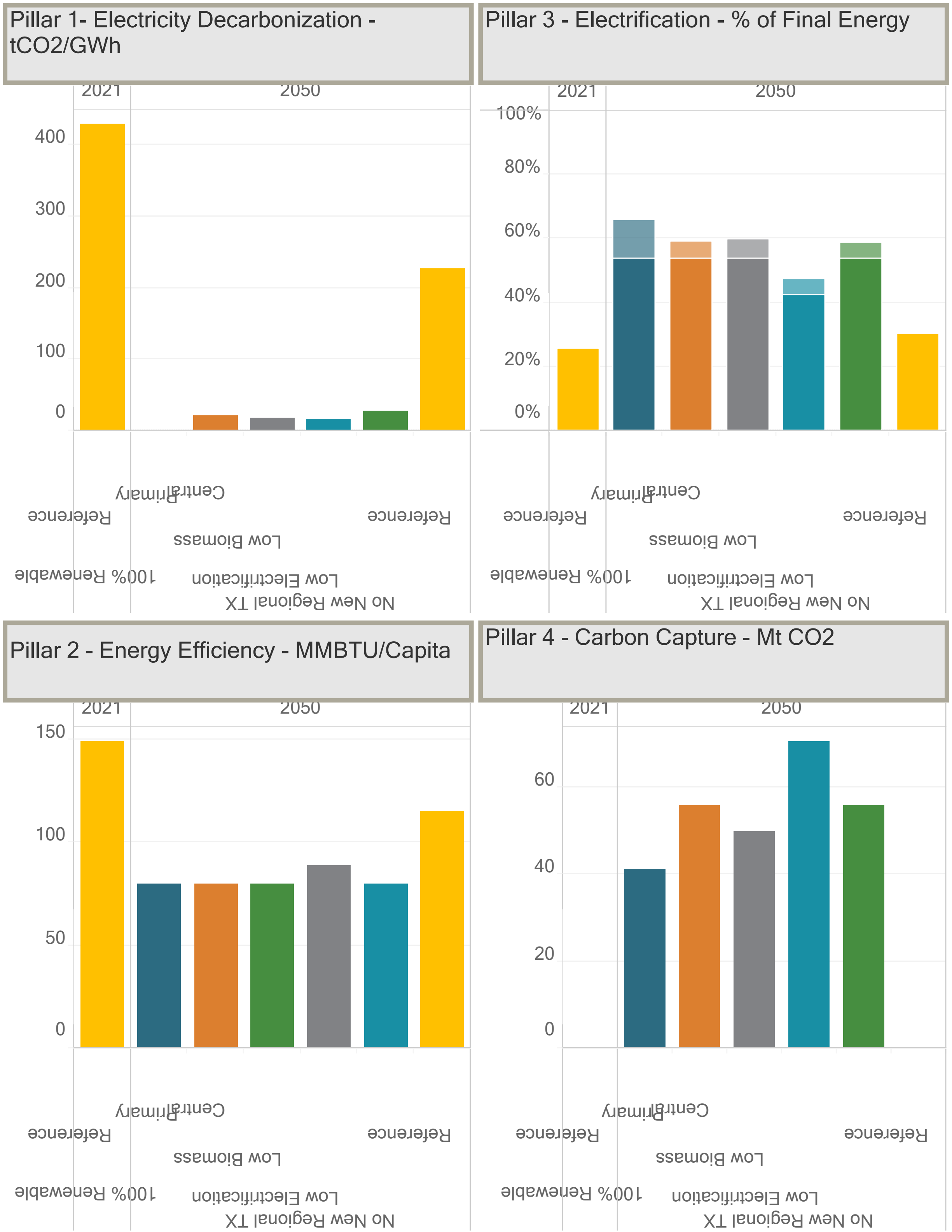
3.2.1. Four Pillars

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 supply 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 6 below shows the four pillars of decarbonization employed in the Central scenario. The emissions intensity of electricity has declined to less than 30 tonnes/GWh in 2050 in all secnarios from over 400 tonnes/GWh in 2021 in the Reference scenario. The 100% Renewable Primary scenario has truly carbon-free electricity emissions, with all generation from thermal plants using carbon capture technology or consuming zero-carbon fuel substitutes (biofuels, hydrogen, or synthetic methane).

Limited heating demands in Florida means that overall demand per-capita is below the national average in 2050 (88 MMBTU/capita – Low Electrification; 79 MMBTU/capita – All Other DDP scenarios). Direct electrification share exceeds 50% in 2050 in all but the Low Electrification scenario, with limited industrial energy demands requiring residual fuel usage. Florida utilizes up to 70 tonnes of captured CO_2 (in-state or out-of-state) by 2050, with the volumes depending on available biomass (Low Biomass), progress in electrification (Low Electrification), and limits to fossil energy use (100% Renewable Primary).

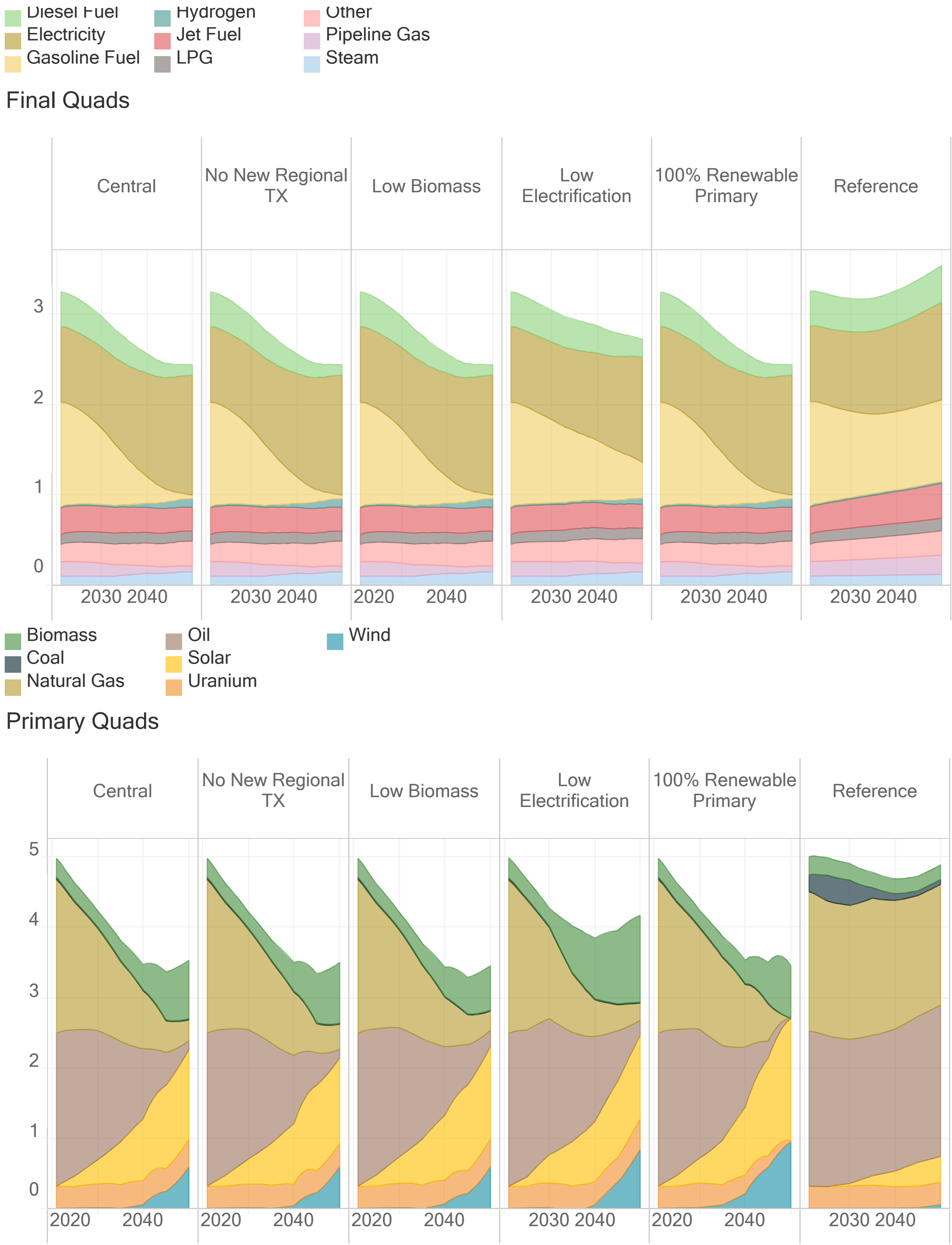
Figure 6 Four pillars of deep decarbonization – Florida



3.2.2. Energy Flow Transformations

Transformation of the 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 7 shows these simultaneous transitions, with the top panel showing final energy demand and the bottom panel showing primary energy supply.

Figure 7 Final and primary energy demand for all scenarios from 2021 – 2050 – Florida

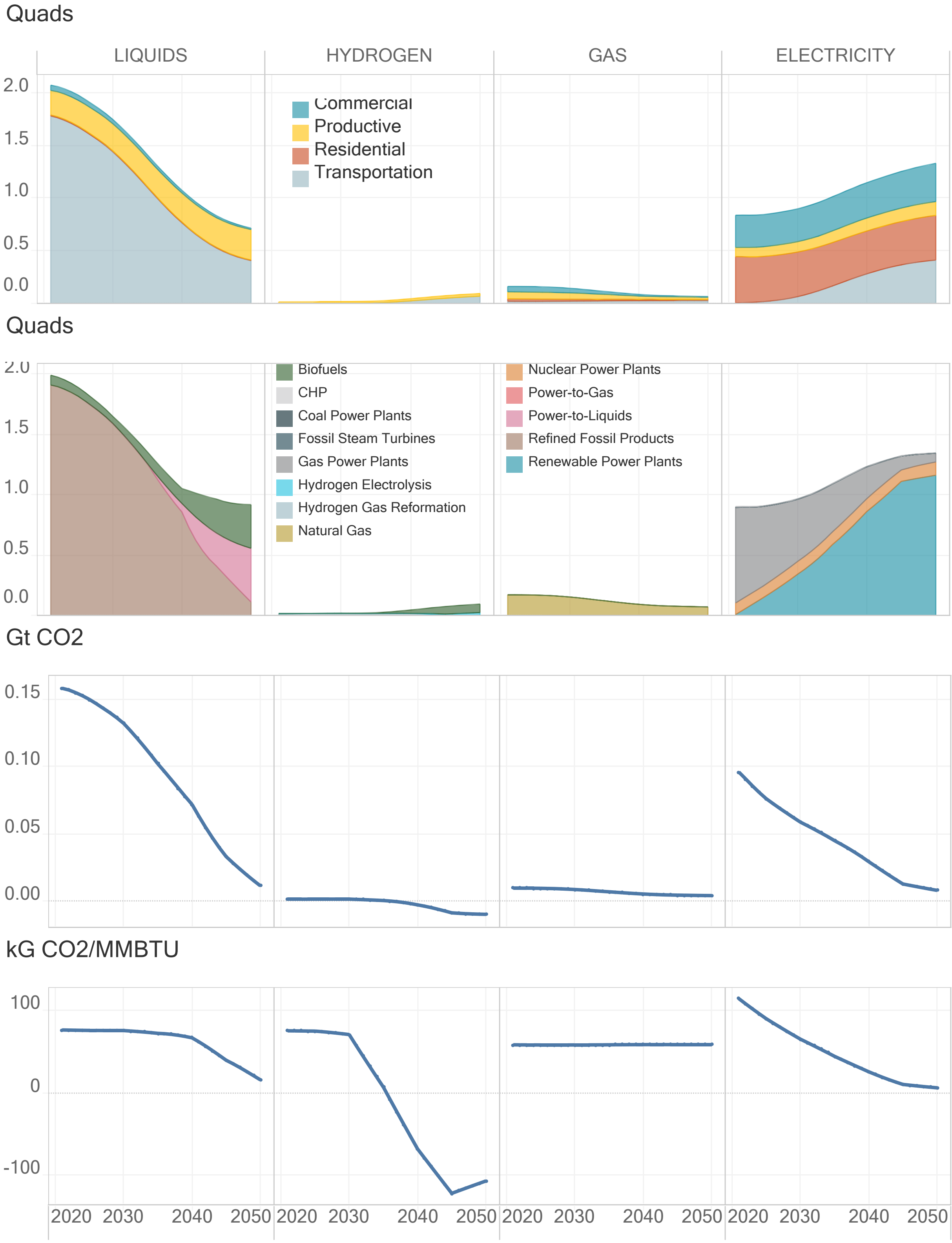


Florida’s uniqueness compared to the rest of the country in terms of final energy demand is its limited use of direct natural gas. Much of Florida’s heating is already electrified, and so a transition to heat pumps represents efficiency as opposed to the electrification found elsewhere in the country. Florida also has a higher share of jet fuel for aviation and distillate/residual fuel (other) used in international shipping.

Florida has a similar initial makeup to the rest of the country in terms of primary energy usage, though as noted it has more limited use of natural gas in heating and more use in power than the country as a whole. This natural gas in power means there is less coal primary usage than elsewhere in the country initially, though the transition from coal happens in all regions during the 2020s.

Figure 8 shows the transition of the energy mix over time, as reflected on both the supply and demand sides of the system. The four columns show energy divided into the main energy carrier types (liquids, hydrogen, gas, 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. Hydrogen also takes over as an energy carrier in industrial and on-road transportation applications. 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 8 Components of emissions reductions by energy form in the Central scenario - Florida



Liquid fuels are prioritized over gaseous fuels for decarbonization due to their higher CO_2 emissions intensities and higher dollar per MMBtu costs. Hydrogen transitions from a product made through natural gas reformation today to one that utilizes electricity (electrolysis) or biomass (BECCS) in the future with commensurate zero or negative emissions intensities. Electricity production is primarily from renewables by 2050, with coal transitioning out by 2025, and gas generation reducing steadily over the period. Existing nuclear is maintained in the Central scenario, so the contribution from nuclear stays constant through 2050. The Turkey Point units are already licensed through 2052 and 2053 (80-year) and we assume the St. Lucie units will also be relicensed to 80-years (currently operating on licenses to 2036 and 2043).

3.3. System Costs

Cost assessment 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 examine a series of alternative 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 State GDP[7] per year (Figure 9). Incremental costs are calculated by comparing the annual 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.

Net annual system costs exceed $12B per year only in the 100% Renewable Primary Energy and Low Electrification scenarios. In the Central scenario, costs never exceed $12B per year and peak at less than 0.8% of projected GDP in all of the remaining 350 ppm-compatible pathways.

While the overall net costs are small compared to projections of GDP, where this money is spent changes substantially. Reduced spending on fossil fuels, primarily refined liquid fossil fuels, offsets incremental investments in the electricity grid (to support electrification), renewable power plants, alternative fuel production, and carbon capture.

In addition to net costs from the Reference scenario, we assess the total (gross) 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. The top panel in Figure 9 shows the historical energy spending in the Florida compared to GDP[8]. Modeled results are shown in the bottom panel. In the Reference scenario, we can see that overall spending as a % of GDP is set to decline. This is a result of anticipated continued economic growth; relatively muted growth in the price of fossil fuels; and continued growth in services as a share of GDP.

