Virginia Electricity Generation Gladiators

Garret Ankeny

Jack Burris

Alex Chizmadia

Daniel Lisco

Harrison McQuillan

Integrated Science and Technology,

James Madison University

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Topic: Clean Energy Transition

Dr. Rod MacDonald and Dr. John Miles

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Abstract

Virginia faces a pressing energy transition challenge, necessitating the shift from fossil fuels to renewable sources while ensuring reliable energy supply to achieve 100% zero-carbon electricity by 2050. While employing detailed systems modeling that span from 2000 to 2050, this study examines Virginia's energy generation transition, while considering coal, natural gas, nuclear, solar, wind, and hydroelectric sources. The model integrates population data, energy generation costs, and historical trends, underpinned by assumptions including a surge in solar uptake, natural gas phase-out by 2040, and large offshore wind farm construction by 2027. The simulation forecasts a transition timeline with solar emerging as the primary energy source by 2025, aligning with legislative goals. Policy analyses highlight the impact of natural gas phase-out and income distribution on energy generation. Sensitivity analyses underscore the pivotal role of wind turbine numbers. Results suggest a gradual decline in fossil fuel reliance and increase in renewable dominance. Challenges include land allocation for solar farms and wind turbine limitations. The study's contributions lie in its educational utility for stakeholders in understanding Virginia's energy transition complexities. Future research should focus on refining the model, incorporating additional variables, and exploring long-term renewable energy expansion strategies to propel Virginia toward energy independence.

Introduction

Background Information

Virginia has undergone a significant shift in energy generation over the past thirty years. It has moved away from its historical status as a coal-exporting state, where half of its electricity was generated from coal, to relying on natural gas. However, drive by a heightened awareness of climate change impacts and a desire for "reliable, affordable, clean, and abundant energy," Virginia is now aiming to further transition its energy sources by replacing fossil-based energy with renewables as outlined in the 2022 Virginia Energy Plan (Virginia Department of Energy, 2022, p. 14).

Virginia's energy transition traces its roots back to the 1990s when the Commonwealth embarked on phasing out coal generation while simultaneously integrating more natural gas.

Natural gas was heralded as a cleaner alternative to coal, aimed at reducing greenhouse gas emissions. By 2010, Virginia's reliance on coal-based generation plummeted from 35% to 4%, while natural gas for power production surged from 23% to 61% (Virginia Department of Energy, 2022). This transition resulted in significant reductions in carbon dioxide, sulfur oxide, and nitrogen oxide emission by 20%, 91%, and 58%, respectively (Virginia Department of Energy, 2022). According to the US Energy Information Administration, Virginia's electric power carbon dioxide emissions experienced a -1.8% reduction since the 1970s (Energy Information System, 2023). Concurrently, the 1990s and 2000s witnessed a heightened focus on renewable energy sources in the United States. Increased capital was injected into the development of more efficient and economically viable renewable energy projects, with the anticipation of their eventual substantial contribution to overall energy generation. In 2004, the United States invested a total of $5.7 billion in renewable energy. By 2019, this investment surged to $62.3 billion (Fernandez, 2022 & Lins, Williamson, Leitner, & Teske, 2013).

Virginia currently relies on natural gas for its electricity generation. According to the Environmental Information Administration (2023), as of 2022, 5.77% of Virginia's total electricity generation comes from solar, 0,05% from wind, 32.44% from nuclear, 3.85% from coal, 1.79% from hydro, and 56.19% from natural gas. Figure 1 illustrates the trajectory of Virginia's electricity generation since 2001, highlighting the transition from coal to natural gas in the early 2010s, with a subsequent uptick in renewables at the onset of 2020.

