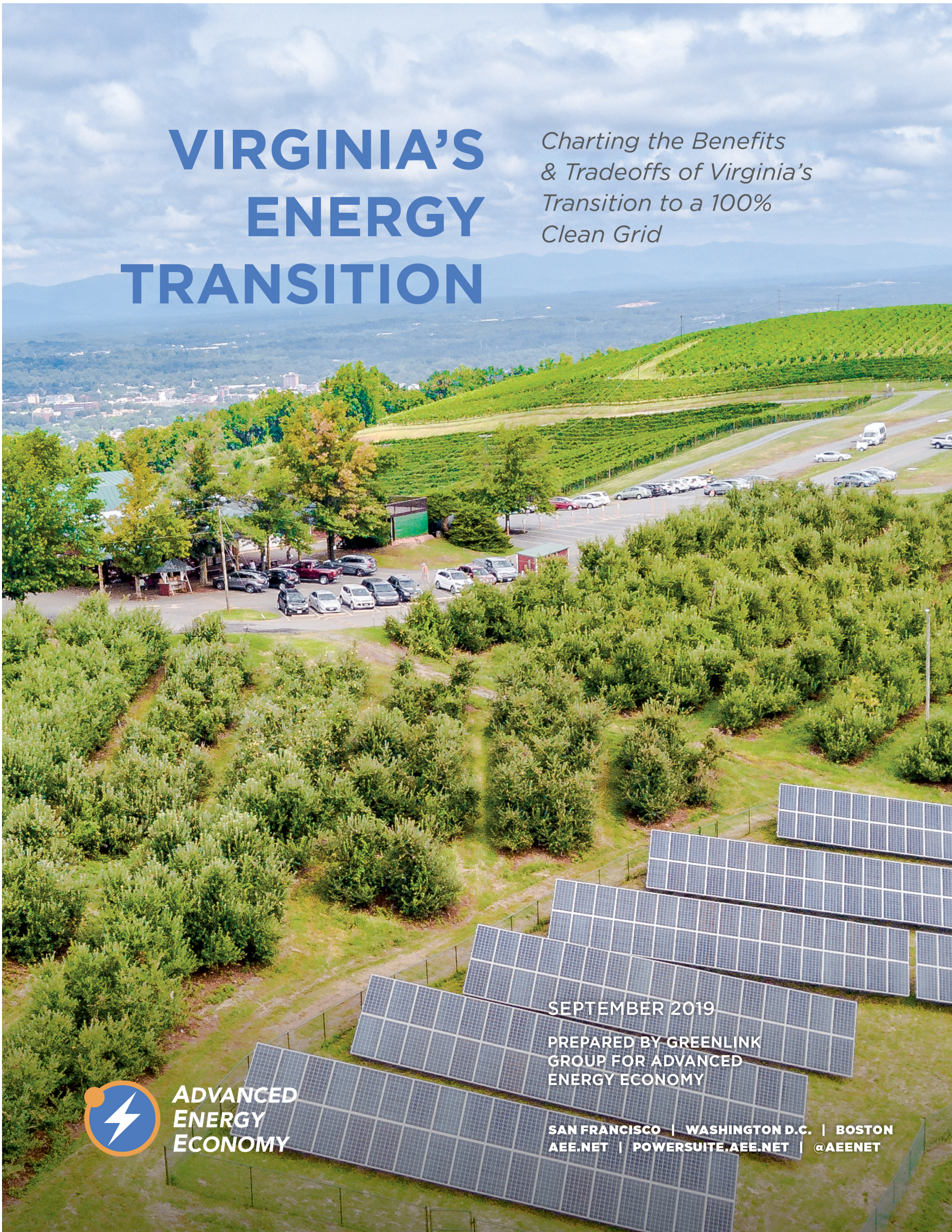

VIRGINIA'S ENERGY TRANSITION

Charting the Benefits & Tradeoffs of Virginia's Transition to a 100% Clean Grid

SEPTEMBER 2019

PREPARED BY GREENLINK GROUP FOR ADVANCED ENERGY ECONOMY

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ACKNOWLEDGMENTS

This report was produced for Advanced Energy Economy by The Greenlink Group, a clean energy technology and research company, with input from GridLab, a technical advisory non-profit.

The Greenlink Group is an Atlanta-based energy research and consulting firm equipped with sophisticated analytical technologies and deep industry knowledge in the clean energy space, receiving accolades from MIT, Georgia Tech, and the National Science Foundation, among others. It uses these technologies to help create a smarter, cleaner, and more equitable future.

GridLab is a non-profit organization which provides comprehensive and credible technical expertise on the design, operation, and attributes of a flexible and dynamic grid to assist policy makers, advocates, and other energy decision makers to formulate and implement an effective energy transformation roadmap. GridLab offers technical expertise, training, and a connectivity platform for sharing information about the rapidly-evolving electric distribution grid landscape.

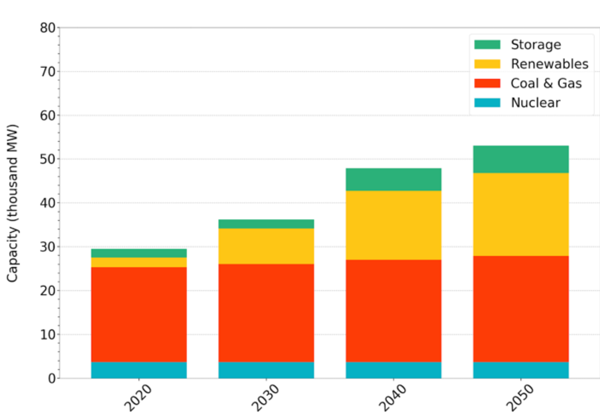
EXECUTIVE SUMMARY

Energy is foundational to Virginia's economy. Cost-effective technologies and resources like energy efficiency, renewable generation, and battery storage have the potential to transform how Virginia produces and uses electricity. *Virginia's Energy Transition* explores the impacts of the Commonwealth employing such advanced energy resources to build a 100% carbon-free grid. Advanced Energy Economy worked in collaboration with GridLab and The Greenlink Group to map out how Virginia could move to a 100% carbon-free grid.

The Greenlink Group used ATHENIA, energy resource modeling software like that used by utility planners, to assess the repercussions of such a transition. The analysis produced the Business-as-Usual (BAU) projection out to 2050, drawing on the Integrated Resource Plans of Virginia's investor-owned utilities. The analysts defined three Zero Carbon Scenarios with different target years – 2030, 2040, and 2050 – by which Virginia would reach a 100% carbon-free grid.

Figure ES-1 illustrates the resulting changes in electricity generation, decade by decade, from transitioning to a carbon-free grid by 2050 compared with the Business-as-Usual projection. This analysis then compares the costs and benefits of each of the Zero Carbon Scenarios against BAU in terms of bill impacts, jobs, labor income, GDP impacts, and health and environmental impacts.

Of the three Zero Carbon Scenarios analyzed (2030, 2040, 2050), Zero Carbon 2030 produces the greatest benefits in terms of GDP, job growth, and labor income. This Scenario also incurs the highest investment costs, resulting in higher electric bills initially, but ultimately producing net household bill savings over the 30-year period. In contrast, by spreading the decarbonization transition out over a longer time horizon (i.e., 2040 or 2050), Virginians realize household bills savings every year through 2050 – with average households benefiting by $2500 to $3500 through 2050.



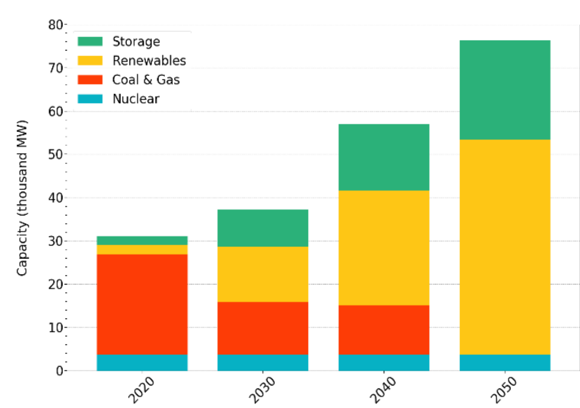


Figure ES-1: Electricity Generation by Source, Business-As-Usual (left) vs. Zero Carbon 2050 (right)

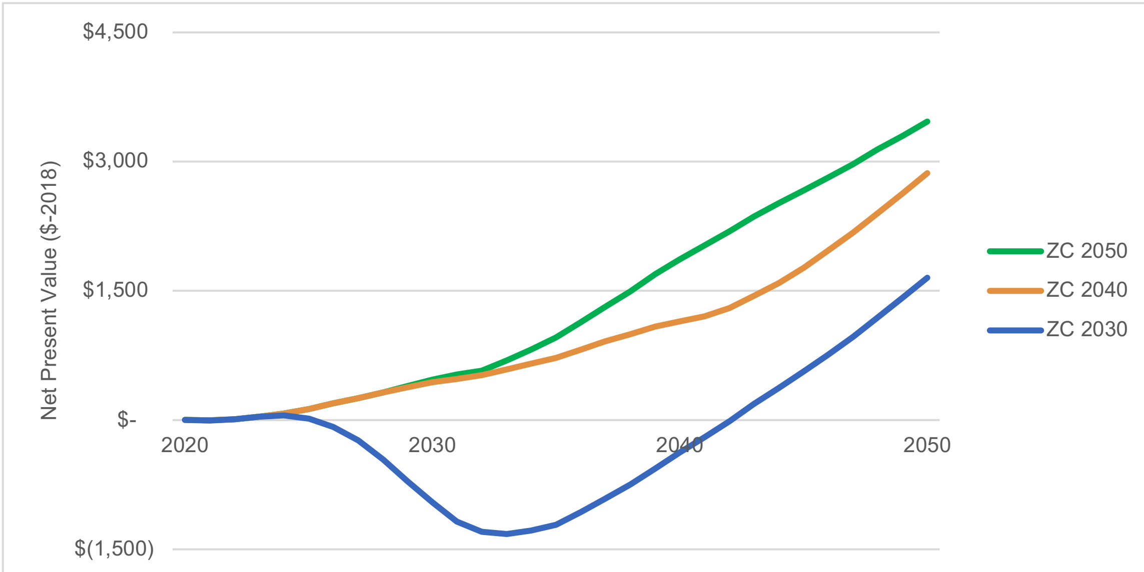


Figure ES-2: Average Virginia Household Bill Savings

In terms of job creation, the Business-as-Usual Scenario is expected to produce an average of 6,000 new jobs per year. In contrast, the Zero Carbon Scenarios lead to an average of 13,000 new jobs per year. Net gains by 2050, beyond BAU, for labor income range from $15 billion to $23 billion, while net gains in GDP range from $14 billion to $42 billion by 2050.

Transitioning to zero-carbon technologies and resources generates health and environmental benefits as well. Each Zero Carbon Scenario reduces sulfur dioxide (SO_2) by 100% in 2030. The rest of the pollutants are reduced by 50% in 2030 and close to zero by the time the last natural gas plant is retired. Avoided damages from reduced emissions of localized pollutants tally into the billions of dollars, with reductions in carbon dioxide (CO_2) emissions – which have local and global impact – adding tens of billions of dollars to that over the course of 30 years.

A cost-benefit analysis of a 100% carbon-free grid reveals that the benefits of decarbonization outweigh the costs (Figure ES-3) in all carbon-free scenarios. Each Zero Carbon Scenario presents a cost-benefit ratio greater than one without including greenhouse gas emissions benefits, which have global impacts as well as local. Including avoided greenhouse gas benefits causes the benefit-cost ratios to jump to more than 4:1.

Overall net benefits are highest in the Zero Carbon 2030 Scenario: $80.3 billion, versus $63.5 billion in Zero Carbon 2040 and $69.7 billion in Zero Carbon 2050, including CO_2 damages. Without CO_2, net benefits are still highest for Zero Carbon 2030: $16 billion, versus $14.5 billion in Zero Carbon 2040 and $13.6 billion in Zero Carbon 2050.

All Zero Carbon Scenarios are cost-effective and a faster transition to 100% carbon-free electricity leads to more benefits along with greater investments.

Key Takeaways

- Virginia can successfully transition to a 100% carbon-free electric grid that will provide affordable, reliable, and cleaner electricity.

- In all Zero Carbon Scenarios, renewable generation and battery energy storage systems become the major source of both energy and capacity. By the late 2020s, battery storage becomes the least-cost capacity resource, replacing more expensive gas peaker plants.

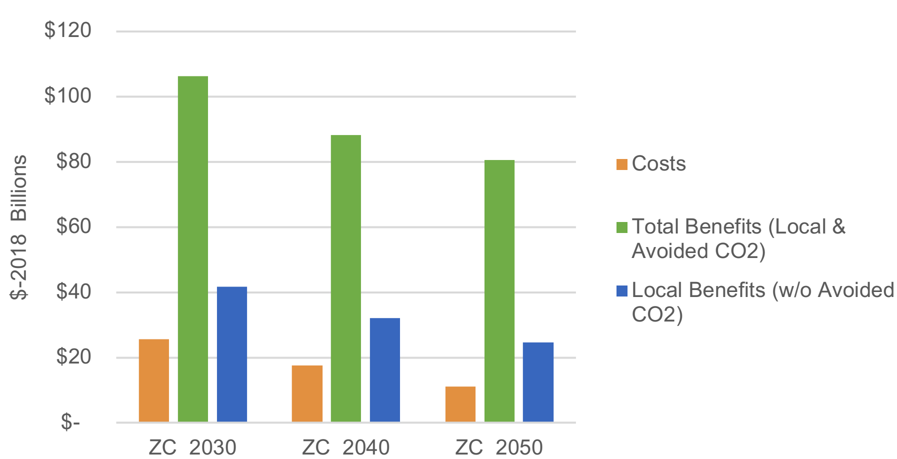
- Under the Zero Carbon Scenarios, by 2050, Virginia's grid is comprised of over 40 GW of wind and solar, and over 20 GW of battery storage. Under BAU, Virginia relies on over 20 GW of coal and gas, and just 20 GW of renewables.