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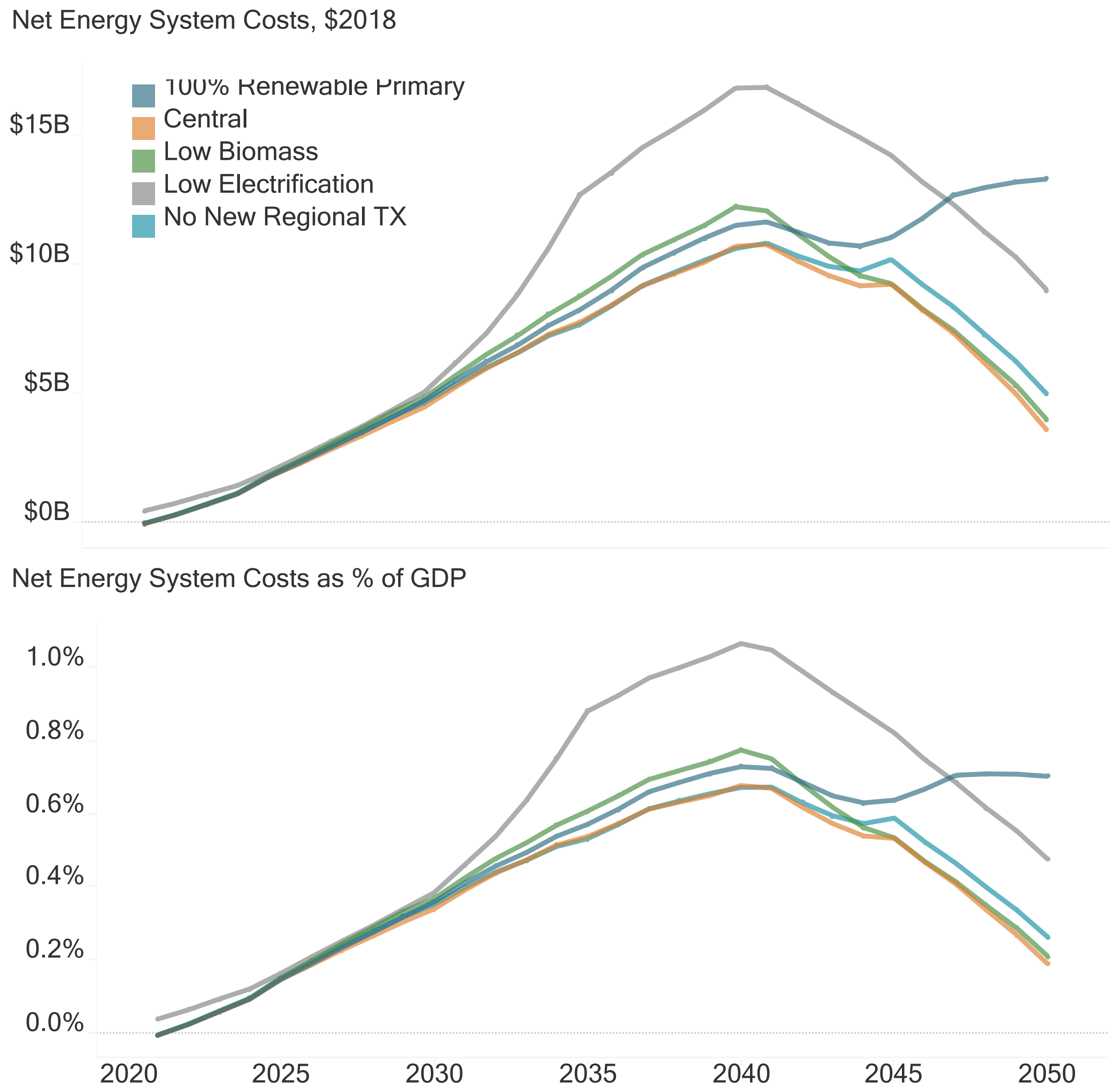
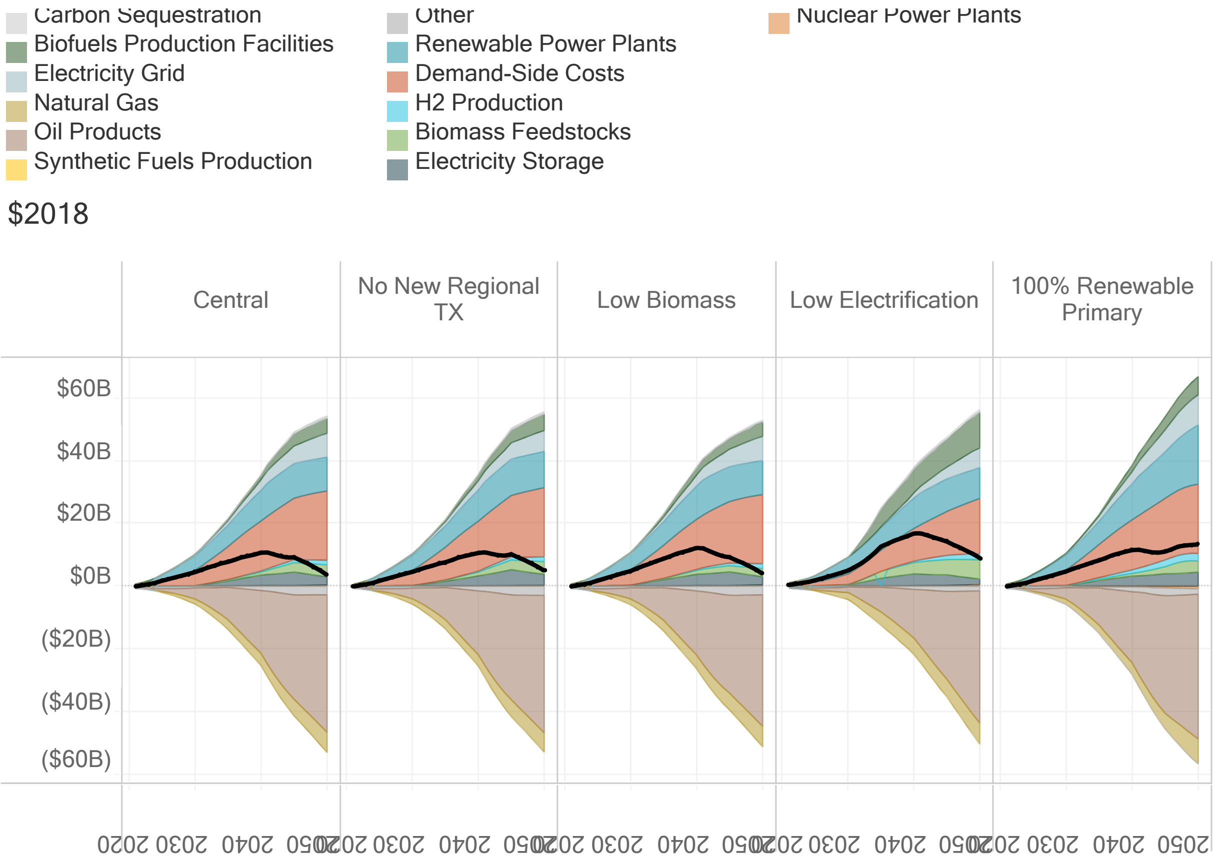
[8] These values are inclusive of taxes and subsidies. Our modeled values do not included taxes (i.e. gasoline tax) or subsidies (i.e. ITC/PTC, etc.). This difference is not substantial enough to alter the fundamental comparison.

Figure 9 Annual net system cost premium above baseline in $2018 and as % of GDP – Florida



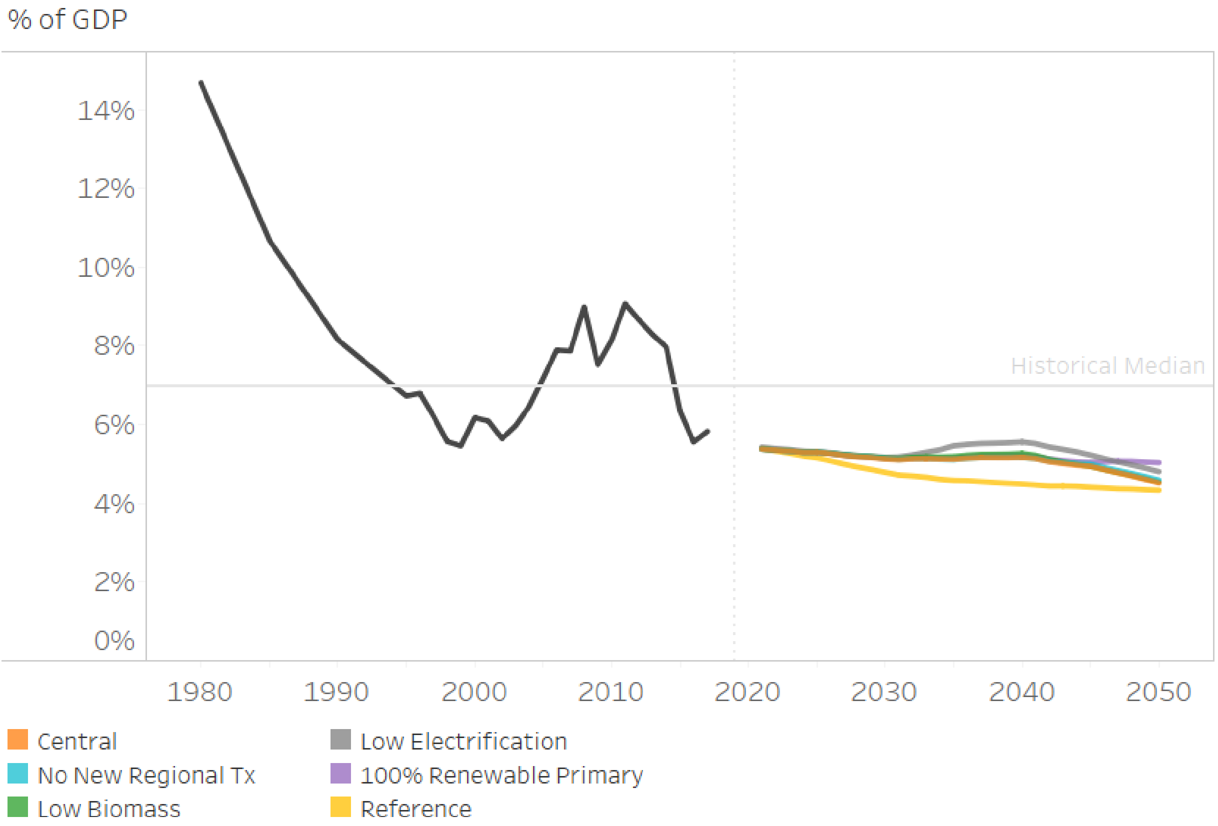
The spending category where Florida differs significantly than the U.S. as a whole is the investment in electricity storage. Florida is unique given its high-quality solar resource and lack of onshore wind potential. These renewable resource endowments combined with the lack of seasonality in load and solar production means that a high percentage of its electric load can be satisfied with solar and storage. This is not the scenario in most areas of the United States. This fact accounts for the large share of investment in stationary electricity storage in Florida.

Figure 10 Net Change in E&I System Spending – Florida



In no scenarios analyzed here does Florida energy system spending approach the historical median. This is due to a saturation of energy services relative to GDP as well as the relative cost-effectiveness of decarbonized technologies compared to their fossil alternatives.

Figure 11 Total energy system costs as % of GDP – historical and projected - Florida



3.4. Sector Results

3.4.1. Electricity

3.4.1.1. Low – Carbon Generation

In Florida, renewable growth is entirely solar PV through 2040[9] and then offshore wind complements the low-carbon mix. Limits on new regional transmission between Florida and Southeast results in double the amount of offshore wind deployed.

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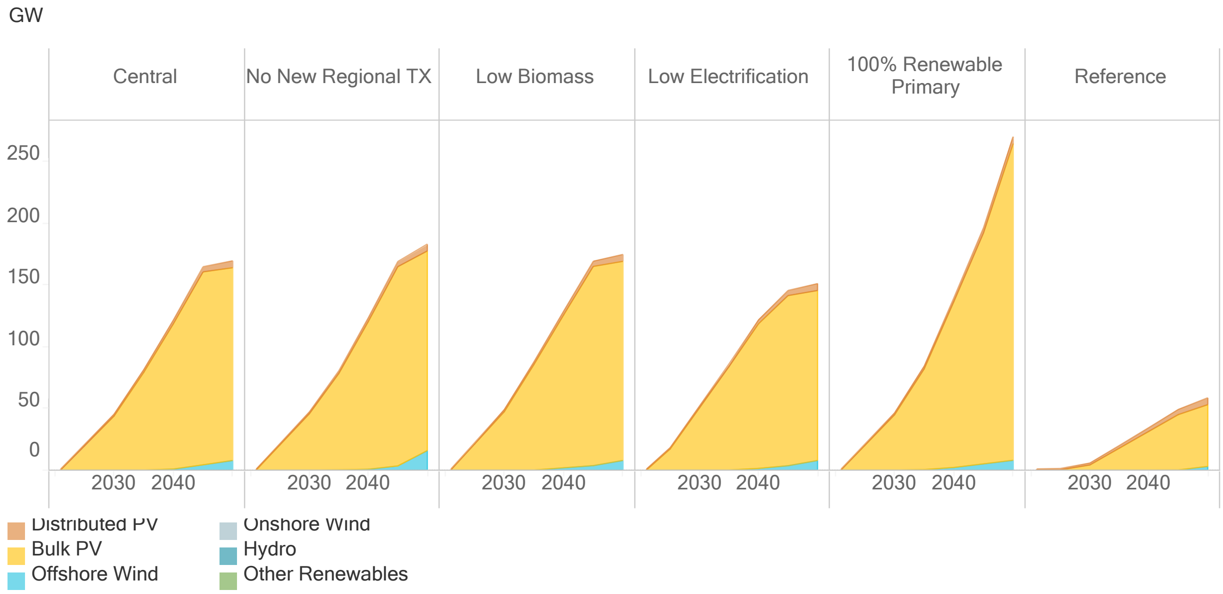
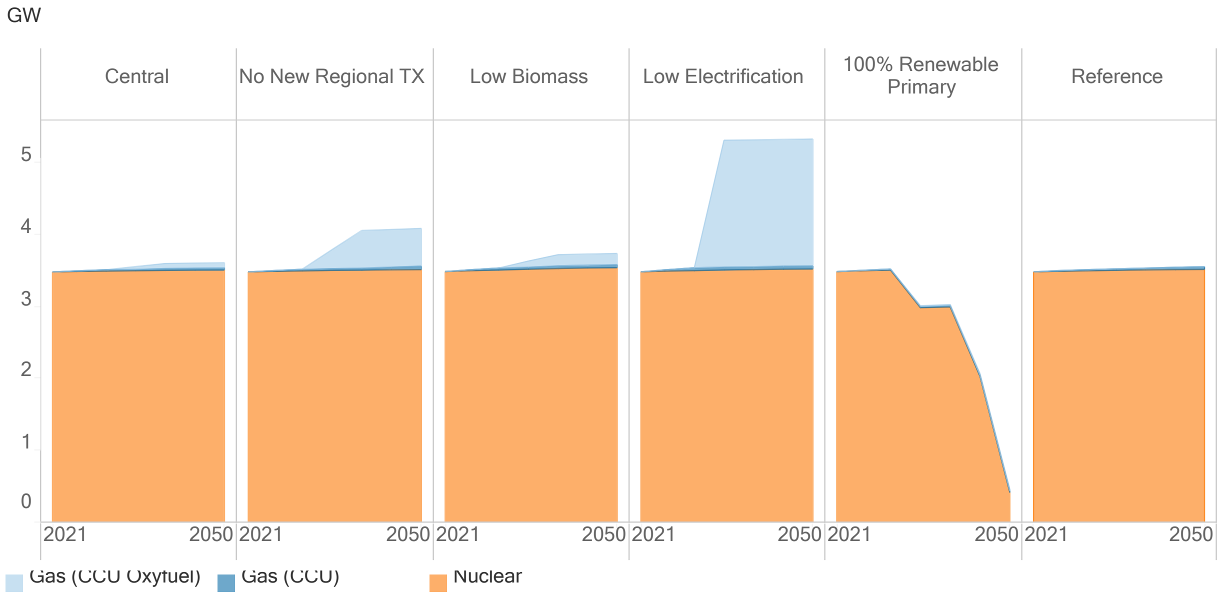
[9] This would represent a maximum of slightly more than 1% of available land in Florida devoted to solar production in the 100% Renewable Primary scenario using a power density of 7.5 square kilometers/gigawatt

Figure 12 Renewables installed capacity - Florida



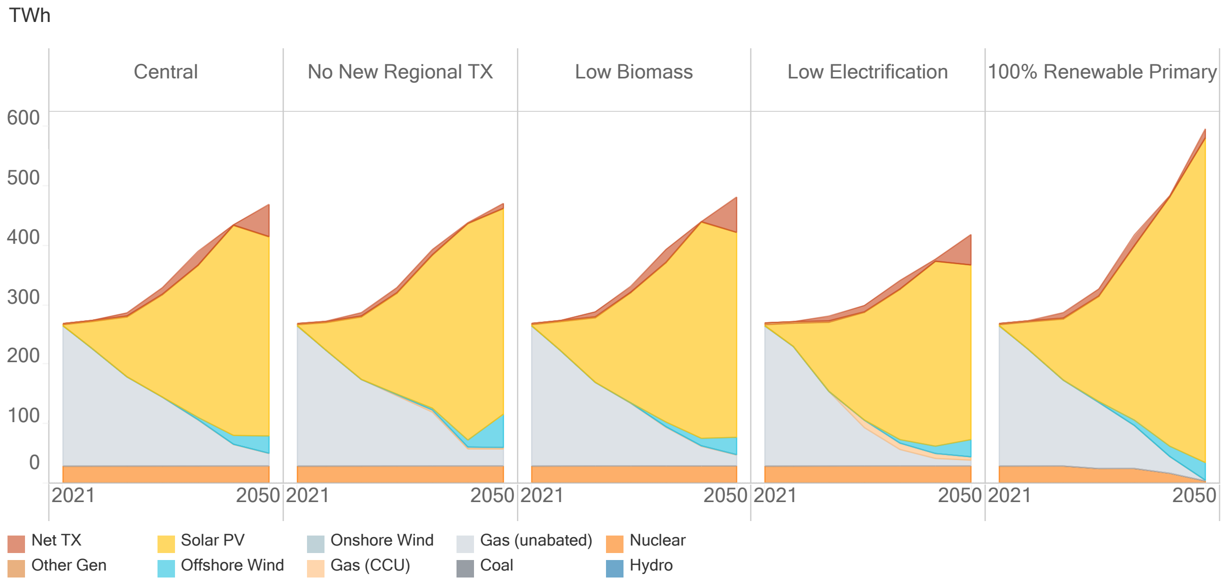
Low-carbon thermal capacity, including existing and new nuclear plants and gas plants equipped with CCU, varies significantly by scenario due to the constraints imposed. Generally, existing nuclear plants are relicensed through 2050 unless they have a planned retirement date. This is the scenario in Florida, where Turkey Point has already received relicensing to continue operations beyond 2050 (e.g., 80-year lifetime). Carbon capture and utilization (CCU) with oxy-fuel combustion is deployed in scenarios where implementation failures relative to the Central scenario persist, such as lower-than-expected end-use electrification.

Figure 13 Low-carbon thermal installed capacity - Florida



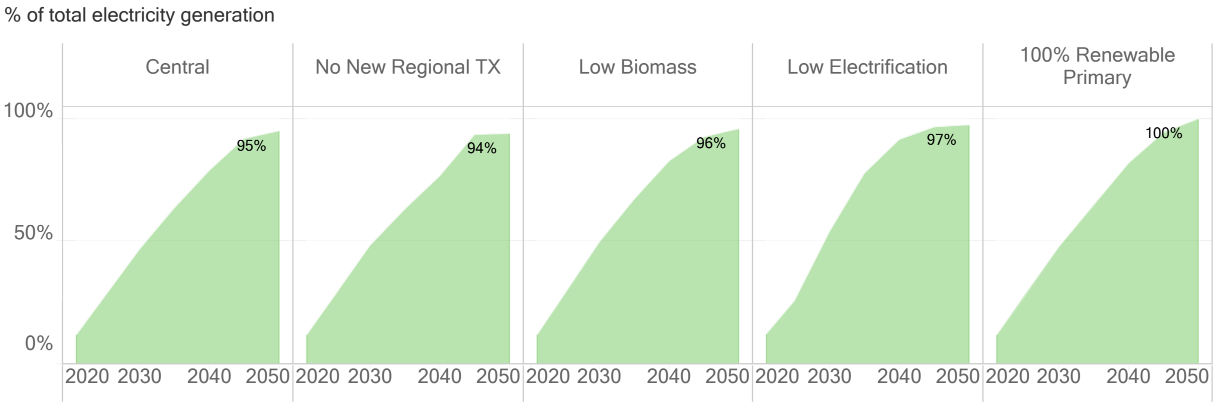
The result of deploying renewables and other low-carbon resources at scale is an electricity generation mix that is nearly zero-carbon in all 350-ppm scenarios. Florida's electricity mix maintains nuclear generation at today's levels, while gas-fired generation in the early years is replaced mainly by solar with more limited energy contributions from offshore wind and imports from the Midwest (transmitted through the Southeast). Coal-fired electricity generation is eliminated from the power sector by 2025.