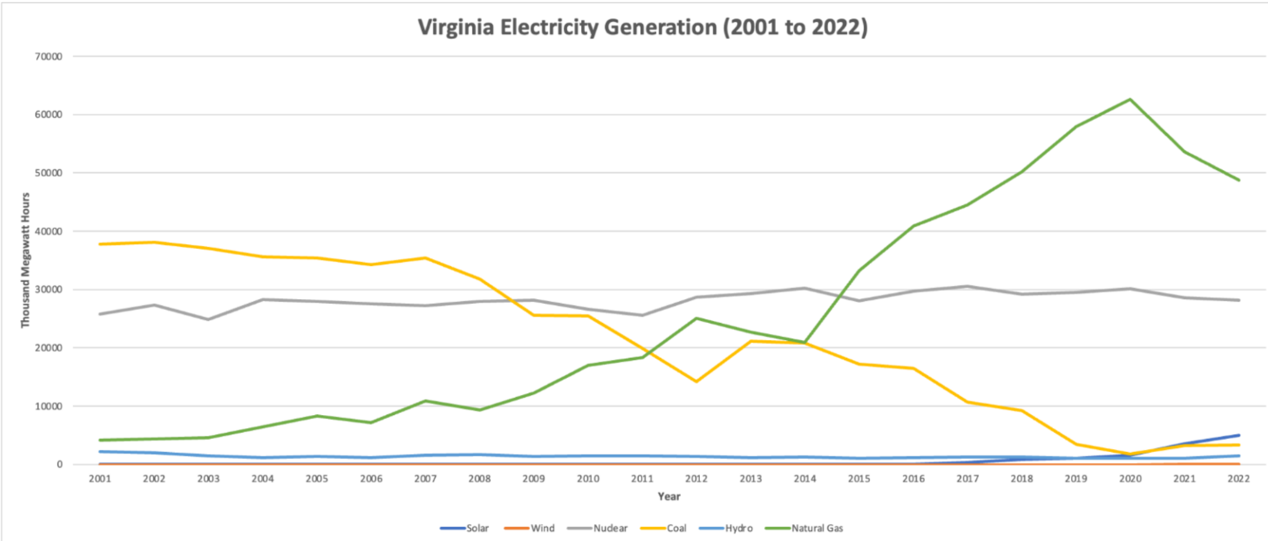

Figure 1: Virginia electricity generation (2001 to 2022).

Today, propelled by the ambitious goal of achieving sustainable, net-zero carbon-emitting energy sources outlined in the 2022 Virginia Energy Plan, renewable energy resources combined with nuclear power generation are forecasted to ultimately supplant fossil fuels entirely. According to the Virginia Clean Economy Act (VCEA), it is projected that by 2045, Virginia will attain this milestone, with 72% of all energy needs being met by renewables and the remaining 28% from nuclear power. This means fossil fuels or "Traditional Sources" will be surpassed in terms of total generation by source from 2020 to 2045 (Virginia Department of Energy, 2022, pg. 17). Figure 2 below presents a behavior over time graph illustrating the change from 1990 till 2045.

Based on the specifications outlined in the 2022 Virginia Energy Pl and Virginia's history of electricity generation, out team developed a sophisticated model that illustrates the interrelationships within each primary source of electricity, their interactions in determining total electricity generation output, and presents a projection of Virginia's energy portfolio until 2050.

Figure 2: Virginia's Energy Portfolio

Problem Statement

~~Virginia's energy transition involves meeting the increasing energy demand, and successfully transitioning from fossil fuels to renewable energy sources, all while ensuring a reliable energy supply to achieve 100% zero-carbon electricity generation by 2050.~~

Virginia faces the dual challenge of satisfying its growing energy needs while transitioning away from fossil fuels towards renewable sources. This transition is imperative for achieving the goal of 100% zero-carbon electricity generation by 2050 while maintaining a dependable energy supply. Effectively navigating this shift if pivotal for reducing carbon emissions and fostering a sustainable energy future for the state.

Objective & Importance of the Study

There has been significant interest in researching Virginia's transition to 100% carbon-free electricity due to the serious environmental and health implications it entails, as well as questions regarding the sustainability for Virginia's future beyond 2050. Furthermore, as previously discussed, the implementation of the 2022 Virginia Energy Plan has placed greater emphasis on developing significantly cleaner, renewable energy infrastructure such as solar and wind farms, while simultaneously phasing out fossil-based energy infrastructure like natural gas and coal. This transition will have significant implications and will affect primary stakeholders, including direct consumers, energy companies, contractors/construction companies, and the state government.

