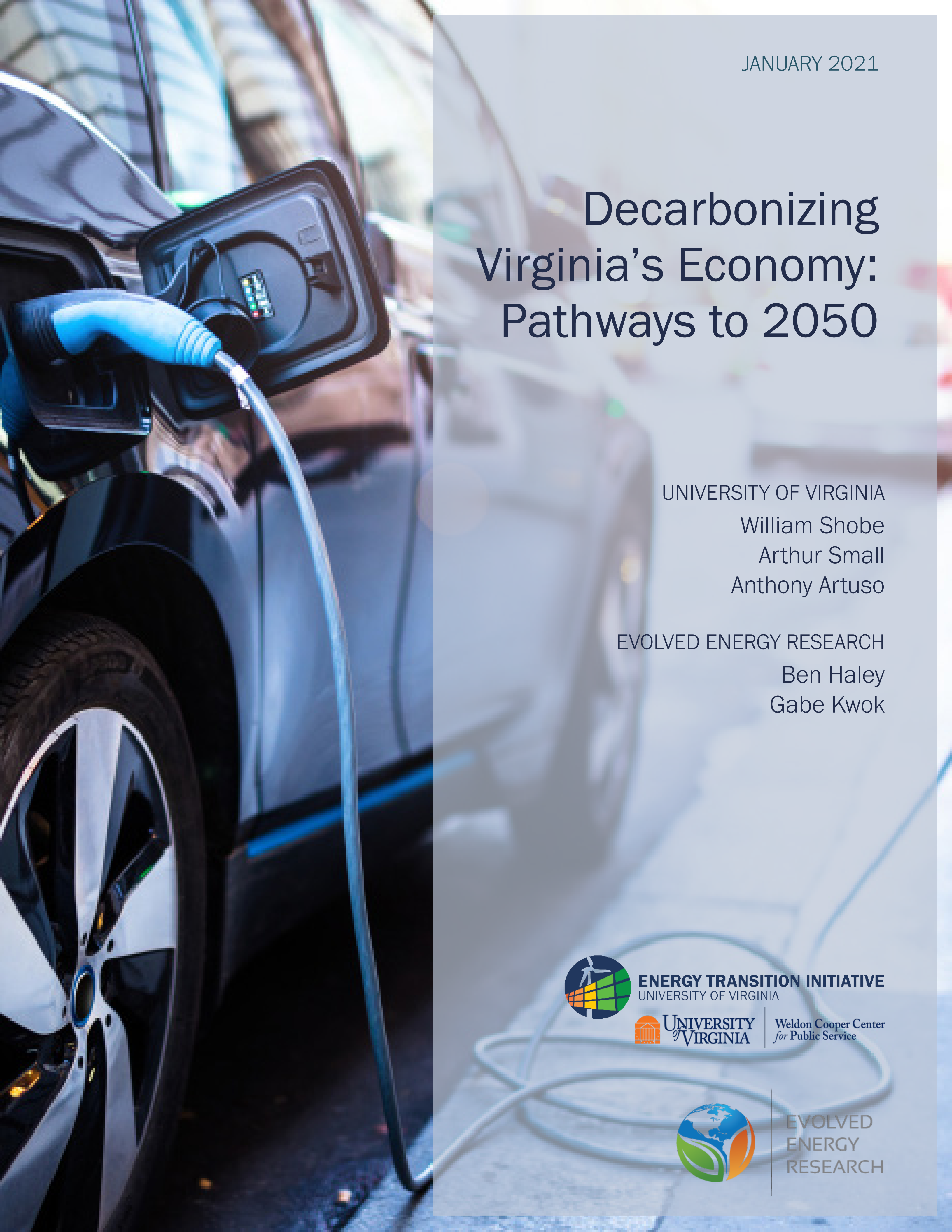

JANUARY 2021

Decarbonizing Virginia's Economy: Pathways to 2050

UNIVERSITY OF VIRGINIA
William Shobe
Arthur Small
Anthony Artuso

EVOLVED ENERGY RESEARCH
Ben Haley
Gabe Kwok

ENERGY TRANSITION INITIATIVE
UNIVERSITY OF VIRGINIA

UNIVERSITY of VIRGINIA
Weldon Cooper Center for Public Service

EVOLVED ENERGY RESEARCH

How can Virginia reach carbon neutrality by 2050?

This report explores four strategies for decarbonization in Virginia: efficiency in energy use, eliminating fossil fuels from electricity generation, electrifying transportation services and building energy use, and capturing and sequestering remaining CO_2 emissions. The authors recognize that reaching carbon neutrality by mid-century will require aggressive deployment of low-carbon technologies.

ABOUT THE AUTHORS

FROM THE UNIVERSITY OF VIRGINIA WELDON COOPER CENTER FOR PUBLIC SERVICE

William Shobe is a professor in the Batten School of Leadership and Public Policy and director of the Energy Transition Initiative.

Arthur Small directs the research team for the Virginia Clean Energy Project and is a senior research scientist.

Anthony Artuso directs the Policy Research team for the Virginia Clean Energy Project. He is a visiting scholar.

FROM EVOLVED ENERGY RESEARCH — SAN FRANCISCO, CALIFORNIA

Ben Haley is a co-founder of Evolved Energy Research, where he develops energy system models to help guide the energy transformation decisions of government officials, utilities and other companies, and researchers.

Gabe Kwok is a principal at Evolved Energy Research, where he utilizes his modeling expertise and institutional and technical knowledge to holistically address decarbonization problems.

ENERGY TRANSITION INITIATIVE
UNIVERSITY OF VIRGINIA

The Energy Transition Initiative (ETI) at the University of Virginia is dedicated to helping policy makers and other stakeholders navigate the challenges that come with shifting Virginia's energy systems away from fossil fuels and towards renewables and other zero-carbon sources. The ETI brings together experts from the Weldon Cooper Center, Virginia Solar Initiative, Virginia Clean Energy Project, and other units at the University of Virginia to research clean energy and sustainability practices; develop and maintain tools to help localities understand the process, costs, and benefits of adopting cleaner energy technologies; and engage directly with policymakers, energy providers, entrepreneurs, consumers, and other interested stakeholders to smooth the transition to a sustainable energy economy.

UNIVERSITY *of* VIRGINIA | **WELDON COOPER CENTER *for* PUBLIC SERVICE**

The Weldon Cooper Center for Public Service combines decades of knowledge about government, communities, and the people of Virginia with contemporary and advanced research, analytical expertise, and focused training for high performance in order to deliver public impact research and multi-sector leadership development to build the capacity of Virginia's communities, organizations, and institutions to serve the Commonwealth.

EVOLVED
ENERGY
RESEARCH

Evolved Energy Research (EER) develops tools and models to analyze energy sector questions posed by policy goals and new technology developments. EER takes a fundamentally new approach to examining energy systems by performing analyses that explicitly acknowledge the connectedness of the new energy economy, leverage technology in the pursuit of understanding, and embrace complexity as a means to confront uncertainty.

Foreword

Virginia has embarked on an ambitious program to revolutionize its energy sector. This is a massive undertaking which seeks to reduce the state's dependence on fossil fuels for its energy supply. Accomplishing this task will require billions of dollars of investment and a transformation in how energy resources in the state are supplied and consumed. This effort should not be undertaken without the best available evidence from both data on past energy use and models of future energy technologies and institutions.

The Energy Transition Initiative (ETI) at the University of Virginia is a center of excellence for rigorous analysis of Virginia energy systems. Organized within the Weldon Cooper Center for Public Service, the ETI works towards three primary goals: to help chart pathways and policies for net zero carbon by 2050; to identify opportunities and roadblocks on the road to zero carbon; and to promote informed, engaged and inclusive decision making on Virginia's energy future. The ETI works with scholars across the University through the efforts of the UVA Environmental Resilience Institute, a pan-university effort to foster cross-disciplinary collaboration for solving today's environmental management challenges.

In furtherance of our goal to provide the best available expertise for solving the challenges faced by state and local governments in Virginia, The Weldon Cooper Center commissioned Evolved Energy Research to evaluate pathways to decarbonize Virginia's economy. The purpose of this study is to provide an understanding of the practical implications of achieving a net-zero energy system by 2050. The study addresses three main questions about Virginia's decarbonization challenge:

- How will energy supply and end-use sectors need to transform?
- What are the infrastructure implications for the electric sector?
- What policy initiatives will likely be needed to achieve cost-effective decarbonization?

Robust public discourse is central to effective policy development: the Cooper Center's Energy Transition Initiative is committed to enhancing opportunities for public input to important policy choices as the state moves to decarbonize. To assure that our analysis was informed by input from the broadest possible representation of communities across Virginia, we partnered with the Institute for Engagement and Negotiation to help design an effective process of public input. With IEN's leadership, we reached out to a broad cross-section of technical experts and community stakeholders to solicit comments and feedback on a preliminary version of this report. These efforts culminated in a four-hour workshop held virtually on October 30, 2020. A summary of their feedback, together with a list of workshop participants, is available as a supplemental document to this report, which can be downloaded from the ETI website (energytransitiion.coopercenter.org). The comments we received from stakeholders have greatly enriched the report, and help inform our plans for future work.

Acknowledgements We wish to thank the Clean Air Task Force and the sPower Corporation for their generous funding for this project. We also wish to thank all the participants in the stakeholder workshop for their time and for their thoughtful comments on this work. We are gratefully especially to Kristina Weaver, Alexandra Cook, and others from the Institute for Engagement and Negotiation for their effective leadership in designing and organizing that workshop.

The Energy Transition Initiative and the Weldon Cooper Center for Public Service benefit immensely from its engagement with the broader intellectual community at the University of Virginia. We acknowledge especially the staff and affiliates of the UVA Environmental Resilience Institute for helping to foster a community of scholars and practitioners at UVA who are engaged keenly with bringing research and education to bear on challenges of energy, climate, and the environment. ERI Executive Director Jonah Fogel deserves particular recognition for his energetic assistance with the workshop, and for his constructive feedback and suggestions on this project as it progressed.

Alex Watkins and Amy Muldoon made essential contributions to the production of this report. We are also thankful to Elizabeth Marshall of ETI for her thoughtful comments and suggestions on a draft manuscript. Without the assistance of such talented colleagues, this would be a poorer document indeed.

Last but surely not least, we gratefully acknowledge the important contributions of an army of student assistants who are dedicated to lives of thoughtfulness and public service. No one who works with such students can long doubt the promise of the future.

Contents

EXECUTIVE SUMMARY

Recent policy initiatives in Virginia reflect an increased urgency in addressing the state's contribution to global warming. This report presents results from the first study to analyze quantitatively and comprehensively the actions needed to make Virginia's economy carbon neutral by 2050.

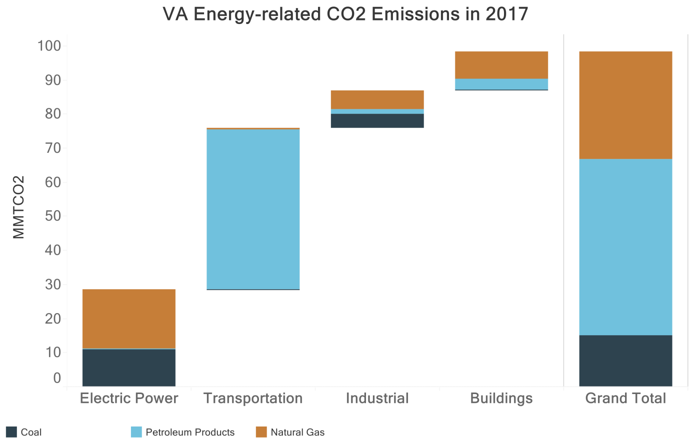

Figure 1: Transportation, buildings, and electricity generation dominate Virginia's current energy-related emissions.

Eliminating greenhouse gas emissions from Virginia's energy system will drive major changes in how the Commonwealth generates its electricity, heats its buildings, powers its vehicles, and charts its economic future. But decarbonization is achievable and affordable. The effort to decarbonize brings with it ancillary benefits in public health and in the reduced need to import energy resources from elsewhere. But the shift away from fossil fuels will not be fast enough or deep enough to achieve mid-century decarbonization targets without careful planning and policy design.

The Virginia Clean Economy Act (VCEA) focused on reducing emissions from electricity generation, which accounts for about 30% of Virginia's CO_2 emissions. Transportation accounts for nearly half, buildings and industry for the remaining 20%. Getting to net zero requires reducing emissions from transportation, buildings, and industry, as well as the electricity sector. Eliminating carbon emissions will require long-term energy storage, producing non-emitting liquid and gaseous fuels and even some amount of CO_2 removal from the atmosphere.

Key Results

The analysis supports several broad findings about Virginia's decarbonization options.

- *Decarbonization by 2050 is* achievable *and* affordable*.* Steep declines in costs for renewable electricity generation and other energy technologies open multiple pathways for bringing Virginia's energy-related carbon emissions to net zero by 2050. In all scenarios analyzed, *Virginia's expenditures on energy, as a share of Virginia's economy, will be lower than in the recent past.*
- *The economic benefits in improved health, reduced global warming and greater domestic energy production outweigh the costs*
- *Virginia has multiple options for achieving decarbonization.* Different policies and priorities imply different resource mixes and different costs. Least-cost options involve aggressive deployment of utility-scale solar and (in later years) off-shore wind, along with other non-emitting generation assets.
- *A quicker start means lower long-run costs; delay is costly.*
- *Careful planning and policy design pay big dividends.*
- *Coordination between state and local governments is essential.*

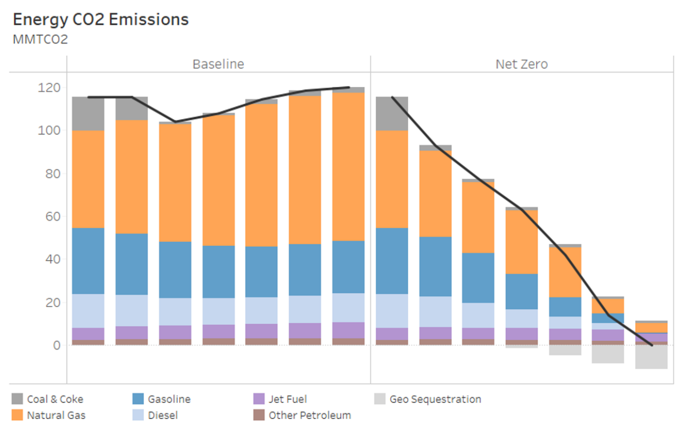

Figure 2: Emissions Trajectory for Baseline and Net Zero scenarios

Decarbonization is achievable and affordable, and will lead to improved health and reduced global warming. But the shift will not be fast enough or deep enough to achieve mid-century decarbonization targets without careful planning and policy design.

Modeling Approach

We developed four scenarios to illustrate some of the trade-offs and uncertainties faced in planning for a large-scale restructuring of Virginia's energy economy over the next 30 years. All of the scenarios assume that we meet the 2050 goal of net zero carbon emissions for the entire Virginia economy. These scenarios illustrate the feasibility of achieving the net zero goal and the advantage of technological innovation in lowering costs. They also illustrate the costs of delay and the costs of constraints on the availability of some energy resources.

The Scenarios

Our four 2050 decarbonization scenarios:

1. **Net Zero:** Identifies the least-cost pathway, given the available resources and the most likely case for available technology.
2. **Constrained Land and Nuclear:** Explores the energy resource trade-offs and increased costs that occur when solar and new nuclear face additional constraints.
3. **Slow Consumer Adoption:** Shows the cost of delay in initiating the transition in the large existing stock of vehicles and buildings.
4. **Rapid Innovation:** Illustrates the effects of higher rates of innovation in clean energy technologies on energy costs and resource mix.

The scenarios were modeled using a suite of energy system and pathways models, RIO and EnergyPATHWAYS respectively, developed by Evolved Energy Research. These models were calibrated for Virginia, taking into account detailed information about Virginia's energy economy. For each scenario, the model performs an energy system optimization given the scenario assumptions. We take as given the current economic and policy environment, which includes 2020 legislation. Technology is assumed to develop in line with historical patterns.

> Our four decarbonization scenarios illustrate different approaches we can take to reach net zero. They are not forecasts, but potential pathways meant to highlight the costs and benefits of different choices we may make and of acting quickly.

Findings This study, and others like it demonstrate that there are four essential components of any cost-effective decarbonization strategy:

- Efficiency in energy end-use -
    - Reducing the energy intensity of providing services like transportation, heating and cooling, etc.
- Decarbonization of energy sources, especially electricity -
    - Replacing fossil fuel generation with non-emitting sources such as solar, wind and nuclear. Deep penetration of renewables will require investments in energy storage, including longer-term storage using hydrogen or synthetic fuels.
- Electrification of energy services in buildings, vehicles and factories -
    - Shifting from direct use of fossil fuels to non-emitting electricity
- Carbon capture and sequestration for residual emissions -
    - Capturing and sequestering some emissions avoids expensive replacement of fossil fuels in some industrial applications.

Even though *electricity* demand can be expected to nearly double by 2050, total *energy* demand in Virginia is not projected to increase in most of our scenarios, because increased electrification of buildings and transportation brings with it substantial efficiencies in energy use.

In feasible decarbonization scenarios, electricity replaces most other energy sources in buildings and in transportation. Electricity is generated using renewables, primarily utility-scale solar and off-shore wind, along with the existing fleet of nuclear plants. Coal is no longer used to produce electricity. Some of our existing natural gas generation fleet will be needed to ensure reliability of electricity service but will be converted to use a zero carbon fuel and will operate infrequently (that is, at low capacity factors). Increasing the share of renewables will require an array of energy storage technologies including batteries, hydrogen and synthetic fuels. Additional sources of dispatchable non-emitting electricity, such as advanced nuclear or bioenergy with carbon capture and sequestration, help keep the costs of transition down. Locally produced hydrogen and imported zero carbon liquid fuels will be used in applications where electrification is difficult or long-term storage is needed.

Some fossil fuel use in industry will be very expensive to replace, so we will need some carbon capture and sequestration (negative emissions) to balance any remaining GHG emissions. Given current technology forecasts, sequestration will likely take one of two forms: (1) natural sequestration in fields, forests and coastal ecosystems and (2) bioenergy with carbon capture and sequestration, where wood waste is gasified to generate hydrogen, and the CO_2 emissions are captured and geologically sequestered.

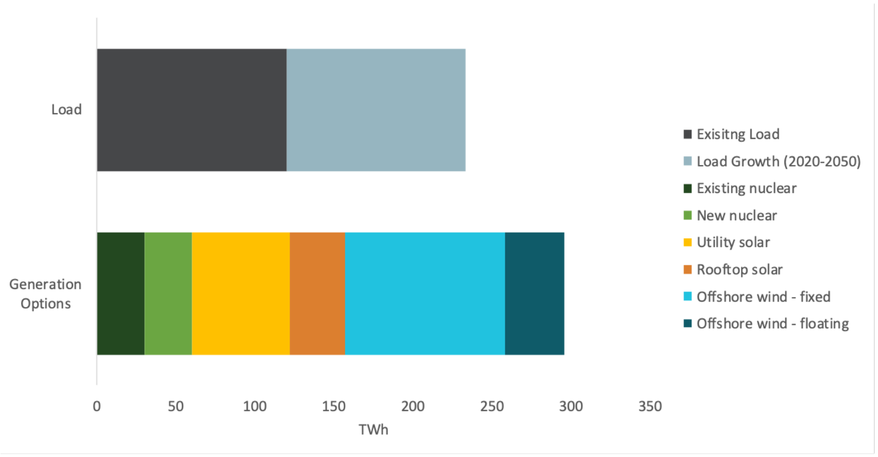

Figure 3: Generation options for meeting projected growth in electricity load

Because of its substantially higher cost, distributed solar energy from rooftops is not a major source of electricity except in cases where other resources are constrained or where rapid innovation reduces its cost relative to other energy sources. Initiatives that lower the installed cost of rooftop solar and provide efficient price signals to consumers could increase the contribution of distributed solar and cost-effectively diversify Virginia's clean energy resource mix.

Costs (and Benefits) of Deep Decarbonization

Decarbonization increases energy expenditures in some areas and reduces them in others. New investment in local clean electricity and end-use equipment, such as electric vehicles and building HVAC systems reduces spending on imported natural gas and petroleum products. Compared to the business as usual baseline, additional annual expenditures on energy in the Net Zero scenario amount to between \$2.3 and \$3.1 billion (\$2018) rising to between \$4.5 and \$11.6 billion (\$2018).[1] Expenditures remain well under 1% of gross state product (GSP) and are less than the current share of GSP spent on energy services and equipment. Costs are significantly higher in the Constrained Land and Nuclear scenario and the Slow Consumer Adoption scenario. The Rapid Innovation scenario shows that attention to research, development and diffusion of clean energy innovations could result in net energy cost savings from implementing decarbonization.

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[1] The range of estimates is based on uncertainty over future fossil fuel prices. These next expenditure calculations do not include health, climate and other benefits.

If implemented efficiently, the economic benefits of decarbonization, in reduced health and climate costs, will be greater than the costs of achieving it. There will also be broader economic gains from substituting cost-effective local production for imported fuels and from reduced exposure to price volatility in international oil markets. For cost-effective approaches to the transition, economic multiplier effects from increased in-state investment could yield additional net benefits for Virginia.

Essential State Policy Initiatives

Since 2007, GHG emissions attributable to retail sales of electricty in Virginia have fallen dramatically. This recent trend does not mean that Virginia's emissions would reach the near zero levels needed to protect the climate without a substantial push from public policy. Recent reductions in emissions have been driven by the substitution of natural gas for coal in generation, and this process is now nearing completion.

Transportation: The reduction in emissions has not touched the transportation sector, the largest source of CO_2 emissions. Virginia should explore policies to ensure the rapid build-out of charging stations for electric vehicles. As electric vehicle costs fall and the EV charging infrastructure becomes more fully developed, placing transportation GHG emissions under a cap, as proposed by the Transportation and Climate Initiative, would accelerate the electrification of the transportation sector, without imposing unreasonable costs on households or businesses in Virginia.

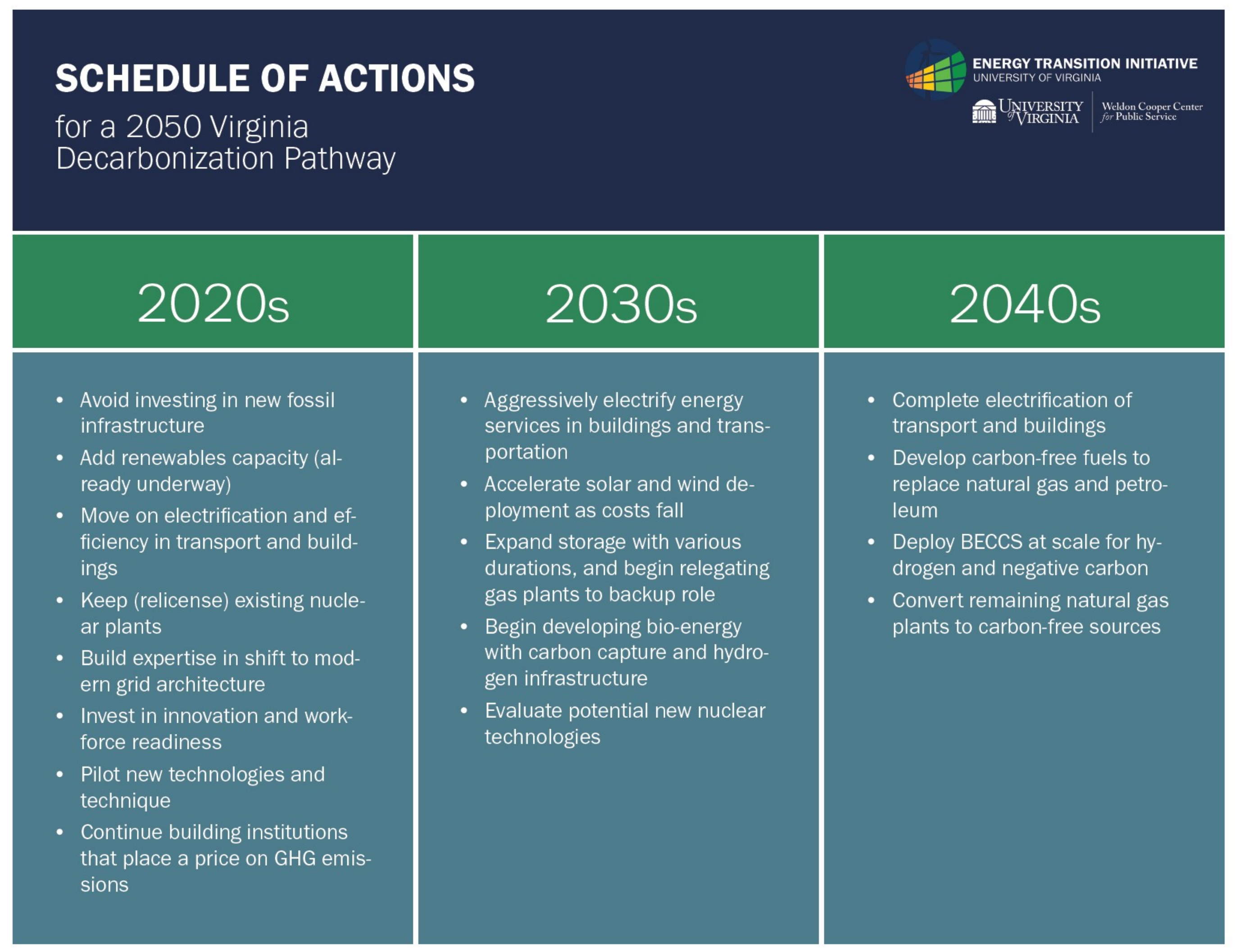
Buildings: Building codes will need to be updated and infrastructure investments will need to be redirected away from fossil fuels towards non-emitting resources. Policies should encourage replacing the direct use of natural gas for HVAC and water-heating applications in buildings with energy efficient electric heat pumps and water heaters, which are already cost effective in Virginia.