Figure 14 Annual electricity generation



350-ppm compatible scenarios provide insights into how clean the electricity sector needs to be to facilitate carbon reductions across the economy. We quantify the clean electricity standard (CES) that must be reached in each year by measuring the share of total electricity generation that comes from: renewables, nuclear, hydro and gas-fired resources with CCU oxyfuel. Today (2021), the implied CES for the U.S. is approximately 40% with most of this being met by nuclear, hydro and onshore wind. The CES rises to approximately 75% by 2030, 85% by 2040 and 95% or more by 2050. This excludes thermal fuel substitution (e.g., burning zero-carbon fuel instead of natural gas), which would be employed as a strategy had we chosen to enforce 100% clean electricity standards in the scenarios.

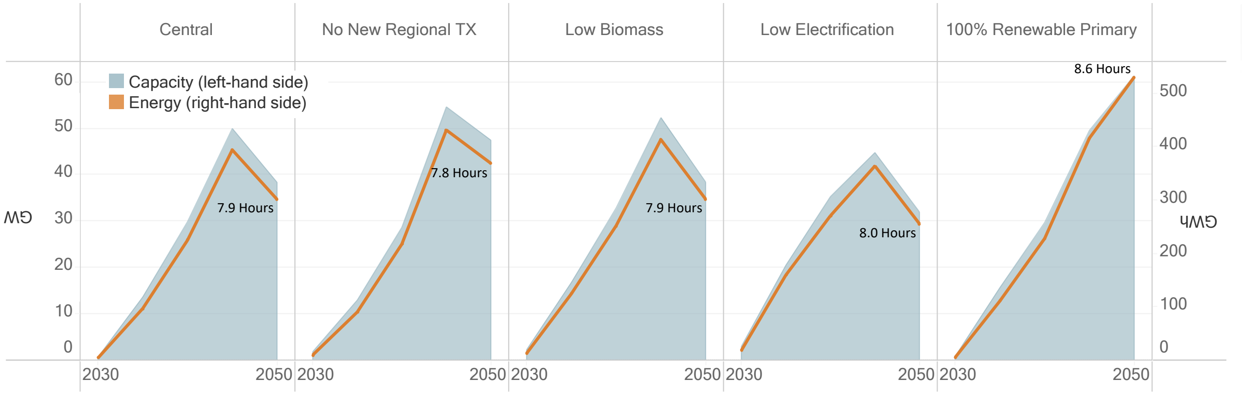
Figure 15 Implied Zero-Carbon Generation Share



3.4.1.2. 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. We find that significant amounts of new electricity storage are needed in all 350 ppm-compatible scenarios starting in 2030 (Figure 16), and this storage is deployed with an average duration of approximately eight 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 off-peak thermal generation (capacity and energy). As noted, Florida is particularly attractive to deploy energy storage due to its heavy reliance on solar, lack of load seasonality, and limited regional interconnectivity.

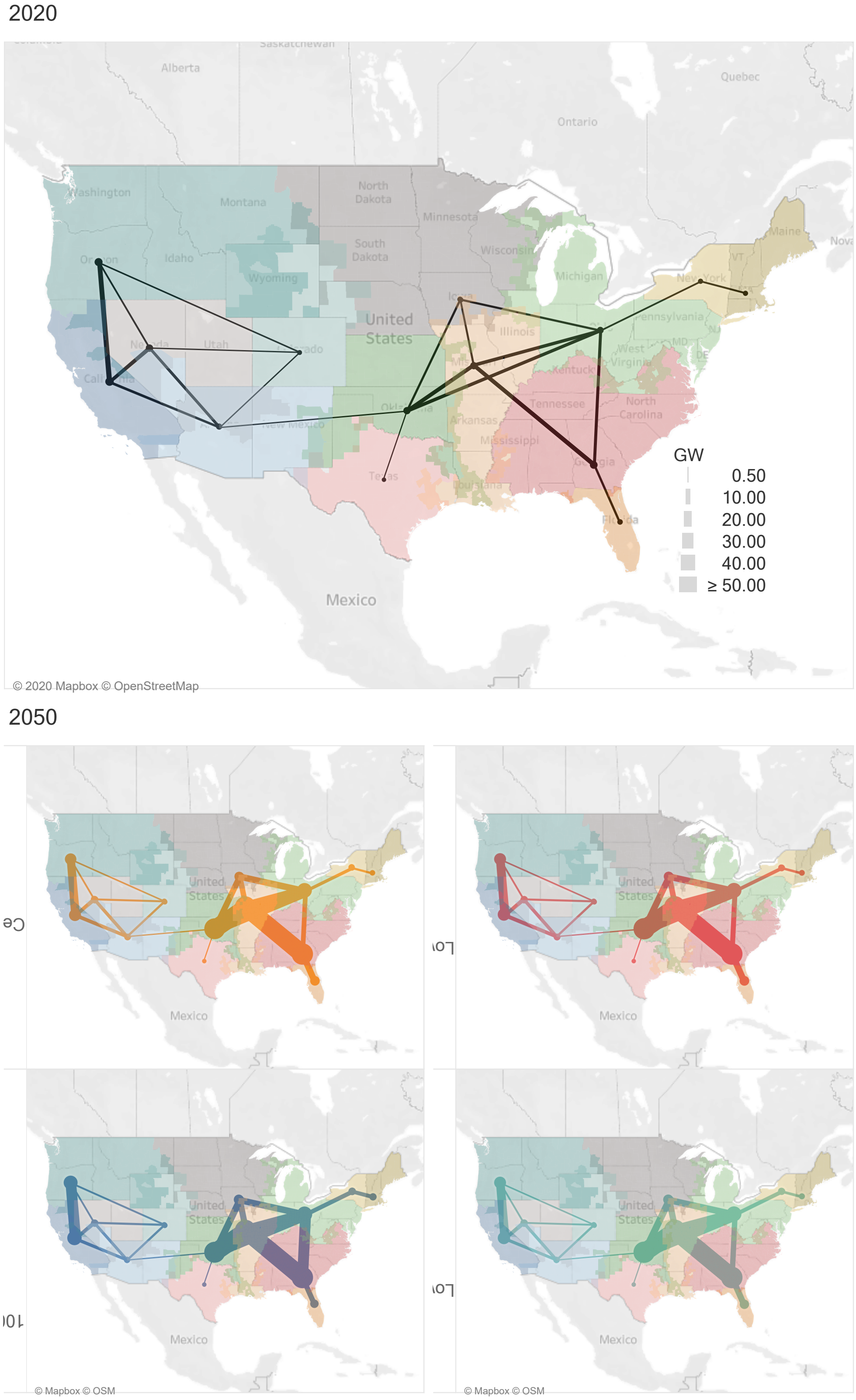
Figure 16 Energy storage capacity in gigawatts, gigawatt-hours, and average duration



3.4.1.3. 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. The map below shows that the principle reason new transmission capacity is developed across the analysis is to deliver wind to regions with limited resources of their own, such as Florida, California, New England, and Southeast. However, assumed technology progress through mid-century in both onshore and offshore wind has somewhat muted the imperative of developing these lines. This is shown in the limited impact on net costs seen in the No New Regional TX scenario (Figure 9). This isn't to underestimate the need for new intra-regional transmission, which is significant at the scales we project for renewables deployment.

Figure 17 Transmission capacity by corridor



3.4.1.4. Electricity Operations in Florida

Today, Florida supplies almost all of its electricity with gas generators and a limited amount of coal. There is very little renewable deployment. However, in a 350 ppm-compatible future the operations of the grid become much more dynamic. Florida has a unique resource endowment, with significant available solar but limited onshore and near-offshore wind resources (most viable offshore wind is located far from shore and in deep water depths requiring floating technology). Coupled with a temperate climate that results in little seasonal load variability, Florida is able to satisfy a large amount of its load with a combination of solar and storage.

Figure 18 Average Hourly Generation and Load: 2021, Florida (Baseline)

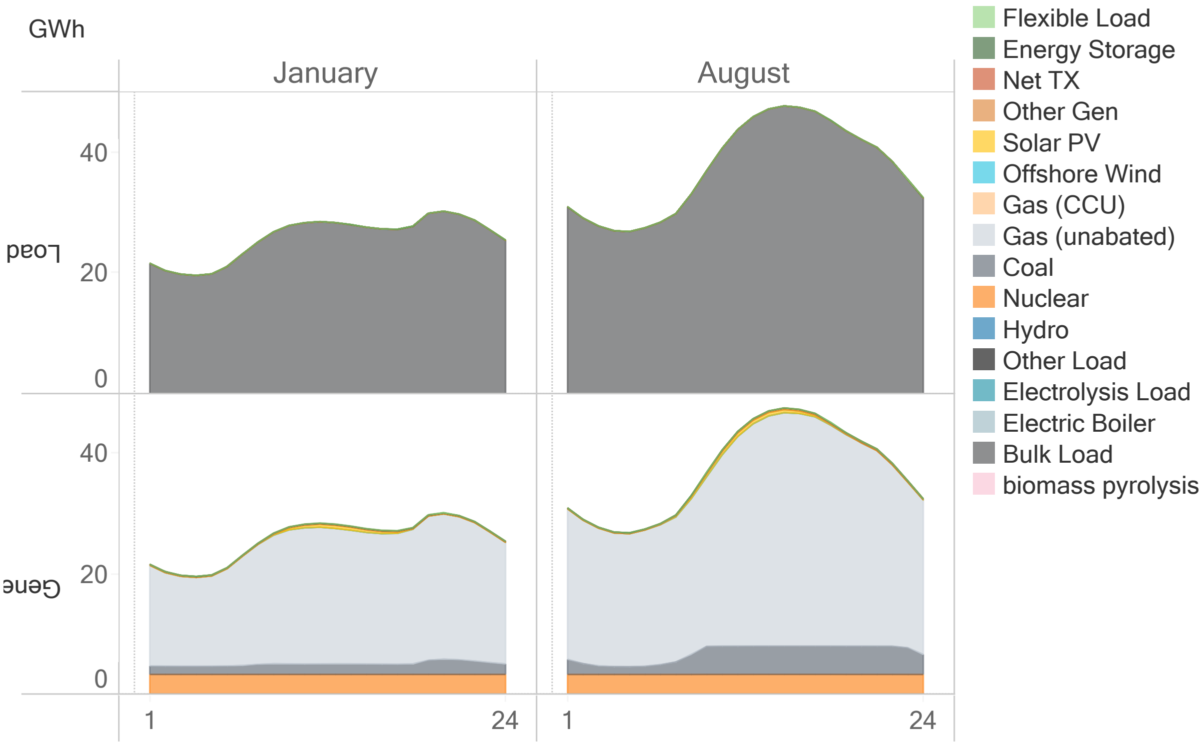
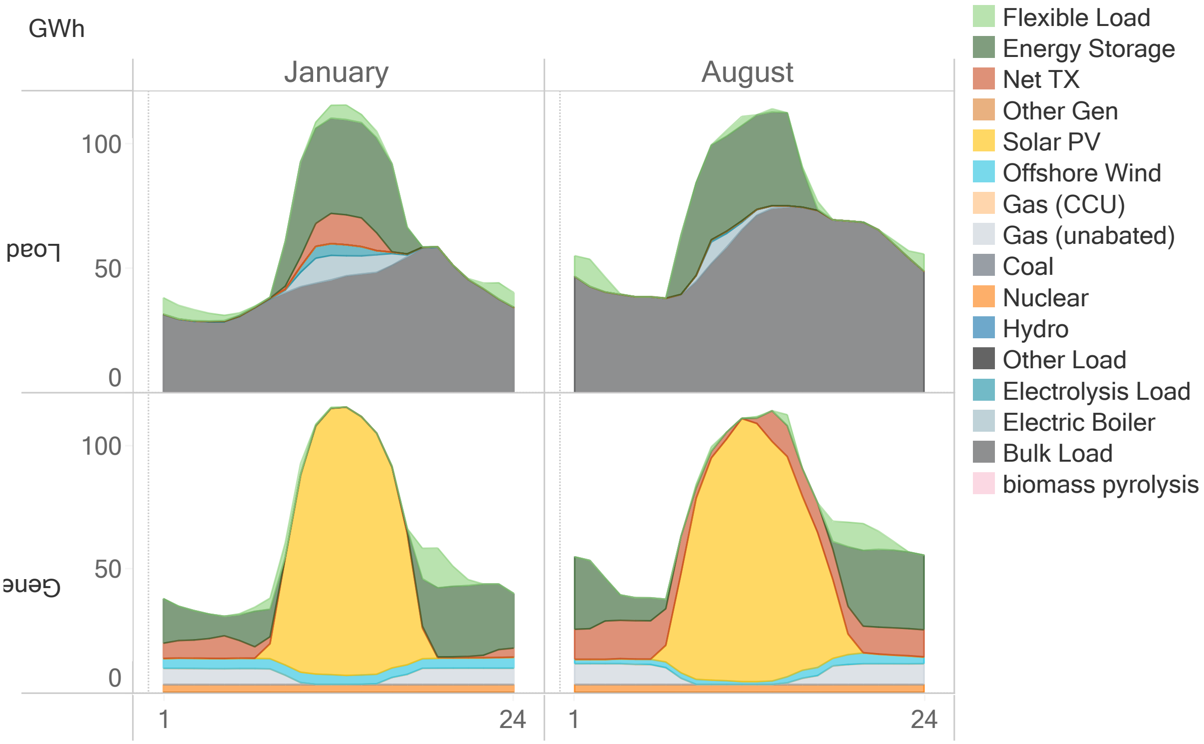


Figure 19 Average Hourly Generation and Load: 2050, Florida (Central)



The importance of flexible end-use loads is also clear from the chart above where flexible load is: (a) shown as generation when flexible load is reduced from its initial operating point, and (b) shown as load when it is increased from its initial operating point. In the absence of flexibility from those resources, these early-evening hour load peaks (after the evening commute) would necessitate a significant buildout of additional gas and storage resources to support them. Instead, the grid utilizes flexible end-use loads to move electricity demands either towards the middle of the day (pre-cooling or pre-heating with heat pumps) when the sun is shining or to moderate the charging of EVs across the night-time hours.

In addition to these flexible end-use loads, the model deploys “opportunistic loads” from electrolysis and electric boilers that deploy in concert with the higher renewable penetrations. They’re able to economically use otherwise curtailed energy from days with high solar output and produce high-value products of steam and hydrogen, which is then used in other sectors to aid in their decarbonization.

The model builds new transmission resources to Florida in all scenarios where it is allowed. This new transmission helps to diversify loads and generation and import wind resources from the U.S. Midwest through our Southeast region. Once built, these lines provide bidirectional value, allowing for solar export during periods of high generation, while allowing the import of wind during other periods. Specifically, this generation is utilized during off-peak periods, where Florida otherwise must rely on battery storage with limited durations that it can discharge.

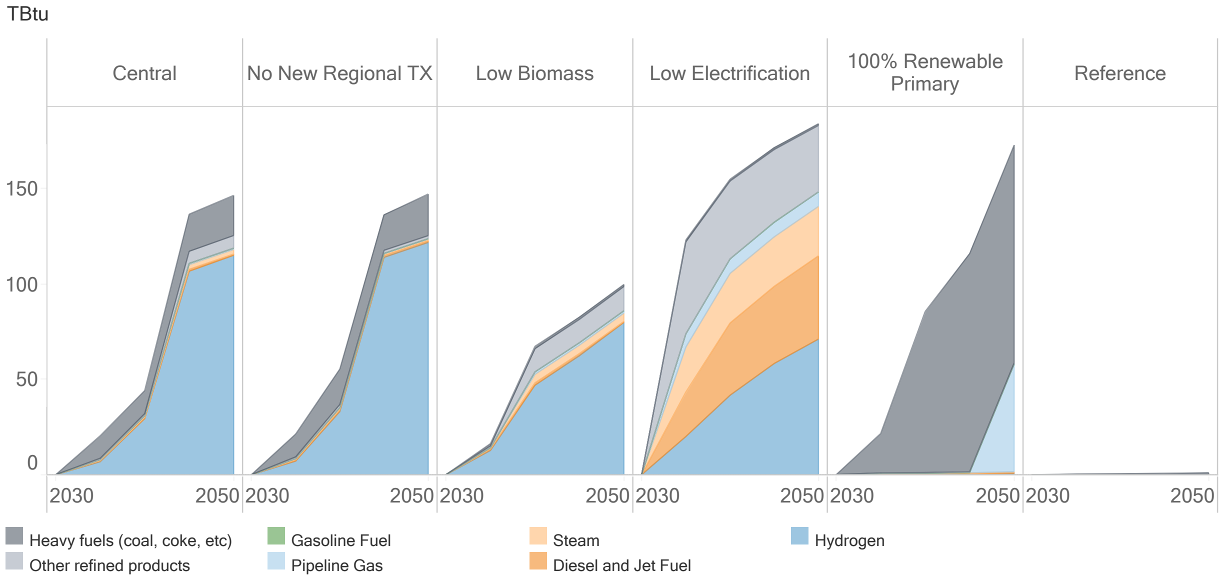
3.4.2. Fuels

3.4.2.1. Biofuels

The expansion of biofuels production is a critical strategy to mitigate emissions even with aggressive end-use electrification. 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).

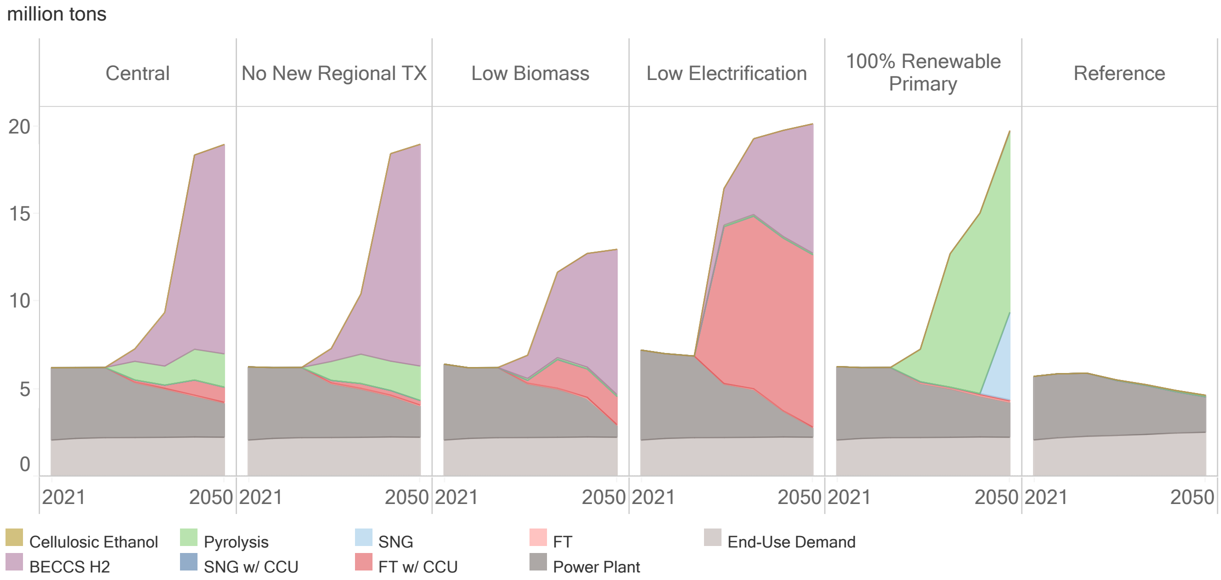
The analysis finds that scarce biomass feedstocks are economically allocated to producing negative-emissions hydrogen and displacing liquid fossil fuels (e.g., diesel and jet fuel) and “heavy fuels” such as coal, coal- and petroleum-derived coke and oil. Liquid fossil fuels are ideal for displacement rather than gaseous fuels since: (a) natural gas has a lower cost per MMBtu than refined liquid fuels; (b) natural gas CO_2 emissions are lower than liquid fossil fuels on an energy basis; and (c) the carbon from converting biomass into liquid fuels can be captured and utilized as a feedstock for producing synthetic fuels or sequestered. Heavy fuels are decarbonized using biofuels produced from pyrolysis since they are primarily consumed in hard-to-electrify end-uses such as heavy industry.