- Residential electric bills are significantly lower over the 30-year period in every Zero Carbon Scenario. Compared to BAU, the average total household savings from 2020 to 2050 range from $1500 under the Zero Carbon 2030 Scenario to $3500 under Zero Carbon 2050.

- Every major local and global air pollutant is reduced substantially. The cumulative value of avoiding the public health costs related to localized air pollution is greater than $3.5 billion and avoiding the greenhouse gas emissions is greater than $25 billion.

- All Zero Carbon Scenarios led to net job growth from energy efficiency measures and renewable and battery storage resources. On average, Zero Carbon Scenario job creation exceeds BAU by an average of 7,000 to 11,000 jobs per year.

- Based on a cost-benefit analysis, Zero Carbon 2030, 2040, and 2050 offer total benefits ranging from $80 billion to $106 billion as compared to BAU, and net benefits ranging from $13.6 billion to $80 billion.



ES-3: Net Benefits and Costs Relative to Business-As-Usual

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1. INTRODUCTION

Transitioning the U.S. energy sector to zero-emission resources has become more feasible with recent technological advancements. Virginia's energy system is no exception. While energy efficiency and other demand-side interventions have been cost-effective options for decades, supply-side options like solar and energy storage have become increasingly capable of displacing conventional generation within the electricity sector. At the same time, electric vehicles are seeing explosive growth, changing fundamental relationships in the U.S. energy mix for the transportation and power sectors. This report investigates pathways to a zero-carbon Virginia grid and discusses the benefits and tradeoffs for full decarbonization by specific target years.

This study is focused on answering two major questions: How quickly can Virginia fully decarbonize its electricity system, and what are the costs and benefits of that transition?

Virginia is interesting for its diversity; it has significant investor-owned utilities subject to strict oversight by its regulators, yet also participates in the PJM market, a regional transmission organization that brings market competition to the electricity sector throughout the Mid-Atlantic and Midwestern region. The generation portfolios for the two major utilities encompass about a dozen different technologies. Politically, the Commonwealth experiences regular changes in party control. Economically, the Commonwealth has large residential and commercial energy usage in addition to its industrial and data center footprint, the latter of which is one of the largest in the world. For these reasons, evaluating how a clean energy transition could occur for Virginia's power sector can provide insights into the opportunities and costs of clean energy for Virginia's residents, as well as identify potential areas for special consideration in other states interested in transitioning.

The Greenlink Group's ATHENIA model was deployed to analyze Virginia's electricity system from the present through 2050. ATHENIA employs deep learning techniques to develop highly accurate electricity generation forecasts predicted to serve Virginia's electricity demand, akin to the computer models used by utilities to develop their integrated resource plans. This report evaluated five scenarios with full electric decarbonization achieved in 2030, 2035, 2040, 2045, or 2050. Each scenario follows least-cost principles and evaluates opportunities for both supply and demand in order to achieve a zero-carbon energy grid. The 2035 and 2045 decarbonization scenarios are not discussed in the main report for two reasons: 1) those cases are similar enough to the other three that differences are adequately reflected, and; 2) in addition, the results presentation is more streamlined when discussing three alternatives to Business-As-Usual rather than five.

The story of Virginia's clean energy transition will be much greater than just the resources and pathways selected to decarbonize. There will be impacts on bills paid by customers as existing energy resources are retired and new resources come online. Billions of dollars of investments will be directed in new and different ways, resulting in changes to GDP, income, and job futures for Virginians. Emissions from the power sector will be reduced significantly, resulting in dramatic changes in public health outcomes and expenditures. Given the full scope of policy considerations, this report compares Business-As-Usual (BAU) and carbon-free scenarios, informing discussions on the tradeoffs required around these critical decisions for the future of Virginia.

Chapter 2 will briefly discuss the study's methodology, including the major assumptions and model used. Results will be explained in the subsequent four chapters. Chapter 3 lays out the resource deployments under a Business-As-Usual scenario through 2050 and then provides a comparison with resources deployed to meet specific target years in the Zero Carbon (ZC) Scenarios. Chapter 4 highlights how the Zero Carbon Scenarios would impact ratepayer bills, showing how customer bills would change if Virginia followed Chapter 3's decarbonization approaches. Other macro-economic indicators related to cleaner electricity, such as job impacts and the Commonwealth's GDP are evaluated in Chapter 5, with each Zero Carbon Scenario showing higher levels of employment and increased economic development. Chapter 6 shows how much pollution is associated with current electric generation and how much pollution would be avoided by achieving decarbonized electricity in 2030, 2040, or 2050. Chapter 7 conducts a comparison of incremental additional investments with incremental benefits of changing the build out of the electricity grid. The benefits far exceed the costs in all Zero Carbon Scenarios.

2. STUDY METHODOLOGY AND ASSUMPTIONS

Forecast Modeling

Greenlink's ATHENIA tool models future energy landscapes by analyzing historical time-varying trends in energy generation along with other market variables, such as fuel prices and generation costs. Coupled with projected energy demand and utility load growth, the resulting model offers the ability to reasonably forecast and closely investigate how various Zero Carbon Scenarios affect energy bills, utility finances, statewide economic benefits, and pollution-related health impacts. A more detailed overview of ATHENIA can be found in Appendix A.1.

Business-As-Usual

Dominion and Appalachian Power Company's (APCo) integrated resource plans (IRP), which are the basis of the Business-As-Usual (BAU) assumptions, have 15-year time horizons. As this study looks ahead to 2050, additional information is required to produce the BAU forecast beyond what is contained in each utility's IRP, specifically future energy demand profiles, generator additions and retirements, technology resources and costs, and energy efficiency and demand response programs.

Greenlink referenced locally and nationally recognized sources, from U.S. Energy Information Administration, PJM and others detailed in Appendix A, for future technology estimates and electricity demand growth. These data were used to develop well-grounded and balanced assumptions that serve as inputs into ATHENIA. In situations where a number of reasonable approaches were considered, this study used more conservative assumptions – i.e., those projecting slower rates of technological progress and more gradual cost declines.

Energy Demand

Data trends suggest that Virginia's electricity demand will grow over the next several decades. Population increases, economic growth, electrification of transport and buildings, and the development of new industries all drive higher energy needs. Profiles for both Dominion and APCo were defined through 2050 in order to evaluate Virginia's capacity and generation needs and BAU electricity demand. Appendix A.2 describes the assumptions used to calculate these demand profiles in greater detail.

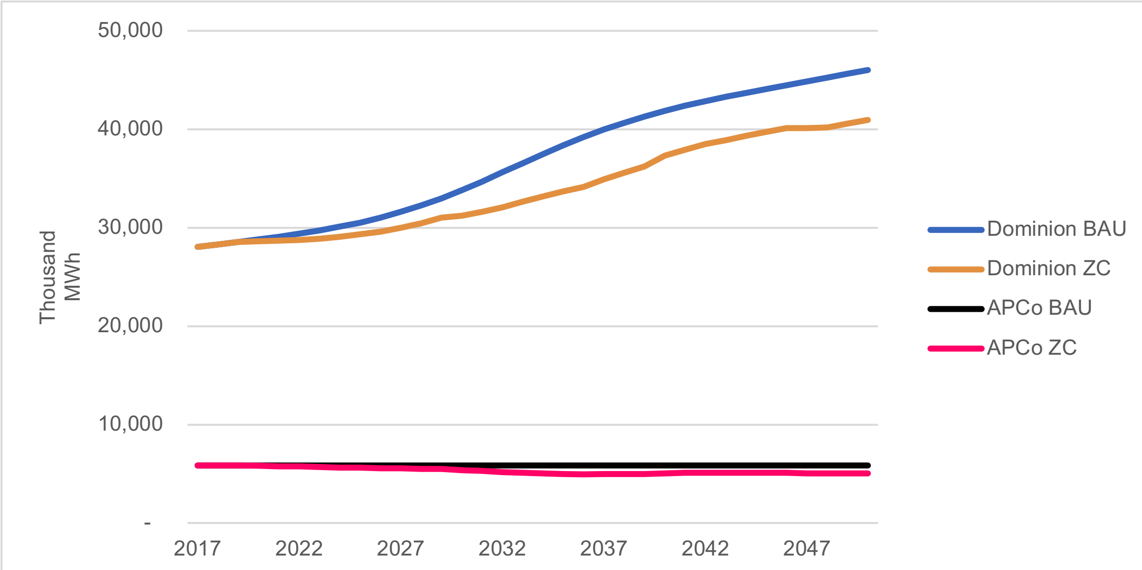


Figure 2-1: Demand Grows in Dominion, Not APCo Territory

Zero Carbon Scenarios

Each Zero Carbon Scenario uses the same demand profile. These are shown in comparison to the BAU demand profile for each utility in Figure 2-1 below. In the Zero Carbon Scenarios, modeled demand growth is slower in the case of Dominion, and declining in the case of Appalachian Power, in contrast to the BAU scenario. These adjusted growth rates (or declines) are the result of additional demand-side resources, such as energy efficiency (EE) or demand response (DR), that are deployed in each Zero Carbon Scenario. Additional discussion of this difference can be found in the next chapter.

Scenarios are defined by the year in which Virginia will fully decarbonize its power sector (2030, 2040, and 2050). Certain rules guide the Scenarios' plant retirements, capacity additions, and investment strategies. Zero-emissions electricity generators will need to grow to meet new demand while simultaneously displacing existing fossil fuel power sources. Details on these technologies are provided in Appendix A.3.

Alternative Scenario Design

Transitioning to a carbon-free electricity sector for Virginia involves a few explicit design parameters for each Zero Carbon Scenario:

1. All net-positive carbon-emitting generators must be retired by the Zero Carbon Scenario target date;
2. All coal units (including co-firing units that are predominantly coal-burning) must be retired by 2030;
3. Solar and battery capacity additions are made incrementally to avoid lumpy investments in unreasonably short periods of time;

4. No new gas generation may be added to the electricity generation system.

With these rules in place, the electricity generation planning proceeded under a least-cost paradigm evaluated through the present value of the revenue requirement and the levelized cost of energy from available generation resources.

Renewable Energy Credits

The modeling conducted by ATHENIA in this analysis does not employ renewable energy credits (RECs) as a substitute for renewable resources. The goal of the study is to investigate the costs and benefits of the retirement and replacement of carbon-emitting resources that currently serve Virginia's grid with non-carbon resources on the grid. However, it is possible that a lower-cost pathway could be designed by procuring RECs from out-of-state resources, such as those within the PJM grid, to offset carbon-emitting generation. This would enable slower deployments of non-carbon resources and, in turn, allow less-mature non-carbon resources to continue to decline in price, but it would effectively make it appear that Virginia's electricity system was decarbonizing faster than it is. The decision not to use out-of-state RECs is, as a result, a conservative one, as it focuses exclusively on the use of in-state resources to accomplish such a transition.

3. RESOURCE DEPLOYMENTS

The previous chapter detailed the growth in energy demand for Virginia over the study horizon, as well as the key assumptions governing this analysis.

Chapter 3 details the shifting deployment of technologies ATHENIA forecasts to meet the needs, constraints, and targets specified in each scenario. This chapter outlines the BAU projection as extrapolated from the utilities' IRP filings, and details the changing retirement and capacity additions driven by specific Zero Carbon Scenarios.

The Business-As-Usual Grid

Under BAU, coal plant retirements are spaced out over the study horizon, with only one plant remaining open in 2050 (Figure 3-1A). In this scenario, natural gas, utility-scale solar, and battery storage see ongoing regular additions to both meet new demand and replace retiring resources (Figure 3-1B). Under BAU, combustion turbine gas-fired plants see extensive deployment during the 2020s, while combined cycle gas-fired plants see several large investments and additions during the 2040s, primarily replacing retired coal capacity. Battery storage becomes the least-cost means of meeting capacity needs by the late 2020s, resulting in growing adoption in the mid-2030s and continuing incrementally through 2050. Utility-scale solar sees multi-gigawatt capacity deployments in each decade, driven by its ever more competitive price point, becoming the largest nameplate capacity resource by the mid-2030s.