Electricity generation: Virginia has already begun decarbonization of the electricity sector by joining the Regional Greenhouse Gas Initiative (RGGI) cap on emission and by accelerating renewables deployment.

Administrative capacity: Achieving cost-effective decarbonization requires establishing the administrative capacity within Virginia state government to plan and coordinate the state's actions across numerous state government agencies and local jurisdictions. In addition to gathering data and advising policy makers, the agency would need to:

- Arrange for pilots of new technologies, programs and policies and evaluate their effectiveness
- Coordinate actions across state agencies in cooperation with federal programs
- Provide assistance to localities
- Study frictions slowing renewables development
- Develop strategies for implementing carbon sequestration

To conclude, we present a schedule of policy initiatives that need to be implemented to achieve full decarbonization by 2050. Some items on this list are urgent, with the path for implementation clear. Others are off into the future and are far less certain.



SCHEDULE OF ACTIONS
for a 2050 Virginia
Decarbonization Pathway

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2020s	2030s	2040s
• Avoid investing in new fossil infrastructure • Add renewables capacity (already underway) • Move on electrification and efficiency in transport and buildings • Keep (relicense) existing nuclear plants • Build expertise in shift to modern grid architecture • Invest in innovation and workforce readiness • Pilot new technologies and technique • Continue building institutions that place a price on GHG emissions	• Aggressively electrify energy services in buildings and transportation • Accelerate solar and wind deployment as costs fall • Expand storage with various durations, and begin relegating gas plants to backup role • Begin developing bio-energy with carbon capture and hydrogen infrastructure • Evaluate potential new nuclear technologies	• Complete electrification of transport and buildings • Develop carbon-free fuels to replace natural gas and petroleum • Deploy BECCS at scale for hydrogen and negative carbon • Convert remaining natural gas plants to carbon-free sources

Figure 4: 2050 Virginia Decarbonization Pathway: Schedule of Actions

1 Introduction

There can no longer be any doubt that mitigating the costly consequences of human-induced global warming is one of the most pressing policy challenges of the twentieth century. In the Paris Agreement of 2015, the nations of the world agreed to work to reduce the concentration of greenhouse gases (GHG) in the atmosphere and to coordinate international actions to achieve a fair and effective response to our global problem. The Paris Agreement set a goal of achieving sufficient reductions in emissions to limit anthropogenic warming to no more than 2° C. Since 2015, many jurisdictions around the world have announced goals of greatly reducing or eliminating GHG emissions by mid-century. Doing so will go much of the way towards achieving the goals of the Paris climate accord.

Virginia is now one of over a dozen states in the U.S. to announce a mid-century decarbonization goal: the elimination of GHG emissions from our electric power sector. Many other states have taken steps in this direction, as well, and cities across the U.S. have also announced their intention to reduce their CO_2 emissions.[2] But global warming is a global problem. Why, then, do states and even cities work to reduce their emissions when the problem clearly requires a national and international policy response? It is as Benjamin Franklin said: "[W]e must, indeed, all hang together, or most assuredly we shall all hang separately." Cooperation is the key to tackling global warming. Cooperation requires building trust among parties, each of whom has incentive to free ride on the others. Local efforts to reduce emissions act as offers to cooperate in a global trust-building exercise.

> Investing in local clean energy resources will bring net economic benefits to Virginia in improved health outcomes, climate benefits, and replacing costly energy imports with increasingly cost effective, locally produced energy.

States are acting partly in response to the recognition of an ethical obligation to join others in acting responsibly to mitigate a global problem. But, given the advances in new energy technologies, Virginia and other states have much to gain from the coming energy transition. Investing in local clean energy resources will bring net economic benefits to Virginia in improved health outcomes, climate benefits, and replacing costly energy imports with increasingly cost effective, locally produced energy.

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[2] See https://www.usclimatealliance.org/state-climate-energy-policies

Virginia began considering state action on global warming with the release, in 2007, of the Virginia Energy Plan (*The Virginia Energy Plan* 2007) during the administration of Governor Timothy Kaine. The 2007 energy plan called for the creation of a governor's commission on climate change and its effects in Virginia. The commission, which was created by executive order in that year, developed conclusions based mostly on an assessment of what other states were doing. It made a number of suggestions for improving energy efficiency and reducing emission intensity in Virginia, but did not approach the question of eliminating GHG emissions, and since the commission's conclusions did not have the force of law, it's influence on state policy was limited. The next step in addressing Virginia's GHG emissions came in the form of Governor McAuliffe's Executive Order 57 (2016) on the "Development of Carbon Reduction Strategies for Electric Power Generation Facilities," and Executive Directive 11 (2017) aimed at "Reducing Carbon Dioxide Emissions from Electric Power Facilities and Growing Virginia Clean Energy Economy" which initiated the process of Virginia putting limits on GHG emissions from the electricity sector.

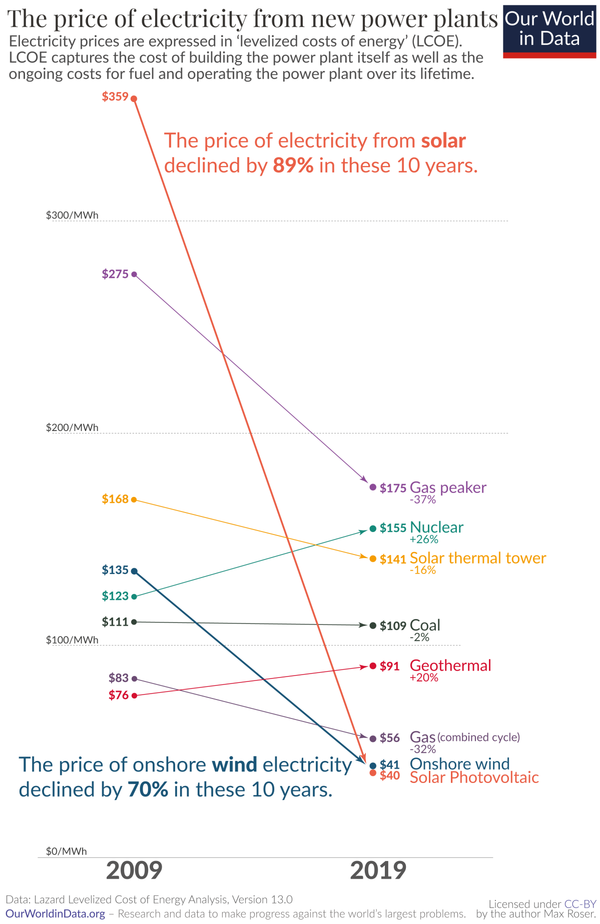

Figure 5: Changes in levelized cost of energy for several fossil and renewable electricity generation resources, 2009-2019 (Roser, 2020).

Much had changed between the time of Governor Kaine's commission and Governor McAuliffe's putting in motion Virginia's first efforts to rein in its emissions. Three factors stand out. First, the Regional Greenhouse Gas Initiative (RGGI), a consortium of northeastern states, established the first binding limits on emissions in the member states and demonstrated that their cap and trade approach worked smoothly.

Second, the cost of generating electricity from non-emitting sources, especially wind and solar photovoltaics (PV), had dropped dramatically, greatly lowering the costs of transitioning to greener electricity generation. Between 2009-2019, the levelized cost of electricity from solar PV dropped by 89%, while costs for onshore wind dropped by 70% (Fig. 5).

Third, climate action at the national level in the U.S. partly stalled with the failure of the Obama Administration's effort to establish national limits on GHG emissions. While the Obama administration continued to work to limit emissions and improve non-emitting energy technologies, during the Trump Administration, much of the policy initiative moved to state and local government.

Governor Northam completed the move initiated by Governor McAuliffe toward having Virginia join RGGI. This development was followed by the first major legislative action to reduce GHG emissions in Virginia: the 2020 Virginia Clean Economy Act (VCEA). The VCEA mandates that Virginia join RGGI, and invest significant resources in energy efficiency, while establishing a schedule for the increasing use of renewables in the generation of electricity. As of January 2021, Virginia will participate in the RGGI cap and trade program. The VCEA requires that Virginia's cap on emissions decline to zero by 2049. Governor Northam has also included Virginia in the consortium of states negotiating a cap on GHG emission from the transportation sector, although it is not clear when Virginia might join in capping its transportation emissions.

The policy momentum in Virginia is now clear. The state has started down the path of decarbonization, with plans to fully decarbonize the electricity sector by 2050. Given recent advances in technology, the question is no longer "can we eliminate our electricity sector emissions," but rather, how might we expand our goal to include all sectors of Virginia's economy.

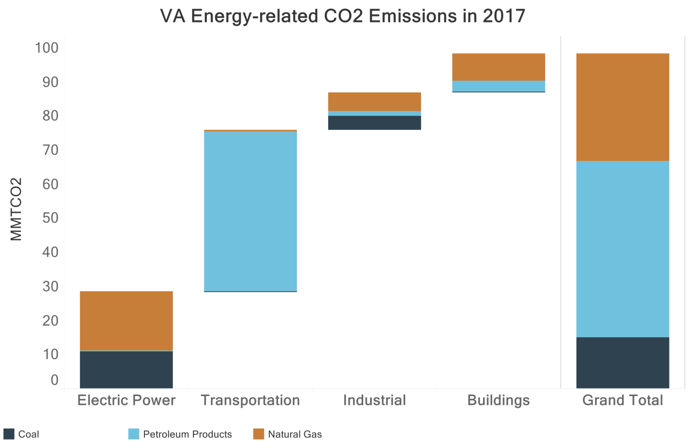

Figure 6: Transportation, buildings, and electricity generation dominate Virginia's energy-related emissions.

If we do choose to take the next step, it is important to identify the most cost-effective pathways for decarbonization, determine how fast can we can reasonably expect to get there, and understand what policy initiatives will be needed to achieve the goal of economy-wide decarbonization.

This report investigates how Virginia might approach full state-wide decarbonization by 2050, expanding the analysis to include all major emitting sectors: electricity generation, transportation, buildings and industry. We use a detailed model of Virginia's energy economy to chart pathways to GHG neutrality for the state. Careful modeling is essential to identify policy initiatives necessary for decarbonization and potential obstacles and missed opportunities that might prevent us from achieving the goal. We also seek to quantify the direct costs and benefits to the state's economy of different pathways to decarbonization. The VCEA and companion legislation focused primarily on reducing carbon emissions linked to production and consumption of electricity generated from fossil fuels. But the electricity sector accounts for only about 30% of Virginia's overall greenhouse gas emissions. As shown in Figure 6, the transportation sector accounts for nearly half of all energy-related CO_2 emissions, primarily due to consumption of refined fossil fuel liquids (gasoline and diesel). The remaining balance of emissions are linked to buildings, industry and agriculture.[3]

To accomplish this transition, we need to plan carefully, coordinate actions and maintain flexibility in our approach so that we can take best advantage of new technologies and opportunities as they become available. Fortunately, we are not alone. Many other states along with an increasing array of countries around the world have pledged to "hang together," as Ben Franklin would have it. There is comfort in knowing that we are in the vanguard of a rapidly growing international community committed to reducing global warming. It is also encouraging to consider that continued policy support and investment in clean energy technologies by a growing cohort of states and countries committed to decarbonization will very likely result in continued cost reducing innovation.

2 Analytic Approach

2.1 Study description

In exploring possible ways of reaching the goal of decarbonization, we seek to answer a key set of questions:

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[3] This study focuses primarily on energy supply and demand. We will not address agricultural emissions in this report.

1. Does Virginia have adequate access to non-emitting resources?
2. What mix or mixes of resources might we use to achieve net zero emissions?
3. What will it cost to achieve the decarbonization goal?
4. What specific actions are needed to accomplish it and on what schedule?
5. Are there notable decision points that if not recognized could foreclose cost-effective options?

We have developed a set of four scenarios, described in detail in the next section, that explore what technologies, investments and policies are needed to accomplish the goal of zero net emissions by 2050. These scenarios are "technological" in nature. We avoid leaning on large changes in current cultural arrangements such as settlement patterns, living arrangements, commuting and other hard-to-engineer factors. We avoid including these factors, not because they are unimportant, but rather because they are difficult to implement, predict and agree upon. Our analysis is *conservative*, in the sense that we leave out a set of options that can contribute to decarbonization. If some of these other changes do occur, then the true cost of reaching zero emissions will be lower than our estimates here indicate.

Our analysis is *conservative*, in the sense that we leave out a set of options that can contribute to decarbonization. If some of these other changes do occur, then the true cost of reaching zero emissions will be lower than our estimates here indicate.

Because our goal is to explore possibilities, *all of the decarbonization scenarios assume that we meet the 2050 goal of net zero carbon emissions for the entire Virginia economy*. These scenarios are not forecasts about what we expect to happen. They are illustrative pathways among a practically infinite set of possibilities. They illustrate the feasibility of achieving the net zero goal and the advantage of technological innovation in lowering costs. They also illustrate the costs of delay and the costs of constraints on the availability of some energy resources.

Even this limited number of possible pathways helps policy deliberations in a number of ways. These pathways:

- Offer a framework to consider the choices and trade-offs to achieve deep GHG reductions

- Outline plausible potential sources and demands for energy types over time
- Provide insights into how economy-wide decarbonization affects electricity planning and operations
- Identify critical roadblocks

The scenarios were modeled using a suite of energy system and pathways models, RIO and EnergyPATHWAYS, respectively (RIO-EP), developed by Evolved Energy Research. These models use highly granular information about Virginia economic sectors, resource geography and hourly information about energy demand and resource availability. RIO-EP use these data and information about future economic activity and technologies to build logically consistent pathways for energy infrastructure, demand-side characteristics and least-cost methods for supplying the resources to meet projected demand.

The models take into account likely future energy demand with and without the emission reduction requirement. For each scenario, the energy system model performs an energy system optimization given the scenario assumptions. It provides a realistic treatment of technology, Virginia-specific resources and existing Virginia law. Given the necessity of meeting both the demand for energy services and the requirement of full decarbonization, we can ask what is the least-cost path to decarbonization and how things change in the presence of added constraints on resource availability or changes in our assumptions about technology and policy.

The Baseline scenario does not include the key VCEA mandates on renewables, joining RGGI, fossil generator closures or energy conservation. Our four decarbonization scenarios all use the Virginia law as it stands after the passage of the VCEA. This is appropriate, since our goal is to assess a policy of decarbonization against a world with no decarbonization policy in place. This means that the costs and benefits of the VCEA are incorporated into our scenario costs and benefits.[4]

An analysis of Virginia's energy transition must simultaneously incorporate two distinct policy targets:

1. *Electricity target*: all generation and energy imports must come from clean resources by 2045, consistent with the VCEA.[5]

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[4] Technically, Virginia was already scheduled to join RGGI prior to the passage of the VCEA, but we have chosen to count the likely effects of RGGI membership in our decarbonization scenarios but not in the Baseline.

[5] There is some uncertainty about what might be in operation between 2045 and 2050. Since VCEA clearly requires that nearly all generation must be non-emitting by 2045, we treat this as applying to all electricity generation.

2. *All energy target*: the electric, transport, buildings and industrial sectors must produce net-zero emissions by 2050.

The full decarbonization target is also applied nationally. This condition ensures against emissions leakage between states, and reflects competition for high-value low-carbon resources (e.g., bioenergy feedstocks).

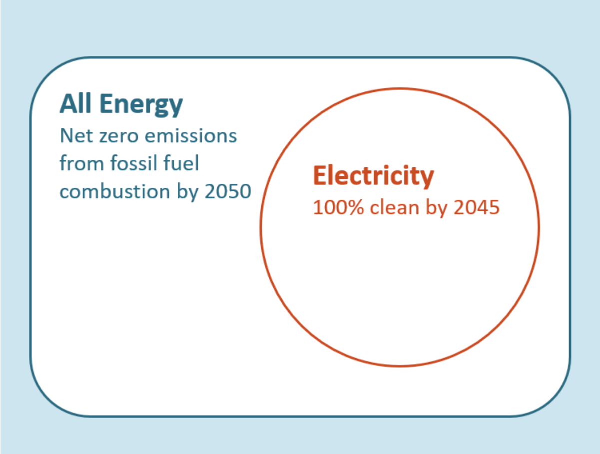

Figure 7: Two Policy Targets

Our analysis extends earlier analysis beyond the electricity sector to include buildings, transportation and industry.[6] It allows for tradeoffs between types of energy resources, such as electrification of functions across all sectors. We distinguish needs for different fuel types and end-use applications, such as storable liquids and high temperature industrial applications. We accommodate the import and export of fuels and electricity. We also take into account key assumptions about future population; growth industries, such as data centers; and extant trends in lower energy use per dollar of economic activity in homes, offices and industry.

The RIO-EP framework accounts for the different rates of turnover for various energy system assets such as power plants, pipelines, cars and appliances. (See Figure 8.) The rate of turnover of these different asset categories places important constraints on the timing of policies and incentives for replacing GHG-emitting assets with non-emitting ones. For example, commercial boilers have an average expected life span of around 15 years. The means that any fossil-fired boilers built after 2035 would need to be retired before the end of their useful economic life. The premature stranding of valuable economic assets raises the cost of achieving emission reductions.

Some economic activities will be expensive to decarbonize, at least in the relevant time frame. Consequently, to achieve net zero emissions, we will need to actively remove some greenhouse gases (probably CO_2) from the atmosphere. We know that Virginia's

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[6] There is an important omission from our analysis, the agricultural sector. While we do account for energy used in and supplied by agriculture, we do not account for direct emissions of greenhouse gases from agriculture or the ability of farms and forests to sequester carbon from the atmosphere. Incorporating these sources and sinks of emissions requires a different modeling framework. We hope to address agricultural emissions in a subsequent study.

farms, forests and coastal estuaries have the potential to sequester very substantial amounts of CO_2. But the techniques for encouraging and counting natural sequestration remain speculative. We have chosen not to attempt to quantify natural sequestration but to focus instead on industrial processes such as bio-energy with carbon capture and sequestration (BECCS) or direct air capture with sequestration (DACS).[7]

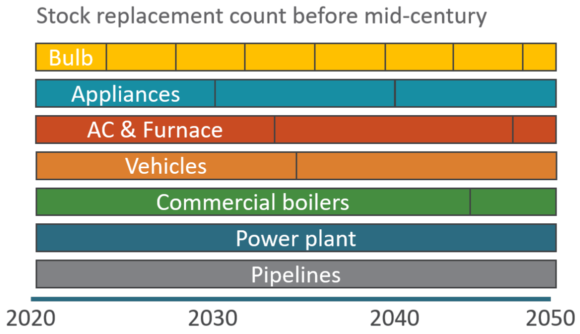

Figure 8: Stock replacement count before mid-century

Since full decarbonization by 2050 will certainly not happen without substantial public policy initiatives, we use our scenarios to learn about what actions are needed (and when). Some emission reductions will take place organically as the costs of non-emitting technologies continue to fall, and other changes will require specific policy interventions. For example, it now seems inevitable that the use of electric cars will increase substantially even without policy intervention. But it is also clear that, without a policy push, the turnover of the vehicle stock from fossil fuels to electricity (or non-emitting alternative fuels) will not happen by mid-century. Here and in other sectors, our scenario analysis can help identify inflection points where policy intervention will be needed if we are to achieve net zero emissions by 2050.

2.2 The Pathways Approach

The analysis has two components, which operate in tandem to generate integrated scenarios: (1) demand-side pathways and (2) supply-side capacity optimization to meet that demand. (Fig. 11) First, *given the assumptions in the particular scenario*, we calculate the likely demand for energy-related services. This "pathways" portion of the analysis takes into account all of the factors that determine energy demand, including energy efficiency investments, electrification of end-uses, and demand-management efforts. The factors vary by subsector: residential, commercial, industry and transportation.

The model also takes into account known trends in Virginia's energy economy, such as the rapidly expanding data center industry with its implied increase in electricity

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[7] Not including natural sequestration in our analysis will tend to inflate our estimated cost of decarbonization.

demand. We account for trends in industry, building stock, vehicle use. We account for Virginia-specific resource availability and attempt to realistically represent Virginia laws and energy institutions.[8]

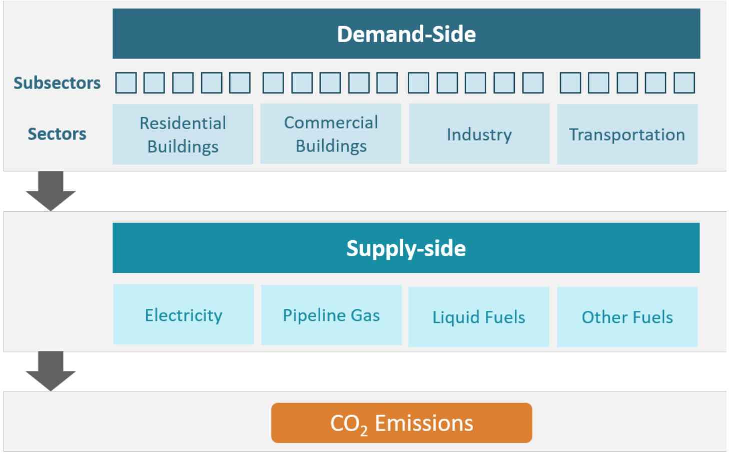

Figure 9: EnergyPATHWAYS and RIO model the demand side and supply side respectively.

The demand-side of our scenario analysis depends on forecast characteristics of Virginia's energy economy plus scenario-specific assumptions about changing patterns of demand. It takes into account the rollover of various asset stocks over time, changes in use patterns and the resulting shift in load shape for specific energy resources. For example, the transition to a greater share of electric vehicles (EVs) may take place quickly or slowly. (See Figure 10.) The assumed annual sales of EVs imply a transition in the stock of vehicles and hence the shift from liquid fuels to electricity, with the implied change in daily patterns of electricity use. Likewise, our forecast of data center demand is based on continued expansion of data demanding activities, resulting in data center growth and increased demand for electricity over the planning horizon.

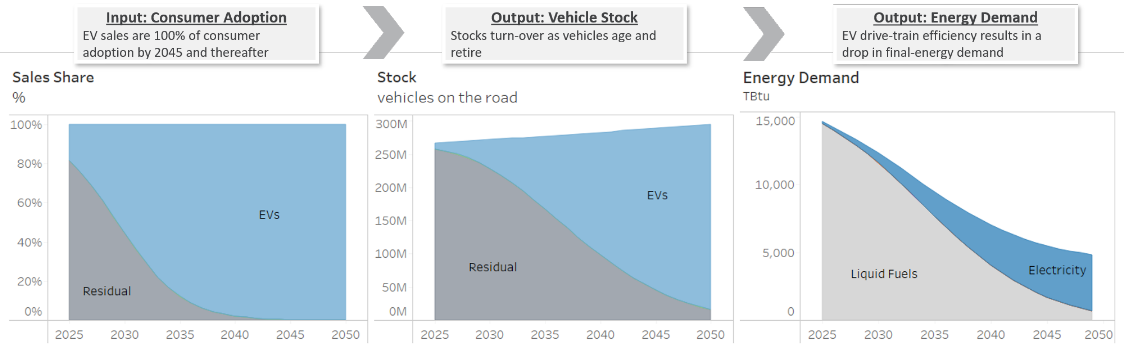

Figure 10: A sample scenario of the transition to electric vehicles.