Figure 20 Next-generation Biofuels Produced



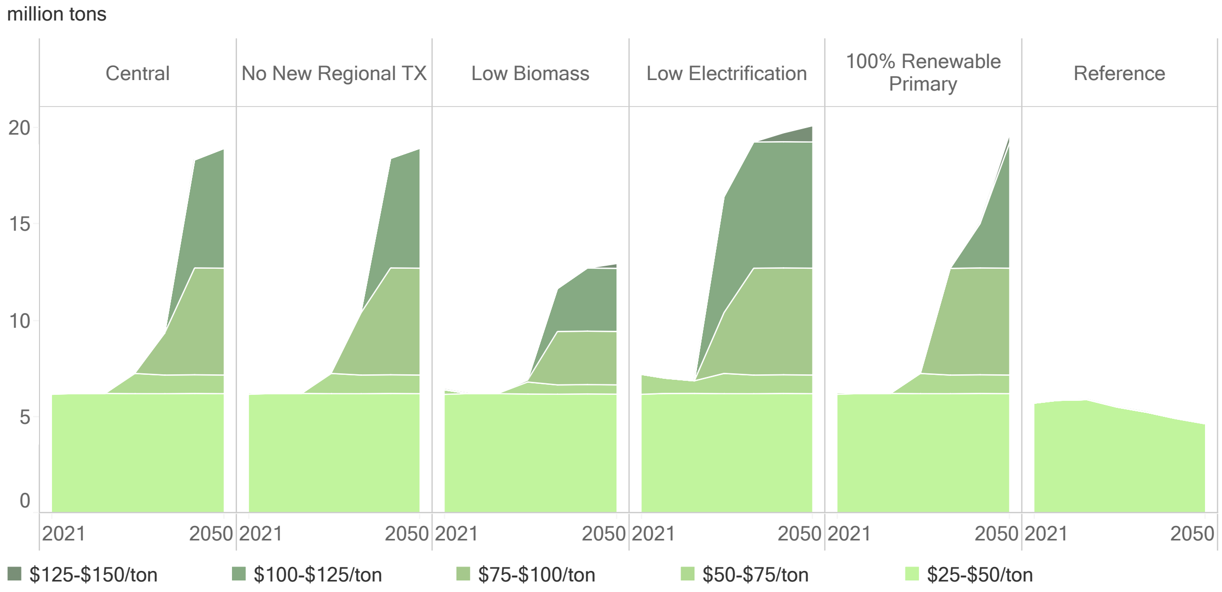
In order to produce next-generation biofuels, biomass feedstocks are directed towards new biorefineries. Most of the biomass feedstocks are used in pyrolysis and BECCS hydrogen production. The Central scenario uses approximately 80% of Florida's biomass feedstock of over 20 million dry tons. Low levels of electrification necessitate a greater reliance on biofuels both in terms of magnitude and timing. The Low Electrification scenario consumes more than double the amount of biomass in 2035 relative to the Central scenario (+10 million tons) and nearly all the available feedstocks by mid-century. An economy that relies on 100% renewables for primary energy requires similar levels of biomass by mid-century, but the lowest levels among the scenarios in this analysis due to a lack of carbon sequestration.

Figure 21 Biomass Feedstock Consumed



The implication of increased biofuels production is the need to harvest increasingly expensive biomass feedstocks, as shown in Figure 22. Initially, most biofuels are produced using the cheapest available feedstocks that range from $25 to $50/ton (~$1.5-$3.0/MMBtu), most of which are low-cost waste resources that doesn't require additional land and fertilizer inputs. In the 2030s, biofuel production escalates and requires feedstocks costing between $50 to $100/ton ($3 to $6/MMBtu), and this includes a variety of waste, wood and herbaceous energy crops. Scenarios that are heavily reliant on biofuels for mitigation (Low Electrification and 100% Renewable Primary) must access the most expensive herbaceous energy biomass feedstocks, which cost between $7-$9/MMBtu.

Figure 22 Biomass Feedstock by Cost Bin



3.4.2.2. Hydrogen Uses and Sources

Hydrogen plays a multifaceted role to ensure that Florida can achieve a 350 ppm-compatible economy and these roles generally fall into three distinct categories. First, hydrogen can be directly combusted in vehicles and power plants. In this analysis, hydrogen fuel cell vehicles (HFCV) are a prominent component of the freight truck fleet (the remainder of the fleet is electric) and hydrogen is directly burned in gas-fired power plants to serve as a low-carbon means of electricity balancing. Second, 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.[10] Third, producing hydrogen from the electrolysis of water plays a key role in balancing the electricity system during periods of renewable overgeneration.

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[10] A schematic of this process is shown here: https://cleanenergytransition.github.io/mtc-report-graphic-p2x/

The demand for hydrogen and its applications is summarized in Figure 23, which separates the amount of hydrogen used by end-uses (e.g., heavy-duty trucks), power plants and power-to-X processes. An energy system with 100% renewable primary energy requires nearly twice the energy of all the other scenarios in order to use additional hydrogen as a feedstock for synthetic fuels. In the near-term, hydrogen demand is primarily met by natural gas reformation (Figure 25). However, electricity sector balancing with high levels in the 2030s and stringent emissions constraint result in BECCS and electrolysis as the primary technologies for hydrogen production beyond 2035.

Figure 23 Hydrogen Demand

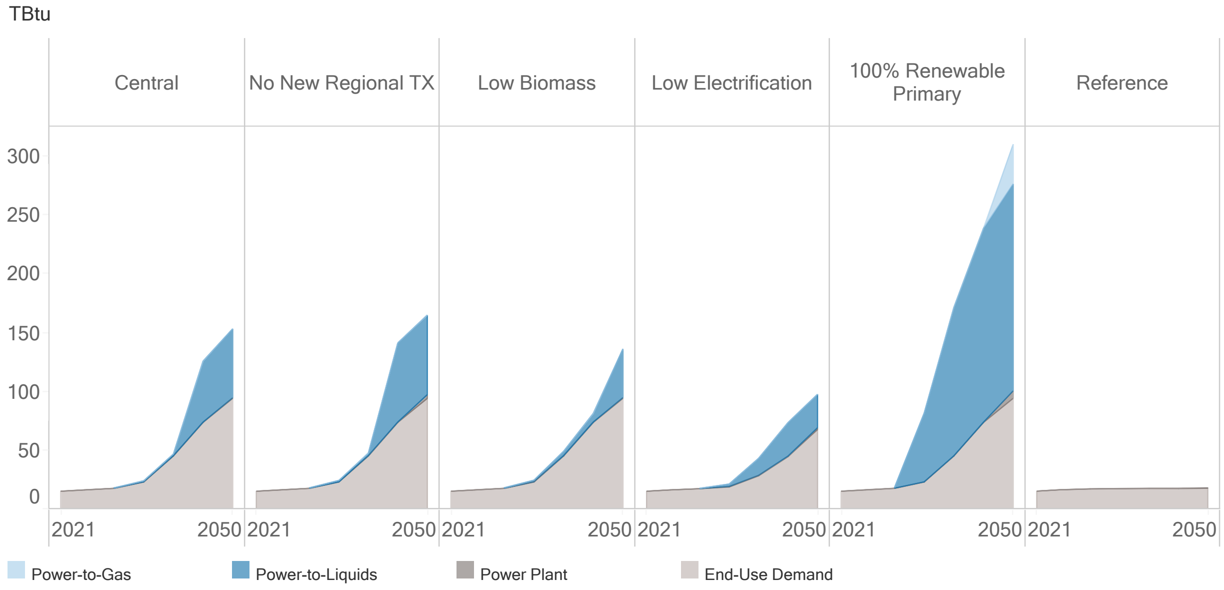
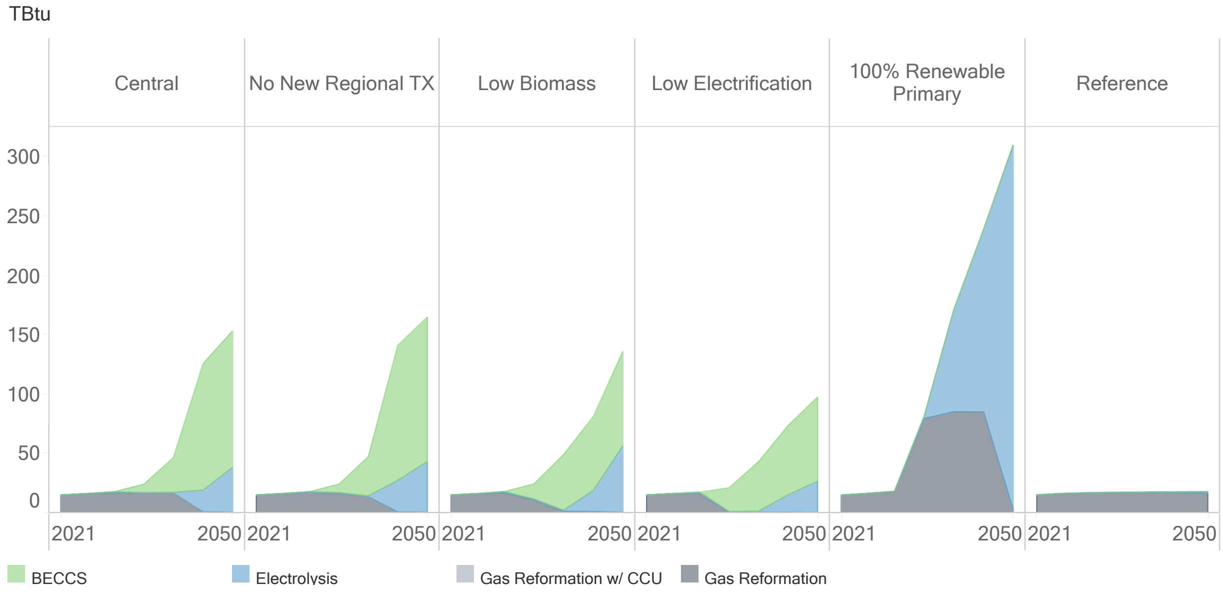


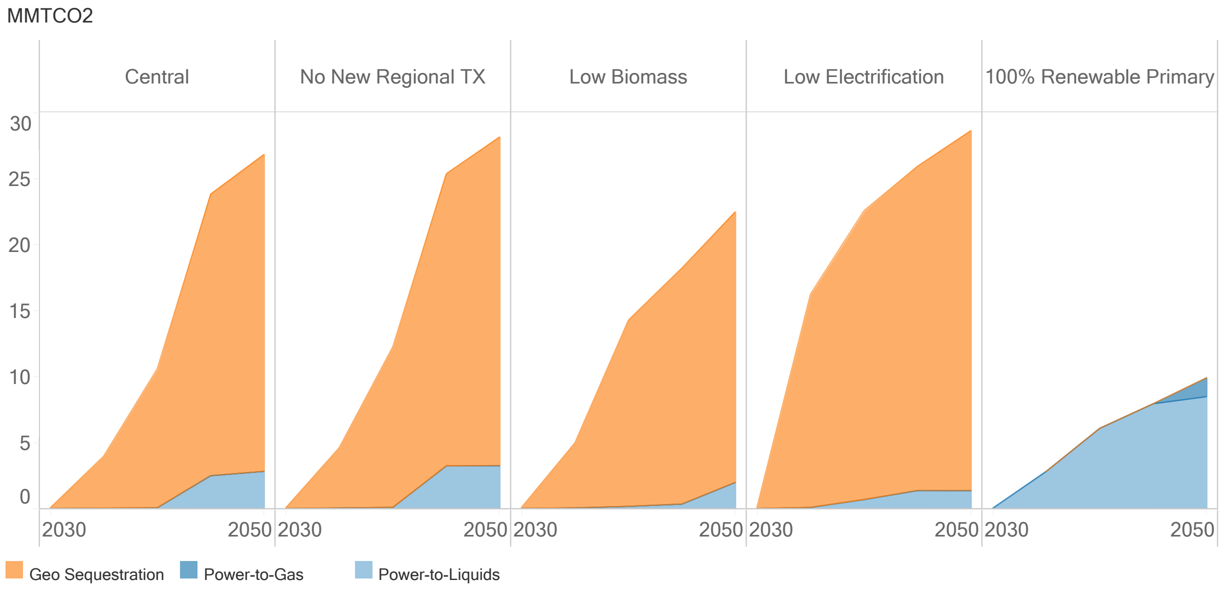
Figure 24 Hydrogen Supply



3.4.3. Carbon Uses and Sources

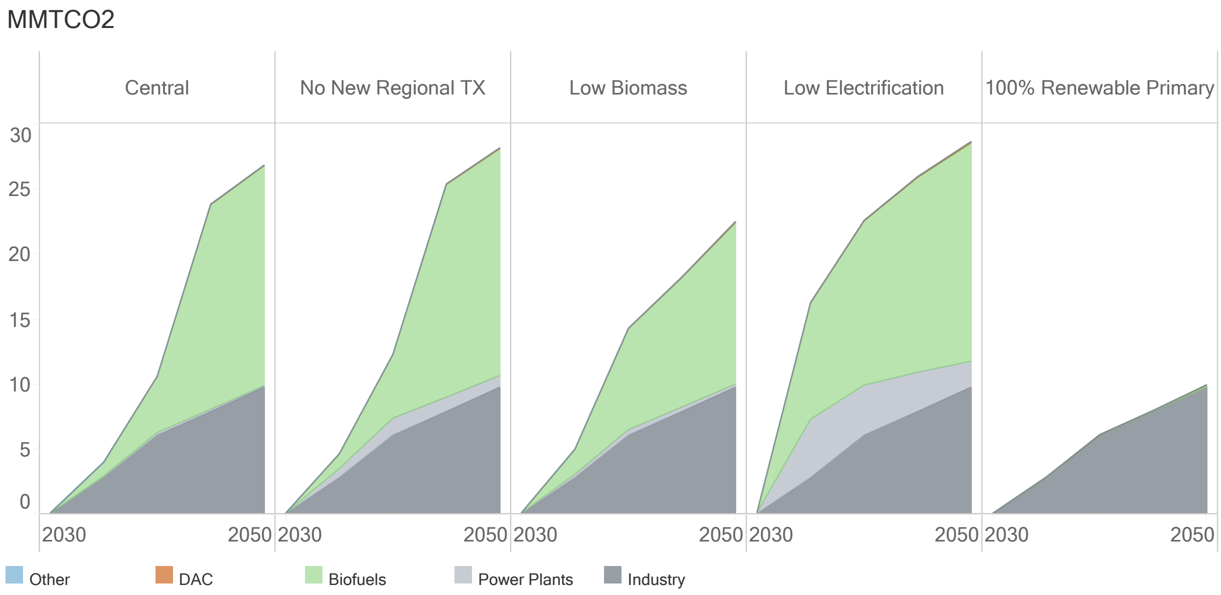
A 350 ppm-compatible energy economy requires millions of metric tonnes of CO_2 to be captured and/or sequestered. Approximately 30 MMT of CO_2 is captured in Florida by mid-century under the Central scenario with the majority sequestered. In areas with better renewable resource endowments, a higher share of captured carbon is directed towards synthetic fuel production. Low levels of end-use electrification require both additional sequestration and utilization, whereas the 100% Renewable Primary energy economy does not rely on sequestration and uses significant volumes of carbon to produce both liquids and gaseous fuels.

Figure 25 Uses for captured carbon



Captured carbon is derived from a variety of sources, including: (1) industrial facilities; (2) power plants; (3) biofuels production facilities; and (4) direct air capture. Across all scenarios, the U.S. primarily relies on capturing carbon from industrial facilities and bioenergy facilities producing hydrogen, heavy fuels and liquid fuels. Direct air capture (DAC) doesn't play a role in Florida, instead any DAC plants are sited in other areas of the U.S. with more favorable renewable resource endowments (primarily areas with high-quality onshore wind).

Figure 26 Sources of captured carbon



3.4.4. Transport

Transportation decarbonization relies on the 1) electrification of the majority of on-road vehicle miles traveled and 2) decarbonization of residual fuel in on-road and off-road end-uses like aviation. By 2050, in all but the Low Electrification scenario, electricity is half of delivered transportation energy. Emissions associated with this new electric load are negligible due to the decarbonization of electricity supply. Emissions associated with residual fuel use also decline precipitously past 2030, with the use of biofuels and electric fuels to displace fossil use. Biofuels produced with carbon capture supply negative carbon fuels to the transportation sector, allowing overall emissions contributions to go net negative.