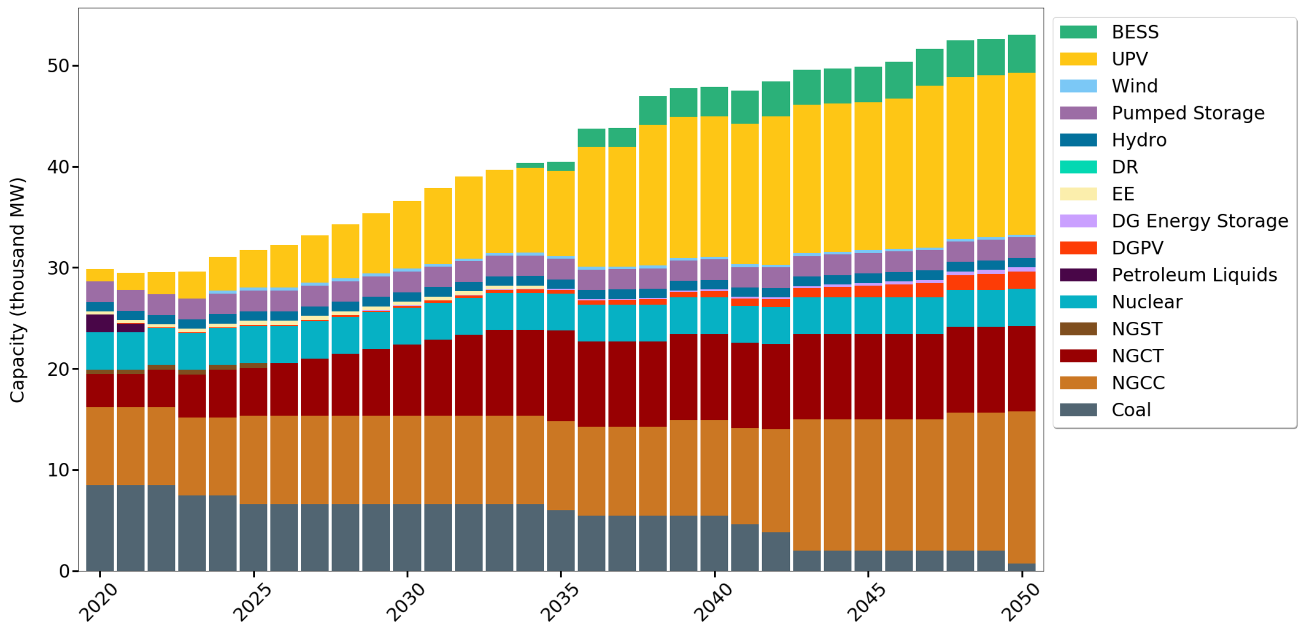


Figure 3-1A: BAU Capacity by Source

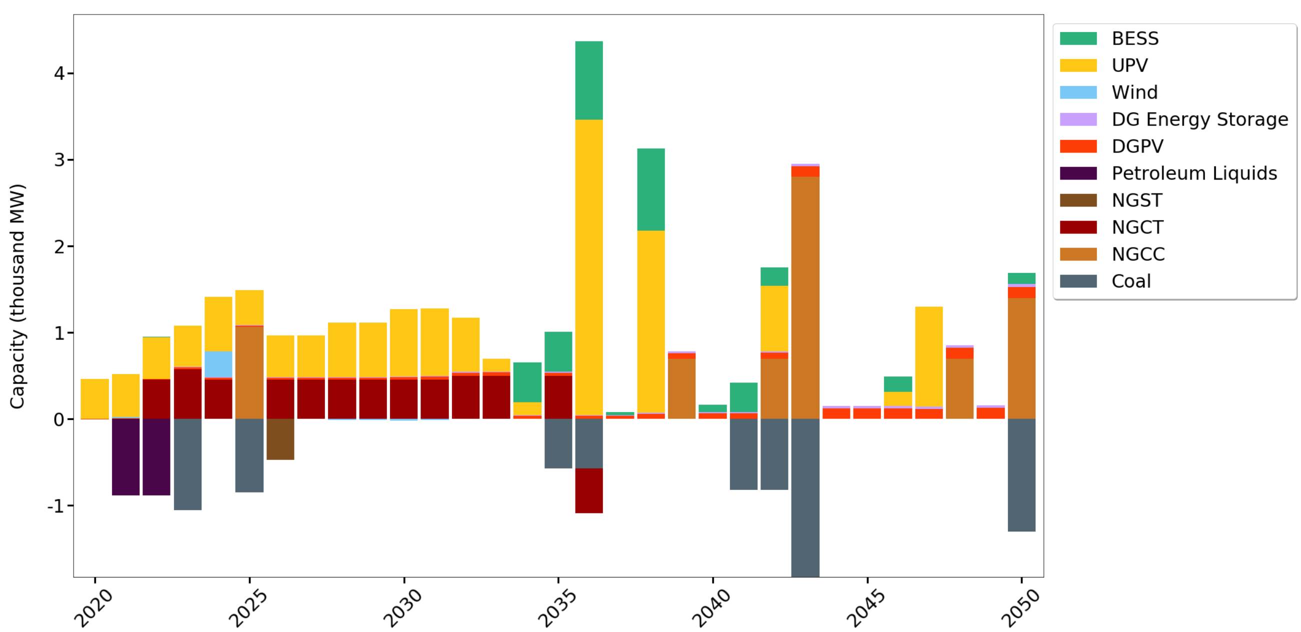


Figure 3-1B: BAU Capacity Additions & Retirement Schedule

Replacing capacity between generating resources is not a one-to-one proposition because of differences in technology performance and availability. A generator's *capacity* measures the potential power output, which does not account for these differences. As a result, capacity from a specific technology may have more or less value to the grid than another technology. For example, a nuclear power plant with 200 MW of capacity (power) could be operated around the clock and produce more kilowatt hours (energy) than 200 MW of solar due to the time limitations of useful sunlight and technological characteristics. Capacity and availability are important for determining how to meet system peak demand while energy demand must consider the quantity of energy generation from different technologies. When determining the economics of operating or replacing any power plant, both energy generation and peak demand elements play a role, and these decisions must account for differences in performance and availability.

As far as energy growth goes, solar sees large growth in all scenarios, growing to 23 million MWh by 2050 in the BAU. Because of performance and availability reasons just mentioned, the percent of solar generated electricity is less than the percent of capacity that solar represents. By 2050, utility-scale solar represents about 30% of total capacity, but only 14% of total generation in that year. Under BAU, both solar and natural gas help displace the generation currently provided by existing coal plants.

In the BAU projection, statewide electricity demand increases on average by 0.83% per year, predominantly in the more urban central and northern regions of the Commonwealth. There are two drivers changing the energy needs in Virginia beyond the regular growth in energy demand: the adoption of electric vehicles (EVs) which further increases demand, and the increased utilization of demand-side management in the form of energy efficiency (which reduces overall demand) and demand response (which reduces peak demand). Under BAU, demand-side efforts offset slightly more than 3 million MWh per year between 2029 and 2033, after which savings from utility-announced efforts begin to decline. By 2043, no additional savings are captured.

EVs are expected to make up an increasing share of the light-duty vehicle fleet for the Commonwealth, eventually exceeding 60% market share by the 2040s, driven by falling battery prices, lower purchase prices, and lower total cost of ownership. Given the projected widespread adoption of the technology, EV charging comes to represent a major new load on the power system. By 2026, annual demand from EVs alone exceeds 1 million MWh in our modeling and continues to grow over the study horizon, eventually representing nearly 12 million MWh by 2050. EVs represent 7% of the total system load under BAU by the end of the forecast.

A Zero Carbon Electricity Grid

This rest of this chapter looks at how transitioning away from Virginia's current fossil fleet would change the composition of the electric grid. New generation resources, including utility-scale solar (UPV) and battery energy storage systems (BESS), existing carbon-free generators such as hydroelectric dams and wind farms, and the effects of energy efficiency (EE) and demand response (DR) on the energy system are all considered when meeting projected electricity demands in these transition plans.

Demand Changes from BAU to Zero Carbon Scenarios

All Zero Carbon Scenarios use the same demand forecast. The most obvious difference between the Zero Carbon Scenarios and BAU is the amount of EE & DR. Figure 3-4 illustrates how much more EE & DR is achieved when they are deployed on an economic basis. As illustrated, demand in the ZC scenarios remains flat or negative through 2030. Demand rises at a rate of 0.5% compared to a demand growth rate of 0.8% in BAU.

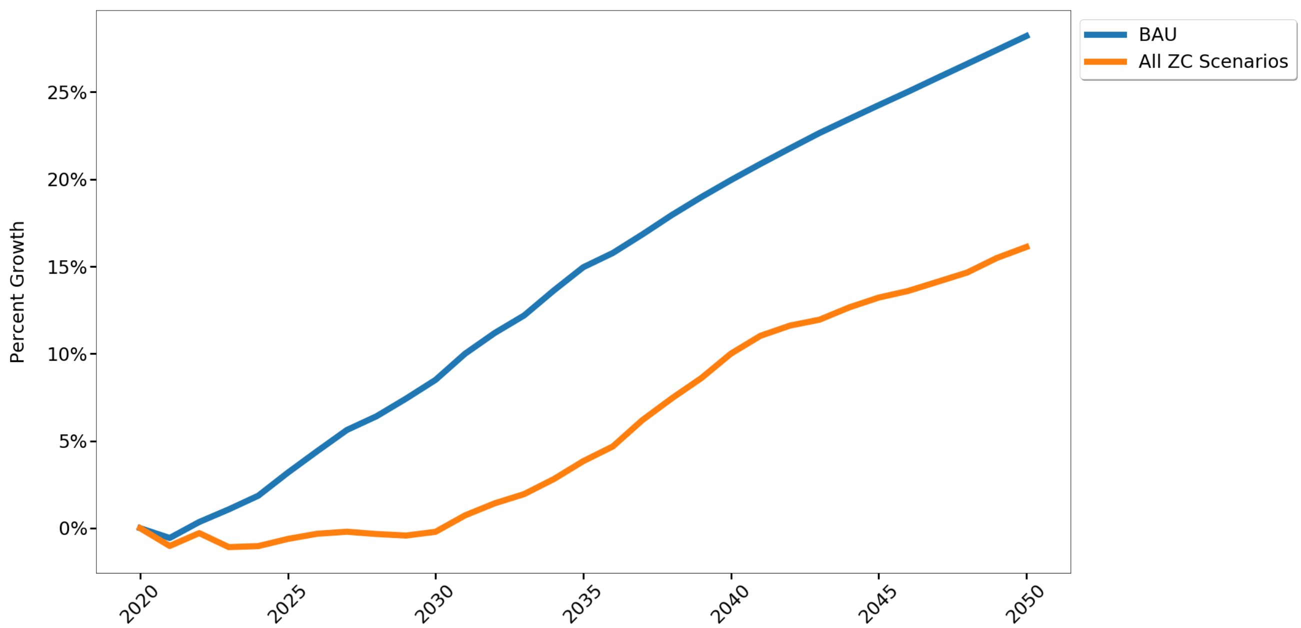


Figure 3-4: Virginia Demand Growth over Time

The EV forecast used for each of the Zero Carbon Scenarios is the same. EVs make up 9% of the total system load in 2050 Zero Carbon Scenarios (EVs make up a higher share of load in ZC than the BAU due to lower total demand). Figure 3-5 shows how electric vehicles as well as EE & DR programs are projected to affect electricity demand. In every Scenario, EE & DR is expected to significantly reduce Virginia's electricity demand more than EVs increase demand.

In the Zero Carbon Scenarios, different quantities of EE & DR are available at different levelized costs. Zero Carbon Scenarios add these demand-side programs up to the point where the marginal cost of additional EE or DR exceeds the wholesale cost of generation. EE & DR savings increase year-over-year until 2036. Starting in the late-2040s, savings pick up again and exceeds the levels of the early to mid-2030s.

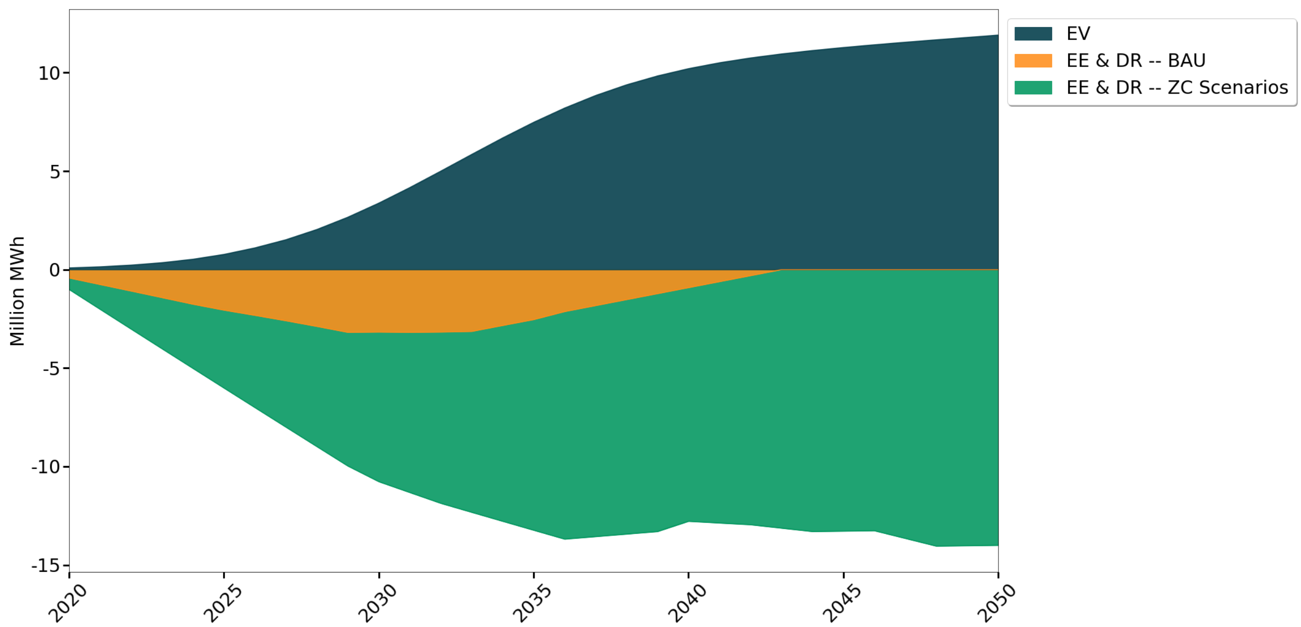


Figure 3-5: EE, DR, and Electric Vehicles' Contribution to Energy Demand

Capacity Buildout in Zero Carbon Scenarios

In the Zero Carbon 2050 Scenario (ZC 2050), as with all other Scenarios, coal plants are retired by 2030, which is illustrated by the disappearing gray bar in Figure 3-6.