We use the calculated pattern of energy demand as the starting point for determining the least-cost clean fuels approach to meeting that demand. The model uses standard

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[8] For details about the RIO and EnergyPATHWAYS models used in this analysis, see the Appendix.

estimates of present and future technology costs including the costs of generation, storage and sequestration. The model selects the lowest cost clean energy build-out that reliably meets the implied hourly electricity demand from the pathway demand analysis. This takes into account the variability in renewable resources and the likely change in demand patterns from increased electrification, as well as the long-term implications of infrastructure investments.

The optimization operates across different energy supply and storage technologies including wind, solar, nuclear, batteries, hydrogen, synthetic fuels, etc. For example, air transport will probably still require energy-dense liquid fuels in 2050. We can either make liquid fuels using carbon free energy sources, or we can use fossil fuels but sequester sufficient carbon to make up for the recalcitrant air transport emissions.

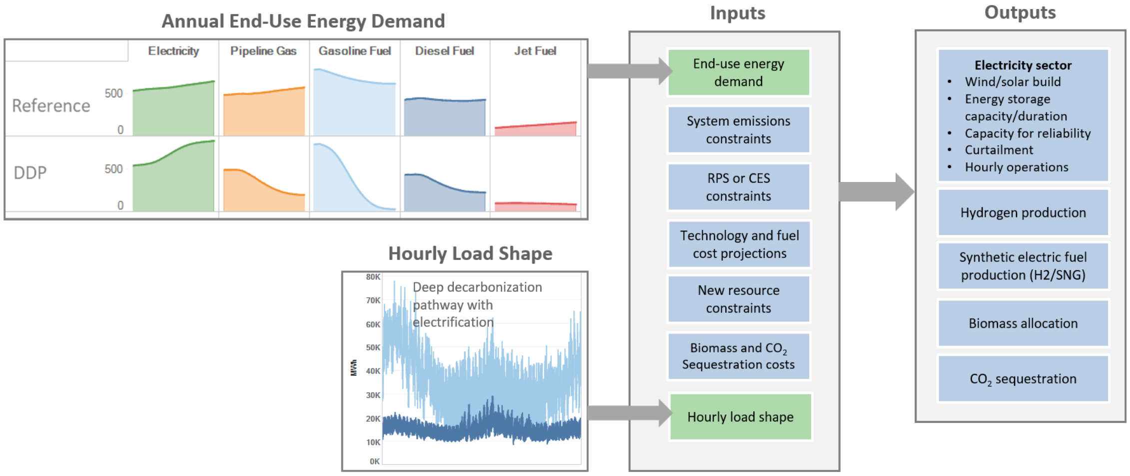

Figure 11: The supply meets demand modeling framework uses the pathways analysis to drive energy system investment and operations.

The energy supply optimization model is co-optimized across technologies (Fig. 11). This means that the model will pair complementary technologies like solar PV and battery storage or bio-energy with hydrogen production. It will also allow substitution among technologies to minimize the cost of meeting the pattern of demand derived in the pathways analysis. The supply-side model incorporates best estimates of future cost and availability of novel technologies.

2.3 Scenario Analysis

We have chosen four representative scenarios to illustrate key features of different pathways to zero net GHG emissions by 2050. Each scenario implies a variety of constraints on required outcomes and allowable actions. These constraints are coded into the EnergyPATHWAYS and RIO simulation models to derive results about Virginia's energy sector. All four scenarios are constrained to meet the 2050 zero emission requirement:

1. **Net Zero (low cost policy path):** The scenario that achieves net zero carbon at least cost, given moderate assumptions about the rate of technical innovation. Of our mid-range technology scenarios, this is the least-constrained, designed to assess an all-options approach to decarbonization.
2. **Constrained Land and Nuclear:** Utility-scale solar limited to 0.5% of Virginia's land area and no new nuclear
3. **Slow Consumer Adoption:** Slow consumer adoption of electrified demand-side technologies (electric vehicles, heat pumps, etc.)
4. **Rapid Innovation**: The least cost policy path, given more aggressive cost reductions for low-carbon and efficient technologies

We compare these policy scenarios to a "Baseline" scenario with no clean electricity or GHG policies. The Baseline is based on the 2019 *Annual Energy Outlook* (EIA, 2019). As we will make clear shortly, the Baseline scenario shows that, without a policy push, Virginia will not achieve significant reductions in CO_2 emissions by 2050.

Further detail on the modeling tools and data sources is available in the Appendix.

3 Modeling Assumptions

3.1 The Scenarios: Common Assumptions

In designing any scenario, there is essentially an infinite combination of assumptions one could make about various factors that affect the modeling outcome. Here, we list some of the more consequential of those choices. The things left off this list are things that would likely happen anyway, things not easily changed by policy and things that would have a smaller influence on the outcome. We will discuss the key scenario assumptions in some detail in the subsequent text.

Assumptions made in most scenarios:

- All scenarios (by design) achieve net zero carbon by 2050.
- Existing law is used, including VCEA, RGGI, utility sector regulations.
- Load growth includes rapid expansion of data centers located in Virginia.
- Energy efficiency technologies are aggressively implemented.
- We use National Renewable Energy Laboratory (NREL) mid-range technology costs, which are thought to be current best estimates
- Utility-scale solar is limited to 1% of Virginia's land area (0.5% in one case).
- We assume the re-licensing of the current nuclear fleet of four reactors, with new nuclear capacity limited to no more than double the current nuclear capacity.
- NREL's estimates are used in determining renewable resource potential for Virginia.
- A $10/MWh subsidy is applied to rooftop solar generation.
- Nationwide decarbonization along with Virginia

Net zero carbon by 2050: As we have already noted, all of our scenarios require that Virginia achieve zero net emissions of greenhouse gases from its energy economy by 2050. The time horizon can, of course, be shorter or longer, and the goal could be made less aggressive. Our primary goal with this exercise is to demonstrate the feasibility of a zero net emissions future and to explore the types of policies and resources needed to achieve it. These scenarios do not assume zero emissions or zero use of fossil fuels. Some uses of fossil fuels are recalcitrant to eliminating fossil fuel combustion, at least in the next 30 years. To achieve net zero, there will need to be some contribution from negative emissions.

Existing law: Except for our Baseline scenario, we take as given in our model the VCEA. This includes the scheduled renewables and storage build-out, the expected contribution of offshore wind and the expenditures on new energy conservation initiatives. We do not assume any significant changes in how the electricity industry is organized or regulated. The VCEA requires that Virginia's investor-owned utilities build certain renewable energy resources, including 16,100 MW of utility-scale solar generation capacity, 5,200 MW of offshore wind generation capacity, and 3,100 MW of energy storage, all by 2035. The VCEA also imposes a clean energy standard on future electricity generation, requiring a minimum fraction of the electricity sold by investor-owned utilities be generated from renewable sources, a percentage that grows over time according to a specified schedule.

These provisions of the VCEA are "binding" in the sense that the model would not choose to build the specific resources required by the VCEA, at least not on the schedule specified. For example, absent the provisions of the VCEA, the model would delay the building of offshore wind facilities until somewhat later than specified in the law.

One of the most important features of the VCEA is the provision that the Virginia allocation under the RGGI cap on emissions from the electricity sector decline to zero by 2049.[9] This policy goes well beyond the current RGGI memorandum of understanding, which has a policy horizon ending in 2030. There is every reason to believe that the RGGI states will continue to tighten the cap past 2030 and may soon establish a zero cap date around mid-century. The price of RGGI allowances appears to reflect the expectation of a tighter future cap on emissions. Since 2013, the RGGI price has been rising at an average annual rate of around 18%.

With the passage of the VCEA, Virginia joined a growing cohort of states that have set a goal of achieving a 100% carbon neutral electricity supply by 2050 or earlier. At least eighteen U.S. states have adopted ambitious goals to transition their energy systems towards net carbon neutrality.[10] Ten other states have established mandatory 100% carbon free targets for electric power. Some of these states including CA, WA, NV, CO, NY and ME have also established legislatively mandated targets of 80% or more for economy-wide decarbonization, while other states, such as LA, MI, MN and NJ have set economy-wide decarbonization targets of 80% or more by 2050 without separately defining 100% clean energy or decarbonization targets for the electric sector.[11]

Load growth: A single forecast for core electricity demand was used in all scenarios.[12] This baseline demand forecast includes flat load growth in the residential, commercial, and industrial sectors through 2050, with the exception of data center use. This is consistent with trends in actual electricity demand since 2010. Electricity demand from data centers located in Virginia has been growing rapidly for nearly a decade and the baseline demand forecast includes a projection of continued growth in data center demand through 2050.

Inclusive of data center growth, baseline electricity demand is forecast to increase

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[9] Virginia had completed the process of joining the RGGI cap prior to the passage of the VCEA. The VCEA made two substantive changes to the original RGGI regulations. First, the VCEA provides for auctioning allowances for revenue rather than grandfathering allowances so that ratepayers would receive the value of allowances. Second, the VCEA specified that Virginia's cap must reach zero by 2049. We have chosen to treat RGGI as part of the decarbonization pathways rather than part of the baseline.

[10] Source: Clean Energy States Alliance, https://www.cesa.org/members/

[11] See usclimatealliance.org for current list.

[12] See the Appendix for detail concerning the electricity demand forecast.

by 83% by 2050 (2.0% annual growth). Data centers represent approximately 75% of load growth. Since 1990, inflation adjusted economic output in Virginia has increased nearly four-fold. Assuming economic growth in Virginia continues at that pace over the next 30 years, the projected growth in electricity demand implies that Baseline electric energy intensity (electric use per unit of economic output) will decrease by more than 50% during that time. The decarbonization scenarios include additional same-fuel energy efficiency improvements not included in the Baseline scenario such as significantly more rapid adoption of high-efficiency end-use equipment.

Increases in electricity demand generated by continued electrification of transportation, space and water heating and other end uses are developed in our analysis as modeling outcomes and are not assumed in our electricity demand forecast. Realized scenario demand is contingent on the objectives and constraints of each scenario. For this reason, the business-as-usual Baseline scenario, in which no requirements were set for clean energy use, resulted in a lower rate of electrification and lower electricity demand versus the decarbonization scenarios. Similarly, the Slow Consumer Adoption scenario, in which adoption of electric vehicles, market share expansion of heat pumps and other expanded uses of electricity proceed more slowly, resulted in slower growth in electricity demand than the other decarbonization scenarios.

Demand for energy services (lighting, heating, cooling) is projected through 2050 for various end-uses. We use the U.S. Department of Energy's 2019 Annual Energy Outlook (AEO 2019; EIA, 2019) Reference Case for macroeconomic drivers (e.g., population and industrial value of shipments) and energy service demand projections (e.g., vehicle miles traveled). Use of the AEO means that the net-zero pathways in the study support an economy, settlement patterns and lifestyle that resemble today. Mitigation does not depend on major changes in hard-to-shift patterns and behaviors. For example, we do not envision major shifts away from personal transport towards trains, buses and other forms of mass transit. If those things were to happen, they would make it that much easier and less costly to decarbonize the state's economy.[13]

Energy efficiency: Baseline energy intensity of the economy falls by about 50% even without additional policies. All of our scenarios include substantial increases in energy efficiency. Some of the increased efficiency arises from the electrification of transportation and building end-uses. Efficiency also improves from improved building energy performance

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[13] Section 7 of the technical appendix from 350 PPM Pathways for the United States (Haley et al., 2019) provides an exhaustive overview of projecting energy service demand for each end-use. These end-use assumptions carry over into our report.

and industrial process efficiency. While efficiency is assumed to steadily increase over the 30 year policy horizon, electricity generation still rises substantially due to electrification of end uses and continued growth in data center demand. A substantial fall in data center energy intensity could reduce this growth, but our current data center forecast already accounts for some data center efficiency improvements.

Technology costs: We use publicly available technical reports to characterize cost trajectories for low-carbon technologies, as summarized in Table 1. This includes studies published by the National Renewable Energy Laboratory, International Energy Agency, and the International Council on Clean Transportation (ICCT).

Battery cost assumptions are consistent across scenarios, including grid-scale battery energy storage resources and electric vehicles, and derived by using the average of two projections through 2030 from Bloomberg New Energy Finance and the ICCT, as shown in Figure 12. We assume battery costs reach $60/kWh in 2040 and remain at that level thereafter. Electric vehicle costs are estimated by combining the battery cost projections with additional cost components for light-duty autos, light-duty trucks, medium-duty trucks, and heavy-duty trucks.

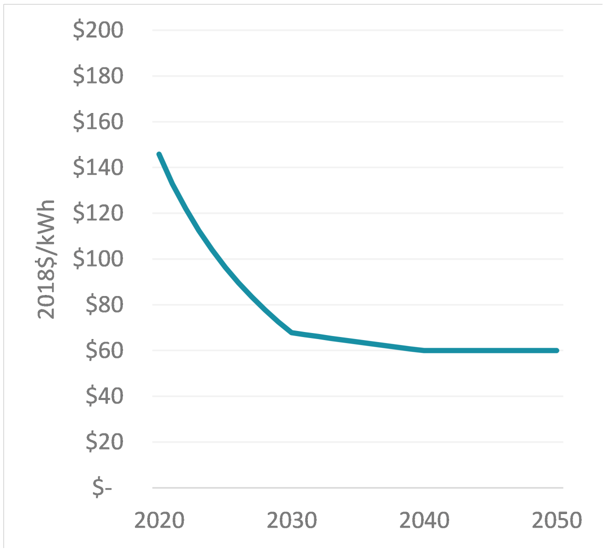

Figure 12: Battery Cost Projection (Goldie-Scot, 2019, Lutsey and Nicholas, 2019)

Transportation electrification assumptions: The Net Zero pathway assumes aggressive adoption of zero-emission vehicles across on-road transportation subsectors. The following sales share targets (percent of new vehicles sold) for battery electric vehicles (BEV) and hydrogen fuel cell vehicles (HFCV) were assumed. These sales share targets were informed by our experience modeling the stock-rollover of the transportation sector and net-zero targets in prior work.

- Light-duty vehicles: 100% BEV by 2045
- Medium-duty trucks: 80% BEV by 2045 and 20% HFCV by 2045
- Heavy-duty trucks: 70% BEV by 2045 and 30% HFCV by 2045

The Slow Consumer Adoption pathway assumes a 20-year delay for each of the sales

Table 1: Technology Cost Assumption Sources

Category	Sub-category	Sources
Clean electricity generation	Renewables	Vimmerstedt et al. (2019)
	New Nuclear	Vimmerstedt et al. (2019)
Energy storage	Lithium-ion	W. Cole and A. W. Frazier (2019) Evolved Energy Research analysis
	Long-duration storage	Energy, Burger, and Ragazzi (2020)
Hydrogen	Electrolysis	De Vita et al. (2018)
	BECCS H2	Larson et al. (2020)
	H2 Storage	Ahluwalia et al. (2019)
Synthetic fuels	Biofuels	del Álamo et al. (2015)
	Electric fuels	Verkehrswende, Energiewende, and Economics (2018)
Electric Vehicles	Light-, medium- and heavy-duty vehicles	Lutsey and Nicholas (2019) Den Boer et al. (2013) Evolved Energy Research analysis

share targets. In practice, this results in the following sales share targets for 2045:

- Light-duty vehicles: 73% BEV by 2045
- Medium-duty trucks: 53% BEV by 2045 and 13% HFCV by 2045
- Heavy-duty trucks: 46% BEV by 2045 and 20% HFCV by 2045

The resulting vehicle stocks (cars and trucks on the road) for 2030 and 2050 are summarized in tables 2 and 3.

Table 2: Vehicle Stock: Percent Battery Electiric Vehicle

	Net Zero		Slow Consumer Adoption	
	2030	2050	2030	2050
Light-duty vehicles	15%	93%	4%	59%
Medium-duty trucks	5%	72%	2%	39%
Heavy-duty trucks	5%	64%	1%	36%

Table 3: Vehicle Stock: Percent Hydrogen Fuel Cell Vehicles

	Net Zero		Slow Consumer Adoption	
	2030	2050	2030	2050
Light-duty vehicles	15%	93%	4%	59%
Medium-duty trucks	7%	90%	2%	49%
Heavy-duty trucks	7%	91%	2%	51%

Utility-scale solar land-area limit: We limited the land area to be used for utility-scale solar PV to account for potential increasing costs of allocating land to solar generation facilities as the acreage dedicated to that use increases. This assumption is quite conservative, in the sense that it makes achieving the net zero emissions goal more difficult and more costly. The constraint is binding in all scenarios; the model would have chosen almost twice as much solar PV (along with more storage) than allowed by this constraint. Limiting the solar land area results in more expensive, floating offshore wind being built in its place or an increase in energy imports. In our Constrained Land and Nuclear scenario, we limit solar PV even further to test the importance of this constraint on the state's ability to achieve net zero and the cost of doing so.

Nuclear plants: In all of our scenarios, we assume that the current fleet of four nuclear reactors are re-licensed to operate through the planning horizon. In all but one scenario, we use available estimates about future nuclear costs and allow for the construction of new capacity up to 100% of existing capacity.

Renewables potential: The cost and potential supply of renewable energy for Virginia is based on NREL state-specific resource estimates for solar PV, distributed (rooftop) solar, offshore wind and onshore wind. Characteristics of renewable resources used in the model include: seasonality, persistence and diurnal patterns. The onshore wind resource is not of high quality due to quite low expected capacity factors in most places in the state.

Distributed solar: Distributed (or rooftop) solar is about three times the cost per kWh of utility-scale solar. Based purely on levelized-cost of energy, the RIO model will not select distributed solar as a significant renewable resource in most scenarios. RIO bases capacity expansion only on cost and value of resources at the bulk power system level and excludes potential value of distributed resources on the retail distribution system. But there is considerable consumer willingness to pay for rooftop solar for reasons not taken into account in the bulk power system optimization model. For this reason, we assume a $10/MWh subsidy for rooftop solar in all of our scenarios. This subsidy is included in calculations of energy system costs.

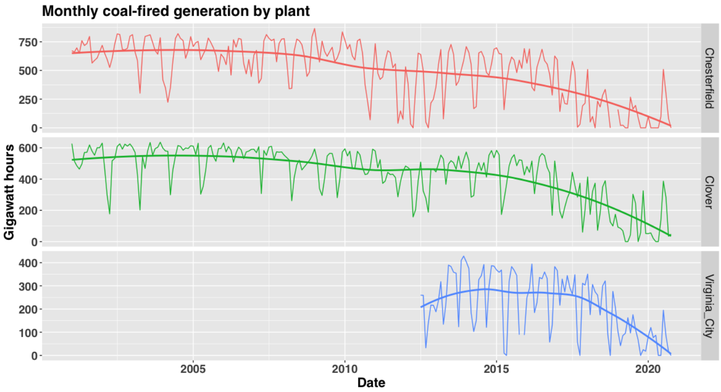

Figure 13: Monthly Generation by Virginia's three largest coal-fired power plants.

Nation-wide decarbonization: For all scenarios, we assume that the rest of the country is also achieving a 2050 decarbonization goal. This assumption prevents the model from choosing the obvious least-cost strategy of exporting Virginia's emissions to other states in order to achieve local decarbonization. Virginia will have to compete with all other states for the available non-emitting resources. We impose an import "hurdle rate" ($ per MWh cost adders) between the "Rest of US" and Eastern states in order to reduce model-selected transmission flows. This is consistent with the expectation that Virginia policy makers will generally choose not to import a significant fraction of its electricity.

Virginia's coal fleet: The VCEA specifies that coal plants owned by Virginia's electric utilities close according to an accelerated schedule. It turns out that the provisions of the VCEA probably have had little or no effect on the economic value of these coal plants. None of the three large coal plants covered by the provisions of the VCEA are economically viable; they sit idle most of the time (Figure 13). None have a 2020 capacity factor exceeding 20% through October. There appears to be little coal generation in Virginia's future whether we explicitly choose to decarbonize or not.

A note on costs: The scope of costs included in this analysis, which are all given in 2018 dollars, is limited to energy system costs, which include:

- Annualized capital costs of demand- and supply-side energy equipment
- Variable fuel costs
- Fixed and variable operations and maintenance costs
- Equivalent to an "energy system revenue requirement"
- Annual cost of producing, distributing and consuming energy in Virginia

The analysis does not include costs outside of the energy system. It does not include the economic benefits of avoided global warming. Nor does it reflect the health and other co-benefits from reduced air pollution from decreased combustion of fossil fuels.

3.2 The Scenarios: Specific Assumptions

Net Zero (normal case): Designed to identify the least cost pathway for achieving economy-wide decarbonization by 2050 with minimal constraints on the potential capacity of clean energy technologies in Virginia. Up to 1% of Virginia's land area was assumed to be available for utility scale solar facilities. Nuclear generating capacity was limited to a doubling of Virginia's current nuclear capacity. This scenario assumes continued but slowing cost reductions for wind and solar energy as projected in the NREL Annual Technology Baseline mid-case trajectory.

Table 4: Pathway Assumptions

		Net Zero	Constrained Land and Nuclear	Slow Consumer Transformation	Innovation
Scenario-Specific	New nuclear resource potential	3.7GW	0.0GW	3.7GW	3.7GW
	Land use for renewables (% land area)	1.0%	0.5%	1.0%	1.0%
	Building and transportation electrification	High	High	Moderate	High
	Renewable technology costs: NREL ATB 2019	Mid	Mid	Mid	Low
	Litium-energy battery cost in 2050 ($/kWh)	$60	$60	$60	$45
Common	Economy-wide GHG policy	Net-zero energy-related CO2 emissions by 2050			
	Clean Electricity Policy	100% clean electricity by 2045 with VCEA renewable resource mandates			
	U.S. decarbonization	Occurs alongside Virginia’s decarbonization			
	Satisfies existing laws	VCEA, RGGI, etc.			
	Net zero carbon by 2050	Yes			
	NREL technology costs	“Mid”			
	Energy Efficiency	High			
	Load growth includes	Expected data center load growth, end-use electrification net of incremental energy efficiency			
	Customer-sited solar subsidy	$10 per MWh			
	Distributed solar subsidy	$0.01/kWh			
	Nuclear	Keep current fleet (re-license 4 existing units)			
	Existing nuclear resources	Resources may economically relicense through 2050			
	Carbon capture utilization and storage	Allowed, but stored carbon must be transported and sequestered outside of VA			
	Offshore wind	Potential identified by NREL			

Table 5: Clean Electricity Resource Qualification Assumptions

	Base Assumptions	Constrained Land and Nuclear
Resource qualification		
Solar: utility-scale and customer-sited	✔	✔
Wind: onshore and offshore	✔	✔
Hydro	✔	✔
Nuclear: existing	✔	✔
Nuclear: new	✔	✘
Gas: 100% carbon capture	✔	✔
Gas: zero-carbon fuels	✔	✔
Imports	✔	✔
Resource potential (GW)		
Nuclear: new	3.7	0.0
Utility-scale solar	30.7	15.3
Customer-sited solar	28.5	28.5
Offshore wind: fixed and floating	35.2	35.2

Constrained Solar and Nuclear Assumes that political, economic and environmental considerations would create more significant constraints on utility scale solar and nuclear generating capacity. The constraint on land area available for utility scale solar was reduced to 0.5% and nuclear generating capacity was limited to current levels. Other assumptions remained the same as the Least Cost scenario.

Slow Consumer Adoption: Assumes that the transition to electric vehicles and increased use of heat pumps for space and water heating in buildings is slower than the pace assumed in the other decarbonization scenarios. Electrification in the transport and building sectors is a key means of decarbonization, but the future rate of electrification is both uncertain and contingent on policy decisions. Other assumptions remained the same as in the Net Zero (standard) scenario.

Rapid Innovation: This scenario uses NREL's Annual Technology Baseline (ATB) low-cost trajectory for estimates of the future costs of electricity system technologies. NREL's low-cost trajectory assumes that cost reducing innovation and gains in economies of scale for wind and solar energy will not slow as rapidly as projected in the ATB mid-case trajectory that was used in the other modeling scenarios. The Rapid Innovation scenario also assumes more rapid reductions in energy storage, green hydrogen production and nuclear facility capital costs versus the assumptions used in the other scenarios.