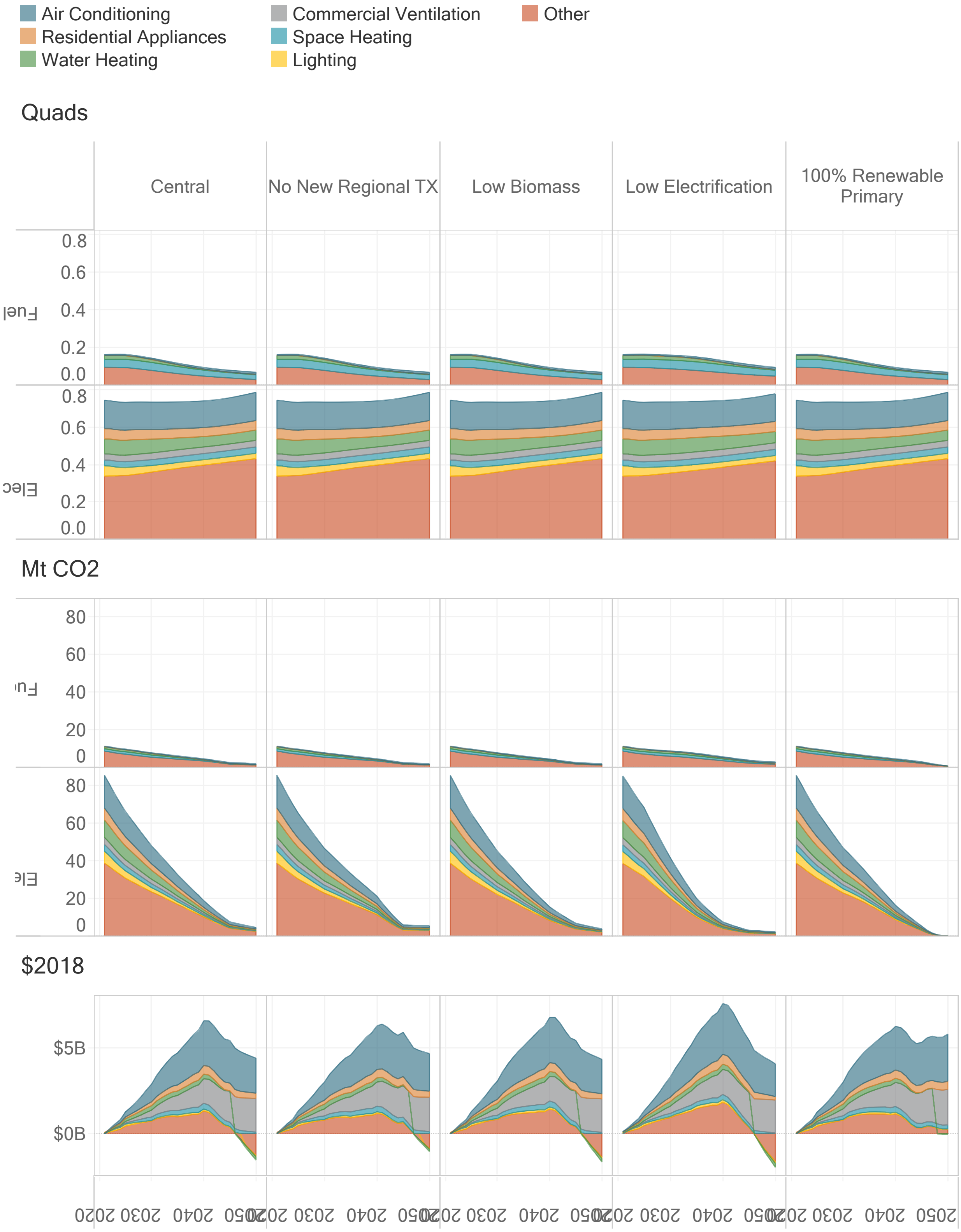
Given the current trajectory of battery costs, a concerted effort towards transportation electrification offers the greatest cost savings of a decarbonized economy over Reference scenario projections. Electrification, of light-duty travel in the near- to medium-term and in the medium to long-term of the majority of freight transportation, represents an opportunity to reduce the costs of these energy services. Similar to energy efficiency today, overcoming any initial cost premiums on these vehicles in order to save money and emissions in the longer-term is critical. Although the transition to electrification comes with a small cost before 2030 (which contributes to emissions reductions), by 2035 the electrification transition is negative cost. By 2045, the electrification transition in medium and heavy-duty vehicles also is negative cost.

Figure 27 Transportation Energy, Emissions, and Net Costs by Key Subsector – Florida

3.4.5. Buildings

Buildings electrify end-uses like space heating, water heating, and cooking, allowing services in these end-uses to access zero-carbon energy from wind and solar. This reduces emissions from on-site combustion, and the decarbonization of electricity means that emissions associated with this electrification do not increase significantly. The costs of these electrified end-uses once the transition is complete are generally moderate, with the increased efficiency of electric delivery of these services offsetting the increased costs per unit of energy. In end-uses where electricity is already used, this story is somewhat different, with efficiency unable to keep pace with the increasing cost of decarbonized electricity. These end-uses generally see the largest cost impacts (appliances, ventilation, refrigeration). Lighting is an exception, with the transition to LEDs seeing such a large efficiency gain that costs are offset.

Figure 28 Building Energy, Emissions, and Net Costs by Key Subsector – Florida



3.4.6. Productive

The productive sector experiences limited transformation of end-use consumption relative to building and transportation sectors. Electrification is limited outside of the expansion of dual-fuel boilers, building electrification, and some process heating. This can be seen in the relatively limited increase in electricity, with most electrification offset by energy efficiency. Increases in fuel demand shown for the cement & lime subsectors are associated with the energy demands of carbon capture (primarily steam).

While the overall changes in energy demand compared to the Reference scenario are relatively limited compared to other sectors, emissions reductions are significant due to the decarbonization of electricity and the application of carbon capture in heavy industry. Additionally, in the bulk chemicals subsector, deployment of alternative, bio-based feedstocks to displace LPG and other petroleum results in net negative emissions from the subsector (when considering the sequestration of the carbon in products like plastics).

Increased costs for industry are primarily due to the increased upstream costs of providing low-carbon fuels and electricity. They're also related to the costs of carbon capture in cement as well as iron and steel production. Energy efficiency moderates these increased industrial costs to some extent and where there is residual fossil use in the energy system, it is generally natural gas used in these industrial applications. Bulk chemical production sees a large increase in costs in the 100% Renewable Primary scenario due to the need to decarbonize chemical feedstocks entirely. Specifically, this removes the residual natural gas at a high net cost.

Figure 29 Productive Energy, Emissions, and Net Costs by Key Subsector – Florida

4. Conclusions

Based on the analyses described in this report, we maintain the conclusion that achieving a trajectory of emissions in Florida consistent with 350 ppm globally is technically feasible and the cost of realizing emissions reductions is affordable in the context of historical energy system spending within the state. This result is robust against four key scenario variants – Low Biomass, Low Electrification, 100% Renewable Primary, and No New Regional TX. 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.

For the State of Florida, decarbonizing its energy system consistent with the country's pathway is also feasible. The State's relative position as an energy consumer and producer doesn't dictate serious deviations away from the Country's overall pathway, but there are a few unique characteristics that bear mention:

1. While the State's renewable resource potential is more heavily weighted towards solar than wind energy, the availability of offshore wind, and the lack of seasonality in its load, means that developing a deeply decarbonized electricity system to support these emissions constraints is possible.

2. The State will continue to rely on fuel imports, as it does now, however much of that fuel will be zero-carbon variants as opposed to refined fossil.

3. Heating electrification is not as important as it is elsewhere in the country. Firstly, electric heating is already prevalent in 2020, moderating electric load growth. Secondly, lower total heating loads because of milder winters in Florida than other parts of the country limit the imbalance between winter and summer electric loads. This mitigates the need for longer duration balancing resources, allowing more capacity provision to be provided by batteries.

These scenarios are intended to answer the question of whether the U.S. as a whole and Florida individually, with the 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 both are achievable. 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 for all regions. 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. and Florida have managed historically. Based on this analysis, achieving 350 ppm-compatible pathways would maintain energy system costs within the low-range of historical values.

Key Actions by Decade

In conclusion, “Key Actions by Decade” below describes the sequence of actions needed to achieve a 350 ppm trajectory in Florida. 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 Florida, with some differences in terms of scenarios and some decisions in terms of infrastructure preference likely to drive different pathway outcomes. In some scenarios, 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 EIA’s

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 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 gas capacity for reliability while running very infrequently; electricity rate designs that rewards demand side flexibility in high-renewables electricity systems and encourages 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 requiring new buildings to be all-electric and developing 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. In Florida, this will represent efficiency gains, as most current heating is performed with electric resistance heating.

- **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. Gas plants also are better complementary resources 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. Offshore wind should be emphasized given its complementarity with solar resources and the lack of onshore wind potential in Florida. 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 gas 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. This means that it will be necessary to use gas (first fossil gas, shifting to synthetic renewable gas over time) for short durations to fill in gaps in renewable generation. While significant gas generation *capacity* will remain, these gas plants will be used very little so their *utilization rate* will be low and by 2040, very little gas will be consumed for this purpose. 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 planning and rate 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 planning processes must also anticipate the need for balancing services, with full symmetry between supply and demand side balancing to avoid significant periods of curtailment**.**

- **Maintain existing nuclear** – While building new nuclear would not be cost effective, existing 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.g., reactors in active seismic zones and those exposed to rising sea levels). 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 from power plants and biofuel production facilities. Carbon storage and utilization of this carbon, including creating drop-in replacement fuels through methanation or Fischer-Tropsch process all need to be demonstrated commercially before they can be scaled up.

- **No new infrastructure to process and transport fossil fuels** – Consumption of every fossil fuel declines in a pathway to 350 ppm. Thus, new infrastructure associated with the consumption of 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. In Florida, this is particularly important for the cement industry.

2030s

- **Large renewables push** – The 2030s is when the bulk of new renewable generation is built. Renewable curtailment is a necessary transient balancing solution until 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 scenario most carbon capture stays focused on industry and refining.

- **Maintain nuclear** – As in the previous decade, continue to maintain nuclear where safe and cost-effective 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.

- **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.

- **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

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.

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.

Haley, Benjamin, Jim Williams, Ryan Jones, and Gabriel Kwok. 2019. “350 Ppm Pathways for the United States.” Evolved Energy Research. https://docs.wixstatic.com/ugd/294abc_95dfdf602afe4e11a184ee65ba565e60.pdf.

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, Makiko Sato, Pushker Kharecha, Karina Von Schuckmann, David J. Beerling, Junji Cao, Shaun Marcott, Valerie Masson-Delmotte, Michael J. Prather, and Eelco J. Rohling. 2016a. “Young People’s Burden: Requirement of Negative CO2 Emissions.” *ArXiv Preprint ArXiv:1609.05878.*

———. 2016b. “Young People’s Burden: Requirement of Negative CO2 Emissions.” *ArXiv Preprint ArXiv:1609.05878.*

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.

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.

James H. Williams, 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/downloads/2015-report-on-policy-implications.pdf.

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.

National Renewable Energy Laboratory. 2019. "Annual Technology Baseline." 2019. https://atb.nrel.gov/electricity/2019/.

Quéré, Corinne Le, 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.

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. "Executive Order B-55-18 to Achieve Carbon Neutrality." https://www.gov.ca.gov/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf.

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., O. Hoegh-Guldberg, T. M. Lenton, J. M. Lough, D. O. Obura, P. Pearce-Kelly, C. R. C. Sheppard, M. Spalding, M. G. Stafford-Smith, and A. D. Rogers. 2009. "The Coral Reef Crisis: The Critical Importance Of<350ppm CO2." *Marine Pollution Bulletin* 58 (10): 1428–36. https://doi.org/10.1016/j.marpolbul.2009.09.009.

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, Jim, Benjamin Haley, Fritz Kahrl, and Jack Moore. 2014. "2014-Technical-Report.Pdf." Energy and Environmental Economics, Inc. http://usddpp.org/downloads/2014-technical-report.pdf.

Technical Supplement

The following technical supplement shows results for the U.S. as a whole as well as scenario figures not shown in the body of the main report for Florida.

U.S. Results

Figure 30 E&I CO2 emissions trajectories – U.S.

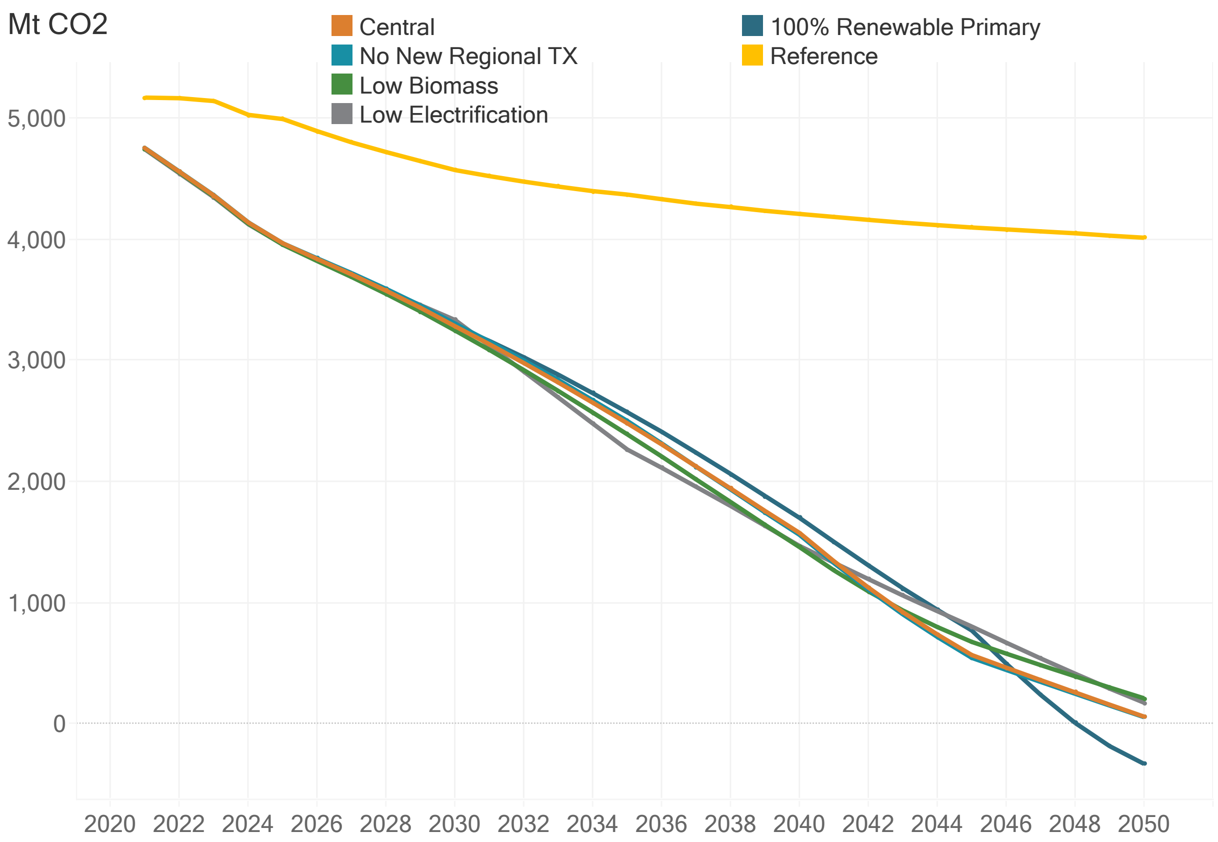


Figure 31 CO2 emissions by final energy/emissions category

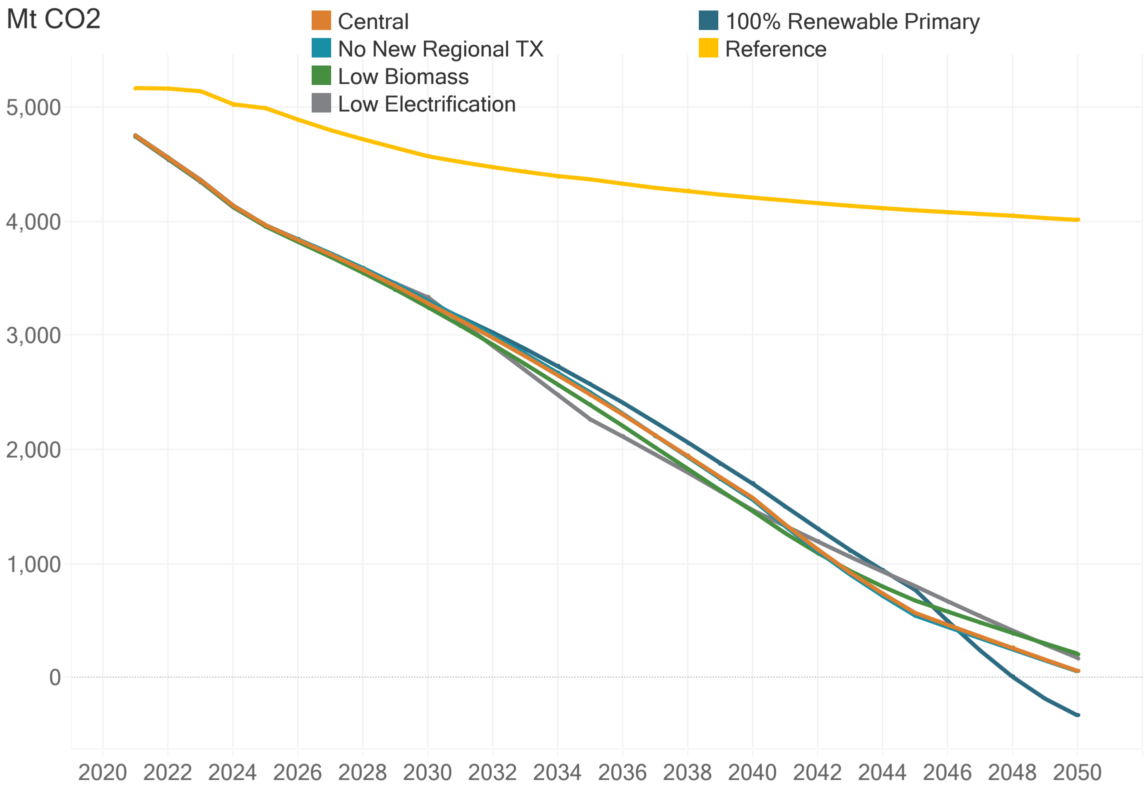


Figure 32 Cumulative E&I CO2 emissions trajectories

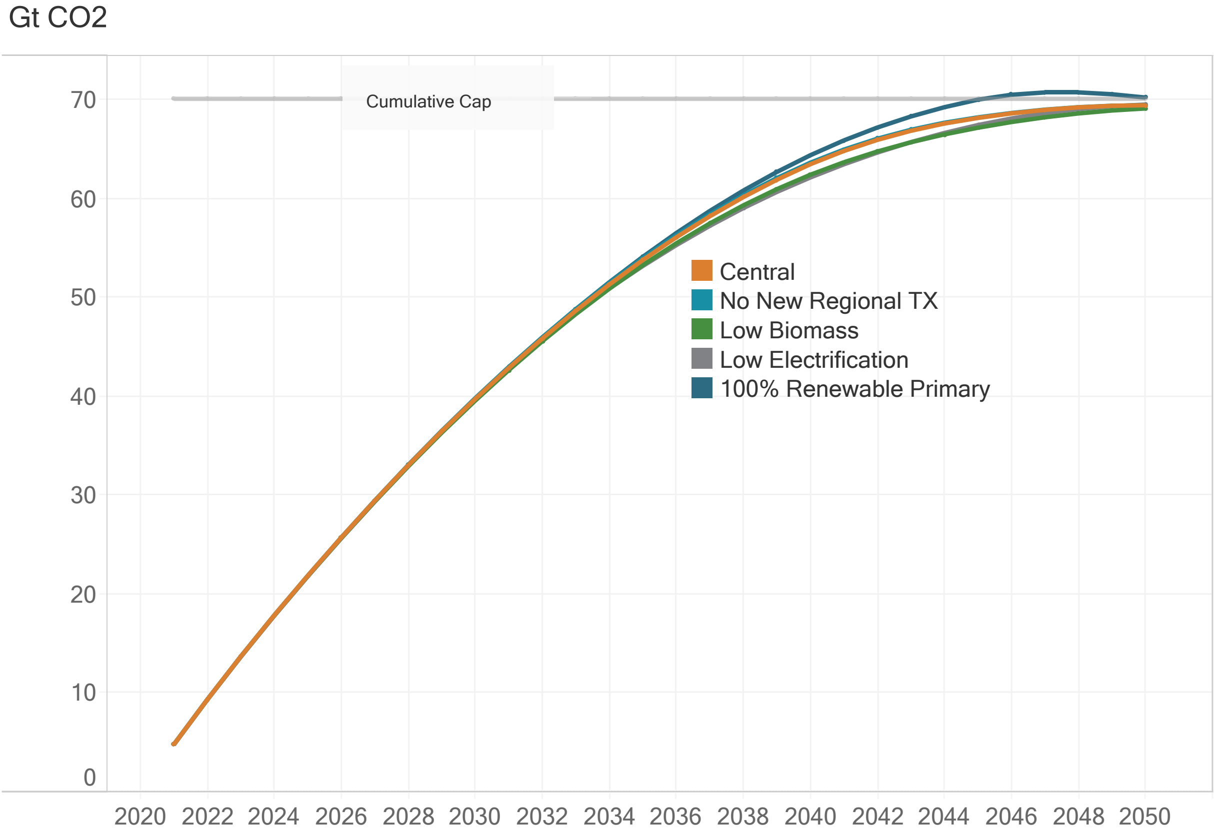


Figure 33 Four pillars of deep decarbonization – U.S.