The loss in BAU coal electricity generation is offset by increased reliance on natural gas combined cycle plants and expansion of UPV and BESS facilities. While existing gas generators run more often, no new gas plants are built to accommodate decreased coal generation. Energy efficiency & demand response, solar, and storage deployments also allow for a gradual reduction in energy imports, or power purchases from the PJM regional grid. While a few natural gas combustion turbines are retired in the 2030s, the bulk of the gas-fired plant retirements occur within the final five years leading up to the target decarbonization year, a pattern repeated in each of the Zero Carbon Scenarios.

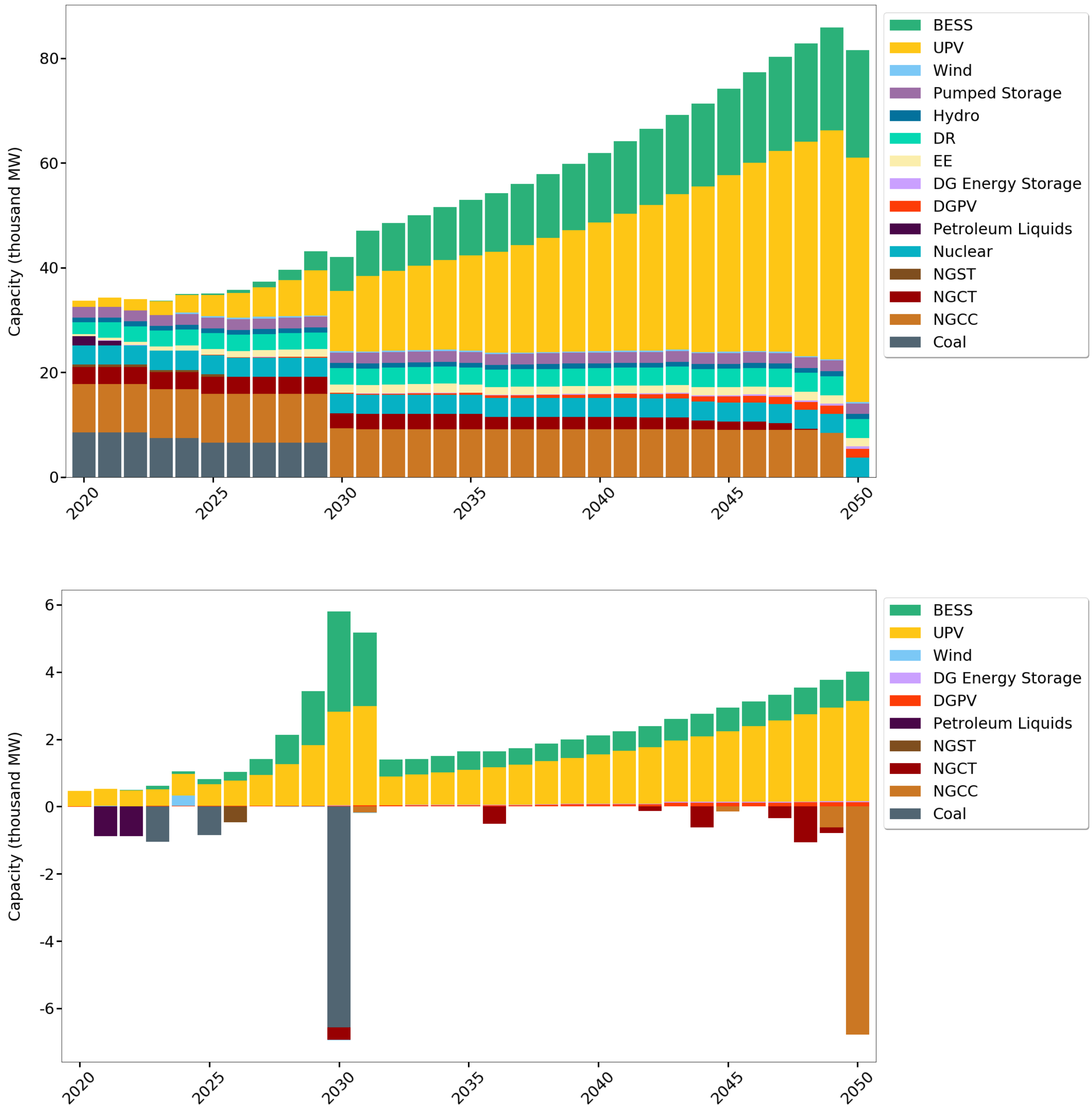


Figure 3-6: Scenario 2050 Capacity by Resource and Additions/Retirement Schedule

The extent of the difference between the three ZC scenarios (ZC 2050, ZC 2040, and ZC 2030) can be seen in Appendix B.

Key Takeaways

When looking at the results for Virginia as a whole, the impact of various technological and behavioral trends emerges as critically important to the energy future of the Commonwealth. In our modeling, the expanded use of energy efficiency and demand response resources enables Virginia to avoid expensive build outs of polluting infrastructure. This is to be expected, as these demand-side resources represent the lowest cost options in a decarbonizing grid. Cost-effective deployment of these critical technologies will require the deployment of financial and behavioral (customer education, engagement, challenges, etc.) approaches to maximize the benefits to all users of the grid.

In a similar vein, it is worth keeping in mind that this modeling selects the least cost resources to meet energy and capacity requirements in each scenario. Demand response, energy efficiency, solar, and battery storage comprise the overwhelming share of new capacity and generation deployed. The model does not consider other priorities, such as social equity, economic development, land use,[i] or resource diversity in forecasting. Policymakers, and Virginians writ large, may consider these additional factors as they chart the Commonwealth's energy transition.

Other key takeaways:

- An important milestone is reached in the late 2020s when battery storage becomes the least-cost capacity resource. As a result, utility-scale battery energy storage systems (BESS) play important roles in the energy future of the Commonwealth in every Scenario.

- The amount of RE generation in the ZC Scenarios is more than twice that of the BAU.

- Utility-scale solar becomes a major source of generation in every Scenario and is the dominant source of new generation in all cases except the BAU. The BAU scenario builds out natural gas generation as specified in Dominion and APCo IRPs. The Zero Carbon Scenarios, on the other hand, mostly add UPV and BESS resources, which become more cost effective for meeting peak demand than natural gas technologies by 2030.

- Widespread adoption of electric vehicles leads to increased demand, coming to represent more than 10% of the entire electricity load in the Commonwealth in every Scenario. Without significant changes in utility rate structures, incentives, and grid integration, EV charging behaviors and patterns are projected to become major drivers of the electricity demand curve for the Commonwealth, not unlike HVAC loads today. At the same time, aggressive energy efficiency investments ensure that demand increases at a reasonable pace.

With thoughtful approaches, supply-side and demand-side resources can be leveraged to provide benefits to users of the grid and all participants can add value to the system. Achieving this vision may require a shift in the current utility paradigm and require cooperation between all participants. A strategic approach to decarbonization can deliver significant benefits for the whole of Virginia like reduced bills, greater economic investment, and lower public health expenditures, as detailed in the chapters that follow.

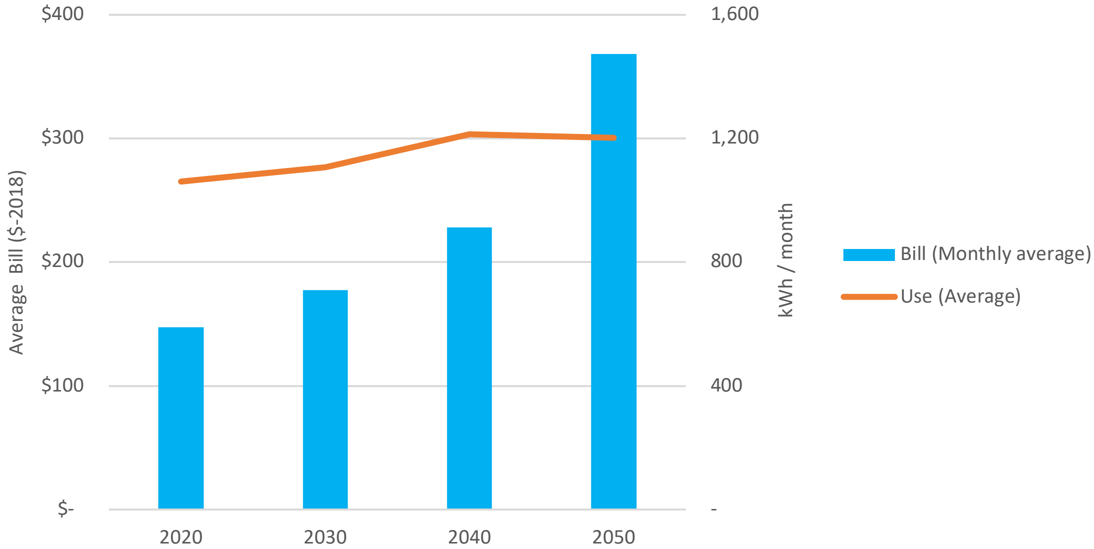
4. RATEPAYER IMPACTS

The differing capacity additions and retirements in Zero Carbon Scenarios from Virginia's Business-As-Usual Scenario will have implications across the Commonwealth. Decarbonizing Virginia's electricity system has a variety of economic impacts, prominent among them are those felt by Virginia families.

The increase or decrease in the average electric bill of a typical Virginian is a very important financial metric to consider. Utility rates, or the per kilowatt-hour cost of electricity, are oft-used measures of impact. But rates alone tell an incomplete story, as higher rates do not necessarily result in higher bills if usage decreases. For example, parts of the country with higher rates often have lower bills due to lower usage. Therefore, this chapter will focus on bill impacts, a more holistic metric that encompasses variations in both electric rates and electricity consumption.

Under the Business-as-Usual (BAU) Scenario, electricity bills are expected to rise over time. The BAU projection for residential customers in VA is shown in Figure 4-1. The average bill grows from approximately $150 per month in 2020 to approximately $370 per month by 2050. Demand grows during that period as well, but at a much lower rate, from an average of 1,065 kWh per month to 1,200 kWh in 2050. This represents a 13% increase in household usage. While energy efficiency slows demand growth in the BAU scenario, in the Zero Carbon Scenarios, per-household demand remains almost flat due to efficiency investments.

The most pronounced difference between the BAU and Zero Carbon Scenarios is that bills are significantly lower in almost every Zero Carbon year (Figure 4-2). For the 2040 and 2050 scenarios, bills are consistently lower across all 30 years when compared with BAU. In sum, the analysis indicates that the average Virginia ratepayer would see a lower electricity bill each month were the Commonwealth to set a zero-carbon target by 2040 or after than they would under Business-As-Usual. In the 2030 Zero Carbon Scenario, bills are higher than BAU for nine of the first 13 years but 5-10% lower by 2035 and 10-15% lower by 2050.



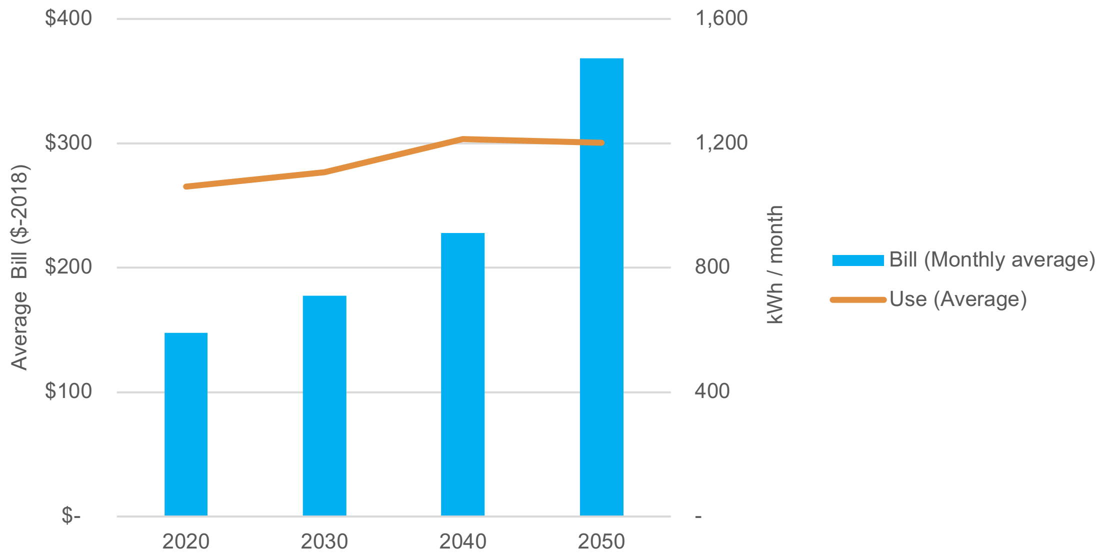


Figure 4-1: Average BAU Residential Electric Bill compared with Household Demand Growth

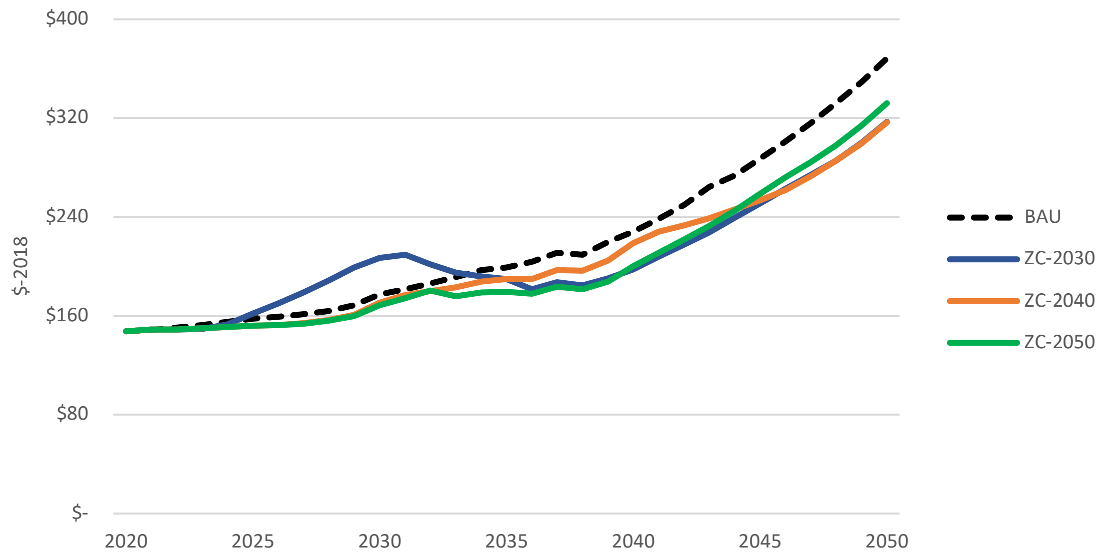


Figure 4-2: Average Residential Customer Bills

As the prior chapter noted, the most pronounced transition in the Zero Carbon Scenarios tends to occur in the years immediately preceding the target date. This transition comes with cost impacts, which may translate to rate increases, but other factors, such as efficiency gains, serve as a counterbalance, particularly in the later target-date scenarios, helping to minimize bill impacts. Two of the major sources of bill savings are realized from energy efficiency & demand response investments and the economic advantages of UPV and BESS. Average EE & DR savings persist for 10 years beyond the initial investment, which leads to flatter demand growth, meaning fewer new utility investments are required. New UPV & BESS investments reach economic parity with natural gas by 2030; further UPV & BESS deployment provides ongoing savings compared to fossil fuel investments. More renewable energy deployment means avoiding the operating and fuel costs for some conventional generation under BAU.