Details concerning costs in the Rapid Innovation scenario:

- Renewables: NREL Annual Technology Baseline 'Low' cost trajectory instead of 'Mid' for utility scale solar, rooftop solar, onshore wind and offshore wind technologies
- Nuclear: Capital cost reduction ($2,100/kW in 2050 versus $5,500/kW base assumption)
- Energy storage: Lithium-ion energy component cost decreases to $45 per kWh in 2050. Long-duration storage (LDS) technology based on Form Energy published estimates.
- Hydrogen: Deeper cost reductions for electrolysis and gas reformation with carbon capture
- Not changed: Land use constraints (effective limit on utility-scale solar PV) and maximum nuclear capacity of 2.0x today's size

4 Results

Our modeling exercise, and many others like it, suggest that any deep decarbonization exercise must ultimately take advantage of four distinct and complementary strategies for transitioning to a zero-carbon energy system, which we will refer to as the Four Pillars of Cost-Effective Decarbonization:

The Four Pillars of Cost-effective Decarbonization

1. Boost efficiency and responsiveness in energy use
2. Decarbonize the electricity sector
3. Electrify energy end-uses
4. Capture carbon emissions (to sequester or use)

Without substantial contributions from all of these components, reaching a zero net emission goal is probably out of reach by 2050. As we present our modeling results in this section, we will emphasize the importance of the four pillars and of policy timing.

Each pillar has many subtasks, some of which we will discuss in this report. A central goal of this study is to identify essential actions and to assess the difficulties or added costs that may occur if we wait too long to take these actions. The transformation of the energy sector of a state is a complex undertaking. Planning ahead and building a schedule of necessary policy steps for achieving that transformation should start now and continue until the CO_2 ledger is balanced.

In presenting our results, our central scenario, the one we call *Net Zero*, gets first billing with an in-depth focus on how Virginia's energy system transforms to meet the study's policy targets in the most cost-effective way, given our central case assumptions. We will discuss how the standard Net Zero scenario compares to the Baseline scenario, which is a characterization of the structure of the energy economy as it would evolve without any policy interventions to advance reductions in greenhouse gas emissions. In particular, the Baseline does not include Virginia joining RGGI, any specific mandates in the VCEA or any special inducements for electrification of building and transportation energy services.

After presenting the comparison between the Baseline and Net Zero scenarios, we will move on to compare the three additional decarbonization scenarios to the central, Net Zero scenario.

We emphasize that none of these scenarios should be treated as a prediction. Many unexpected things will happen on the way to 2050; policy will need to respond to the unexpected. We have based our scenarios on what we believe are reasonable projections of how various technologies might evolve. As the price imposed on CO_2 emissions rises in many localities worldwide, so do the incentives for innovation.

None of these scenarios should be treated as a prediction. Many unexpected things will happen on the way to 2050; policy will need to respond to the unexpected.

We have worked to make sure that our analysis is "conservative," in the sense that we make a number of assumptions to ensure we have not underestimated the cost of decarbonization. One of the key cautious assumptions is that Virginia will not make full use of our solar PV resource for generating electricity. This forces the model to choose a more expensive pathway than it would if we allowed cost considerations alone to determine which energy sources were built. We also assume a relatively slow adoption of electric vehicles, even as the estimates of future costs of EV batteries seem to be falling faster than previously expected.

4.1 Comparing the Net Zero and Baseline Scenarios

4.1.1 Energy Demand Our Baseline, business as usual scenario has total, final energy demand rising almost 30% between now and 2050 (Figures 14 and 15). Electricity demand rises sharply due to increased data center demand and some increased demand from electric vehicles.[14] Demand for *Other petroleum products* rises due to increased use of aviation liquid fuels. Gasoline and diesel demand (liquid fuels) fall somewhat due to the increasing penetration of electric vehicles.

In the Net Zero scenario, greatly improved energy efficiency causes total energy demand to fall even as the economy grows steadily; the energy intensity of the economy falls sharply. Partly this is due to the increased efficiency of electric energy services in transportation and buildings as compared to using fossil fuels directly. Partly it is due

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[14] Data center electricity sales are included in the building sector. For a discussion of our electricity demand forecast, please refer to the Appendix.

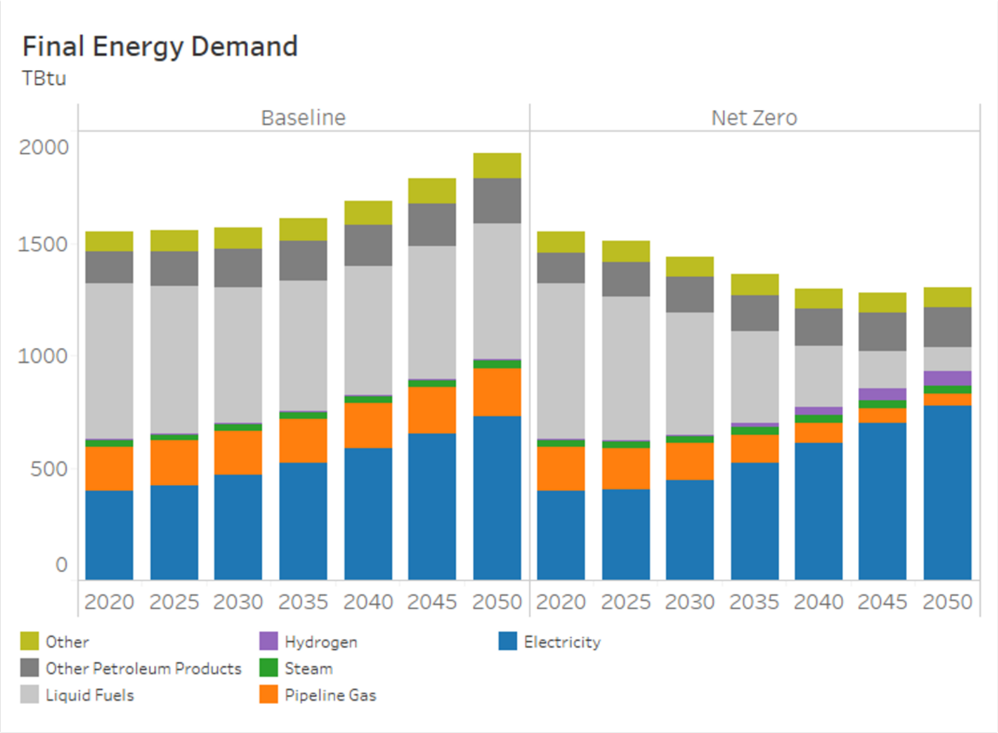

Figure 14: Final energy demand, 2020 to 2050, Baseline and Net Zero Pathways.

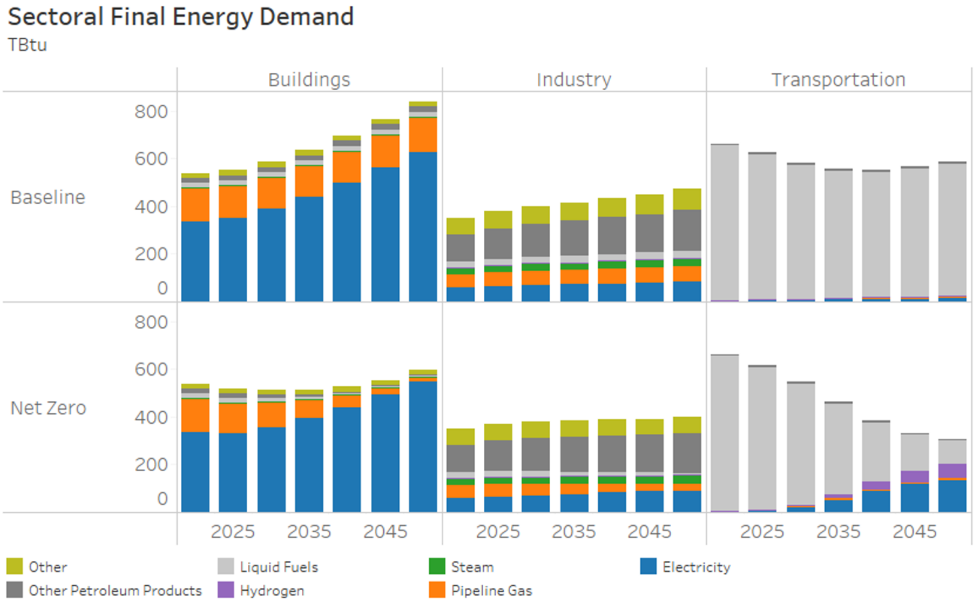

Figure 15: Final energy demand by sector, 2020 to 2050, Baseline and Net Zero Pathways.

to policies such as pricing emissions, changes to building codes and appliance energy efficiency standards, which address energy efficiency directly.

Our Net Zero scenario sees greatly improved energy efficiency, which causes total energy demand to fall, even as the economy steadily grows.

Net Zero scenario electricity demand rises somewhat more than in the Baseline. Improved efficiency the building sector is offset by electricity replacing petroleum fuels in transportation and replacing natural gas in building energy services and boilers. Electricity is also used in electrolysis for generating hydrogen, which begins to replace some liquid fuels, especially in long-distance transport applications.

The liquid fuels that remain will largely be non-emitting synthetic fuels used in applications that are recalcitrant to electrification (see Fig. 16).

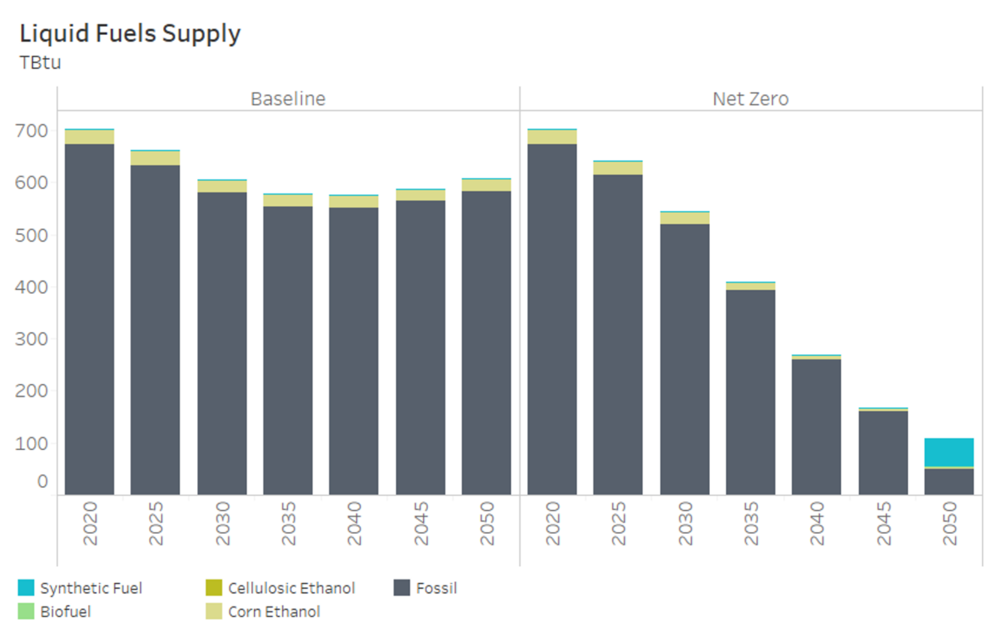

Figure 16: Liquid fuels supply, 2020 to 2050, in the Baseline and Net Zero Pathways.

4.1.2 Electricity Generation Energy Sources

The Baseline scenario shows clearly changes that are already underway in the electricity sector. Coal continues its rapid decline and essentially disappears as a generation fuel by 2030. This happens without any policy intervention because coal is no longer a cost-effective option for generating electricity. As we noted earlier, all three of Virginia's largest coal-fired power plants have operated at a capacity factor of under 20% through October of 2020. These plants are no longer economically viable. Given the Baseline assumption that natural gas prices stay relatively low, gas continues to grow and is the dominant energy source through 2050. Because natural gas prices remain low, no new nuclear is built before 2050, although not long after 2050, consideration must be given to what will replace the then aging nuclear fleet. In the 2040s, solar and offshore wind begin to displace natural gas and take significant shares of electricity generation as advances in technology bring capital costs down.

The most striking feature of the Net Zero scenario electricity generation is the dominance of utility-scale solar PV and offshore wind power; 70% of all electricity supply by 2050. These two resources, along with a modest increase in nuclear generation, completely displace coal and natural gas.[15] Most coal is retired by 2025 under the VCEA, but no coal plants remain economically viable into the 2040s; the alternatives are simply too cheap. Imports of electricity do not increase substantially. Two factors keep imports low: (1) new transmission capacity is expensive and (2) all other states are decarbonizing as well, so there is not likely to be a large surplus generation capacity in nearby states. Trade may increase for balancing, but net imports should not rise to any great extent.

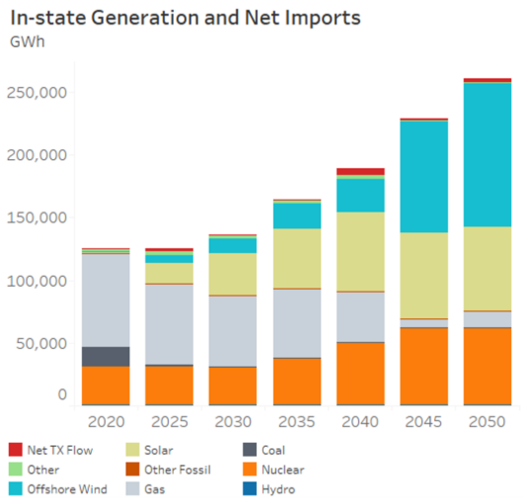

Figure 17: Virginia electricity generation and net imports, 2020 to 2050, in the Net Zero Pathway.

Decarbonization forces a dramatic shift in energy sources for generation. Figure 18 shows the difference in non-emitting installed capacity between the Baseline and Net Zero scenarios. Solar, in particular, rises very rapidly starting much earlier. Almost all of the new solar is utility-scale PV rather than rooftop solar even though we apply a \$0.01/kWh subsidy to rooftop solar. The cost differential favors utility-scale solar in our model.[16]

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[15] In our model, offshore wind dominates onshore wind in Virginia. This result is due to the relatively low quality of the onshore wind resource, which results in uneconomically low capacity factors for wind power in most of Virginia. Even the higher cost floating wind turbines have lower electricity costs than onshore wind. We should note that this result is quite sensitive to assumptions about the capital costs of onshore and offshore wind turbines and the quality of the wind resource. If it turns out that onshore wind performed better than we predict here, then the development of onshore wind would lower our estimates of the cost of achieving decarbonization.

[16] We note that consumer preferences and willingness to pay for rooftop solar as well as cost savings in the

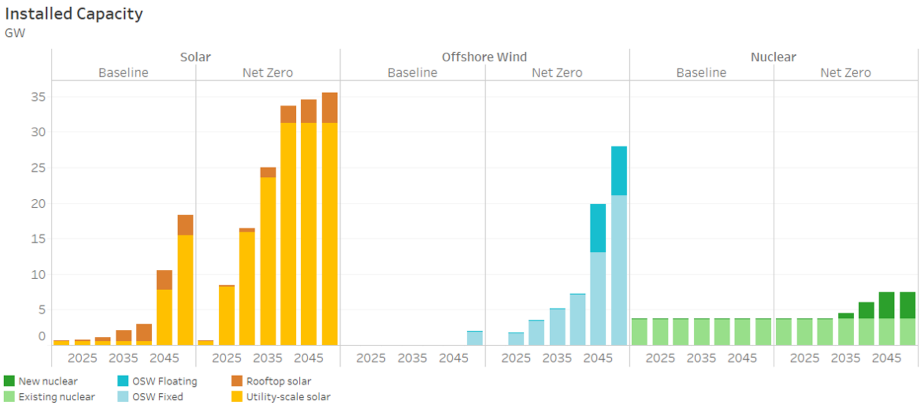

Figure 18: Installed capacity of selected low-carbon power technologies, 2020 to 2050, in the Net Zero Pathway.

The deployment of offshore wind, not used to any great extent in the Baseline, begins immediately in Net Zero, as mandated by the VCEA, and expands rapidly in later years as capital costs fall. The increased value of firm non-emitting power alongside the variable renewables resources results in a doubling of the installed capacity of nuclear generation, which supplies nearly one-quarter of electricity in 2050. This only begins after 2035, allowing several years for improvements in technology and learning-by-doing with newer nuclear technologies.

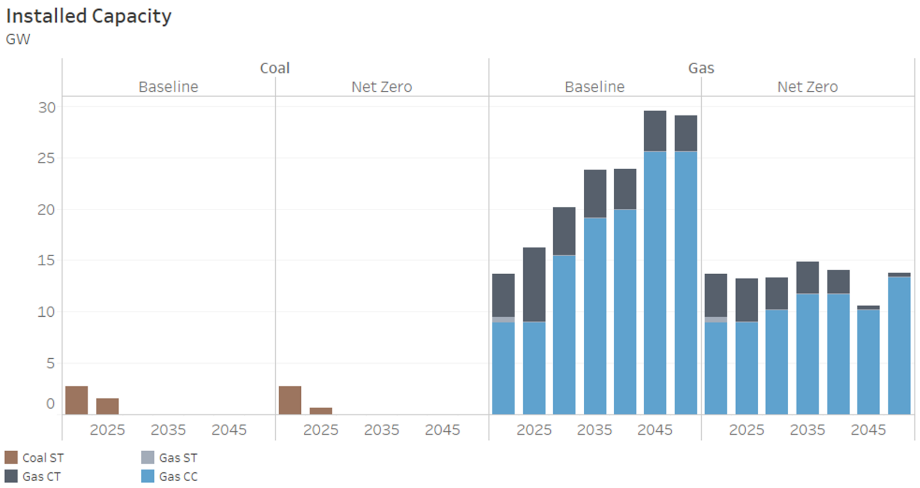

Figure 19: Installed capacity of thermal resources, 2020 to 2050, in the Baseline and Net Zero Pathways.

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distribution system may give an advantage to distributed resources beyond what is accounted for in our model, which operates at the bulk distribution (transmission) level (Trabish, 2020).

Fossil energy resources are largely displaced by non-emitting solar, wind and nuclear. Figure 19 confirms that coal generation disappears rapidly regardless. The current fleet of natural gas plants, on the other hand, continues to serve an important role (Figure 20). They shift from being bulk, firm energy sources operated at high capacity factors, to serving a load balancing function. The installed natural gas capacity remains about the same in 2050 as today, but its capacity factor falls from 62% to 11%. In order to comply with the VCEA, this remaining natural gas fleet operates entirely on zero carbon fuel after 2045.

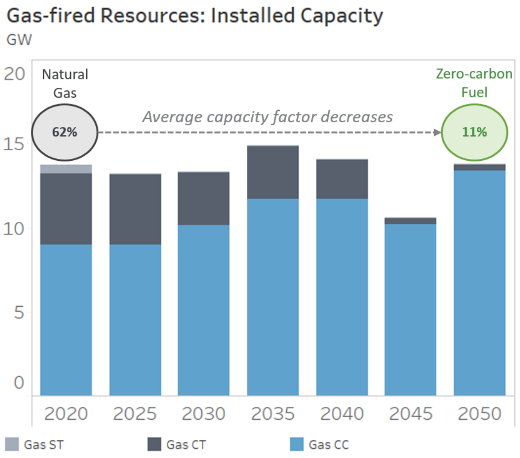

Figure 20: Installed capacity of gas-fired resources, 2020 to 2050, in the Net Zero Pathway.

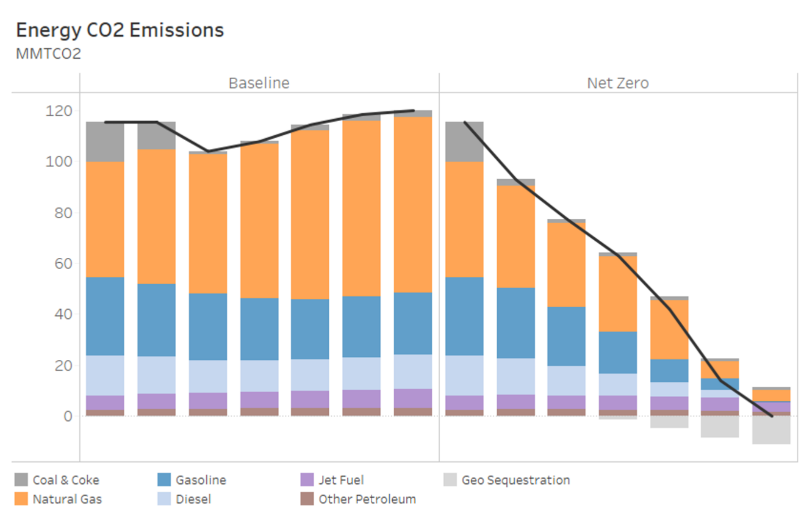

Figure 21: CO_2 emissions from energy, 2020 to 2050, in the Baseline and Net Zero Pathways.

4.1.3 Emissions

As we noted in discussing our modeling assumptions, we have limited our scenarios to cases where net GHG emissions from the energy services sector are zero by 2050. Figure 21 shows the difference in the net emissions path between the Baseline and Net Zero scenarios. The comparison of this Net Zero trajectory with the Baseline illustrates the importance of policy in achieving substantial reductions in emissions.

Even though coal disappears as a fuel and energy efficiency improves gradually in the Baseline, emissions rise steadily after 2035.[17] In our Net Zero case, emissions from coal, natural gas and gasoline, currently the dominant sources, fall to near zero in 2050 as mandated by the VCEA.

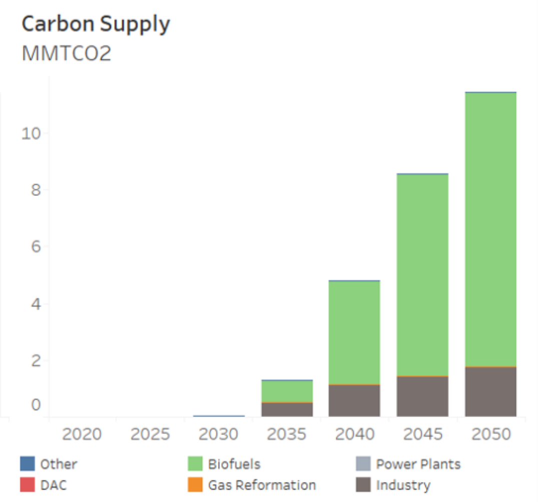

Figure 22: CO_2 supply for sequestration

The few emissions that remain, jet fuel and recalcitrant industrial uses, are balanced by *negative emissions* from the capture and sequestration of CO_2 from biomass gasification facilities that process (current levels of) wood waste to produce hydrogen. The CO_2 emissions from the combustion of the wood waste captured and geologically sequestered. A small quantity of capture and sequestration may also take place at industrial facilities. Sequestration by harnessing natural processes in fields, forests and coastal estuaries adds substantially to the potential for negative emissions, but we do not account for those resources here. The availability of those sequestration resources would tend to lower the cost of achieving net zero emissions.

To achieve the negative emissions, sequestration will need to be compensated. In our model, this compensation is implicit. Each ton of greenhouse gases sequestered earns the current (avoided) marginal cost of reducing emissions elsewhere in the economy. In the outer years of the planning horizon, the marginal cost of GHG mitigation rises well above $100/ton of CO_2 equivalent. In early years, the funds for compensating sequestration activities could come from earnings in selling RGGI emission allowances. As the allocation of allowances goes to zero by 2050, some other source of funds will need to be found. A fee or imposition of offset requirements on residual emissions of GHGs could be used to pay for the needed amount of sequestration.

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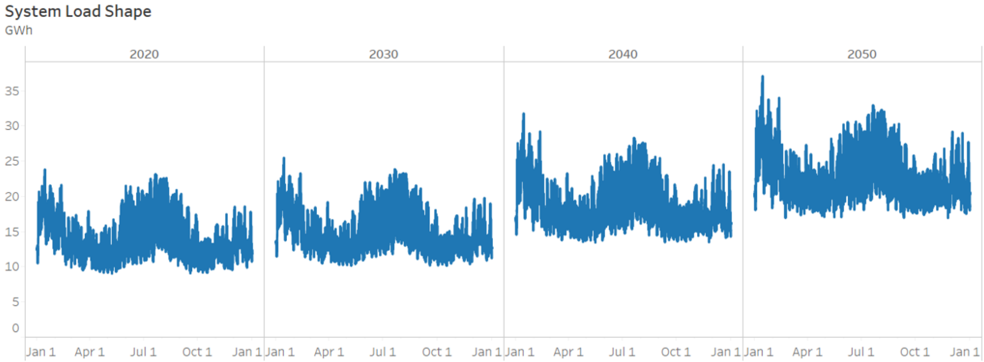
[17] Should all jurisdictions choose this path, then we could expect warming greater than 3.5℃ by 2100, far in excess of levels considered extremely costly by most observers (Hänsel et al., 2020).