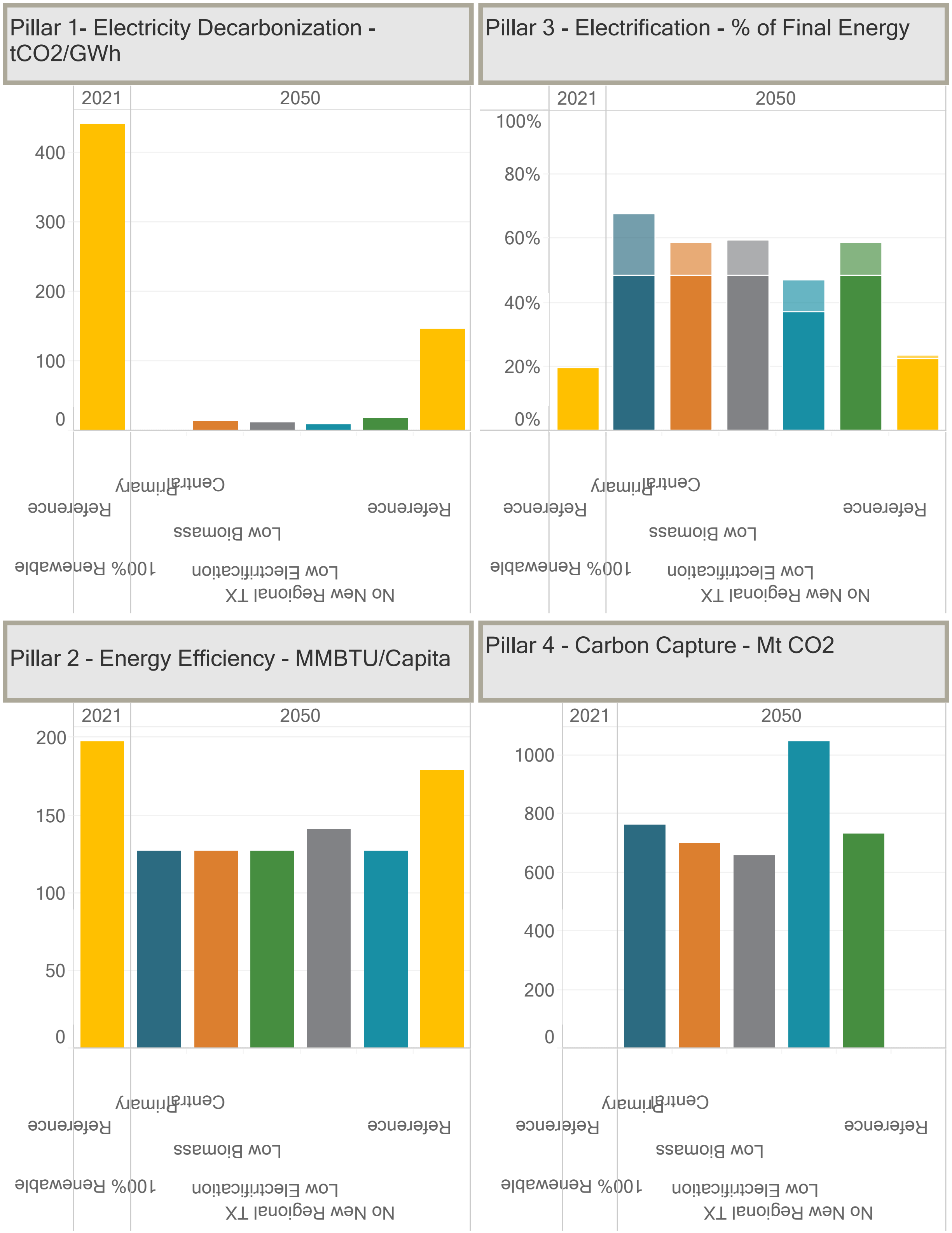


Figure 34 Final and primary energy demand for all scenarios from 2021 – 2050 – U.S.

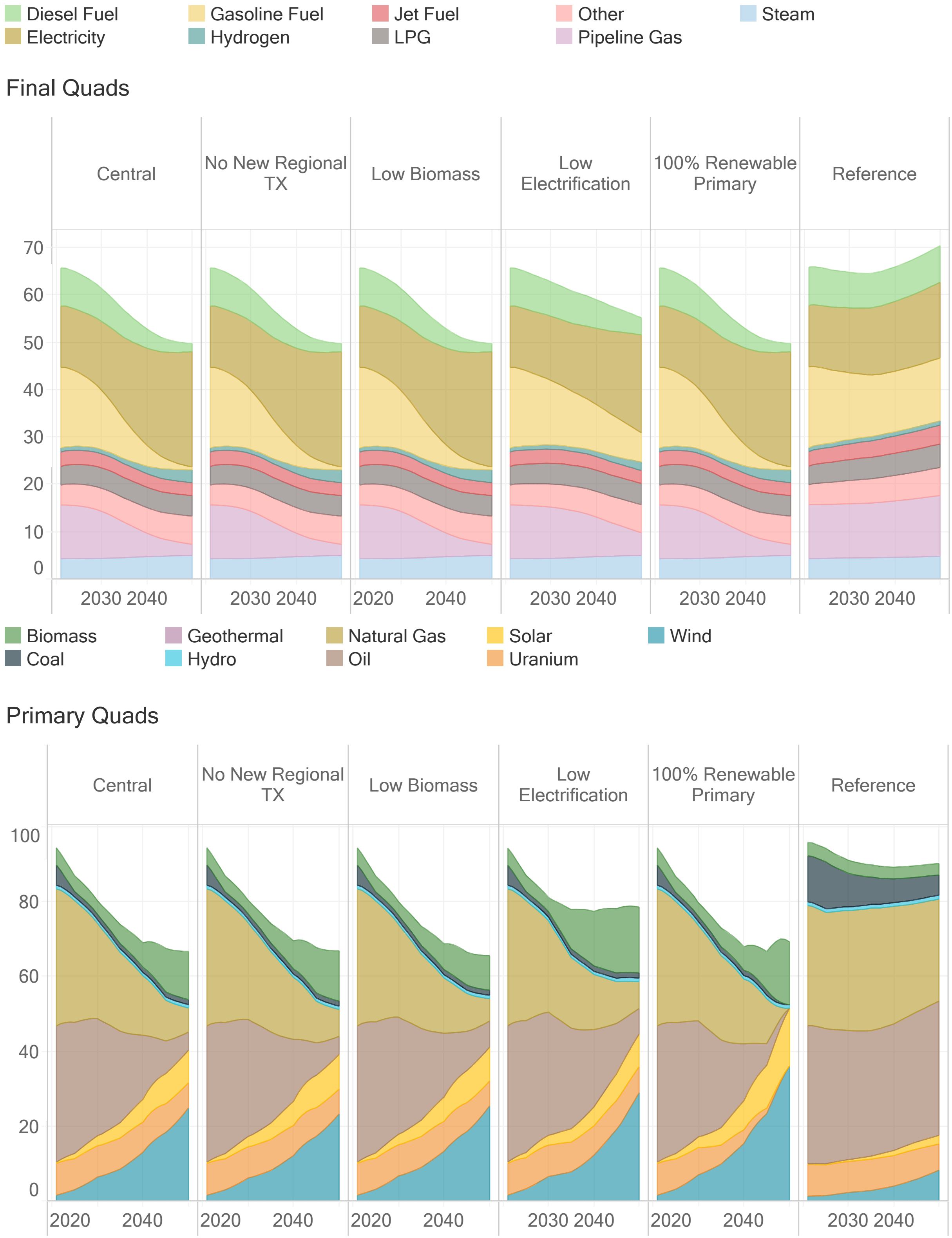


Figure 35 Components of emissions reductions in the Central scenario – U.S.

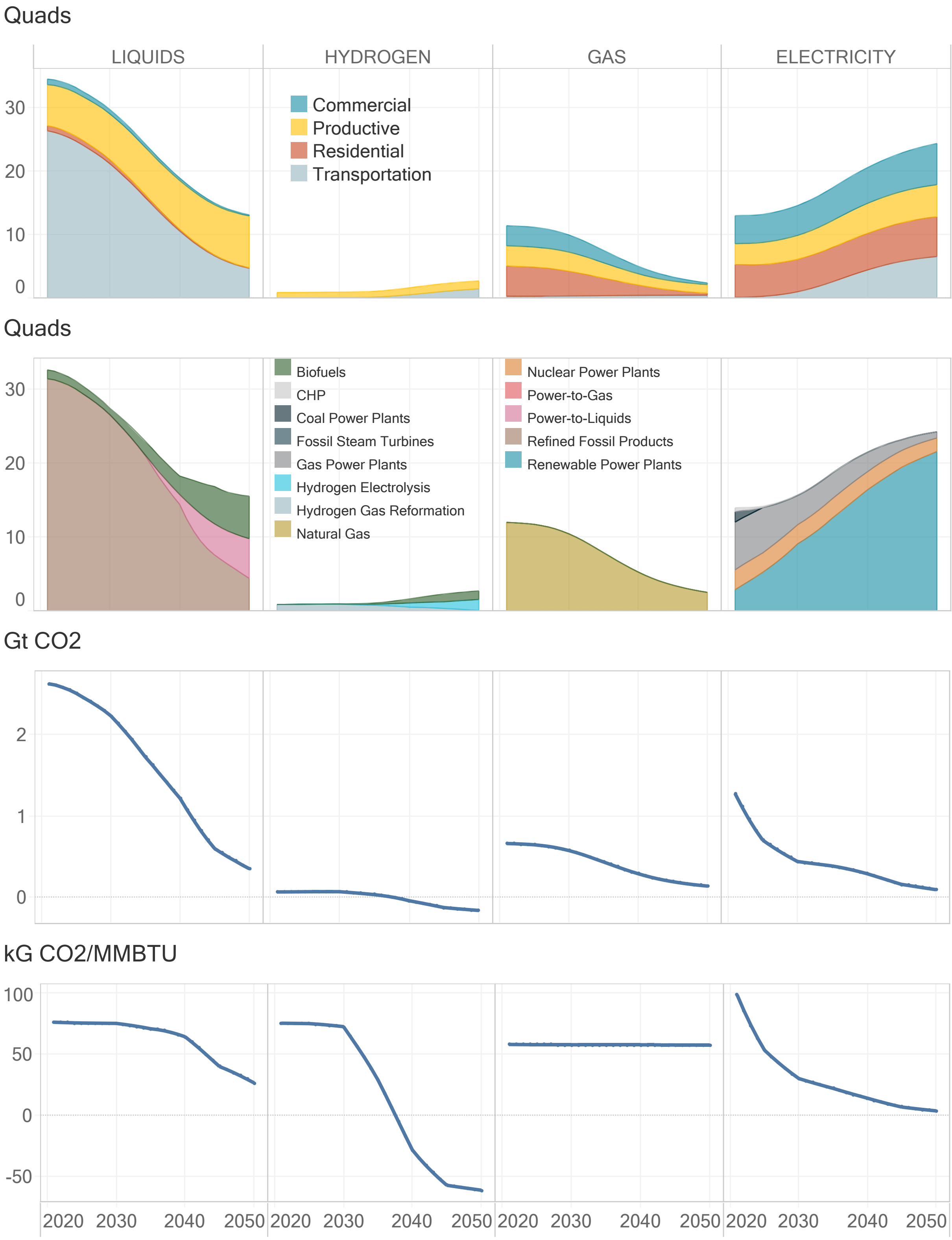


Figure 36 Components of emissions reductions in the Low Biomass scenario – U.S.

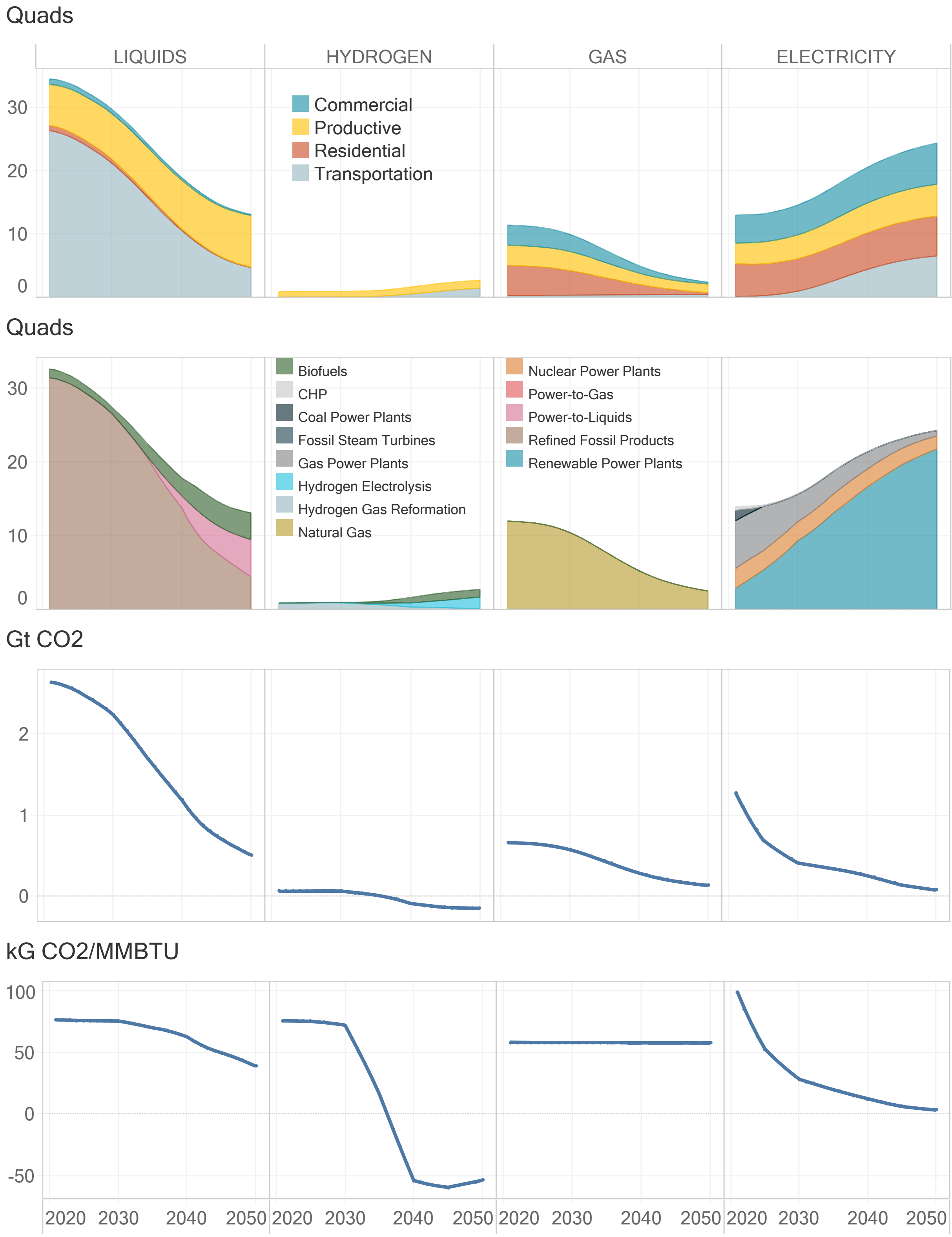


Figure 37 Components of emissions reductions in the Low Electrification scenario – U.S.