Another way to compare how a zero-carbon grid would impact ratepayers is to look at changes in homeowner electricity bills. Figure 4-3 shows the net present value of Zero Carbon Scenario's bill impacts relative to BAU.

There are two major takeaways from Figure 4-3. First, in the long run, all Zero Carbon Scenarios are financially positive for households. Compared to BAU, the average total household discounted savings from 2020 to 2050 will range from $1,600 (ZC 2030), to $3,400 (ZC 2050).

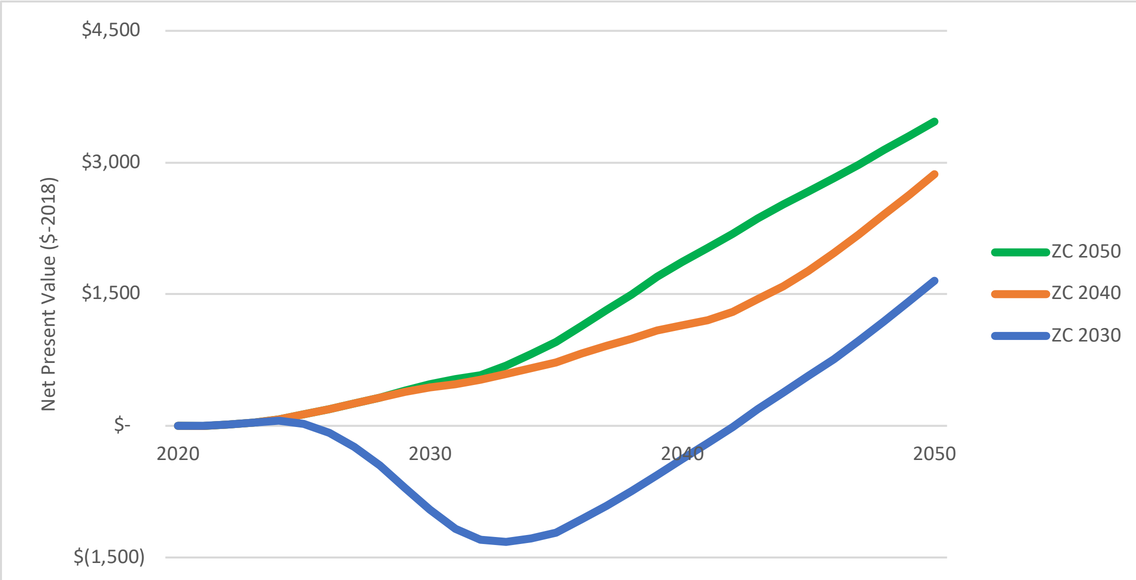


Figure 4-3: Average Household Bill Savings

Second, under ZC 2040 and ZC 2050, customers save money each year throughout the 30-year period, enjoying monthly lower bills compared to BAU. The ZC 2030 scenario, which represents a faster transition, leads to higher bills early in the period, but by 2035 even this scenario turns positive for customers, ultimately producing net savings over the entirety of the 30-year period.

The main reason that ZC 2030 leads to bills higher than BAU in some years has to do with the lead time for new plant additions. Under ZC 2030, almost all of the investments needed to reach zero emissions are made in the first 10 years, rather than over the course of 20 to 30 years. With a zero emissions target of 2040 or 2050, investments are spread out over a longer time period and thus benefit from continually declining resource costs, leading to lower electric bills overall. Under ZC 2040 and 2050, monthly bills quickly fall below BAU, and the gap widens over the 30-year period (Figure 4-2). Under ZC 2030, with its accelerated timeline, monthly bills initially rise but begin to fall by 2030, and cross below the BAU trend line by 2035, with lower monthly bills thereafter. Over the 30-year period, even ZC 2030 results in total savings for the average Virginia household (Figure 4-3).

Key Takeaways

- In the BAU, residential electricity bills are expected to double by 2050.
- From 2020 to 2050, the average customer will pay less for electricity each year under the Zero Carbon 2040 and 2050 Scenarios, as compared to the BAU.
- From 2035 to 2050, the average customer will pay less for electricity under the ZC 2030, as compared to the BAU. Only under ZC 2030 do average household bills rise higher than BAU, and only for the first half of the 30-year period.

- In the long run, all Zero Carbon Scenarios are financially positive for the average Virginia household, producing net savings ranging from $1,600 to $3,400 over the 30-year period.

5. ECONOMIC DEVELOPMENT IMPACTS

This chapter will explore the statewide economic impacts of shifting electricity generation to clean energy technologies and of aggressively increasing energy efficiency programs. The Bureau of Labor Statistics reports well over 4 million jobs in Virginia in 2019 and the Commonwealth's GDP was just under $500 billion in 2016.[ii, iii] This section analyzes changing investments in the electricity sector between the BAU and Zero Carbon Scenarios, which are used to forecast impacts on the Virginia economy. The ATHENIA model evaluates the impacts of variations in energy sector investments and cash flows as called for by the Scenarios through a combination of the IMPLAN economic development model and its own algorithms.[iv] IMPLAN is a widely utilized regional economic impact model.

The energy sector in Virginia consists of about 50,000 workers statewide, accounting for approximately 1.3% of Commonwealth employment.[v] The advanced energy industry, which is comprised of workers in a variety of fields including energy efficiency, renewable generation, battery storage, advanced transportation, and grid technology, is twice that size today, accounting for over 101,000 jobs in the Commonwealth.[vi] Shifting to a decarbonized economy by investing more in energy efficiency, battery storage, and zero-emission generating technologies results in more jobs. Building, operating, and buying fuel for a fossil power plant are less labor-intensive tasks than similar investments in clean energy technologies; as a result, clean energy creates more jobs per invested dollar. A significant shift in employment and economic opportunities will occur under Zero Carbon Scenarios versus BAU because different jobs are created directly and indirectly as a result of the deployments of the various technologies outlined in Chapter 3.

Employment, Income, and GDP

This analysis measures employment gains and losses in job-years. A job-year is equivalent to the labor performed by one full-time employee for one year. Job-years are used to account for the persistence of job creation and loss, putting short- and long-term jobs on equal footing. For example, two jobs created in 2030 and sustained through 2045 equals 30 job-years created.

The BAU Scenario investments add about 45,000 job-years in the natural gas sector, as well as 133,000 job-years related to energy efficiency and renewable energy. Approximately 177,000 job-years are created through the BAU Scenario. Each of the Zero Carbon Scenarios results in more than twice as much employment activity – over 400,000 total job-years. New gross job-years related to each electricity technology are shown in Figure 5-1. Solar is the largest job-creating sector, followed by energy efficiency and battery storage. Jobs in the solar industry make up about 60% of the new jobs.

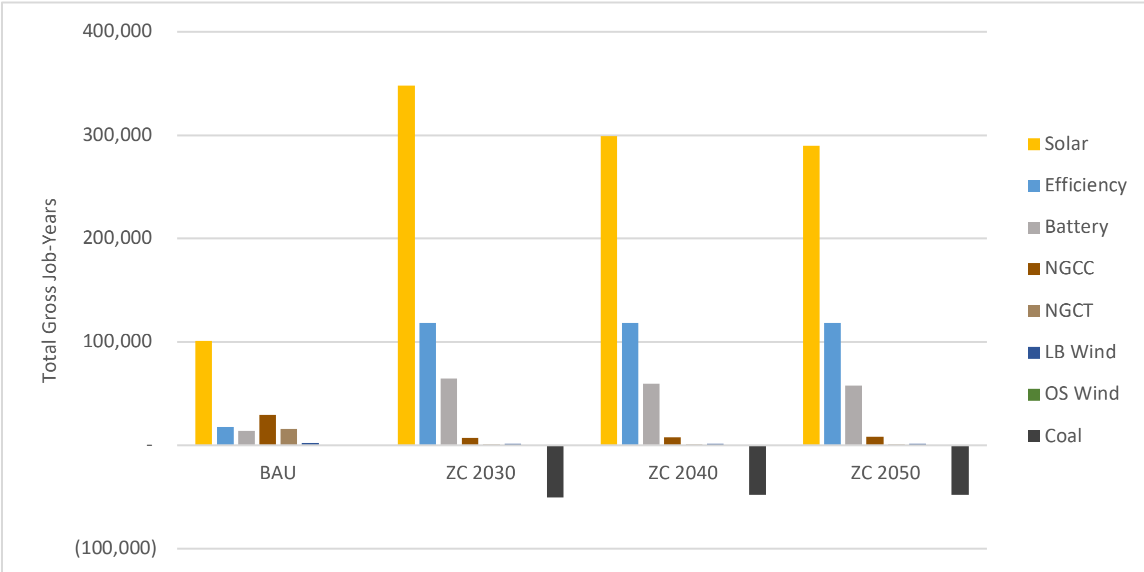


Figure 5-1: New Gross Job-Years Created by Each Scenario through 2050, Relative to 2018

While the jobs are not evenly distributed over the 30-year period through 2050, it is useful to consider the numbers in annual terms. The BAU's 177,000 new job-years average almost 6,000 jobs per year. Comparing these numbers with the Zero Carbon Scenarios, the clean energy investments lead to an average of about 13,000 new jobs each year until 2050. Retiring coal plants early results in 2,800 annual jobs lost, though it is worth noting that 2,100 of those jobs are not located in Virginia, but in neighboring states where those plants are located. However, most of the large coal units are already expected to retire between 2035 and 2043 under BAU, limiting the job-loss impacts of earlier retirements. A retirement schedule for coal plants under different scenario projections can be found in Appendix B.

The Zero Carbon Scenarios' impacts on economic development in Virginia are shown in Figures 5-2A and 5-2B. The ZC 2030 Scenario shows the greatest net job-year creation, as well as the greatest amount of net total labor-income and GDP. This is mostly a result of accelerating retirements of fossil-fuel-dependent power sources and the shifting to UPV & BESS.

As jobs shift from fossil fuel-related services to those that support cleaner energy, household bill savings, identified in Chapter 4, begin to contribute to overall economic growth within Virginia. For example, a household that experiences a decline in their electricity bill will likely spend that additional income on other activities in Virginia. Furthermore, spending on fuels primarily bought from out-of-state markets (such as natural gas) falls dramatically, which helps keep energy dollars local, supporting economic development in Virginia.

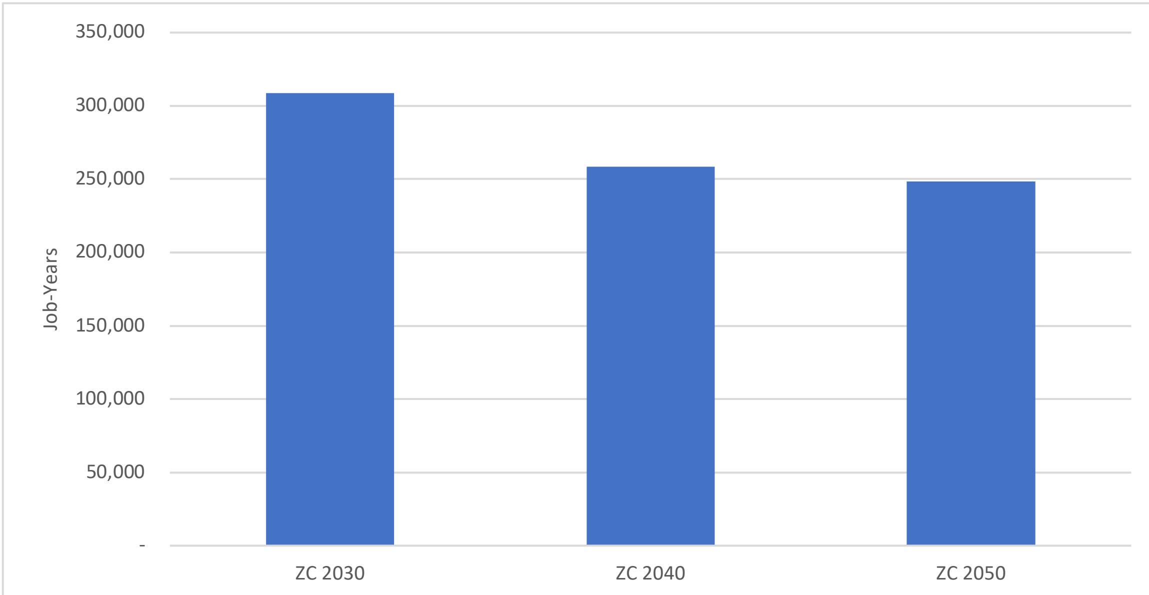


Figure 5-2A: Net Job-Years Gains in ZC Scenarios (Relative to BAU)

Virginia's net labor income (i.e. employee compensation) and state GDP follow a similar story to that of job creation. The introduction of clean energy technologies more than offsets the decline in labor income from retiring fossil fuel plants. Net gains ranging from $15 billion to $23 billion in labor income are realized as a result of clean energy technology deployment and the retirement of coal and natural gas power plants, with the ZC 2030 scenario providing the largest gains.