4.2 Additional Details About the Central Net Zero Scenario

4.2.1 Matching Electricity Demand and Supply

We emphasize that we only consider electricity generation asset portfolios capable of reliably meeting the anticipated demand as it varies across days and seasons. The model takes account of daily and seasonal patterns of both electricity demand and renewables supply. As decarbonization progresses, the patterns of demand and of resource availability both shift, but in every case, enough supply must be made available at the appropriate times so that the instantaneous supply is equal to or greater than the demand at that instant. Given our demand scenario, we calculate the system load (Figure 23) and match this load with supply. Because renewables are variable, there will be more or less supply than the current demand during most times of the year. A combination of firm, non-emitting power and storage matched to renewables availability turn variable electricity resources into dispatchable power that can always match realized demand.

Figure 23: Electricity hourly system load, 2020 to 2050, in the Net Zero Pathway.



Includes building and industrial end-use loads, and reflects energy efficiency and electrification of heating services. Excludes transportation loads due their expected flexibility (smart EV charging) and ‘opportunistic loads’ such as electrolysis and electric boilers that consume electricity in response to oversupply conditions.

Figure 24 shows how load and generation are matched for the year 2050 in the Net Zero case. The upper panel shows the pattern of supply for a typical day in a given month. The lower panel shows how the supply is matched to load. When wind and solar are in ample supply, they generate far more electricity than is needed. This excess electricity is used to store energy in batteries and in various longer-term storage options such as hydrogen, synthetic fuels, mechanical energy storage or others. Imports and exports can also serve to balance local demand and supply.

The gross quantity of imports and exports rises as renewables penetration reaches

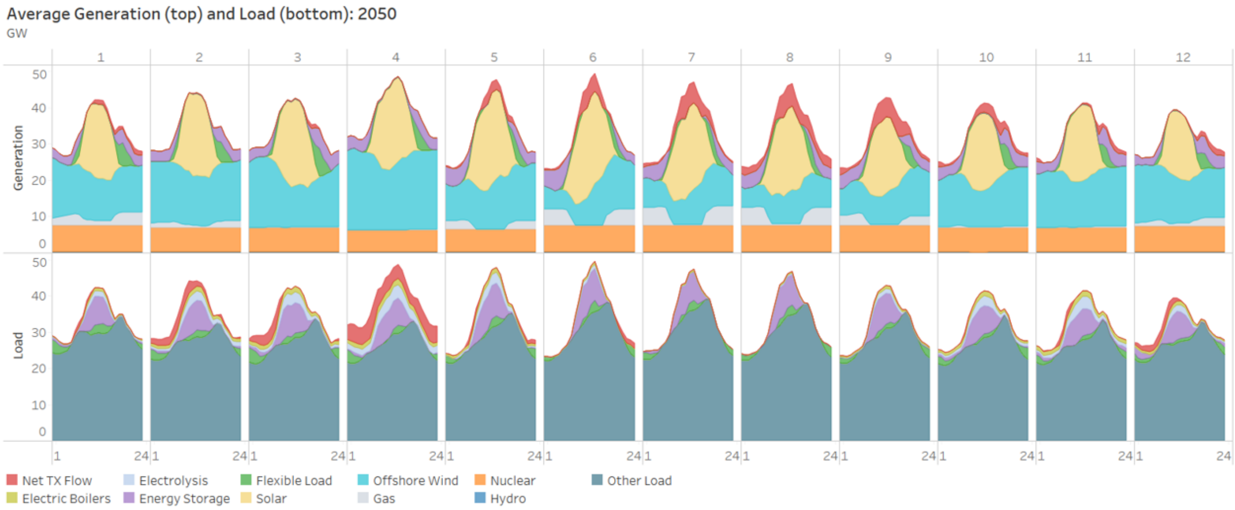


Figure 24: Virginia 2050 electricity generation and load, by hour and by month, in the Net Zero Pathway.

very high levels after 2045, but net imports do not rise appreciably as increased exports nearly balance increased imports (Figure 25). The key observation is that the system must be built so that the demand is always balanced against supply, even during extended periods of lower output from renewables.

4.2.2 Fuels in the Net Zero Scenario

The demand for pipeline (imported) natural gas drops steadily starting in the 2020 to 2024 time period. The use of natural gas in electricity generation and direct end use never exceeds existing pipeline capacity. Much of existing pipeline capacity will become stranded unless it can be re-purposed, possibly for the transport of hydrogen. In the years after 2040, a small fraction of current pipeline capacity will be used to transport synthetic fuels from states with a comparative advantage in producing them.

Given current projections of future technology costs, we would expect to see an increasing use of hydrogen as a gaseous fuel. Hydrogen can be generated by the reformation of natural gas, by electrolysis using excess renewable electricity or by bio-energy with carbon capture and sequestration (BECCS).[18] The transition from natural

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[18] BECCS is a process that derives energy from biomass while capturing and sequestering the resulting carbon emissions. The BECCS technology with the most value for Virginia's future energy mix involves gasifying wood waste and other plant material to create hydrogen (or other fuel). The carbon emissions from the gasification process are captured and geologically sequestered. In later years, as the cost of carbon emissions rises, most of the economic value of BECCS comes from its value in sequestering carbon rather

gas to hydrogen as the primary gaseous fuel may involve a transition from production of hydrogen via methane reformation in the early years to non-emitting production processes after 2035, as improved technologies for electrolysis and gasification become available. Starting with natural gas reformation provides a smooth transition to the use of hydrogen in existing infrastructure.[19]

Electrolysis is a natural complement to deep penetration of renewables, especially solar. The pattern of renewables availability does not match the pattern of energy demand, but our model requires that energy demand be met at all times. Using excess electricity from solar in times of high solar generation for energy storage, including electrolysis, helps turn the energy from solar PV into a dispatchable resource.

Figure 24 shows how the 2050 generation portfolio balances instantaneous demand and supply with storage and electrolysis.

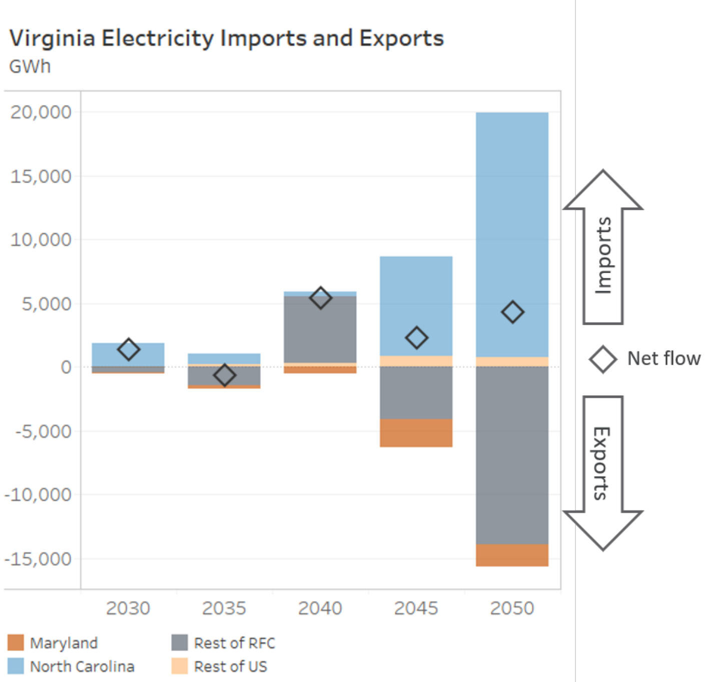

Figure 25: Virginia Electricity Imports and Exports, 2020 to 2050, in the Net Zero Pathway.

Figure 26 shows the growth in use of hydrogen, which can be burned directly in boilers or power plants to generate heat and electricity, converted to ammonia or liquid fuels, or used directly as an end-use fuel. In our Net Zero scenario, hydrogen is mostly used for long-distance freight hauling, for example as a fuel for fuel-cell electric vehicles. Much will depend on the outcome of near-term research and development in determining the mix of uses for hydrogen, although it takes on an increasingly central role in later years of all decarbonization scenarios.

Figure 27 shows the mix of in-state production versus imports of zero-carbon fuels

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than in the generation of hydrogen fuel.

[19] This transition may be more costly if the infrastructure transition is delayed until large-scale electrolysis is economically attractive.

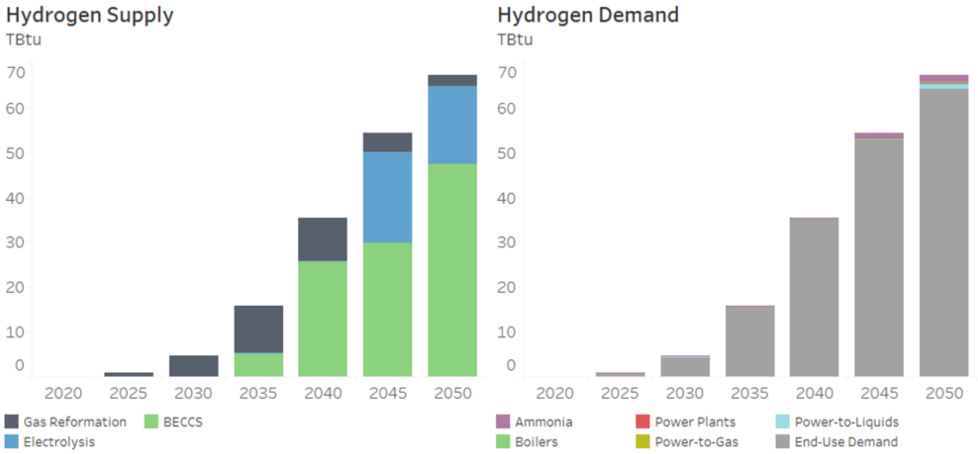

Figure 26: Hydrogen supply and demand in the Net Zero Pathway, 2020 to 2050.

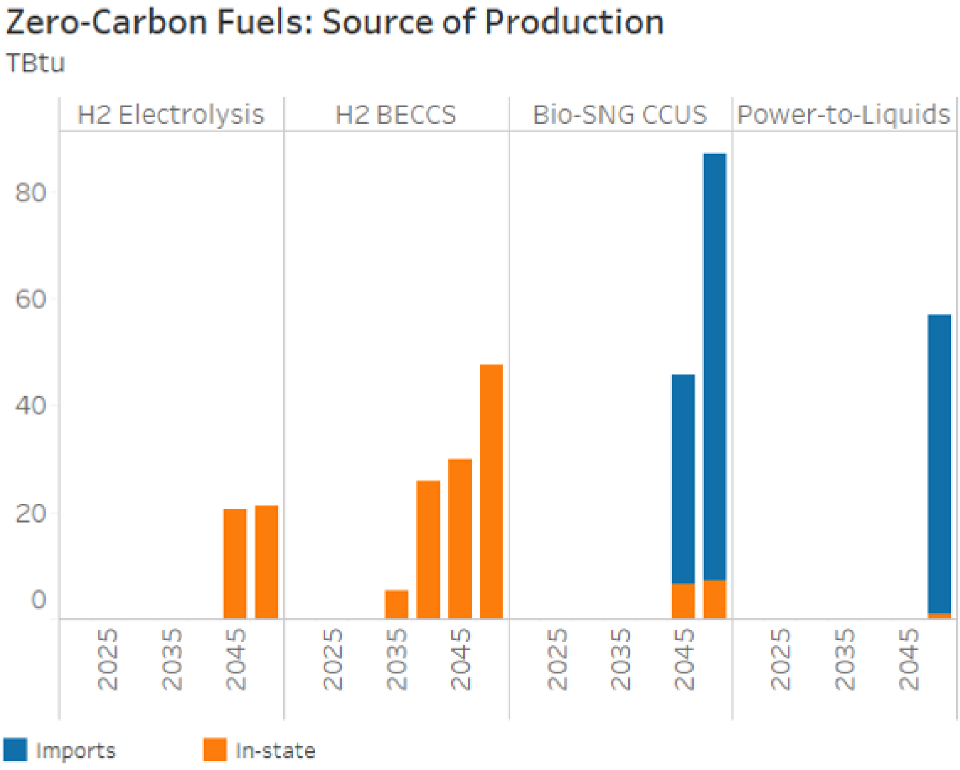

Figure 27: Sources of Zero-carbon fuels, 2020 to 2050, in the Net Zero Pathway.

in the Net Zero scenario. Hydrogen is produced in Virginia by electrolysis and BECCS, in conjunction with the increased dependence on renewables. Other zero-carbon fuels are largely produced in other states and transported to Virginia via pipeline. These imported zero carbon fuels include synthetic natural gas and *power to liquids*.

4.3 The Constrained Land and Nuclear Scenario

This scenario was chosen as a *stress test* of the state's ability to achieve full decarbonization if two of its key non-emitting technologies were limited. We assumed that political, economic and environmental considerations constrain the deployment of utility scale solar and that new nuclear generation technologies are not forthcoming. The land area available for utility scale solar was reduced from 1% to 0.5% and nuclear generating capacity was limited to the current fleet of four reactors. The scenario maintains the requirement that net emissions are zero in 2050. Given the reliance on utility-scale solar and on a doubling of nuclear generation capacity in the standard Net Zero scenario, it is not surprising that limits on solar and nuclear capacity cause substantial shifts in the resource mix. It is of some comfort that it is still possible to reach a 2050 decarbonization goal, although it is substantially more expensive than in the unconstrained case.

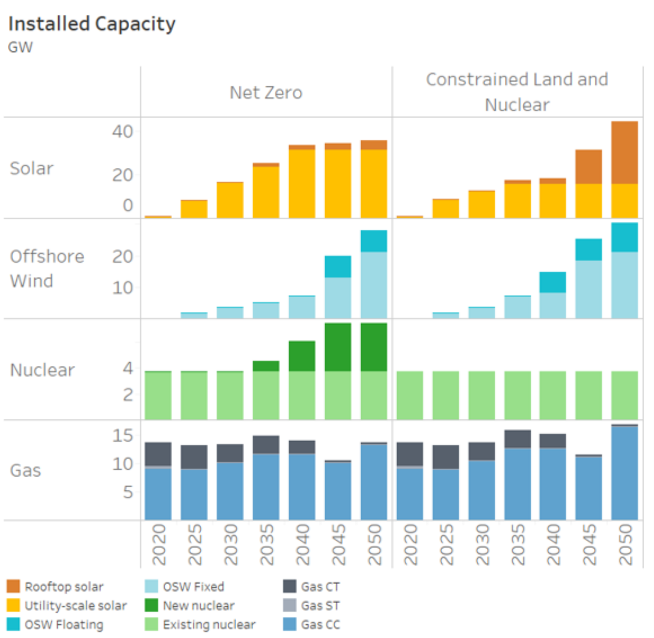

Figure 28: Installed generation capacity, 2020 to 2050, Net Zero scenario and Constrained Land and Nuclear scenario.

With so little land available for utility-scale solar development, this resource reaches its maximum capacity as early as 2035. After that, all renewables expansion must come from offshore wind and rooftop solar. Rooftop solar and electricity imports expand to fill much of the void in later years, although rooftop solar remains substantially more expensive than utility-scale solar. Net imports of electricity grow substantially, with the imported clean electricity generated by burning expensive, non-carbon fuels.

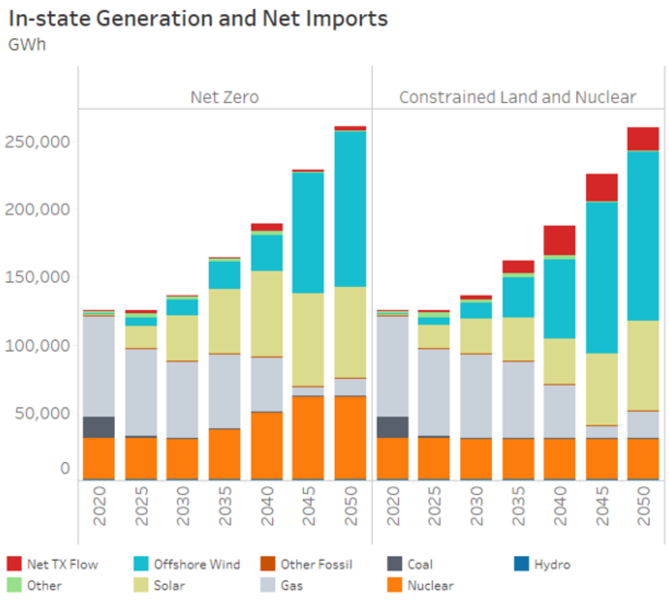

Figure 29: In-state generation and net imports, 2020 to 2050, Net Zero and Constrained Land and Nuclear scenarios.

The expansion of wind along with the increased imports mean that offshore wind now accounts for half of in-state electricity generation. Wind generating capacity is developed much more quickly than in the Net Zero scenario. Twice as much offshore wind is needed by 2040. The acceleration implies considerably greater costs, since there is less time for the cost of offshore wind development to fall before Virginia must proceed with expanded offshore wind development. The greater reliance on wind plus the loss of the additional firm, non-emitting nuclear capacity means more reliance on load-following gas plants fired by expensive, imported non-emitting fuels in order to ensure resource adequacy.

4.4 The Slow Consumer Adoption Scenario

The relatively low cost of the standard Net Zero scenario depends to a very great extent on the electrification of end-use energy services, such as building energy services and transportation, which would otherwise be served by fossil fuels. Electrification of end-uses has two compounded advantages: (1) improved energy efficiency from the electrification itself and (2) reliance on increasingly decarbonized and comparatively inexpensive electricity generation. The Slow Consumer Adoption scenario assumes that the transition to electric vehicles and increased use of heat pumps and other electric technologies for space and water heating is slower than the pace assumed in the other three decarbonization scenarios. This prevents full realization of the advantages of electrification and imposes much higher costs than in the Net Zero scenario.

To decarbonize the transportation sector without electrification requires less electricity but also larger quantities of imported zero-carbon liquid fuels. The costs are high not just because the fuels themselves are expensive, but also because there is less improvement in the energy efficiency of transportation. For the building sector, the same logic works to raise costs, but carbon-free gaseous fuel would substitute for direct end use of natural gas. Because of the much slower rise in electricity generation but with the doubling of the nuclear fleet, much less natural gas (or later, synthetic gas) will be used.

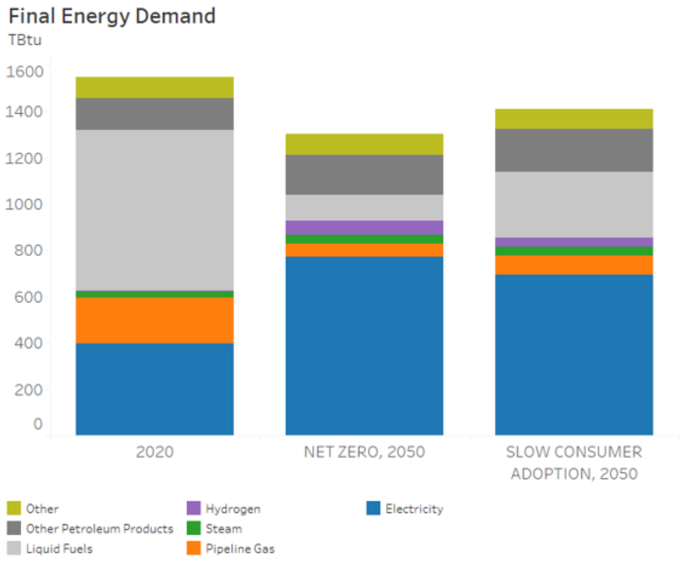

Figure 30: Virginia final energy demand: in 2020 vs. 2050 in the Net Zero scenario vs. 2050 in the Slow Consumer Adoption scenario.

While, this scenario has considerably higher costs than the others, it should not be taken as a likely outcome. Efforts to replace fossil fuels with expensive, non-emitting alternatives, would raise the cost of using internal combustion engines and would make electrification more financially attractive in both the transportation and building sectors. There is good reason to believe that market forces will short-circuit this higher cost pathway, but policies designed to speed the electrification of end-uses would ensure a smoother, lower cost transition. *The sooner those policies are implemented, the lower the long-run costs.*

One promising possible policy initiative is to place transportation fuels under an emission cap like RGGI does for electricity generators. The Transportation and Climate Initiative (TCI) is a collaborative effort of Northeast and Mid-Atlantic states to explore the option of capping carbon emissions from the transportation sector. By limiting the allowances for emissions from the transportation sector, Virginia would be assured of meeting the goal specified by the cap, and the scarcity of emission allowances would impose a cost on the use of fossil fuels in transportation services. A cap on transportation emissions can be an effective way to support the transition to electric vehicles. As electric vehicles reach reasonable price parity with internal combustion vehicles, the pace of that transition can be accelerated.

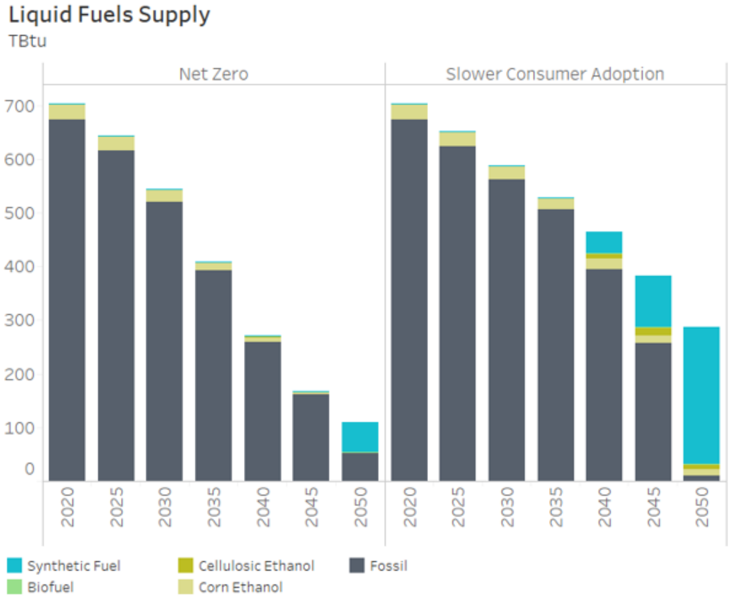

Figure 31: Virginia liquid fuels supply, 2020 to 2050, in the Net Zero scenario and the Slow Consumer Adoption scenario.

4.5 Rapid Innovation Scenario

In the Rapid Innovation scenario, we explore what more rapid energy innovation can do to lower the cost of achieving net zero emissions by 2050. The modeling results show why early investment in innovation is so important to any decarbonization effort. The key question raised by this scenario is: what opportunities does Virginia have to accelerate development and diffusion of energy system innovations over the next 30 years.

Our Rapid Innovation pathway assumes a broad array of improvements in cost and performance of renewables, storage, nuclear and end-use technologies. This scenario uses NREL's Annual Technology Baseline low-cost trajectory for estimates of the future costs of electricity system technologies. Cost reducing innovation and gains in economies of scale for wind and solar energy continue more quickly than in the ATB mid-range trajectory used in the other modeling scenarios. The scenario also assumes more rapid reductions in energy storage, green hydrogen production and nuclear facility capital costs. These innovations make it cheaper for Virginia to provide its own energy resources rather than import them.

The Rapid Innovation scenario looks very different than our central Net Zero case. While utility-scale solar is still limited to 1% of land area, rooftop solar now becomes cost effective and is much more widely deployed. Solar resources are paired with much more storage, since storage is so much cheaper—more than 10 GW of battery storage capacity of varying durations. The cheaper storage displaces some gas-fired generation for load-balancing.