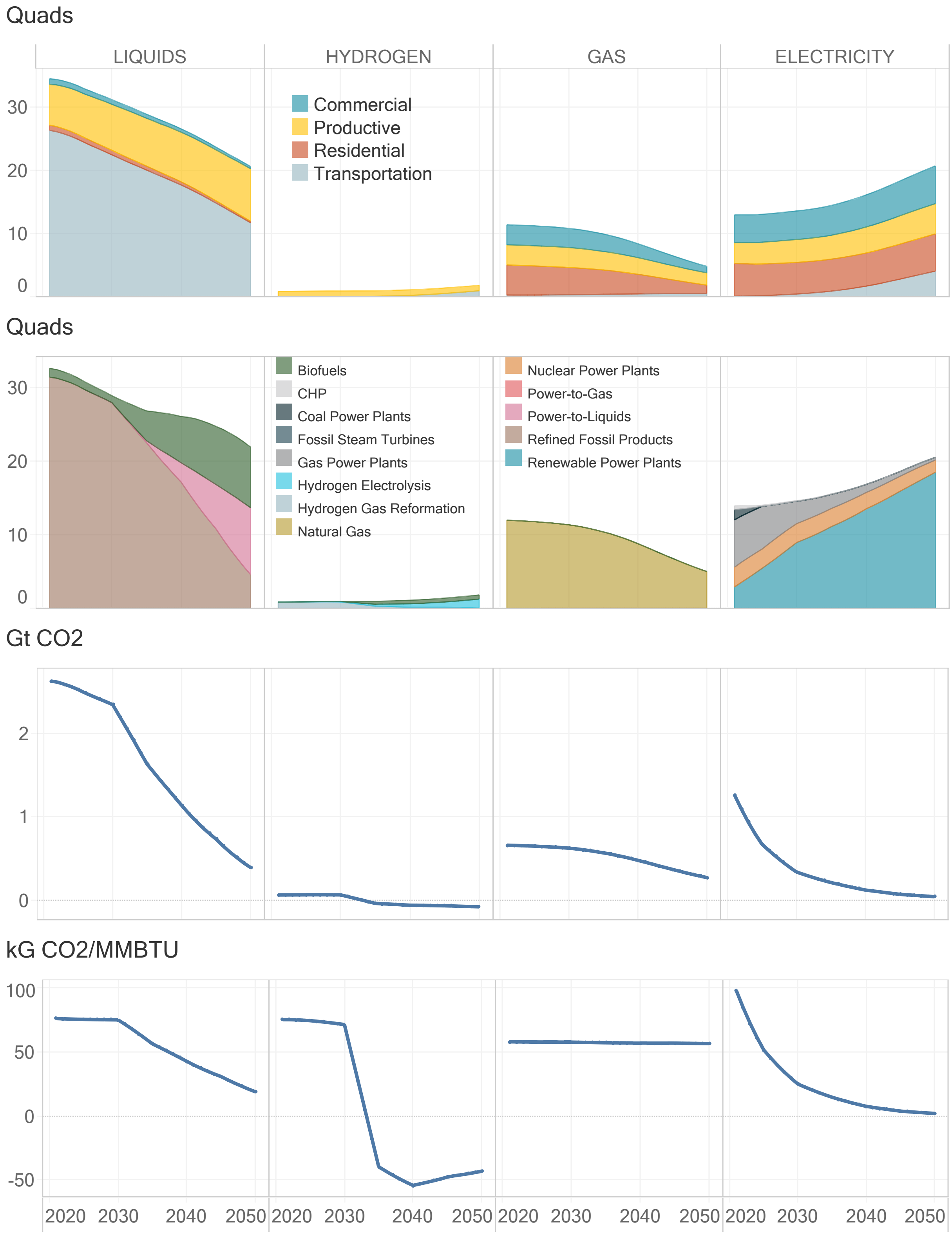


Figure 38 Components of emissions reductions in the No New Regional TX scenario – U.S.

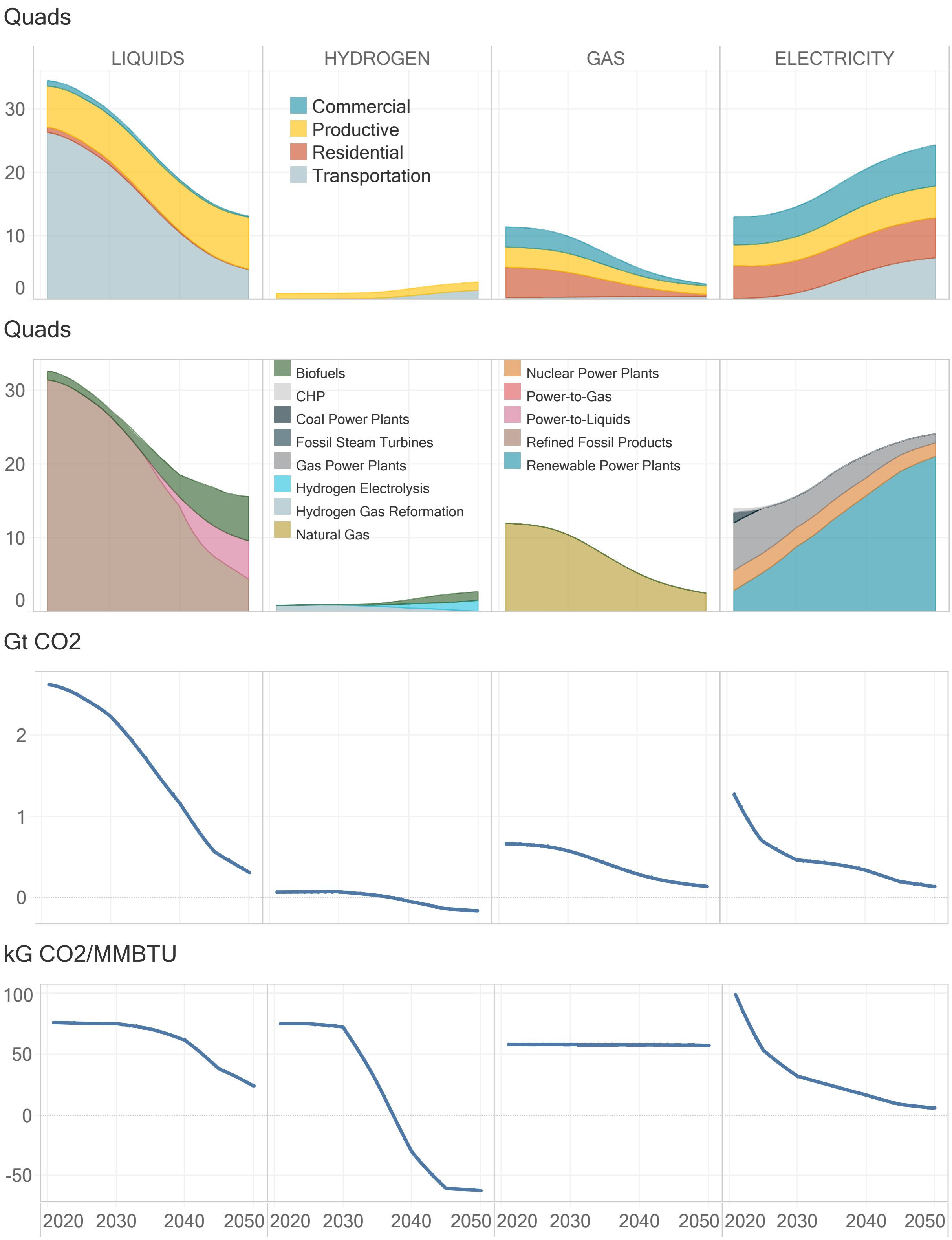


Figure 39 Components of emissions reductions in the 100% Renewable Primary scenario – U.S.

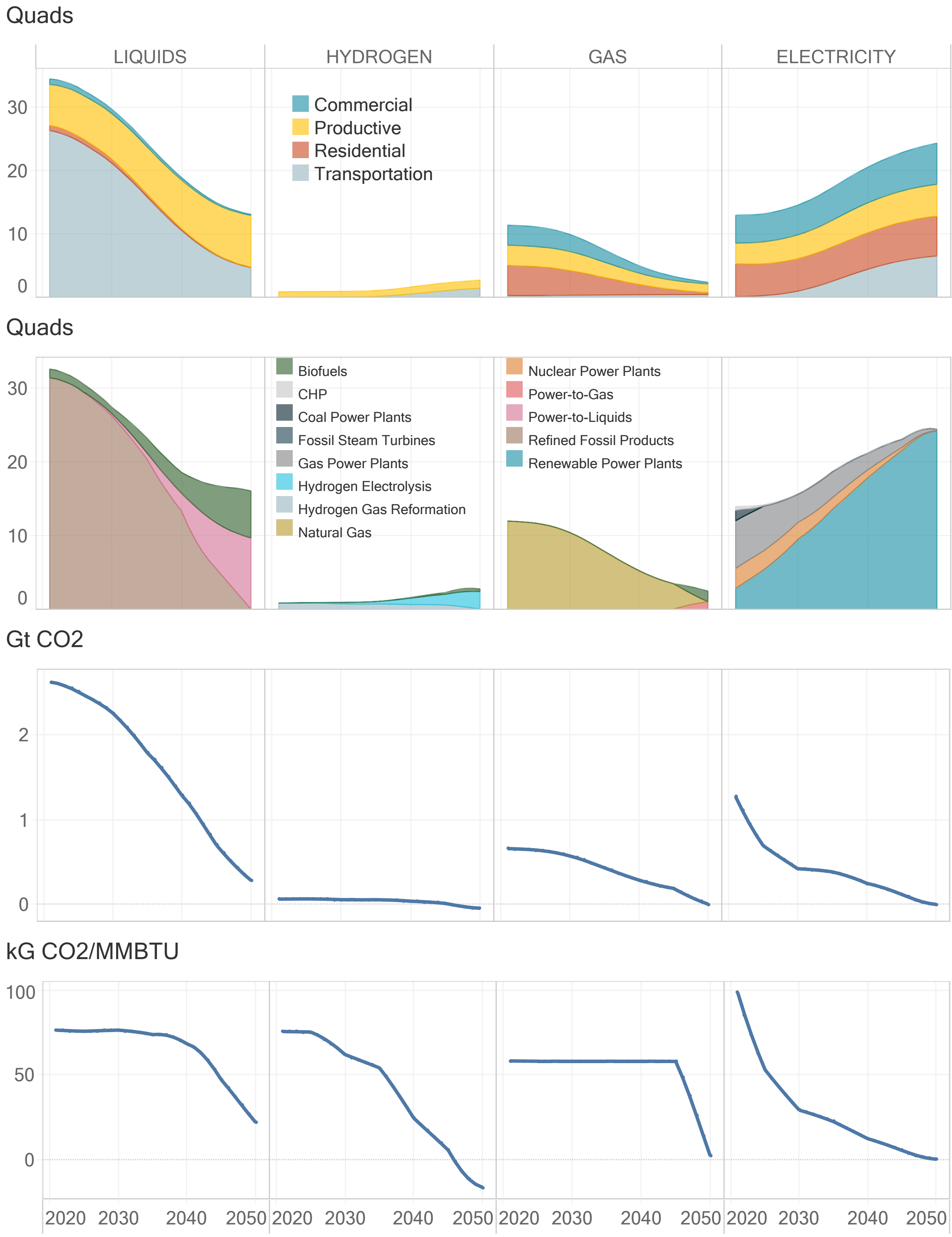


Figure 40 Annual net system cost premium above baseline in $2018 and as % of GDP – U.S.

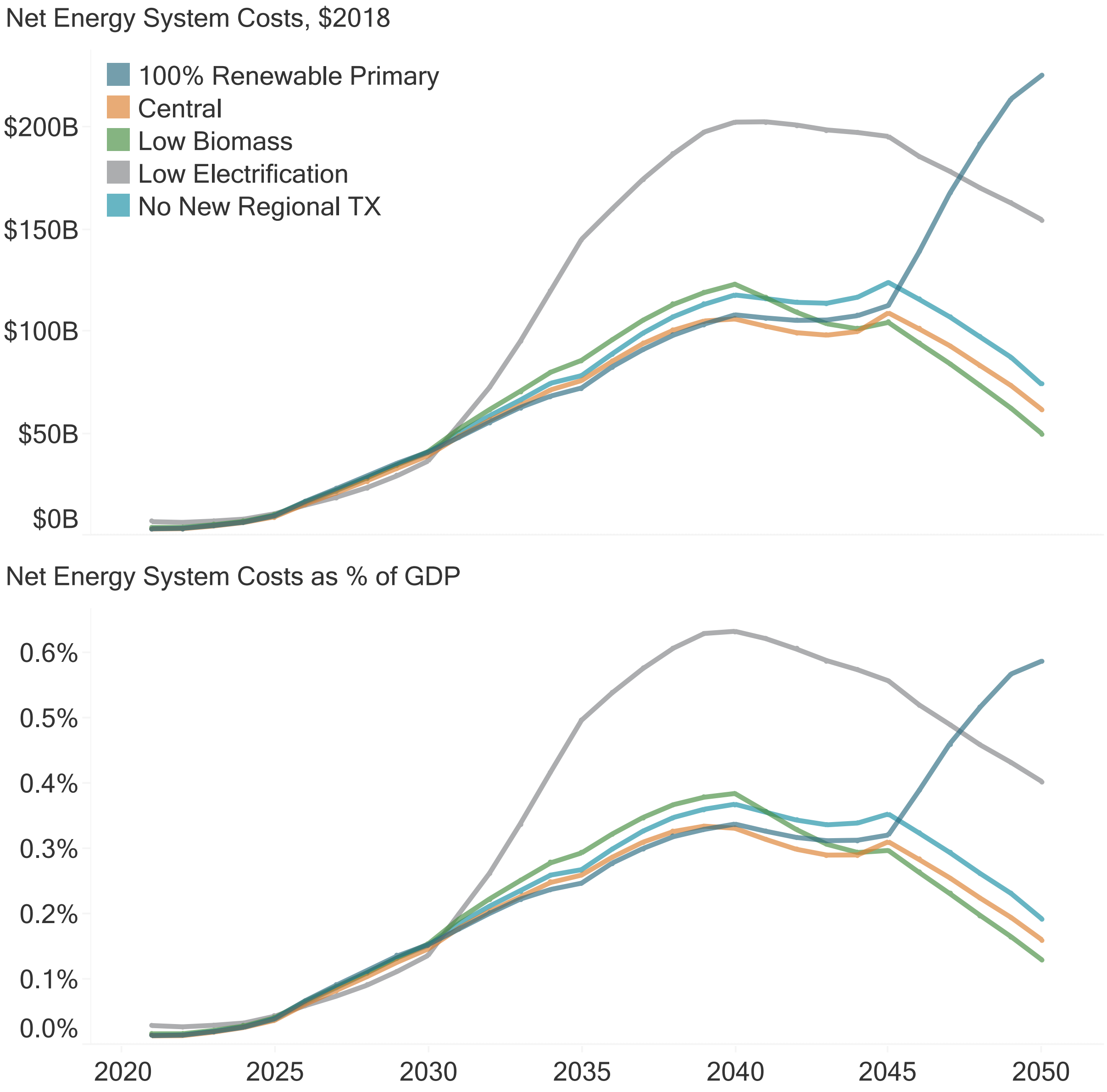


Figure 41 Net Change in E&I System Spending – U.S.

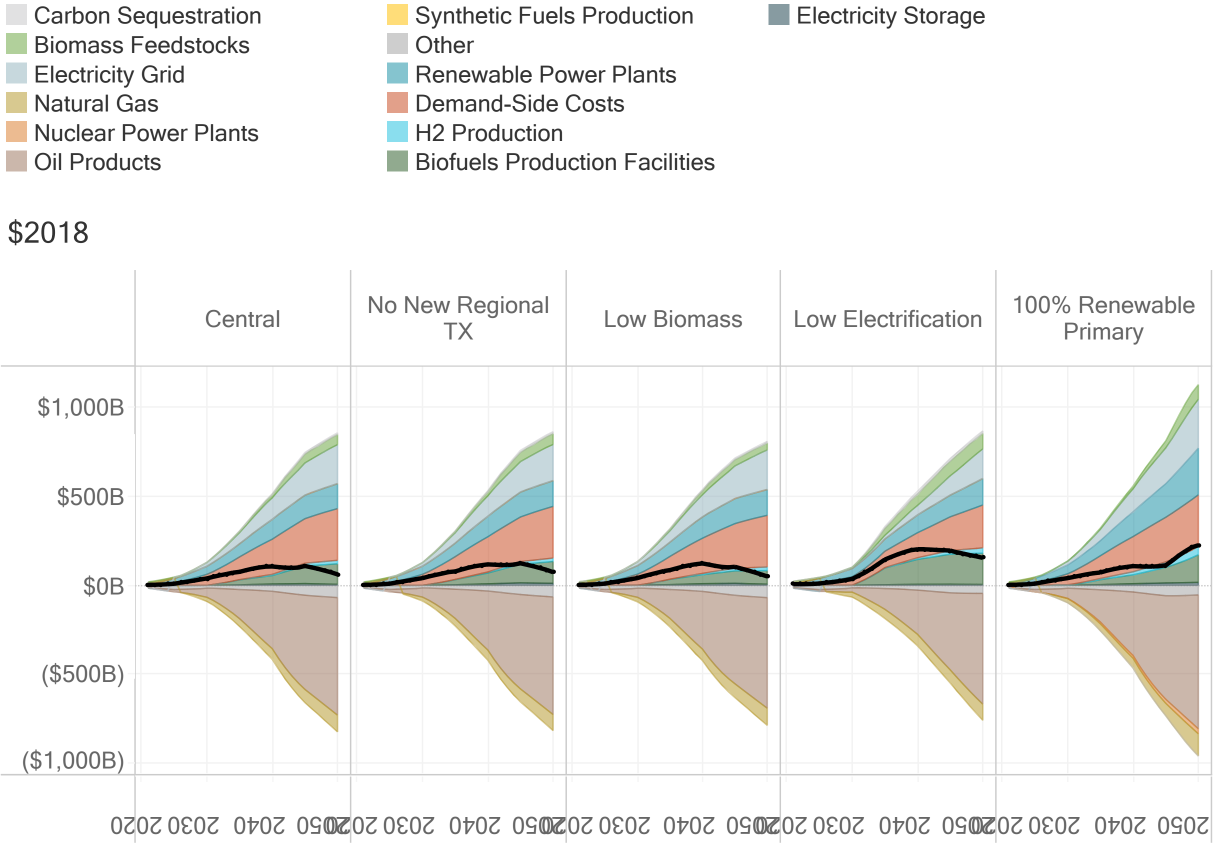
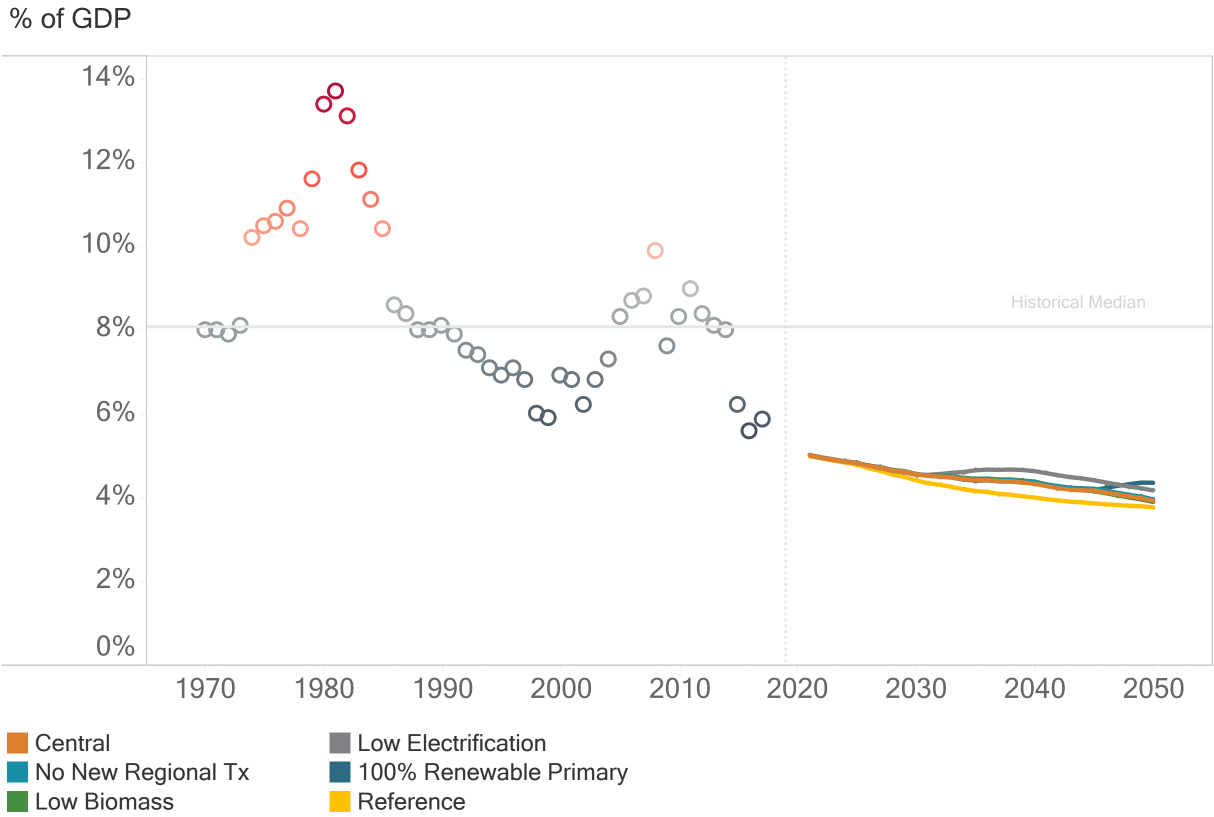