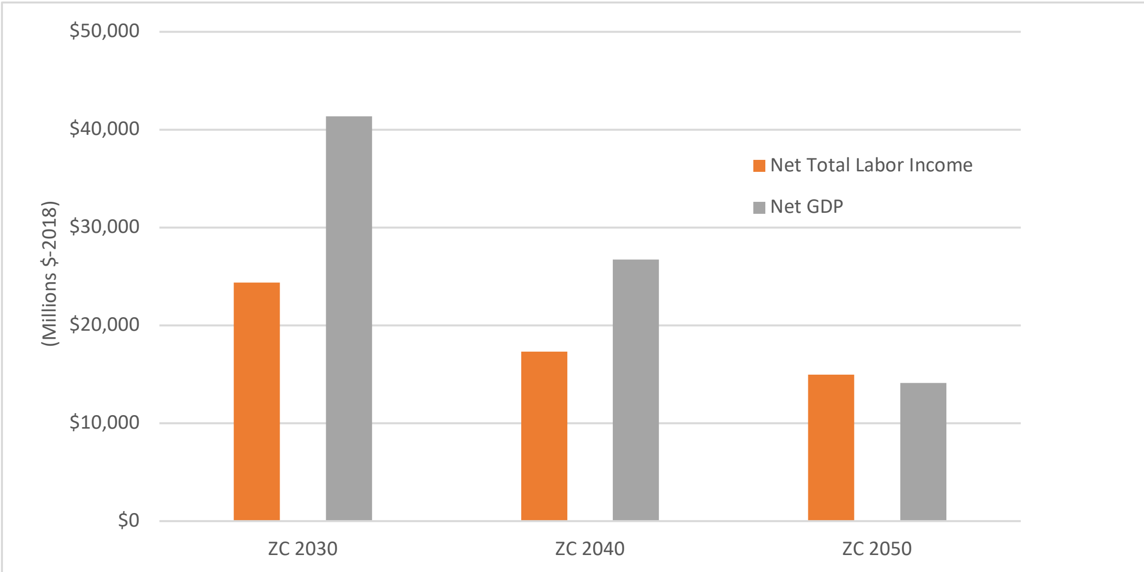


Figure 5-2B: Increase to Virginia Net GDP and Labor Income (Relative to BAU)

Net job-years gained or lost for each technology are shown in Figure 5-3. Retirements of coal and natural gas power plants produce job-year losses within each Zero Carbon Scenario; however, this is substantially outweighed by job creation from the deployment of carbon-free resources. Although the ZC 2030 has the most net job-years, each Zero Carbon Scenario comes out ahead of the BAU, even after accounting for the job losses in fossil fuel generation.

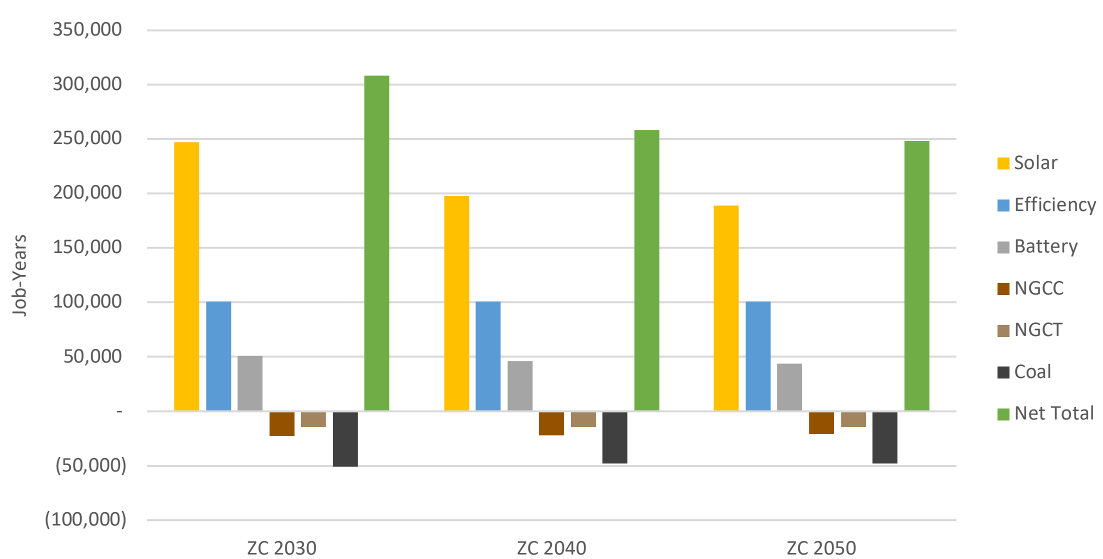


Figure 5-3. Virginia's Net-Job Years, Relative to BAU

This economic development analysis shows that shifting Virginia away from fossil fuel energy production to an energy system grounded in clean energy and energy efficiency should yield net job growth, increased labor income, and state GDP growth. The increase in clean energy investment leads to positive job, income, and state GDP outcomes. Job creation, labor income, and GDP growth are highest under ZC 2030, demonstrating that earlier investments and a faster transition to clean energy will produce the most economic development in the Commonwealth.

Key Takeaways

- ZC 2030 is expected to create about 500,000 job-years, while ZC 2050 is expected to create about 400,000. The BAU projected job-year growth is less than half that – 177,000 by 2050.

- The most aggressive scenario, ZC 2030 leads to the greatest net job-year creation, as well as the greatest amount of net total labor income and increase in state GDP.

- Earlier investments and a faster transition to clean energy will produce the most economic development in Virginia but comes at a higher initial cost to electricity consumers (see Chapter 4).

- All Zero Carbon scenarios lead to stronger economic development results than BAU.

6. CO-BENEFITS OF VIRGINIA'S ZERO-CARBON FUTURE

In addition to the financial benefits of shifting to carbon-free electricity sources, a clean grid would improve air quality for Virginia by reducing air pollutant emissions generated by the electricity and transportation sectors (an important facet as the two become more interconnected through transportation electrification). Decreasing these emissions not only provides short- and long-term public health benefits, but also helps achieve the Commonwealth's goals related to the mitigation of climate change impacts. This chapter explores the environmental and social benefits achievable through different decarbonization scenarios.

Emissions Impacts Under BAU

ATHENIA tracks the major byproducts of electricity generation, including six localized public health pollutants – sulfur dioxide, nitrous/nitric oxide, particulate matter (2.5 microns), particulate matter (10 microns), ammonia, and volatile organic compounds (SO_2, NO_x, $PM_{2.5}$, PM_{10}, NH_3, and VOCs, respectively) – as well as carbon dioxide (CO_2). The majority of Virginia's electric-sector pollutant damages come from two sources: the social and global cost of CO_2 emissions and the localized public health impacts of SO_2 emissions. The bulk of additional damages are attributed to the localized public health impacts of $PM_{2.5}$ and NO_x emissions. Under BAU, the cumulative damage from localized pollutants is projected to grow from $500 million in 2020 to over $7 billion by 2050, while social and global pollutant damages from CO_2 grow from $2.5 billion in 2020 to $56 billion in 2050.

Avoided Emissions

The Zero Carbon Scenarios phase out all coal plants meeting Virginia's energy demand by 2030. The impact of this transition on air pollution is striking in all Scenarios, with the most significant emissions reductions in NO_x, SO_2, and $PM_{2.5}$ levels. Additionally, total emissions for the full scope of monitored pollutants are reduced by at least 50% in each Zero Carbon Scenario (Figure 6-1), with most of these savings occurring after 6.5 GW of coal plants are retired in 2030.

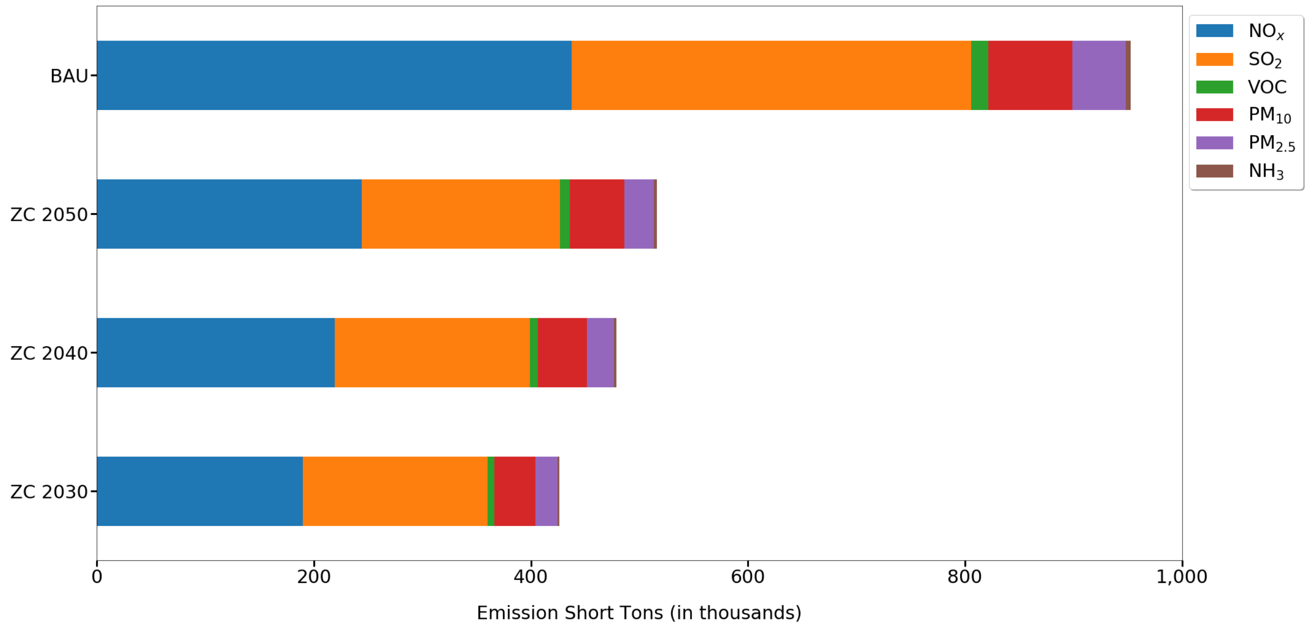


Figure 6-1: Cumulative Localized Pollutant Emissions through 2050 by Scenario

Particulate matter (PM) is tracked under two major categories – particulates sized 10 microns or less (PM_{10}) and those sized 2.5 microns or less ($PM_{2.5}$). Both are primarily generated by coal-fired and natural gas-fired power plants, and subsequently trend with the dispatch of these sources. Cumulative $PM_{2.5}$ emissions under BAU are projected to reach 45,000 tons by 2050 but are expected to be cut by 45% to 60% under the various Zero Carbon Scenarios. Meanwhile, PM_{10} emissions, which exceed 65,000 tons cumulatively through 2050 under BAU, are also cut by 35% to 50% in the Zero Carbon Scenarios. This spread in reductions is tied to different Scenarios that rely on varying amounts of natural gas after 2030, at which point coal plants are taken offline, until these too are retired on or before the Scenario's target year.

Although nitrous oxide (NO_x) is a known byproduct of gas-fired plants, both NO_x and sulfur dioxide (SO_2) are primarily produced by coal-fired plants. As a result, in the BAU, NO_x and SO_2 emissions cumulatively reach over 425,000 tons and 350,000 tons, respectively. NO_x emissions are cut by 45% to 55% and SO_2 emissions are cut by 50% under the Zero Carbon Scenarios.

Ammonia (NH_3) is primarily a byproduct of gas-fired plants – more specifically from natural gas-fired combined cycle facilities. NH_3 emissions are expected to reach 4,000 tons cumulatively in BAU and will be cut by 30% to 65% under the various Zero Carbon Scenarios.

Volatile organic compounds (VOCs) consist of a large group of organic chemicals created during fossil fuel combustion that are themselves chemical precursors to many toxic aerosols and gases. VOC emissions are expected to reach over 15,000 tons cumulatively and will be cut by 45% to 60%.

Finally, carbon dioxide (CO_2) emissions are projected to reach 1.4 billion tons cumulatively between 2020 and 2050 under BAU. In each Zero Carbon Scenario, these emissions are expected to be cut by at least 50%. Figure 6-2 shows the ZC 2030, ZC 2040, and ZC 2050 Scenarios' avoided CO_2 emissions. The earlier the target decarbonization year, the more emissions are avoided.