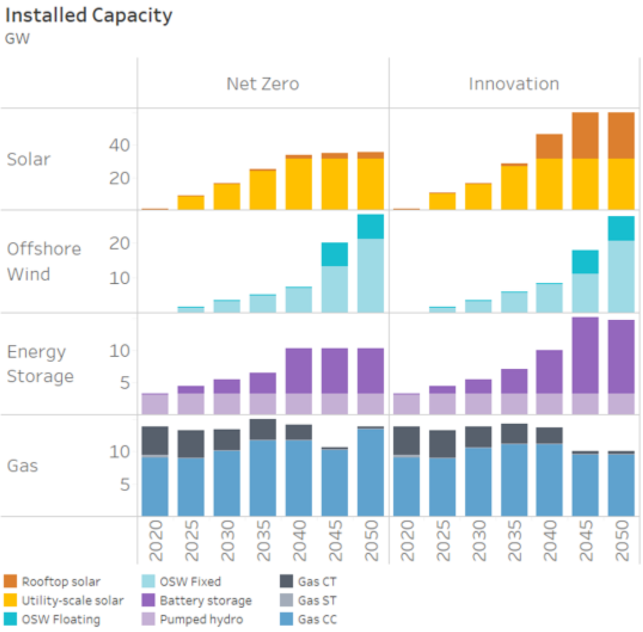

Figure 32: Installed capacity, 2020 to 2050, Net Zero scenario and Innovation scenario.

Domestic hydrogen production expands, using now comparatively inexpensive electrolysis, resulting in greater use of hydrogen for gas-fired load balancing and to produce synthetic liquid fuels. The expanded domestic electrolysis further displaces energy imports. As in the other decarbonization scenarios, we limit the use of BECCS in hydrogen production by limiting wood waste inputs to the same level used in combustion in 2020. So hydrogen production via gasification of biomass is approximately the same as in other scenarios and is valuable for delivering both hydrogen and negative emissions.

4.5.1 Innovation and State Policy

Our model confirms one thing we already know about innovation: it serves to increase the productivity of our resources. Virginia stands to gain a great deal by advancing the pace of innovation and the adoption of innovative technologies in the energy sector. Fortunately, there are steps Virginia can take to advance local innovation in a global technology sector such as energy.

All technologies require process and systems integration knowledge that increase

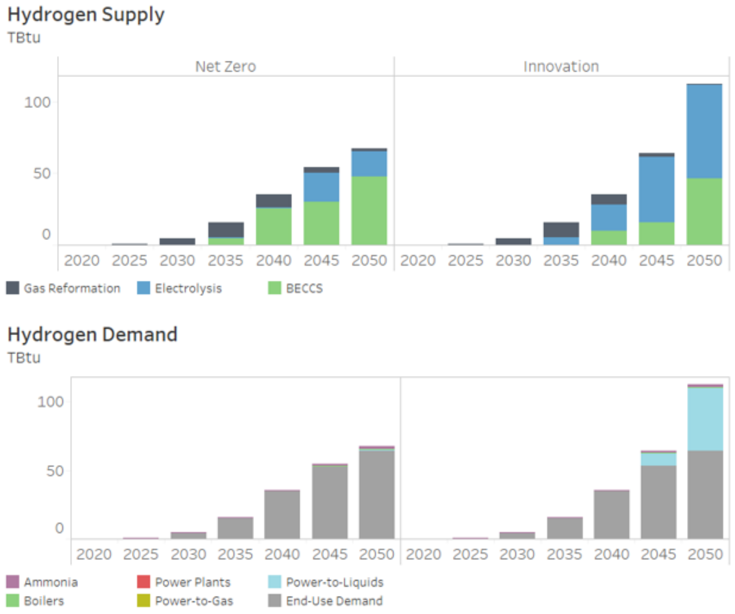

Figure 33: Hydrogen supply and demand, 2020 to 2050, Net Zero Pathway and Innovation Pathway.

with the exposure that workers, firms and government agencies have to working with a those technologies. This knowledge improves with experience, cross-pollination among workers in the field and integration with other technologies. This "learning-by-doing" enhances productivity of those engaged in the activity, and these learning effects can expand and accelerate as the ecosystem of innovating firms, workers and customers expands.

This suggests that if Virginia is intent on achieving decarbonization by 2050, it can improve its chances of benefiting from new technologies by strategically investing in knowledge and experience in promising new ideas. A first step is to regularly evaluate new technologies for their potential to lower the costs of emission-free energy in Virginia. The second step is to invest in carefully chosen pilot projects that can reap the benefits of learning-by-doing in techniques critical to the decarbonization program. A final step is to provide support for adoption and diffusion of new technologies that have been demonstrated to provide net benefits.

A recent example in Virginia can be found in the piloting of two small offshore wind turbines to gain experience thought to be valuable for pursuing the much larger subsequent investment in offshore wind.

Given the huge economic stakes in the transition away from fossil fuel energy resources, there is a strong argument to be made for building a process for identifying important new technologies that will likely contribute to the new energy economy and to develop essential experience with the new energy technology as it approaches economic viability. The early investment in learning-by-doing can shift the likely path of technological development to a lower-cost trajectory within the state. Given the size of the investment that the state is anticipated to make, even modest gains from piloting new technologies can pay large dividends.

There is much to be gained from investing in local experience with emerging technologies. Doing so effectively would require an agency with the expertise to track emerging technologies and energy system pathways and develop plans for implementing sometimes risky pilots projects. A new technology investment program is one way to help shift the energy transition onto a lower-cost technology trajectory.

4.6 Summary of Results Across Scenarios

The next two figures present capacity and generation for the four decarbonization scenarios. These charts display essential similarities and differences across the scenarios.

Utility-scale solar is developed up to the scenario limit early in all scenarios. If solar development had been unconstrained, nearly twice as much utility-scale solar would have been built by 2050. Solar development is a substitute for offshore wind. Increased solar development substitutes for more expensive floating offshore wind resources. Furthermore, solar is a complementary technology to storage (batteries as well as hydrogen). Distributed (rooftop) solar, even with a modest subsidy, has higher costs than the alternatives and does not contribute significantly unless other solar is not available or distributed solar costs fall faster than anticipated. There is an opportunity for state and local governments to cooperate to lower the so-called soft costs of distributed solar development to enable distributed solar to contribute more to the decarbonized energy mix. Rate structures that reflect system-wide costs and benefits of installing distributed solar can also allow investment in distributed solar to be efficiently influenced by consumer willingness to pay.(Trabish, 2020)

Virginia's offshore wind resource is of medium quality but is potentially quite large. Some delay in developing more expensive wind resources is beneficial because it provides more time for new technology to lower costs. The more costly floating offshore wind substitutes for solar when the latter is not available. [20] There are opportunities for pairing

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[20] Virginia's wind resource may be subject to institutional limits not modeled here. Interaction with offshore

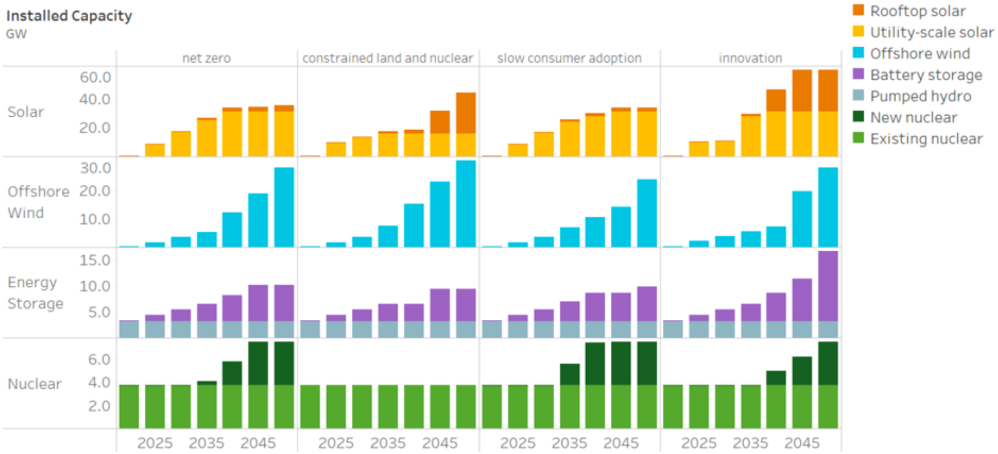

Figure 34: Installed capacity of key generation technologies: 2020 through 2050

offshore wind with large-scale energy storage such as compressed air storage should the cost of these technologies fall sufficiently quickly.

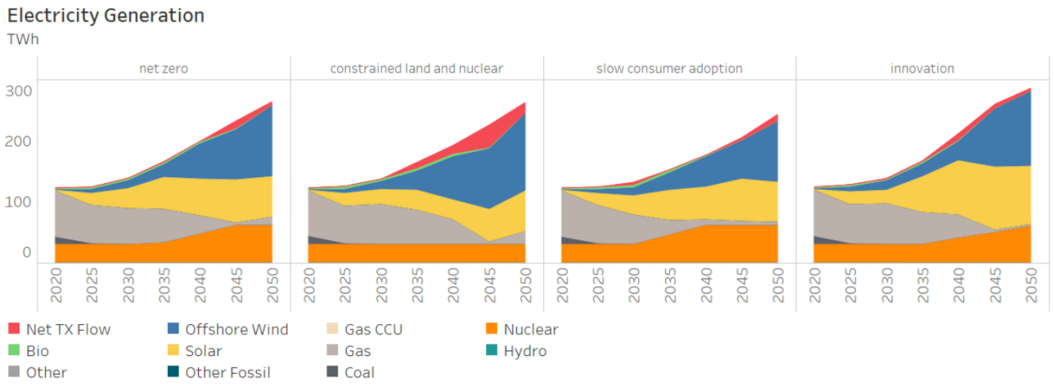

Figure 35: Electricity generation by decade in four modeled scenarios

Nuclear energy provides a valuable source of firm, non-emitting power in all scenarios. Where it is not constrained, we expect that new, lower-cost nuclear technologies are likely to contribute to lowering the costs of future, decarbonized electricity. The Rapid Innovation scenario illustrates the tradeoff between firm, non-emitting power and energy storage. As long-term energy storage becomes cheaper, it can take the place of nuclear and of some load-following resources.

In all scenarios, natural gas is relegated to a balancing resource where the existing capacity is converted to operate on zero carbon fuels and runs at low capacity factors on

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military activity and with commercial fishing may impose additional costs or even physical limits on deployment of offshore wind. This is a subject of ongoing research.

the order of 10%.

Although trade in electricity is much higher in a national decarbonized electricity sector, net electricity imports into Virginia rise only marginally. Most electricity imports are from North Carolina, while exports are primarily to the western part of the PJM regional transmission organization, to which Virginia belongs. Electricity imports remain well below 25% in all scenarios.

Table 6: Electricity Net Imports (2050) in Four Modeled Scenarios

	Imports (GWh)	Exports (GWh)	Net Imports (GWh)	Net Imports (% load)
Net Zero	41,745	34,999	6,745	2.6%
Constrained Land and Nuclear	47,620	29,838	17,782	6.9%
Slow Consumer Adoption	40,665	29,458	11,207	4.7%
Innovation	17,916	12,817	5,099	1.8%

Total energy imports to the state fall dramatically as Virginia finds it cost effective to generate a much larger share of its total energy requirements. Fossil fuel imports are largely displaced by domestic production of electricity from renewables, although in the slow consumer adoption scenario, Virginia does import significant amounts of carbon-free liquid fuels to replace gasoline and diesel in non-electric vehicles.

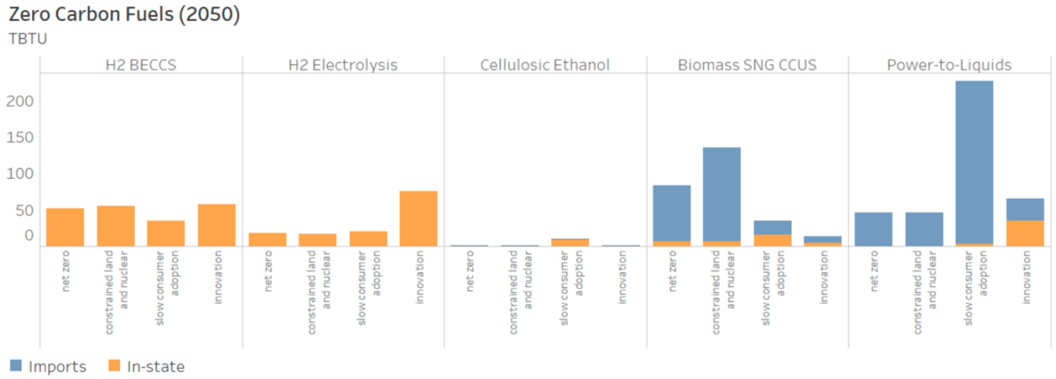


Figure 36: Zero carbon fuels in 2050 under four scenarios

Hydrogen becomes an important adjunct to renewables in all of our scenarios. Hydrogen is generated using electrolysis when renewable resources would otherwise be curtailed due to production levels in excess of electricity demand. Hydrogen is also generated as a co-product with carbon sequestration in BECCS facilities using wood waste as fuel. In our model, a large fraction of hydrogen produced is used in long-range transport, substituting for batteries in that application.

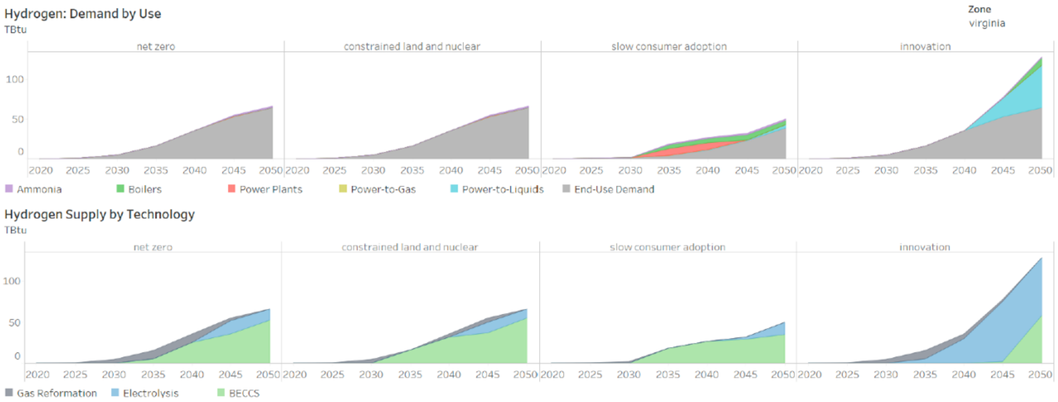


Figure 37: Hydrogen demand and supply

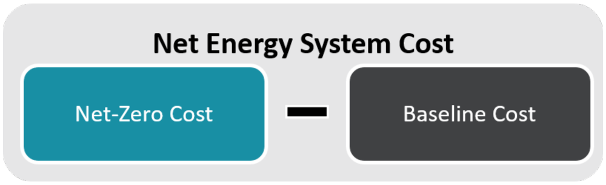
Table 7: Four Scenarios Overview

Scenario	Results
Net Zero	Diverse deployment of utility-scale solar, offshore wind and new nuclear facilities Gas power plants burn hydrogen or synthetic fuels for reliability and load-balancing
Constrained Land and Nuclear	Nearly 30 GW of rooftop solar is added to fill the clean energy gap Additional offshore wind is deployed and imports of electricity increase
Slow Consumer Adoption	Electricity generation decarbonizes more quickly in the 2030s to compensate for higher residual demand for fossil fuels in buildings, transport, industry Large volumes of imported (out-of-state) zero-carbon liquid fuels are required
Innovation	Electricity generation shifts more towards a solar plus storage system Reduced dependence on gas-fired resources (and biofuels) Higher renewables penetration encourages use of electrolysis and H2 use Much higher use of rooftop (decentralized) solar PV

5 Costs and Benefits of Decarbonization

To determine whether it is worth working to decarbonize the state's economy and, if so, how it should be done, there needs to be a careful accounting of the costs and benefits possible pathways. In this report, we will not attempt a complete accounting but rather estimate some likely magnitudes and how they stack up against each other. A complete benefit/cost analysis must take into account not only the economic relationships within Virginia but also how Virginia's economy interacts with other economies, which, in turn, depends on the actions they do or do not take toward decarbonization. Local costs and benefits also depend on the likely nature of national and even international policies.

5.1 Calculating Costs



The calculation of changes in energy system costs, along with any likely benefits of those changes, starts with the choice of a baseline. Our Baseline scenario makes a relatively strong assumption that no policy action is taken in Virginia or elsewhere to decarbonize beyond what would occur without any policy changes. We believe that this assumption probably understates the reductions in emissions that would take place in the absence of policy and thus overestimates the costs of achieving full decarbonization. First, there are other actions being taken that will lower future emissions. The national government is likely to have an active climate agenda over the next four years. And private firms and individuals are taking action to reduce CO_2 emissions in response to increasing concerns about climate damages among consumers and business owners and managers. These non-policy driven actions are already having measurable effects on emissions in Virginia and elsewhere.

This consideration aside, we will make some rough calculations of the likely incremental energy system costs of decarbonization. The costs of new investments along with their operation and maintenance costs will be netted against the savings from improved efficiency to calculate the net annual cost of providing the energy services or the "energy system revenue requirement" of each scenario. The scope of the cost analysis is limited to energy system costs, which includes the annualized capital costs of all demand and supply side equipment, variable costs (such as fuel) and operation and maintenance costs.[21] The savings from improved end-use efficiency are included in this calculation. Our cost metric is the incremental cost of low carbon energy compared to the baseline of no decarbonization activity.

An aside on fossil fuel prices: Since the alternative to decarbonization is to continue using fossil fuels, then the cost of decarbonization will depend on the likely prices of fossil fuels in the future. The lower the cost of petroleum and natural gas, the greater the

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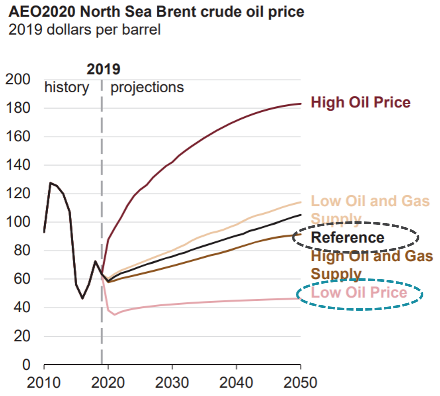
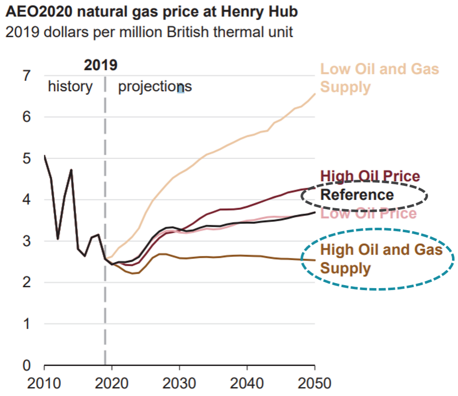
[21] For example, the costs of purchasing, operating and maintaining electric vehicles or new heat pumps are included in our cost estimates.

incremental cost of replacing them with other energy sources. In our pathways analysis, we use standard assumptions about future fossil fuel costs from the U.S. Energy Information Administration *Annual Energy Outlook 2020* (AEO2020; EIA, 2020). In particular, we use AEO2020 cost scenarios for crude oil (Brent) and for natural gas (Henry Hub).



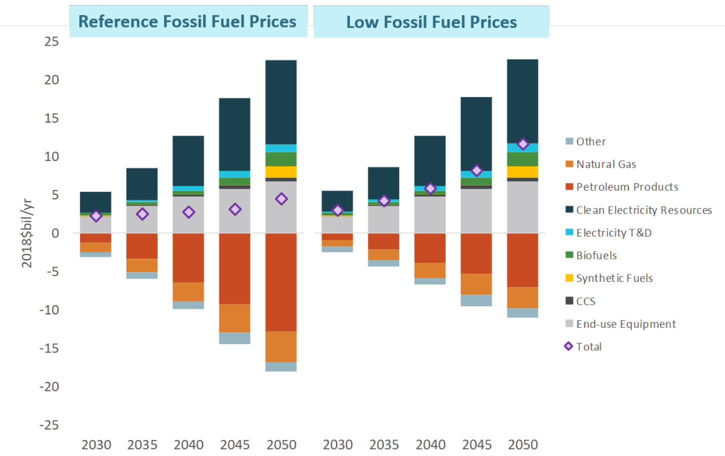


We use the AEO2020 *Reference* case along with a low fossil fuel case, which uses the AEO2020 *Low Oil Price* case for oil and the *High Oil and Gas Supply* case for natural gas. Given our decarbonization assumption that all jurisdictions decarbonize along with Virginia, we consider the lower price fossil scenario as much more likely in our decarbonization scenarios, with the possible exception of the slow consumer adoption case. The decarbonization scenarios reduce dramatically the demand for fossil fuels across the U.S. This drives higher marginal cost producers out of the business of producing fossil fuels. For example, expensive tar sands deposits will no longer be cost effective. Because marginally economically recoverable reserves are no longer economical to extract, only reserves with lower marginal costs will be left in production. This demand destruction drives down the world price of oil as high-cost producers exit. To give some idea of just how far prices can fall as decarbonization proceeds, the marginal cost of delivering a barrel of Saudi Arabian crude is approximately $5, including shipping costs. Low prices for oil and natural gas, at least in the later years, would seem much more likely in the decarbonization scenario than the higher costs of the AEO2020 reference case.

Figure 38 decomposes the net energy system costs into components. This graphs illustrates, for the Net Zero scenario, how the investments in local clean energy resources and end-use equipment are offset by reduced spending on imported fossil fuels. The key difference between the left and right panels is in the value of fuel savings, which is much lower in the case of low-priced fossil fuels. This leads to higher net costs of decarbonization when fossil prices are low. Again, these costs are only energy system costs and do not reflect any non-energy system benefits of decarbonization.

The net energy system costs *for the Net Zero scenario* are \$2 - \$3 billion per year in 2030, \$3 - \$6 billion per year in 2040 and \$4.5 - \$12 billion per year in 2050. The range reflects the two fossil fuel price cases from AEO2020. The costs rise because investments in the most expensive non-emitting resources are delayed until later in the transition period. Delay has two beneficial effects. First, costs farther into the future are discounted and count less from today's point of view. Second, delay allows time for cost-reducing improvements in technology. The costs of all non-emitting technologies and storage are falling quite rapidly, so delay saves on transition costs.

Figure 38: Net costs of Virginia decarbonization



5.1.1 Comparing Costs Across Scenarios

The estimated 2050 costs of the decarbonization scenarios are listed in Table 8 along with the costs of the alternative scenarios. This table shows clearly the importance of three key factors in determining costs: (1) constraints on low-cost solar and, to a lesser extent, new nuclear, (2) the timely initiation of transition in end-uses that have a slow turnover in asset stock and (3) early investments in technological innovation.

Planning for a smooth transition from fossil fuels pays large dividends. If Virginia is to decarbonize in a cost effective way, then early implementation of policies that remove barriers to deployment of utility-scale solar PV and speed consumer adoption of electric vehicles, heat pumps and other electrified end-use energy services will be critical. Of equal or greater importance is assessing how the state can best contribute to the local benefits of technological innovation. Accomplishing these tasks requires an administrative machinery that is capable of marshalling and coordinating state actions across agencies to advance low cost decarbonization.

Table 8: Net Costs Relative to Baseline and Unconstrained Pathways

	Relative to Baseline	Relative to Net-Zero	Drivers of Results
Net Zero	\$4.5-\$11.6	N/A	
Constrained Land and Nuclear	\$5.4-\$12.5	\$0.9	Additional spending on low-quality offshore wind and rooftop solar
Slow Consumer Adoption	\$7.2-\$14.7	\$3.0	Higher spending on imported synthetic fuels due to lower realized electrification
Innovation	\$0.3-\$7.4	-\$4.3	Cost savings due to lower technology cost projections for renewables and electric vehicles, the two dominant sources of incremental costs for Virginia

NOTES: In billions of dollars (\$2018).

5.2 Benefits of Decarbonization

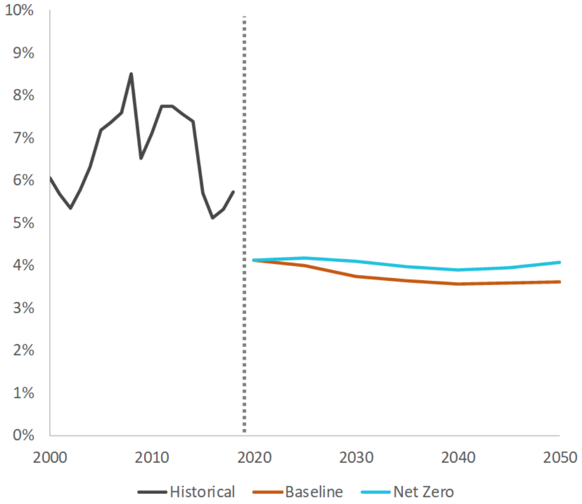
Our modeling focused on the net energy sector costs of decarbonization. We did not attempt to model any benefits outside of the net annualized energy system costs. But there are substantial additional benefits of reducing fossil fuel use. The two largest sources of these are health benefits of reduced exposure to combustion by-products and reduced damages from global warming.