Figure 42 Total energy system costs as % of GDP –historical and projected – U.S.



Florida Results

Figure 43 Components of emissions reductions in the Low Biomass scenario - Florida

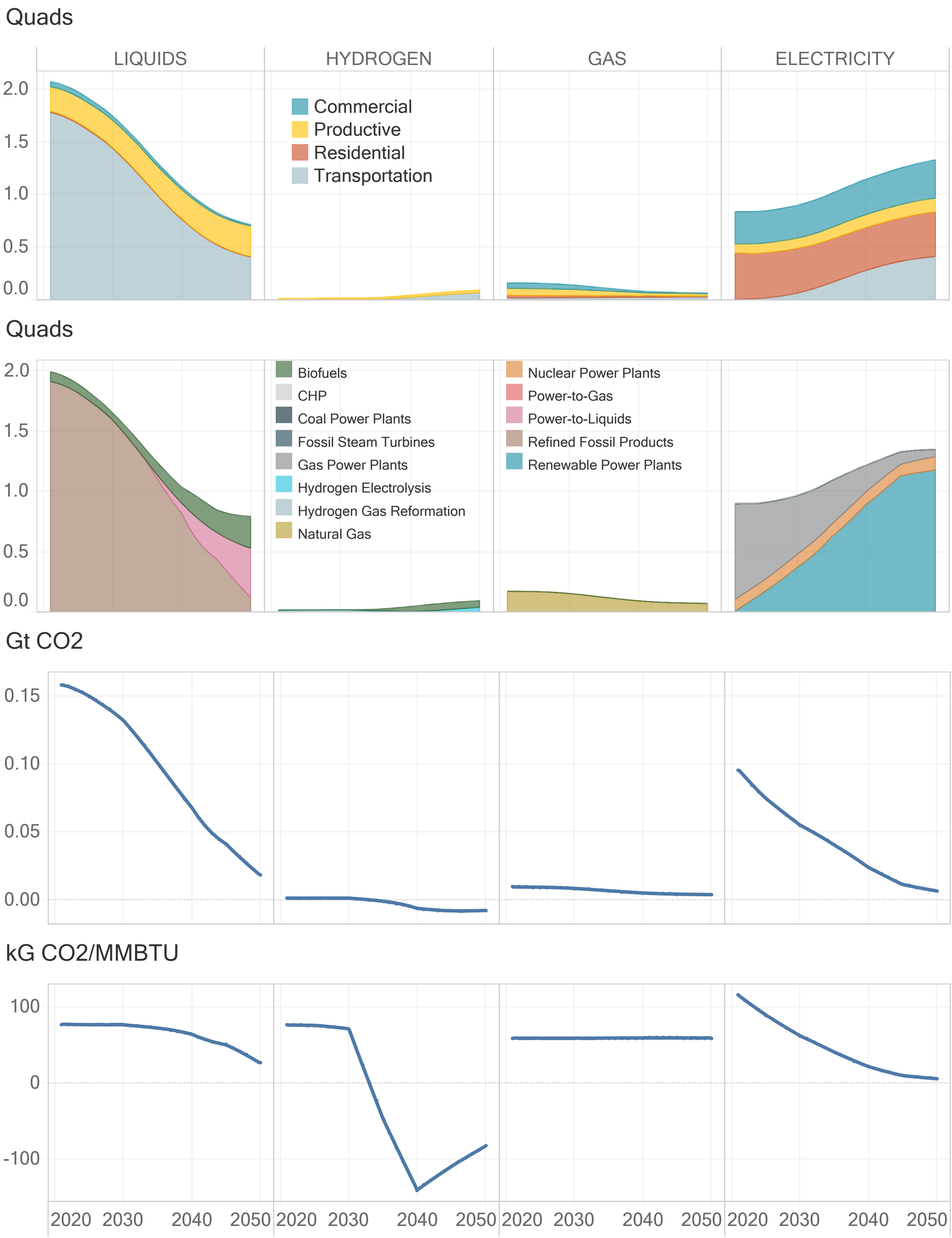


Figure 44 Components of emissions reductions in the Low Electrification scenario - Florida

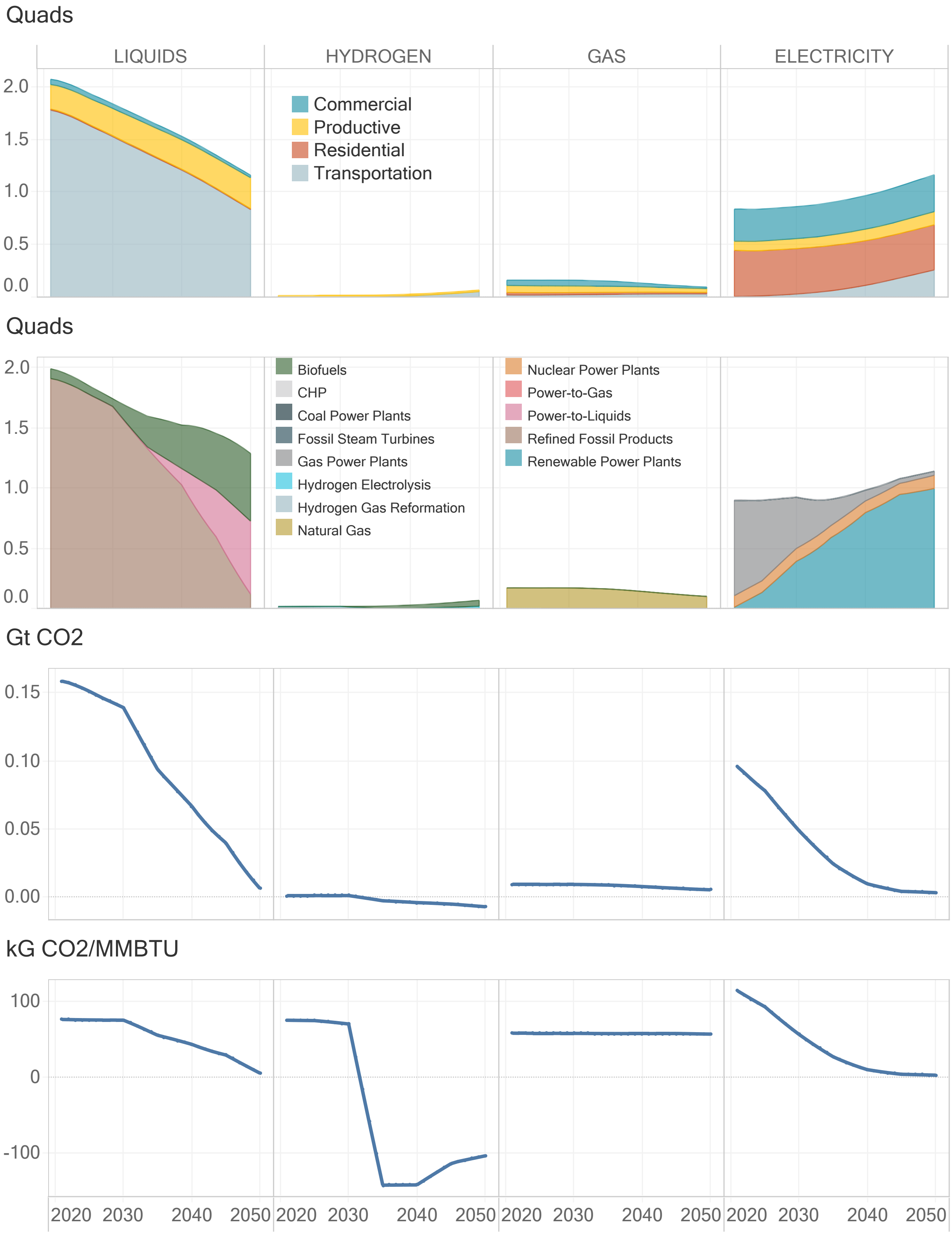


Figure 45 Components of emissions reductions in the No New Regional TX scenario - Florida

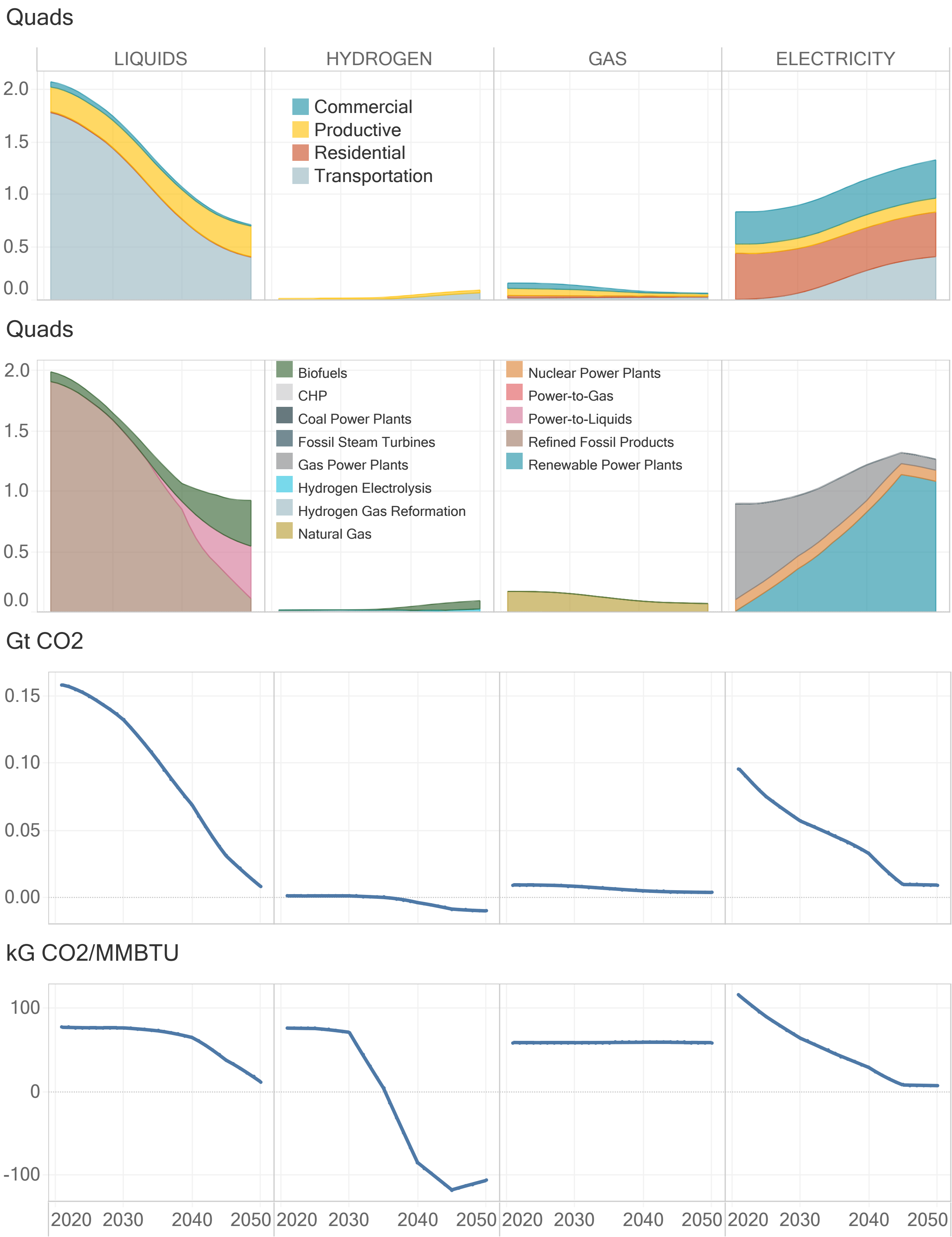
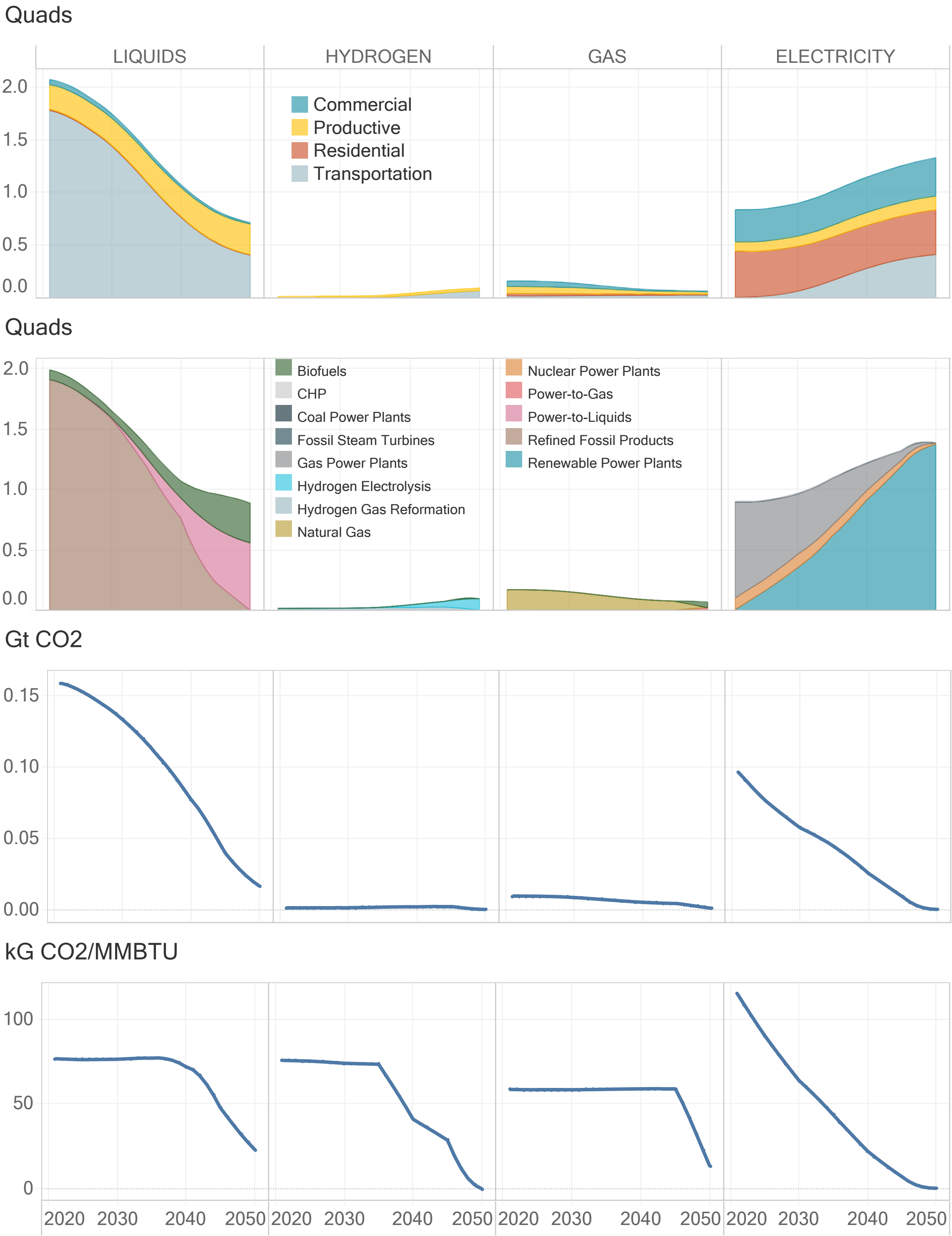


Figure 46 Components of emissions reductions in the 100% Renewable Primary scenario - Florida



📍 2443 Fillmore Street,
No. 380-5034 San Francisco,
CA, 94115

✉ info@evolved.energy
☎ (844) 566-1366
🌐 www.evolved.energy

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