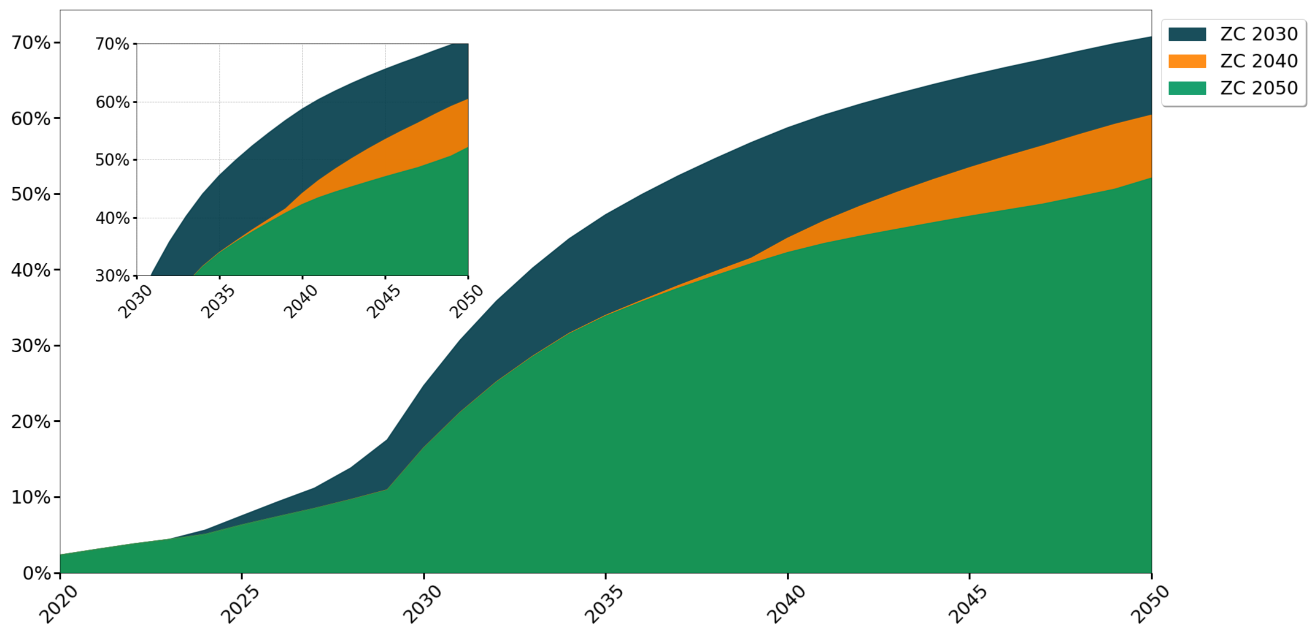


Figure 6-2: Cumulative Avoided CO_2 Emissions through 2050

Avoided Social and Economic Damages

The link between air pollutant emissions and a suite of social and economic damages is well established. For non-carbon emissions, ATHENIA assigns plant-specific damages associated with each emission's links to human health, agricultural damages, and other physical effects.[vii] For CO_2 emissions, the damages are derived from the social cost of carbon found in the Technical Update to the U.S. Government's Interagency Working Group Social Cost of Carbon.[viii] The social cost of carbon accounts for changes to agricultural productivity, sea level rise, rainfall changes, extreme weather, and risks to human health. It is worth noting that the Social Cost of Carbon is a global measure of the damages resulting from CO_2 emissions, whereas other pollutants' damages are more regional in nature, and thus more likely to impact the immediate geographic area – in this case the Commonwealth. We discuss these damages separately.

Figure 6-3 shows the annual trajectory for public health benefits for each scenario relative to BAU emissions damages. The impact of removing all coal plants from Virginia's power grid can be seen by the 2030 spike in benefits, accounting for nearly $250 million or more in avoided annual public health damages.

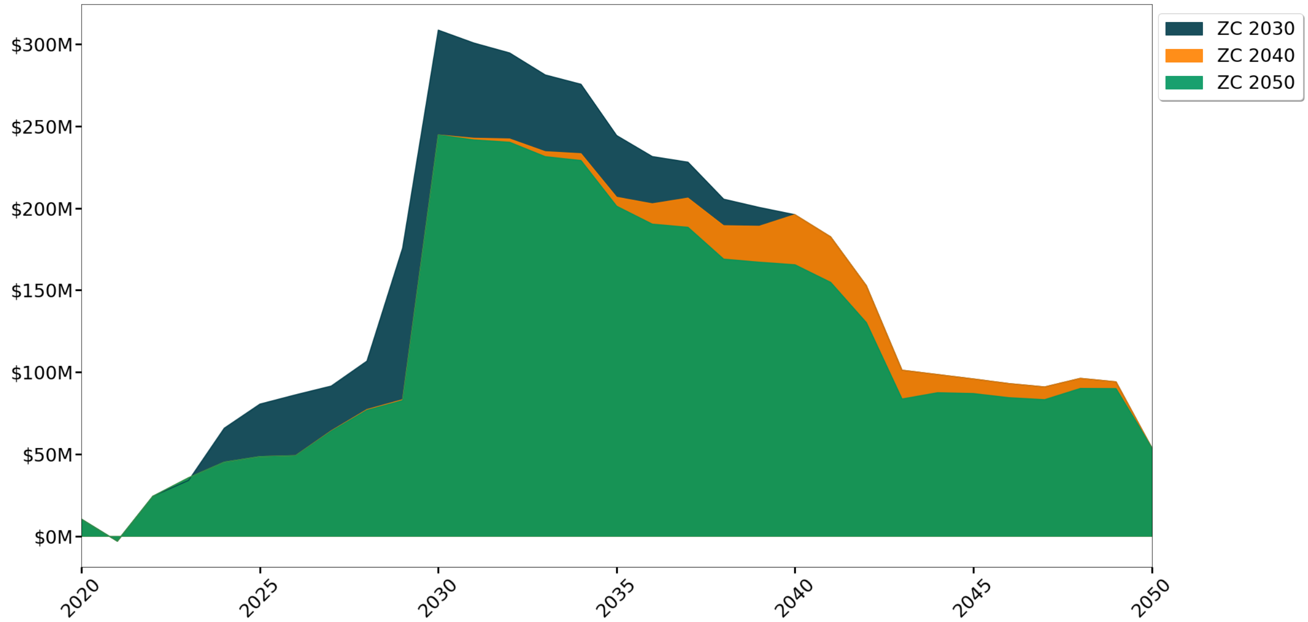


Figure 6-3: Non-Carbon Public Health Benefits in the Zero Carbon Scenarios

Overall, the Zero Carbon Scenarios are projected to reduce the total social and economic damages of non-carbon pollutants by at least $2 billion between 2020 and 2035 (Figure 6-4). By 2050, each Scenario avoids more than $3.5 billion in damages, approximately 40% of the projected damages under BAU. Given the localized nature of the impacts from these pollutants, these avoided costs can be closely linked to improved health and economic outcomes for Virginians.

The avoided damages associated with CO_2 emissions leads to an additional $25 billion to $35 billion benefit between 2020 and 2050, as seen in Figure 6-5.

Key Takeaways

- Each Zero Carbon Scenario offers a 50% or greater reduction in both localized public health pollutants and CO_2 emissions compared to the BAU.
- Cumulative public health benefits, in the form of cleaner air, less illnesses, and premature deaths due to avoided emissions, in each Zero Carbon Scenario are $3.5 billion or greater by 2050.
- Cumulative environmental benefits due to avoided CO_2 emissions in each Scenario are $25 billion or greater, with a portion of those benefits accruing to Virginia.
- The greatest public health benefits come from reductions in $PM_{2.5}$, NO_x, and SO_2

emissions, which are air pollutants with damaging impacts on local populations in Virginia.

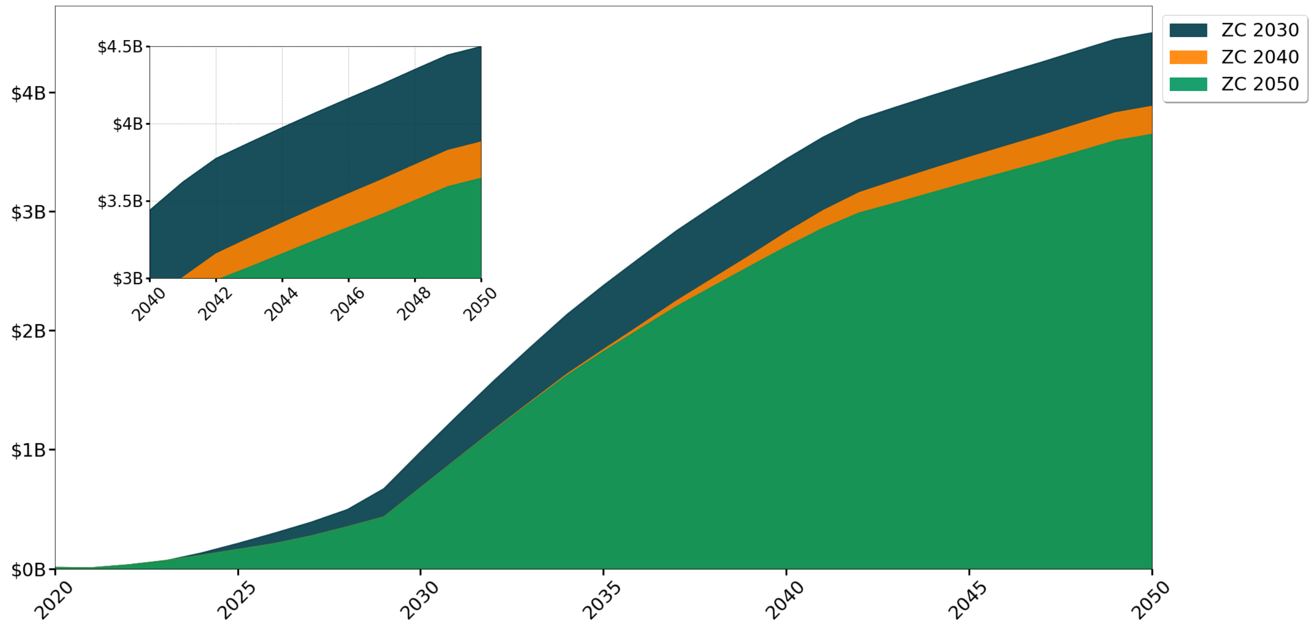


Figure 6-4: Cumulative Value of Avoided Public Health Damages

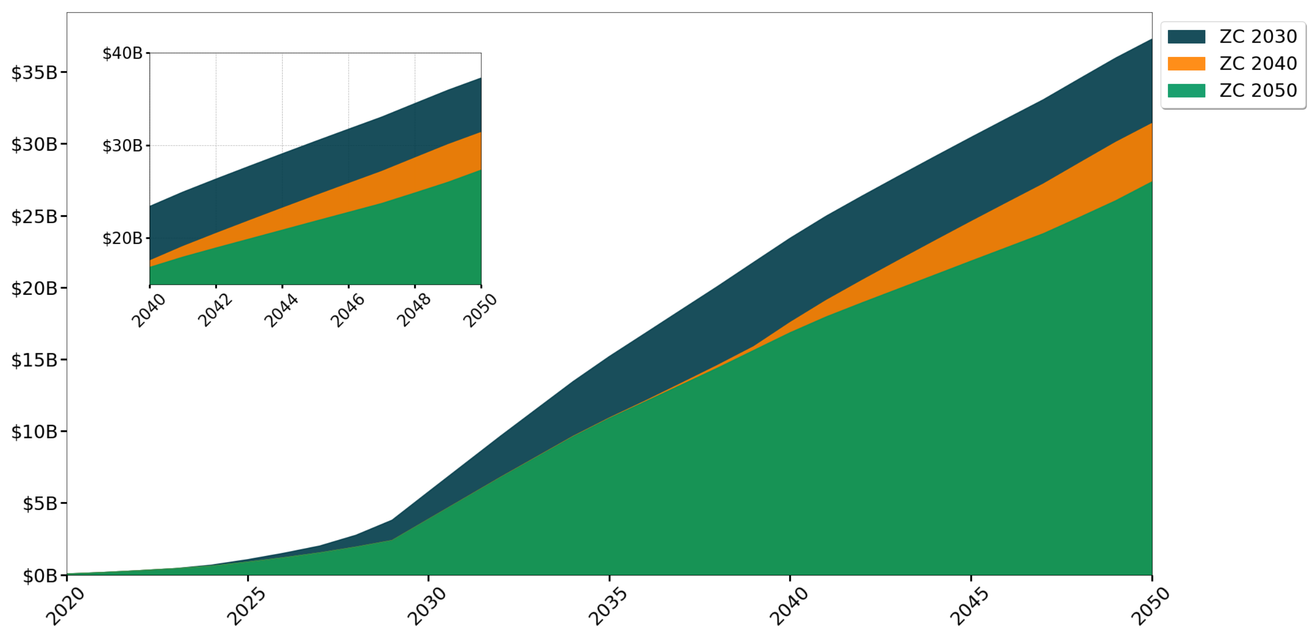


Figure 6-5: Cumulative Value of Avoided Social Damages

7. COST-BENEFIT ANALYSIS

A cost-benefit analysis is a standard, systematized approach to evaluating the economics of business or public policy decisions. One goal is to determine whether a proposed policy's benefits outweigh its costs. Another way to use a cost-benefit analysis is to compare the scale of costs required to achieve different levels of benefits. Both of these are useful in determining the net benefits (the sum of all benefits minus the sum of all costs) of a decision, which is a common consideration in evaluating different policy options. Lastly, cost-benefit analysis can be used to judge how effectively benefits relate to costs by calculating the ratio between them, with a higher ratio representing a more cost-effective policy decision. Policymakers are regularly called-upon to consider both the scale of the net benefits and the cost-effectiveness of a policy decision. Cost-benefit analysis is a reasonable way to compare options with a range of different benefits and costs.