Health benefits: It has long been known that burning fossil fuels in cars, trucks and power plants harms those exposed to the combustion by-products. Even after years of successful efforts to reduce emissions from combustion, evidence is very strong that the remaining emissions cause considerable damage to people's health, to agricultural production and to natural assets. Many studies have been done to try to quantify these health costs. Recent reviews of the available evidence suggest that the health co-benefits of reducing carbon emissions from fossil fuel combustion are on the order of \$50 to \$80 per ton of CO_2 abated if one includes health benefits from both the electricity and transportation sectors (Thompson et al., 2016).

Climate benefits: From shipping to coastal resources to viticulture to forests, Virginia has many valuable resources at risk from increased global temperatures arising from human greenhouse gas emissions. The need for global cooperation to address global warming imposes costs on Virginia of continuing to emit greenhouse gases. As was amply demonstrated by the Paris Accord of 2015, controlling global emissions is a long-term, trust building exercise. All countries have a strong incentive to free ride on the reductions of others, so no appreciable reductions can be expected unless all countries find a way to cooperate. Signalling a willingness to cooperate by offering some reductions builds a foundation of trust that can then provide the basis for countries, regional compacts, and sub-national jurisdictions to proceed with deeper, more consequential emission reductions. Failing to cooperate risks bringing the entire structure down.

With the election of the Trump Administration, the U.S. withdrew its initial offer to cooperate. In order to bolster international cooperation, sub-national entities across the U.S. signalled their intent to continue to cooperating to reduce emissions, notwithstanding the lack of a national commitment. These offers came in the form of unilateral emission reduction policies at the local level. So far, the Paris Agreement appears to be holding and even strengthening as many countries have recently increased their emission reduction offers well-beyond those made in 2015.

Figure 39: Virginia's total energy expenditures as a share of state GDP



The social cost of carbon is not a single number but rather a calculation of the present value of future damages from continued emissions based on a number of assumptions. Using a conservative 2017 estimate from Nordhaus, the SCC starts at around $31 in 2020 and rises to $104 by 2050 (Nordhaus, 2017). More recent estimates, using improved representation of climate dynamics and using the Nordhaus integrated assessment model, place the SCC between $100 and $200 in 2020 rising to several hundred dollars by 2050 (Hänsel et al., 2020).

Break-even benefit values: Virginia had about 115 million tons of CO_2 emissions in 2019, with emissions likely to rise somewhat by 2050, as indicated in the Baseline scenario. The net present value of decarbonization is positive if we add health benefits of just $20 to a social cost of carbon starting at $31 in 2020. Given that both of these benefit estimates are at the very low end of the range of damages found in the literature, we can conclude that the Net Zero decarbonization policy, if implemented efficiently, likely has substantial positive net benefits for Virginia relative to the business as usual case.

Other considerations: There may be other benefits of decarbonization and investments in clean energy technologies that we have not included in our simple benefit/cost analysis. First, decarbonization reduces the exposure of Virginia's economy to risks associated with the variability of oil and gas prices. Second, the health costs of pollution fall disproportionately on lower income families, so decarbonization ameliorates concerns over injustice in the distribution of pollution costs. Third, Virginia's energy system us heavily reliant on gas and petroleum products imported from out of state. Developing the clean energy resources and technologies needed to decarbonize Virginia's energy system will require shifting energy system expenditures to projects and business activities within the state. That shift will likely result in creation of additional jobs directly and through multiplier effects within the economy.

5.3 Net Cost Summary

Decarbonizing Virginia's economy is a very substantial undertaking, but it will not result in significant increase in the share of the states economy as measured by the gross state product (GSP) that is devoted to energy system expenditures (Fig. 39). Historically, spending on energy has accounted for 5% to 9% of GSP. Much of this spending has been on fossil fuels, nearly all of which are imported. Expenditures on energy as a share of GSP are expected to fall even in the business-as-usual case as the energy intensity of the economy declines. Our model estimates that the decarbonization effort will add on the order of 0.5% to the share of GSP spent on the energy sector (including the replacement of internal combustion engines with electric vehicles). We use the AEO2020 assumption of 1.9% average real growth in GSP over the transition period. This means that, even with the added transition expenditures, energy expenditures will probably remain lower as a share of economic activity than has been the case in the past two decades.

Table 9: GDP and Net Cost Projections

	2000	2019	2030	2040	2050
Gross state product (2018$bil)	$390	$547	$674	$808	$969
Net costs (2018$bil)	$0	$0	$2.3-$3.1	$2.8-$5.9	$4.5-$11.6
Net costs (% of GDP)	0%	0%	0.3%-0.5%	0.3%-0.7%	0.5%-1.2%

6 Key Insights

Decarbonization is achievable and can produce net economic benefits for Virginia. But there are many different ways of pursuing the goal of decarbonization. Some are much more costly than others. Much depends on making deliberate choices that maximize the net benefits of eliminating fossil fuels from the energy supply. For an investment of this magnitude, Virginia needs to establish an effective administrative capacity for planning and coordination.

6.1 Summary of Modeling Results

It is valuable to summarize briefly several main findings from the pathways analysis.

- Solar, offshore wind and existing nuclear together form the foundation of a cost-effective solution
- Storage complements solar
- Natural gas capacity remains but transitions to carbon-free fuel
- Hydrogen (and synthetic fuel) plays an increasingly important role
- Bio-based synthetic fuels are imported, electricity is homegrown
- Some negative emissions (BECCS) will be needed
- Decarbonization substitutes made-in-Virginia energy for fossil fuel imports
- Virginia has sufficient non-emitting resources to meet anticipated load if effective use is made of available resources

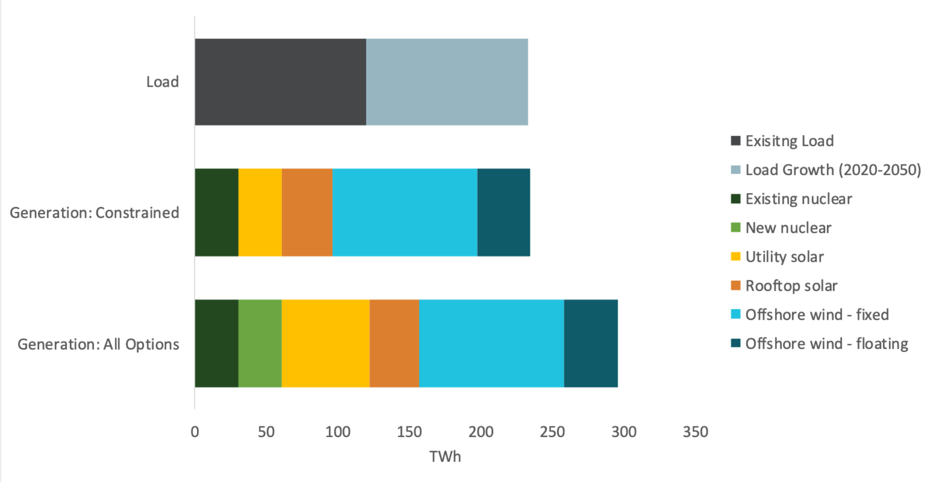


Figure 40: Generation options for meeting projected growth in electricity load

6.2 Findings

The analysis supports several broad findings about Virginia's decarbonization options.

Finding: Virginia should establish the administrative capacity for planning and coordinating the transition to a clean energy economy.

Decarbonization is not a regulatory action to control carbon emissions, it is rather a full-scale transition of energy use across all sectors of the economy. It is an economic and environmental initiative that will involve many separate state agencies and local governments along with regulated utilities and other major corporations, as well as emerging energy system innovators. The approach will need to be flexible enough to respond to new information and rapidly benefit from cost-reducing innovations. The state currently does not have the administrative capacity for planning and implementing a cost effective decarbonization path. Without investing in this planning and coordination function, decarbonization will almost certainly be a more costly and lengthy process.

Finding: An effective decarbonization pathway includes four critical components: (1) energy efficiency, (2) non-emitting electricity generation, (3) electrification of end-use energy services and (4) some capacity for carbon removal or negative emissions.

It is unlikely that decarbonization can be accomplished at a reasonable costs without contributions from all four of these "pillars of decarbonization". As decarbonization proceeds, the costs of finishing the transition to a net zero economy will rise rapidly unless all of the available tools are applied. As we have already noted, this will require the coordination of actions across agencies, levels of government and private actors. The ability to evaluate the shifting technology landscape and develop policies and programs to promote efficient use of each pillar can greatly lower the ultimate cost of the transition.

Finding: A decarbonized electricity sector will depend primarily on wind and solar generation. It will also include other non-emitting energy resources and various load-balancing technologies including batteries and carbon neutral-fuels. Diversity will be a hallmark of reliable and resilient clean energy system.

Investment in renewables is essential but, by itself, insufficient. Although it is possible to build an "all renewables" solution, this would be a much more costly undertaking than continuing to rely on a significant contribution from firm, non-emitting sources such as advanced nuclear or possibly bio-energy fueled combustion with carbon capture and sequestration. As we approach 2050, energy planners will need to address the challenge of replacing the aging, existing fleet of nuclear plants. What options are available at that time will depend on technological developments in the next two decades.

Storage technologies with durations from hours to days will need to be deployed. Batteries will be an important part of the mix, particularly for daily load balancing. It is not yet clear what technologies for long-duration storage will be cost effective. Some longer duration storage will quite likely come in the form of carbon-neutral liquid or gaseous fuel. Our model incorporates sufficient amounts of such fuel to operate low capacity load-balancing power plants as a complement to other storage technologies.

Finding: Localities need to be empowered to take on the key role they will play in the new energy economy.

Local governments in Virginia have a much larger role in an economy based on renewables than in one based on fossil fuels. Solar energy, in particular, requires local government involvement from project planing and permitting through decommissioning. Utility-scale solar PV will cover between 1% and 2% of the state’s land area in any cost effective pathway, and arranging this deployment so that it is consistent with local land use plans and economic priorities is essential. Rooftop solar can play a larger role than is indicated in our model, particularly if the state and localities work together to lower permitting and installation costs.

Energy derived from locally produced crops and forest products is likely to be a part of the transition to a carbon-neutral economy. Several of the scenarios we have modeled include significant use of BECCS to achieve net zero emissions at reasonable cost.

Local planning, building regulation and transportation infrastructure will all be needed to efficiently utilize the state’s bioenergy resources. State government can smooth the transition by providing localities with the information and incentives needed to contribute to the energy transition. Failure to do so has the potential to delay implementation and increase costs.

Finding: The state needs to examine existing administrative and regulatory processes to reduce unnecessary frictions to the energy transition.

Some of the things that will affect the pace of the energy system transition are the direct responsibility of state agencies. Among these are energy permitting and licensing, building regulations and transportation infrastructure rules. Solar facility permitting is a case in point. The authority for solar facility planning and permitting should be carefully examined for opportunities to reduce costs and speed development without abandoning needed oversight. Solar facility development requires approvals from DEQ, SCC, local planning agencies and PJM, our regional transmission organization. There is good reason to believe that the permitting process can be streamlined while still ensuring effective regulatory oversight. Our modeling shows clearly how expensive unnecessary restrictions on solar development can be.

Finding: The state needs to act quickly in areas in sectors of the economy where the stock of energy assets turns over slowly.

Two asset stocks in particular, the building stock (and its associated appliances) and vehicles, have replacement cycles that will require steps to be taken within the next few years to accelerate the transition from fossil fuels to decarbonized electricity. Transportation electrification, for example, can be advanced by supporting rapid development of charging infrastructure. In buildings, encouraging the replacement of fossil fuel consuming space and water heating equipment with high efficiency electric heat pumps will be essential for minimizing the cost of economy wide decarbonization.

Finding: More rapid innovation and diffusion of innovative technologies reduces the costs of a decarbonized energy system below that of the business as usual base case.

Because more rapid innovation increases the net benefits of decarbonization for Virginia, the state should seek to create a supportive policy and market environment for experimentation and demonstration of new clean energy technologies. Pilots projects accompanied by supportive policies for broader adoption off innovative technologies can serve two distinct functions: evaluation and learning-by-doing. Piloting for evaluation needs to be designed so that it is informative about the potential of the new technology for accomplishing its intended function. Too often, pilots are not accompanied by careful *ex ante* experimental design and *ex post* evaluation. Incentives and other policies to accelerate technology adoption learning-by-doing should be reserved for technologies with a high likelihood of providing net benefits but that requires new, specialized skills or network effects to lower the cost or increase the benefits of implementation.

Finding: Price-based tools such as RGGI (and TCI) can help minimize the cost of decarbonization.

Cap and trade programs like RGGI have a long and successful record of lowering the costs of achieving environmental goals by limiting emissions and inducing a price on the emissions that remain. A market price (or well designed fee) harnesses normal economic incentives in reducing emissions in the most cost effective way. Many avenues of substitution away from fossil fuels can better be handled by incentives rather than detailed regulation. The Transportation and Climate Initiative, by expanding the emissions cap to cover the transportation sector, has considerable promise as a tool for starting the essential transition away from petroleum-based transportation services.

6.3 Research Agenda

The pathways modeling exercise highlights areas where additional research can help lower the costs of achieving the 2050 decarbonization target.

- *Estimate costs and constraints for increasing deployment of offshore wind resources.* The contribution of offshore wind is potentially very large. We need to develop a greater understanding of physical potential, likely costs, and institutional constraints.
- *Investigate the potential on-shore wind resource capacity given current and projected future wind energy technologies.* Different models of wind energy development in Virginia come to different conclusions about onshore wind potential.
- *Undertake a comprehensive analysis of utility-scale solar siting.* There is a pressing need to evaluate (1) optimal transmission and substation infrastructure investments, (2) regulatory and permitting process frictions, (3) the likely costs of expanded solar deployment and (4) effective strategies for coordinating infrastructure investment and regional economic development strategy.
- *Evaluate workforce training needs for expanded domestic energy investment and production.*
- *Analyze the system-wide potential for rooftop solar, behind the meter storage and other distributed energy resources (DERs) to the energy supply and to grid resilience.* The analysis should include, among other things, avoided generation, distribution and transmission system costs, ancillary services and the benefits of reduced demand for land resources. This research should also address net metering policies and how the state can contribute to lowering the “soft costs” of DER deployment.

- *Analyze policy options and build demonstration projects to support development of green hydrogen production, storage, and transmission in Virginia.*

- *Implement detailed modeling and assessment of the potential for demand management, demand response and real-time metering.* The analysis should investigate the effect of increased adoption of smart home systems and appliances and vehicle to grid charging systems combined with dynamic electricity rate structures that reflect system-wide load conditions.

- *Comprehensive economic modeling of net zero pathways including changes in energy expenditures, investment and end use efficiencies and the effects on income and employment in Virginia.* This should include an analysis of the distribution of monetary and non-monetary costs and benefits of energy system decarbonization in Virginia given current policies and pricing structures.

7 Conclusions and Recommendations

Our modeling exercise clearly demonstrates that eliminating greenhouse gas emissions from Virginia's economy by 2050 is not only possible, but can also be economically beneficial. Direct incremental energy system costs are small relative to projected GSP and the health and climate benefits of decarbonizing all sectors of the economy are greater than the costs of doing so. Virginia has sufficient non-emitting energy resources to produce nearly all of its energy needs.

To accomplish the transformation of Virginia's energy economy, from dependence on fossil fuels to a system with net zero GHG emissions, is a large and complicated undertaking. It will require changes in the way buildings are heated, the type of cars we drive, the technologies we use to generate electricity and in the design and operation of industrial processes. Changes such as these to large stocks of assets such as buildings, vehicles and factories take time because these assets have long useful lives. This means that, to achieve the ambitious but reachable goal of economy-wide decarbonization by 2050, we must start the process today. A quicker start means lower long-run costs.

Many of our future choices, especially with respect to generation and storage technologies, will depend on what new technologies prove to be cost-effective and how quickly costs decline for currently available technologies. For these choices, it will be necessary to balance the need to build momentum for energy system transformation with the option value of maintaining flexibility to benefit from new technologies as they emerge. This can be accomplished by monitoring new developments closely, supporting technology experimentation, and fostering an ecosystem for energy market innovation in Virginia.

Successful decarbonization will require contributions from four distinct *pillars*:

The Four Pillars of Cost-effective Decarbonization

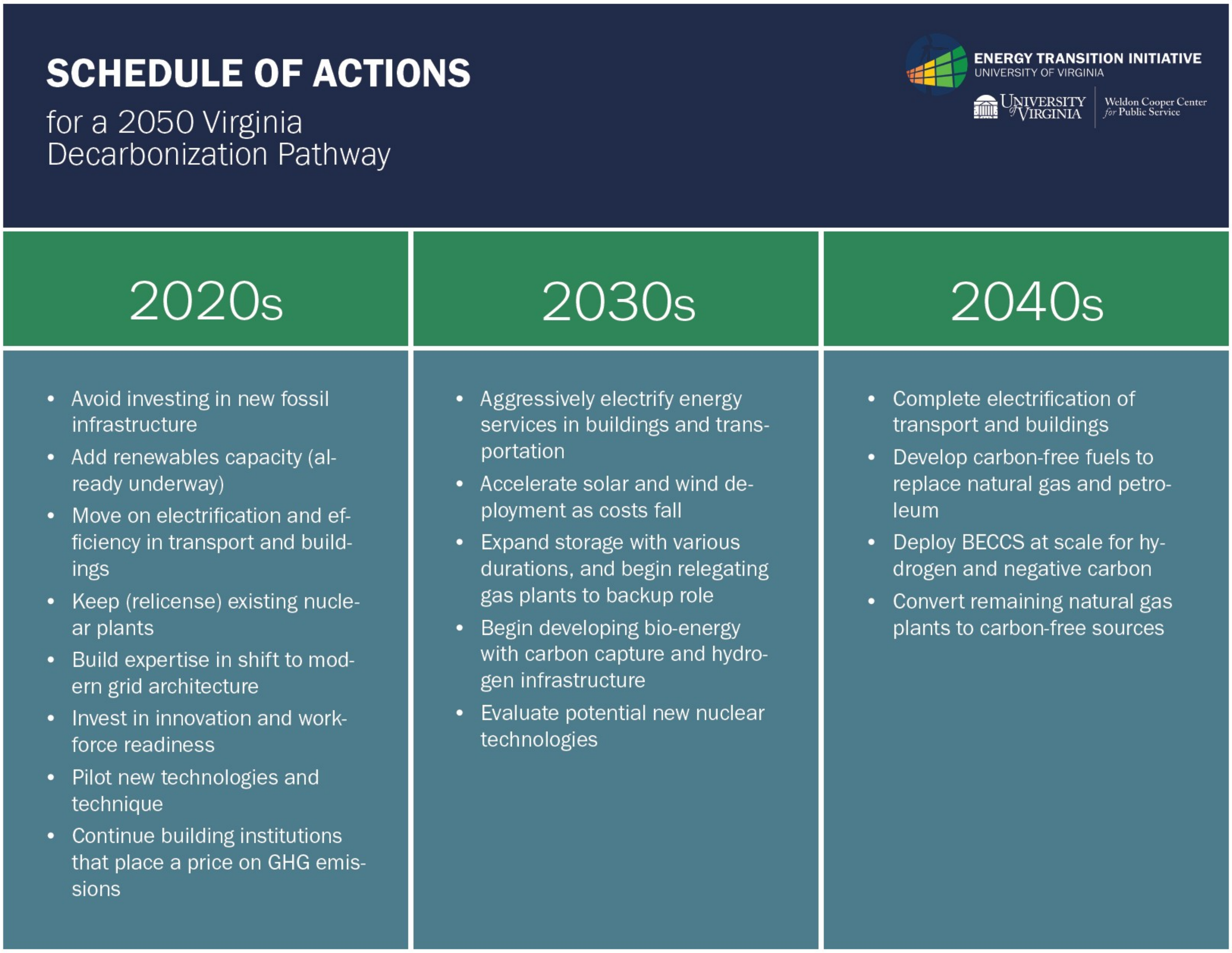
1. Boost efficiency and responsiveness in energy use
2. Decarbonize the electricity sector
3. Electrify energy end-uses
4. Capture carbon emissions (to sequester or use)

Our model also points out clearly that the costs of decarbonization will depend on how we approach it. Limits on our ability to develop our energy resources or delays in starting the process of moving the economy away from dependence on fossil fuels will significantly increase costs. On the other hand, if Virginia can arrange to contribute to the development of lower cost clean energy technologies and systems, then the costs of the transition can be greatly reduced. To help identify and maintain support for cost-effective options, it will be critical to implement efficient energy system pricing mechanisms and complementary policies that lead to an equitable distribution of costs and benefits.

Because changes are required in practically all sectors of the economy, numerous state government agencies and local governments will need to be actively involved. These agencies and localities must be asked to plan activities on an unfamiliar, 30 year time horizon where both early action and the flexibility to respond to new opportunities will be important. The planning agency needs to evaluate roadblocks and frictions that can derail or delay progress. With billions of dollars at stake, the Governor and the General Assembly should work quickly to establish an office for planning and coordinating state decarbonization efforts. Because its role is primarily in planning and coordination, this function should be separate from regulatory decision making.

7.1 How Shall We Proceed?

Here, we provide a rough chronology of what needs to be done to transform Virginia's energy economy.



SCHEDULE OF ACTIONS

for a 2050 Virginia Decarbonization Pathway

ENERGY TRANSITION INITIATIVE
UNIVERSITY OF VIRGINIA
UNIVERSITY of VIRGINIA | Weldon Cooper Center for Public Service

2020s

- Avoid investing in new fossil infrastructure
- Add renewables capacity (already underway)
- Move on electrification and efficiency in transport and buildings
- Keep (relicense) existing nuclear plants
- Build expertise in shift to modern grid architecture
- Invest in innovation and workforce readiness
- Pilot new technologies and technique
- Continue building institutions that place a price on GHG emissions

2030s

- Aggressively electrify energy services in buildings and transportation
- Accelerate solar and wind deployment as costs fall
- Expand storage with various durations, and begin relegating gas plants to backup role
- Begin developing bio-energy with carbon capture and hydrogen infrastructure
- Evaluate potential new nuclear technologies

2040s

- Complete electrification of transport and buildings
- Develop carbon-free fuels to replace natural gas and petroleum
- Deploy BECCS at scale for hydrogen and negative carbon
- Convert remaining natural gas plants to carbon-free sources

Figure 41: 2050 Virginia Decarbonization Pathway: Schedule of Actions

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List of Figures

List of Tables

A Appendix

A.1 High-level Approach to Model Virginia's Energy system

Applied electrification and energy efficiency levers

Strategies vary by sub-sector (residential space heating to heavy duty trucks)

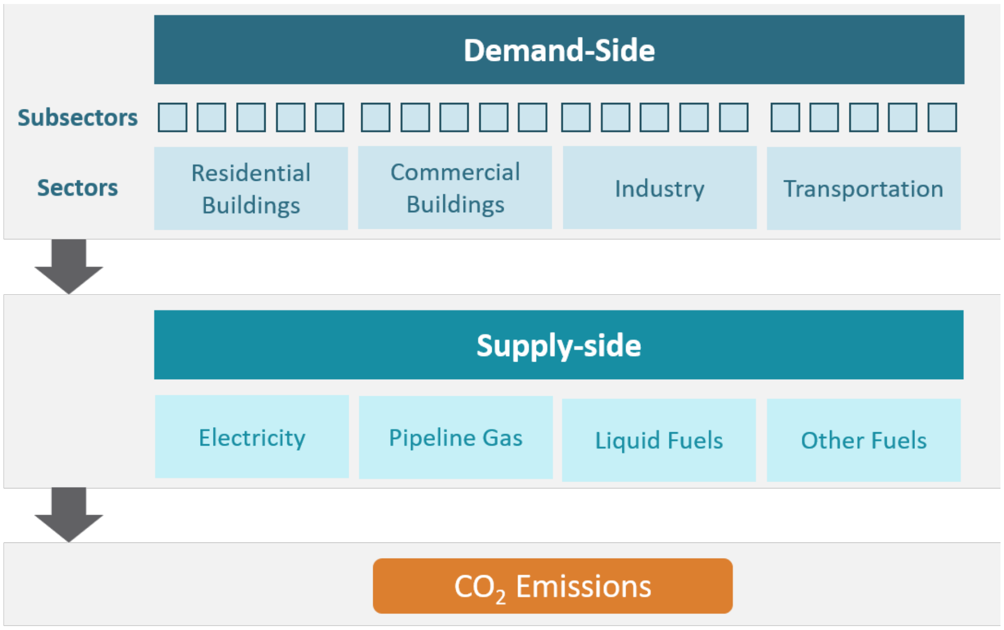


Figure 42: Demand and Supply side sector $CO_2$2 Emissions

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. It can be used to represent both current fossil-based energy systems and a 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 (EPA, 2018) geographies. The aggregation was done for computational purposes to reduce the total number of zones to a manageable number.