This chapter assesses the costs and benefits of changing the build out of the electricity grid and reducing pollution associated with generating electricity from fossil fuels. In order to assess Virginia's benefits associated with decarbonizing the electric grid, several elements from previous chapters will be brought together. These elements include the difference in new power plant and EE & DR investments, the difference in plant operating costs, and the difference in local public health and social damages associated with electricity generation. The cost-benefit analysis does not separately account for employment gains, losses, and GDP growth discussed in Chapter 5. Those are macroeconomic effects rather than inputs for a cost-benefit analysis.

Each of the three Zero Carbon Scenarios costs and benefits relative to the BAU Scenario will be identified. In this analysis, benefits are quantified as the dollar value of avoided pollution damages and the avoided cost of generating fossil fuel-reliant electricity for Virginia customers.[ix, x] All dollar values of costs and benefits are analyzed using a 3% discount rate, the value recommended by the Federal government for long-lived investments.[xi] On this basis, all three Zero Carbon Scenarios are cost effective.

Results

Figure 7-1 shows the total benefits within each Zero Carbon Scenario relative to the BAU Scenario. In order to visualize the local versus global impacts, benefits are broken out to include (green bars) or exclude (blue bars) avoided CO_2 damages.

The ZC 2030 Scenario shows the highest total gross benefits relative to BAU: $106 billion through 2050 when including avoided CO_2 damages, 17% and 24% higher than the 2040 and 2050 Scenarios, respectively (Figure 7-1 and Table 7-1). Avoided generation costs constitute approximately 30% of total benefits, when including avoided CO_2, within all ZC Scenarios. Benefits from avoided generation and local air pollution alone (excluding CO_2) total $41.7 billion under ZC 2030, $32.1 billion under ZC 2040, and $24.6 billion under ZC 2050.

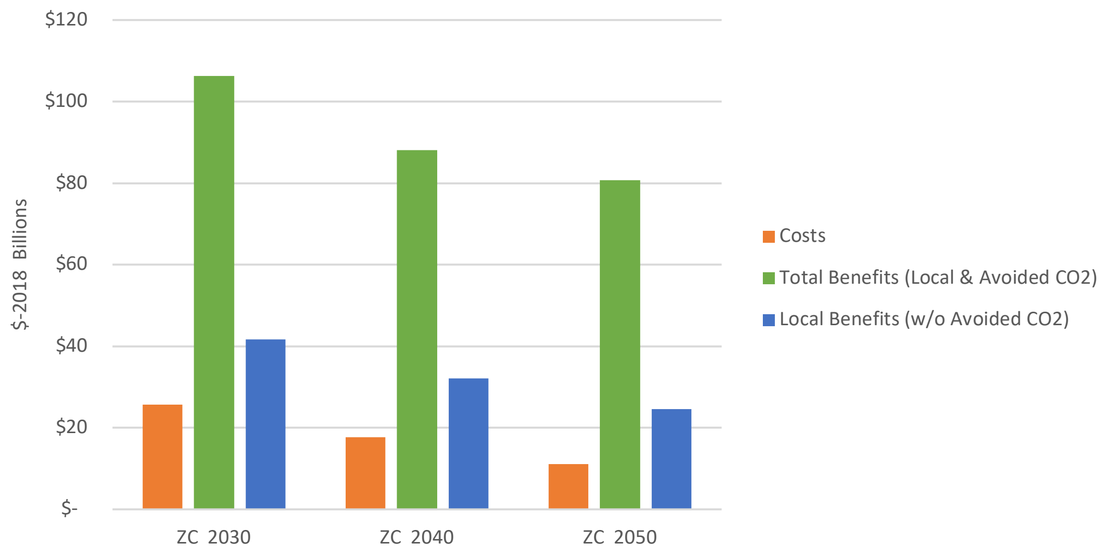


Figure 7-1: Benefits and Costs Across all Zero Carbon Scenarios

The costs associated with the Zero Carbon Scenarios are the incremental investments required for the deployed technologies explained in Chapter 3. These investments include equipment costs for each added technology, energy efficiency and demand response measures, and demand-side administrative and program costs. The costs associated with these factors ranges from $12 billion to $26 billion in all Zero Carbon Scenarios compared to the BAU, as shown in Figure 7-1 above and Table 7-1 below.

The benefit cost ratios of each Scenario compared to BAU is represented along the horizontal axis of Figure 7-2. The vertical axis represents the net benefits. A scenario in the upper-right quadrant would represent high net benefits and high cost-effectiveness.

Overall, all Zero Carbon Scenarios present a benefit-cost ratio greater than one when avoided CO_2 damages are excluded, and a benefit-cost ratio greater than four when CO_2 damages are included, showing strong cost-effectiveness for all three Scenarios. For every extra dollar invested in EE & DR, BESS, and PV, between $1.62 and $7.23 of benefits should be realized.

The ZC 2040 and ZC 2050 both have higher benefit-cost ratios than the ZC 2030 Scenario. However, overall net benefits are highest in the ZC 2030 scenario: $80.3 billion in ZC 2030, versus $63.5 billion in ZC 2040 and $69.7 billion in ZC 2050, including CO_2 damages. Without CO_2, net benefits are still highest for ZC 2030: $16 billion, versus $14.5 billion in ZC 2040 and $13.6 billion in ZC 2050.

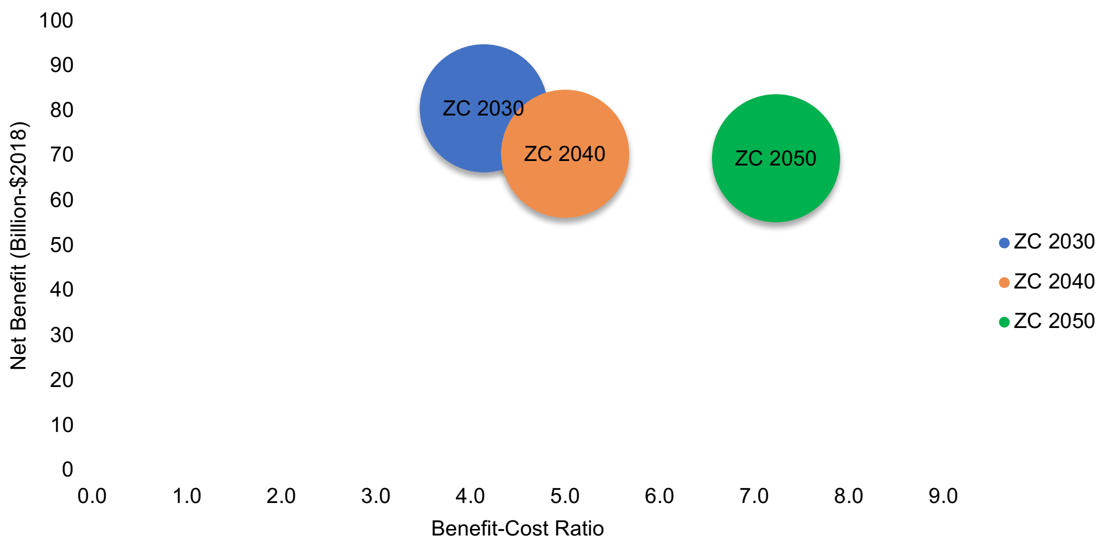


Fig 7-2: Benefit-Cost Ratios and Net Benefits beyond BAU by Scenario

This report tries to paint a full picture of what Virginia can expect form a strategic approach to decarbonizing its grid. Chapter 3 showed what different build-outs of the grid could look like. Chapter 4 highlighted ratepayer impacts of the three Zero Carbon Scenario buildouts. Chapter 5 & 6 spoke to economic development and public health considerations, respectively. When policymakers determine what sort of electricity grid to support in the future, the cost-benefit analysis of the Zero Carbon Scenarios is one more piece of information to help inform their vision of the future.

Key Takeaways

- The ZC 2030 Scenario sees the highest total benefits of $106 billion through 2050.
- The ZC 2050 Scenario yields the highest cost-benefit ratio of 7.23 (when avoided CO_2 emissions are included) and 2.21 (when CO_2 is excluded).
- The benefit-cost ratio for all Zero Carbon Scenarios is greater than one when avoided CO_2 damages are excluded, and greater than four when CO_2 damages are included, highlighting the dramatic impact that current carbon emissions have on human health and economic productivity in Virginia and nationwide.
- While there is variation in the ratios and net benefits of each ZC Scenario, based on this analysis, all ZC scenarios lead to net benefits even before counting CO_2 social benefits. ZC 2050 has the highest benefit-cost ratio and ZC 2030 the lowest, but all are more cost-effective than BAU.

- Macroeconomic impacts like GDP and job creation are not considered in a cost-benefit analysis and should be considered separately in evaluating the three Zero Carbon Scenarios.

Table 7-1: Cost-Benefit Summary Table

COSTS ($M)		ZC 2030	ZC 2040	ZC 2050
Change in Total investments		$25,700	$17,600	$11,000
BENEFITS ($M)				
Avoided Pollution Damages	Total	$70,700	$61,700	$62,000
	CO_2	$64,600	$56,000	$56,000
	Local Pollutants	$6,090	$5,610	$5,610
Avoided Generation Costs		$35,600	$26,500	$19,000
Benefits ($M) (Including CO_2 Avoided damages)		$106,000	$88,100	$80,700
Benefit-Cost Ratio (Including CO_2 Avoided damages)		4.14	5.00	7.23
Benefits ($M) (Not including CO_2 Avoided Damages)		$41,700	$32,100	$24,600
Benefit - Cost Ratio (Not including CO_2 Avoided Damages)		1.62	1.82	2.21

8. CONCLUSION

Based on analysis using the Greenlink Group's ATHENIA model, all three Zero Carbon Scenarios – making Virginia's electric power system zero-carbon by 2030, 2040, and 2050, respectively – show net benefits compared with a Business-as-Usual Scenario through 2050. This holds true in terms of bill savings, economic development (jobs, income, and GDP), and cost-effectiveness over the course of the period 2020 to 2050.

Of the three Zero Carbon Scenarios, the 2030 Scenario incurs the highest investment costs – and initially higher average household electricity bills – but produces the greatest benefits in jobs, income, and GDP, as well as substantial total bill savings over the 30-year period, while also providing the most benefits in reducing local and global pollution. By spreading the transition to zero-carbon electricity out over time, the 2040 and 2050 Scenarios produce household bill savings from the start of the 30-year period , while also generating more economic gains – jobs, income, GDP – and less public health and environmental damages (especially avoided CO_2 damages, which have global impact as well as local impact on Virginia).

- Virginia can successfully transition to a 100% carbon-free electric grid that will provide affordable, reliable, and cleaner electricity.
- In all Zero Carbon Scenarios, renewable generation and battery energy storage systems become the major source of both energy and capacity. By the late 2020s, battery storage becomes the least-cost capacity resource, replacing more expensive gas peaker plants.
- Under the Zero Carbon Scenarios, by 2050, Virginia's grid is comprised of over 40 GW of wind and solar, and over 20 GW of battery storage. Under BAU, Virginia relies on over 20 GW of coal and gas, and just 20 GW of renewables.
- Residential electric bills are significantly lower over the 30-year period in every Zero Carbon Scenario. Compared to BAU, the average total household savings from 2020 to 2050 range from $1500 under the Zero Carbon 2030 Scenario to $3500 under Zero Carbon 2050.
- Every major local and global air pollutant is reduced substantially. The cumulative value of avoiding the public health costs related to localized air pollution is greater than $3.5 billion and avoiding the greenhouse gas emissions is greater than $25 billion.
- All Zero Carbon Scenarios led to net job growth from new energy efficiency measures, as well as new renewable and battery storage resources. On average, Zero Carbon Scenario job creation exceeds BAU by an average of 7,000 to 11,000 jobs per year.
- Based on a cost-benefit analysis, Zero Carbon 2030, 2040, and 2050 offer total benefits ranging from $80 billion to $106 billion as compared to BAU, and net benefits ranging from $13.6 billion to $80 billion.

ENDNOTES

[i] The solar build out is expected to utilize < 1% of total land in Virginia.
[ii] Bureau of Labor Statistics. 2019. "Economy at a Glance: Virginia" https://www.bls.gov/eag/eag.va.htm
[iii] Federal Reserve Bank of St. Louis. 2019. "Total Gross Domestic Product for Virginia." https://fred.stlouisfed.org/series/VANGSP
[iv] IMPLAN. 2019. "IMPLAN: Economic Impact Analysis for Planning." https://www.implan.com/
[v] U.S. Energy and Employment Report. U.S. Department of Energy, 2017, U.S. Energy and Employment Report. Virginia specific information can be found within the USEER State Charts
[vi] Advanced Energy Economy 2019 Virginia Employment Fact Sheet, August 2019. Data collected for the 2019 U.S. Energy & Employment Report by the Energy Futures Initiative.
[vii] For more information on the monetization methodology, see https://public.tepper.cmu.edu/nmuller/APModel.aspx
[viii] Interagency Working Group on Social Cost of Greenhouse Gases, United States Government. "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866." August, 2016. https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf
[ix] Pollution damages include monetary losses incurred through the production of CO_2, PM_{25}, SO_2, NO_x, NH_3, VOCs, and PM_{10}, as discussed in Chapter 6.
[x] Avoided generation means the reduction in costs due to operating a renewables and battery-storage heavy grid rather than one reliant on conventional generation. Particularly worth mentioning is the fact that less kilowatt-hours are being generated, fuel costs are much higher for fossil fuels, and operation and maintenance (O&M) costs are lower for renewables.
[xi] Office of Management and Budget. "Circular A-4." 2003. https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/circulars/A4/a-4.pdf