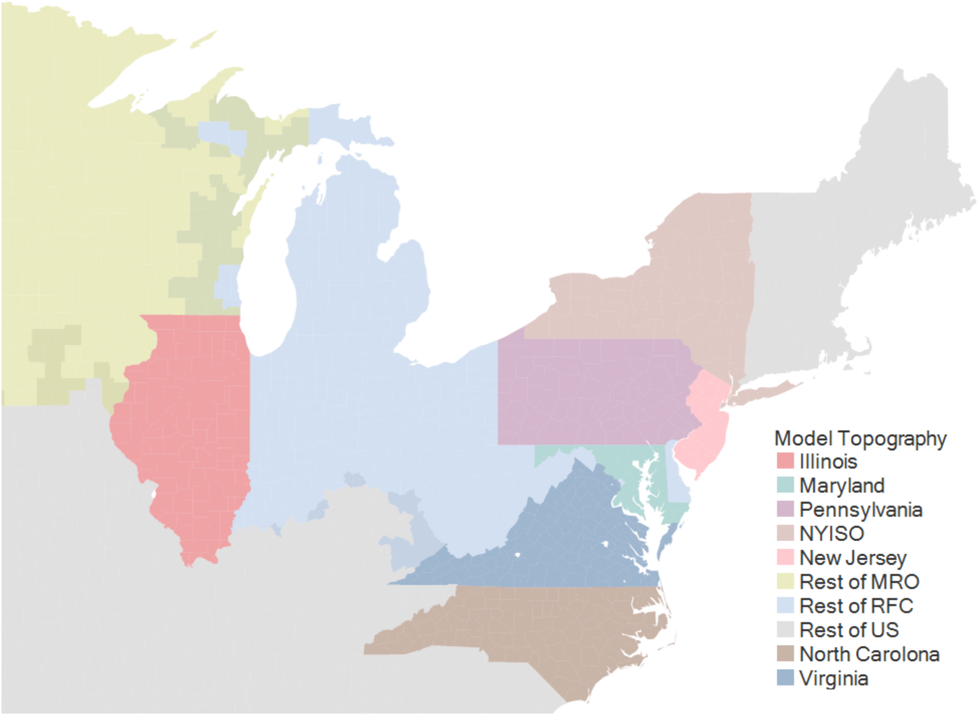


Figure 43: Viginia within the PJM model topography.

EnergyPATHWAYS and its progenitor models have been used to analyze energy system transformations at different levels, starting in California (Williams et al., 2012) then expanding to U.S. wide analysis (Bataille et al., 2016; Business, 2016; Jadun et al., 2019) 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.

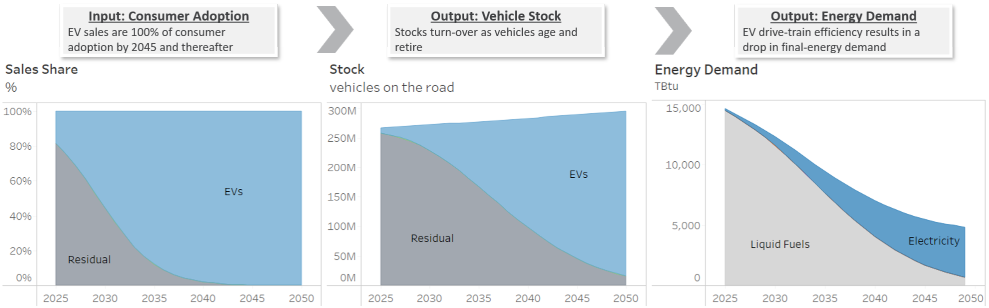


Figure 44: Illustration of EnergyPATHWAYS Inputs and Outputs for Light-duty Vehicles

A.1.1 Supply-side Modeling: Regional Investment and Operations (RIO) Platform

Capacity expansion tool producing cost-optimal resource portfolios across the electric and fuels sectors - Identifies least-cost clean fuels to achieve emissions targets, including decarbonized gas and hydrogen production

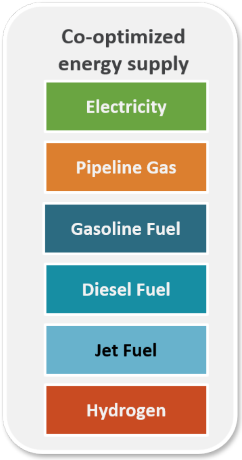


Figure 45: Illustration of RIO for production of hydrogen from electricity via electrolysis. Electricity and fuels are co-optimized to identify sector coupling opportunities.

Simulates hourly electricity operations and investment decisions - Electric sector modeling provides a robust approximation of the reliability challenges introduced by renewables

Electricity and fuels are co-optimized to identify sector coupling opportunities - Example: production of hydrogen from electrolysis

EnergyPATHWAYS 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. RIO's strength is in optimization of supply-side decisions where least cost economic frameworks for decision making are either applied already (e.g., in utility integrated resource planning), or are regarded as desirable. 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.

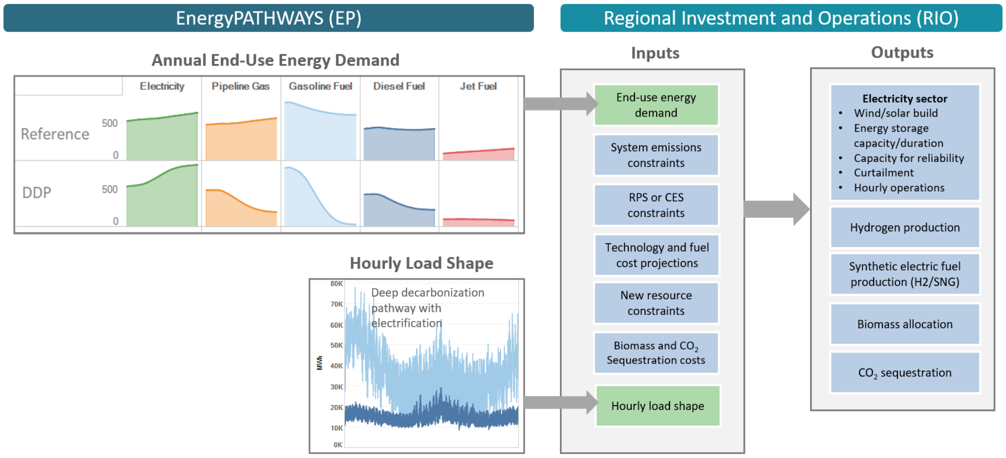


Figure 46: Linkage of EnergyPATHWAYS and RIO models.

A.1.2 Demand- and Supply-side Modeling Framework

A.1.3 Geography

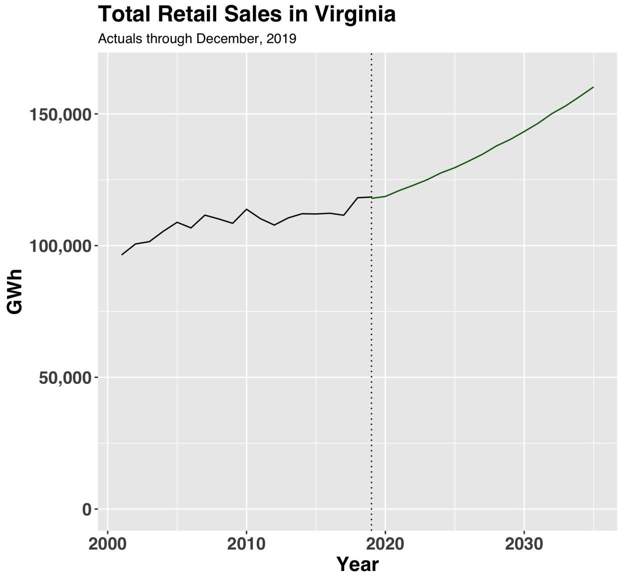
Includes state-level and PJM region detail

Each zone reflects resource endowments such as renewable resource potential and quality, bioenergy feedstock supply and geologic sequestration potential

A.1.4 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 used the 2019 *Annual Energy Outlook* (EIA, 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 (Vimmerstedt et al., 2019) and input files to their ReEDS Model (Brown et al., 2020). 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.

A.2 Electricity Demand Forecast



Source: Energy Information Administration and Weldon Cooper Center

Figure 47: Total retail electricity sales in Virginia: actuals and forecast

The Weldon Cooper Center has forecast electricity sales in Virginia based on data through the end of 2019.[22] We expect total retail electricity sales to grow from 118,000 GWh in 2019 to 160,000 GWh by 2035.[23]

The aggregate sales forecast is based on separate forecasts of a number of components of the total. We separately forecast sales for Dominion Virginia Power, APCO and for Rest-of-State. Dominion Power sales are further disaggregated into residential, industrial, data center and commercial (excluding data centers). Of these components of sales, only two are experiencing any significant growth in our forecast: Dominion data center sales and Rest-of-State sales. Even for Rest-of-State, most growth in sales is due to growth in data center sales.

This forecast does not include any provision for future increased use of electric vehicles. The data on which the forecast is based ends in December of 2019. Because of the small number of EVs in use in Virginia at that time, electricity sales to power EVs will not have a significant influence on this sales forecast. We expect that increased EV use will increase in the future even in our Baseline case. The anticipated increases in electricity sales for vehicle charging is included in all of our scenarios and not in this sales forecast.

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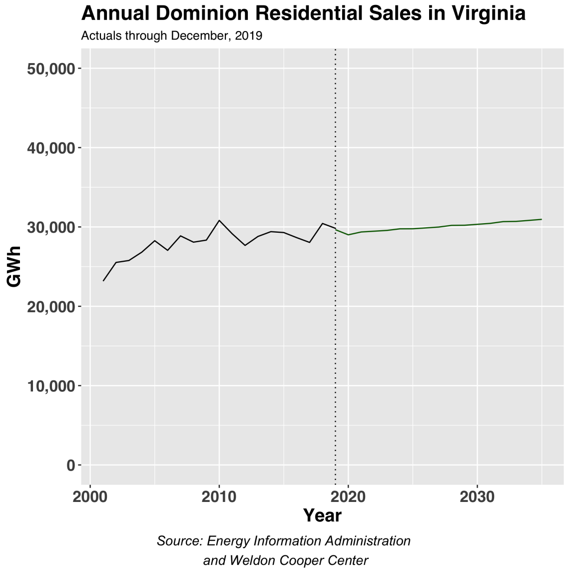
[22] We have tested whether the 2020 pandemic has influenced our long-term forecast. It has not. There has been some shift of energy use between residential and commercial sectors, but the long-run trend does not change appreciably when we include data through September of 2020.

[23] For years beyond 2035, we made a simple linear extrapolation based on the forecast growth from 2034 t0 2035.

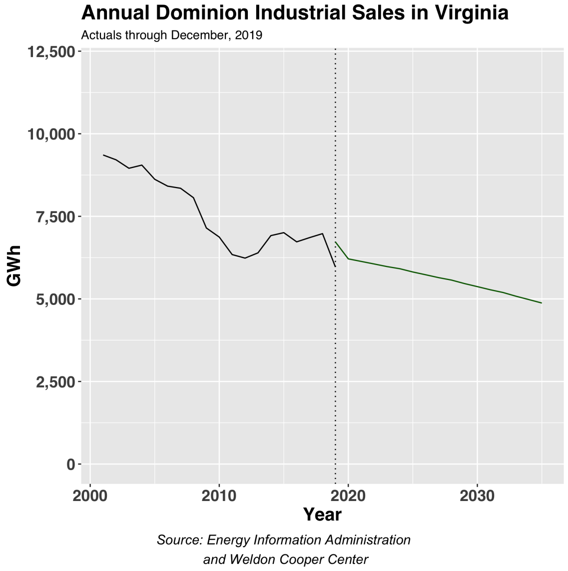
A.2.1 Dominion Virginia Power Sales



Source: Energy Information Administration and Weldon Cooper Center

Figure 48: Dominion Residential Sales: Actuals and Forecast

Dominion residential sales have been growing very slowly since around 2005. This trend shows no sign of changing Figure 48. We expect Dominion residential sales to grow by about 3% between now and 2035.

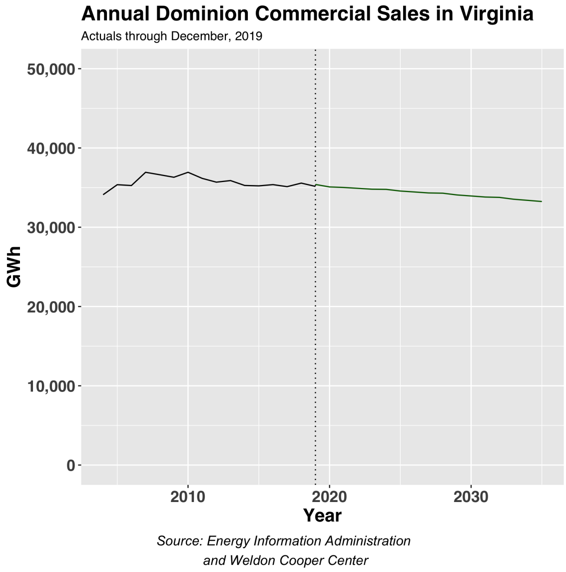


Source: Energy Information Administration and Weldon Cooper Center

Figure 49: Dominion Industrial Sales: Actuals and Forecast

Dominion industrial sales are a small share of sales and have trended downward since at least 2001. While the downward trend seems to have flattened in recent years, we expect that Dominion industrial sales will be flat or declining over the forecast horizon.

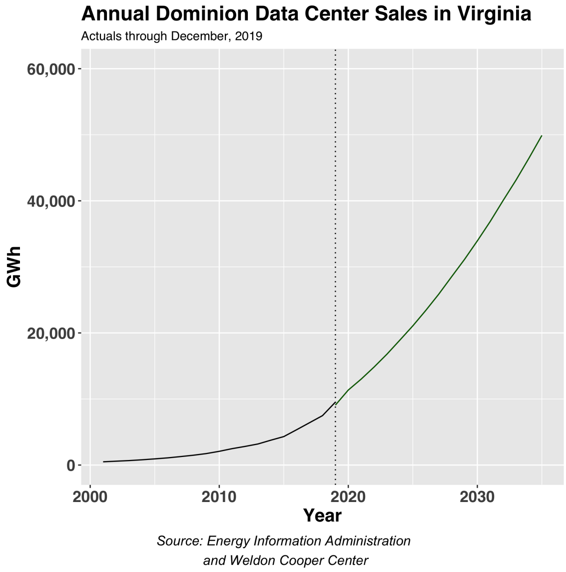
Dominion commercial sales (excluding data center sales) have also been trending modestly downwards since 2010. There is little prospect for a return to growing commercial sales in the near future. We expect flat or even slightly falling commercial sales through 2035.



Source: Energy Information Administration and Weldon Cooper Center

Figure 50: Dominion Commercial Sales (ex-data centers): Actuals and Forecast

Data center sales are the only growing sales category for Dominion. Data center sales are growing at an increasing rate in each successive year, although forecasts of future data center activity carries a high degree of uncertainty. But the rate of increase has been getting faster in each of the past several years, and this pattern shows no signs of slowing through the end of the available data. To date, data center sales growth have been quadratic in the time trend. If that growth process continues for even a few years, data center sales will rival total residential sales. Our forecast has data center sales growing by a factor of four by 2035. [a]



Source: Energy Information Administration and Weldon Cooper Center

Figure 51: Dominion Data Center Sales: Actuals and Forecast

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[a] For our scenarios, we slowed out-year growth by replacing the quadratic trend with simple linear growth from 2036 to 2050.

A.2.2 APCO Electricity Sales

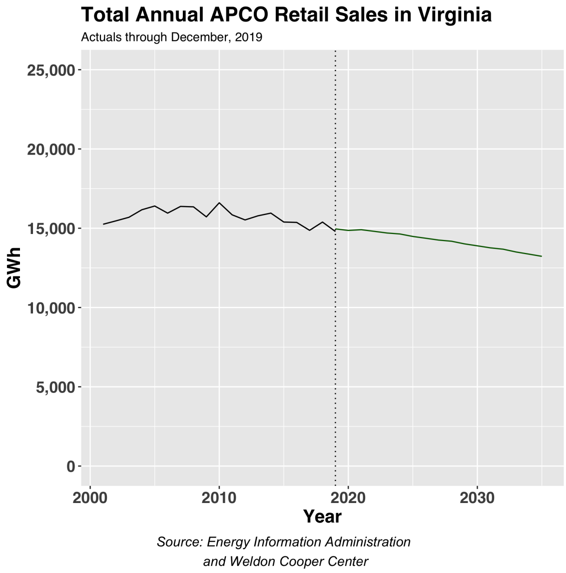

Figure 52: APCO Total Electricity Sales: Actuals and Forecast

APCO sales have been declining since 2005 through the end of the actual data in December of 2019. It can be expected to be flat or even declining between now and 2050.

A.2.3 Rest-of-State Sales

Residential sales in the rest of Virginia are flat. Industrial sales are rising modestly. Total rest-of-state sales, while flat until recently, jumped sharply in the last two years. This jump is mostly due to a jump in commercial sales, which in turn, is mostly the result of increased data center sales by the Northern Virginia Electricity Coop. We did not break rest-of-state sales down by category, but rather forecast total sales. Although these sales are a small share of total state sales, they are rising and, given recent growth, can be expected to rise from 22,000 GWh in 2019 to around 30,000 GWh by 2035 and could rise to as much as 35,000 by 2050.

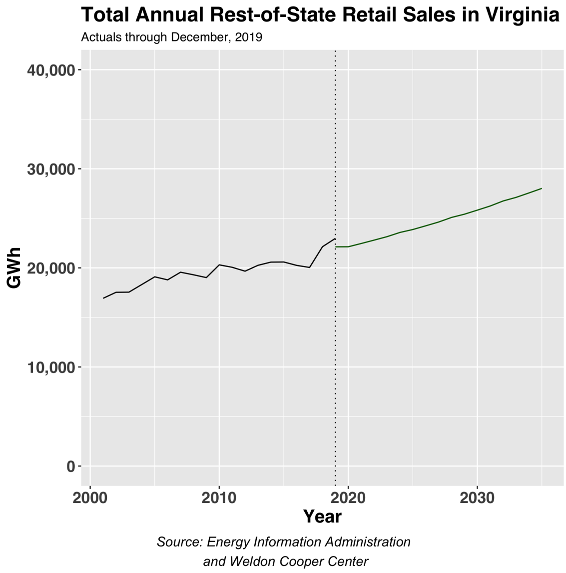

Figure 53: Rest-of-state Total Electricity Sales: Actuals and Forecast

A.3 Key Terms

1.5℃ – One-and one-half degrees Celsius (2.7℉) of global warming over pre-industrial temperatures, an aspirational goal in the Paris Agreement climate accord.
2℃ – Two degrees Celsius (3.6℉) of global warming over pre-industrial temperatures. The Paris Agreement States the intention of parties to remain “well under” this upper limit.
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
Bioenergy – Primary energy derived from growing biomass or use of organic wastes
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
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
GHG - Greenhouse gas GSP - Gross state product 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
MMT – Million metric tonnes
NET – Negative emissions technology, one that absorbs atmospheric CO_2 and sequesters it
Net-negative CO_2 - 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.
Oxyfuel - A combustion process where fuel is burned using pure oxygen rather than air, and the resulting flue gas is primarily CO_2 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
SNG – Synthetic natural gas
TBtu – Trillion British thermal units, an energy unit typically applied to in power generation natural gas
TX – Transmission
VMT – Vehicle miles traveled

A.4 Annual Transmission-level Loads

Transmission-level load reflects: End-use loads grossed up for losses in the transmission and distribution system, as well as flexible industrial scale loads, such as electrolysis and electric boilers.

The latter is used to balance renewable-heavy electricity systems and to decarbonize other sectors (“sector coupling”).

Electrolysis produces hydrogen with zero emissions that can be used directly (e.g., hydrogen fuel cell freight truck) or as a feedstock into synthetic fuel production.

Electric boilers produce steam that displaces the use of gas in commercial and industrial applications.

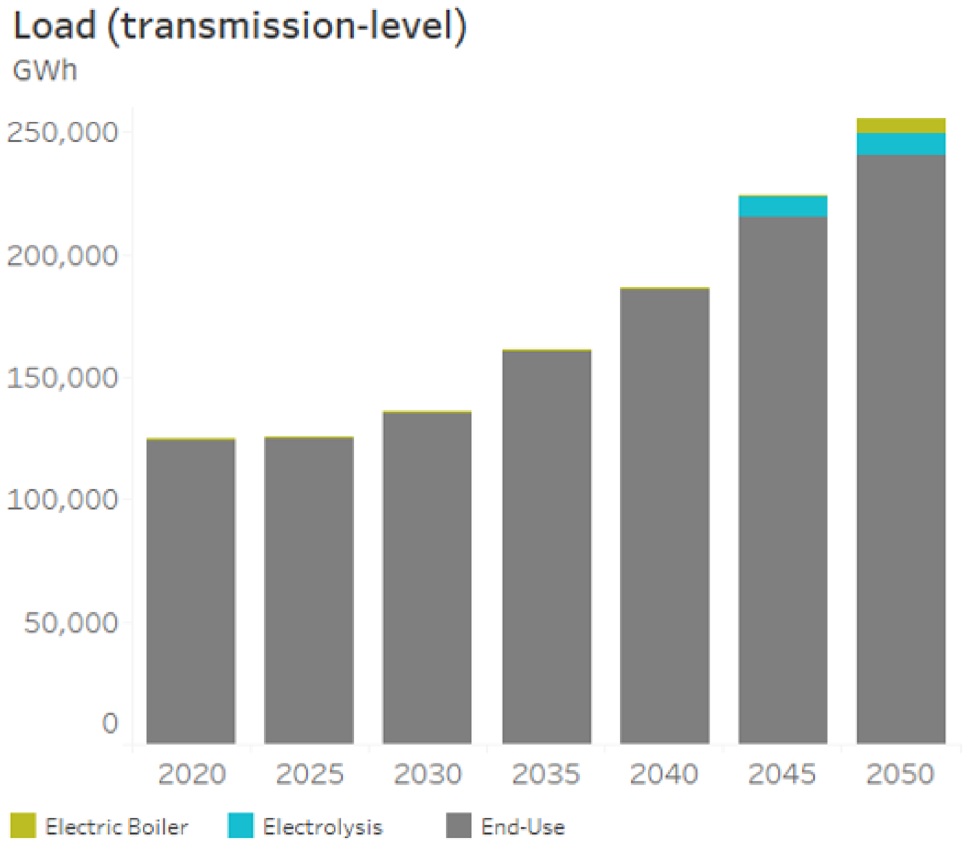

Figure 54: Annual transmission-level load, 2020 to 2050, in the Net Zero Pathway.

The Energy Transition Initiative

The Energy Transition Initiative at the University of Virginia consists of a team of researchers at UVA's Weldon Cooper Center for Public Service exploring clean energy sourcing in response to new legislation mandating net carbon emission neutrality in Virginia by 2050. We advance these goals by researching clean energy and sustainability practices; by developing and maintaining tools to help localities understand the process, costs, and benefits of adopting cleaner energy technologies; and by engaging directly with policymakers, energy providers, entrepreneurs, consumers, and other interested stakeholders to smooth the transition to a sustainable energy economy.

The Weldon Cooper Center for Public Service

In every project we undertake and every community we serve, the Weldon Cooper Center draws on eighty years of experience and expertise from across the organization to support the needs of our clients and partners. Cooper Center professionals embrace mission- and impact-driven service to individuals, organizations, governmental bodies, and communities seeking to serve the public good. We conduct advanced and applied research in collaboration with clients so they may make a difference in governance and community life. We offer training programs and expert assistance to public leaders and skill development for political leaders who seek to work cooperatively with others. Our values of access, collaboration, commitment to community, and impact guide our work. We welcome partnerships and invite conversation about your goals and needs.

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