Overview of the Paper

For the remainder of the paper, we will present our literature review where we'll present critical statistics and information regarding each generation's sources. Then, we'll present our methodology, introducing the model that replicates Virginia's energy system, along with verification assessments to demonstrate its validity and usability. Due to the model's comprehensive nature, it will be segmented into sections based on generation sources, allowing for easier comprehension of each source and their interrelationships when considering total energy generation. Subsequently, we will analyze the results and engage in discussions drawing insights from the data and simulations performed. This section will feature behavior over time graphs developed by altering variables such as income allocation to wind and solar, increasing maximum wind turbines, adjusting the cessation of natural gas, and more, to observe how these changes affect the outlook for electricity generation from each source and the total electricity generation in Virginia. Finally, we will conclude the paper by synthesizing the data collected from the literature review and the results from the behavior over time graphs, taking a holistic view by considering other variables that influence total electricity generation, such as income allocation and land use, to determine the feasibility of Virginia's energy transition as depicted in the 2022 Virginia Energy Plan.

Literature Review

Coal Energy Generation

Coal has played a significant role in America's energy landscape, particularly in Virginia, where it emerged as a vital resource in the 1700s, initially used locally before becoming a major export. The 1800s saw coal production escalate with the rise of steam engines and railroads, bolstered further by the demand surge during the Industrial Revolution. Thomas Edisons' coal-fired electric generating station in 1882 marked a pivotal moment, spurring economic growth, railroad expansion, and establishment of coal towns, fueling a century-long period of increasing production and electricity generation.

The average age of a coal-fired generating unit in the U.S. is 45 years, but many lack a specified retirement age. In Virginia, coal power plants began facing economic challenges in the 1900s, leading to phase-out statutes driven by factors like the emergence of more efficient technologies like renewables and natural gas and the comparatively higher operating costs to revenue. The IEA estimated the Levelized Cost of Electricity (LCOE) for coal was $110/MWh while natural gas was $45/MWh, which is presented in ***Figure 3.*** These economic pressures, along with environmental regulatory requirements like the Clean Air Act of 1970, have accelerated the retirement of coal-fired power plants.

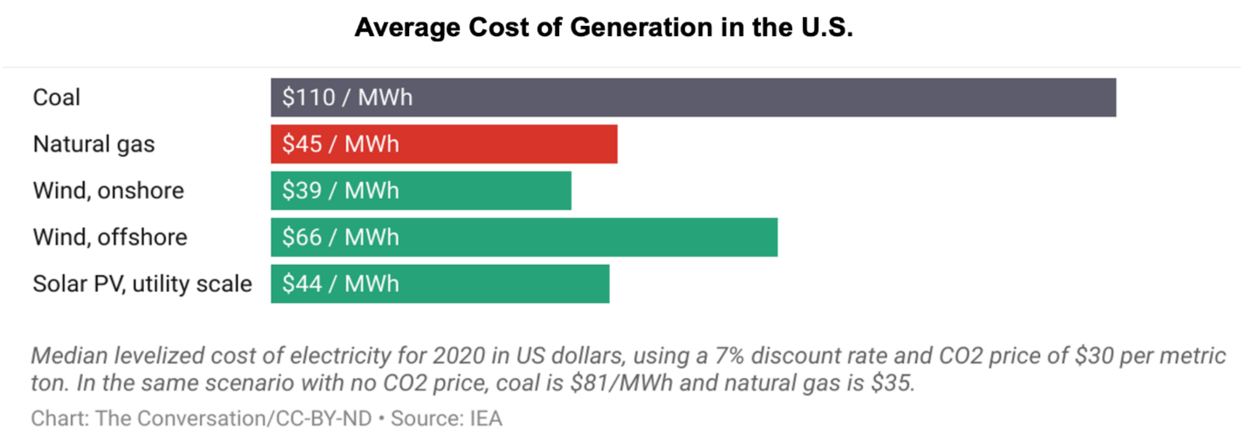

Figure 3: Average Cost of Generation in the United States by Source

As of November 2023, Virginia has only two remaining coal-fired power plants, both owned by Dominion Power. One, the Clover Power Plant, with 887 MW capacity, is slated for closure by 2025. The Virginia City Hybrid Energy Center, commissioned in July 2012 after four years of construction, can produce up to 610 MW of electricity from gob coal and biomass. Despite its expected operation until 2045, in line with the Virginia Clean Economy Act, Dominion plans to operate it at only 10% capacity, aligning with the state's shift towards renewables as shown in Figure 4.

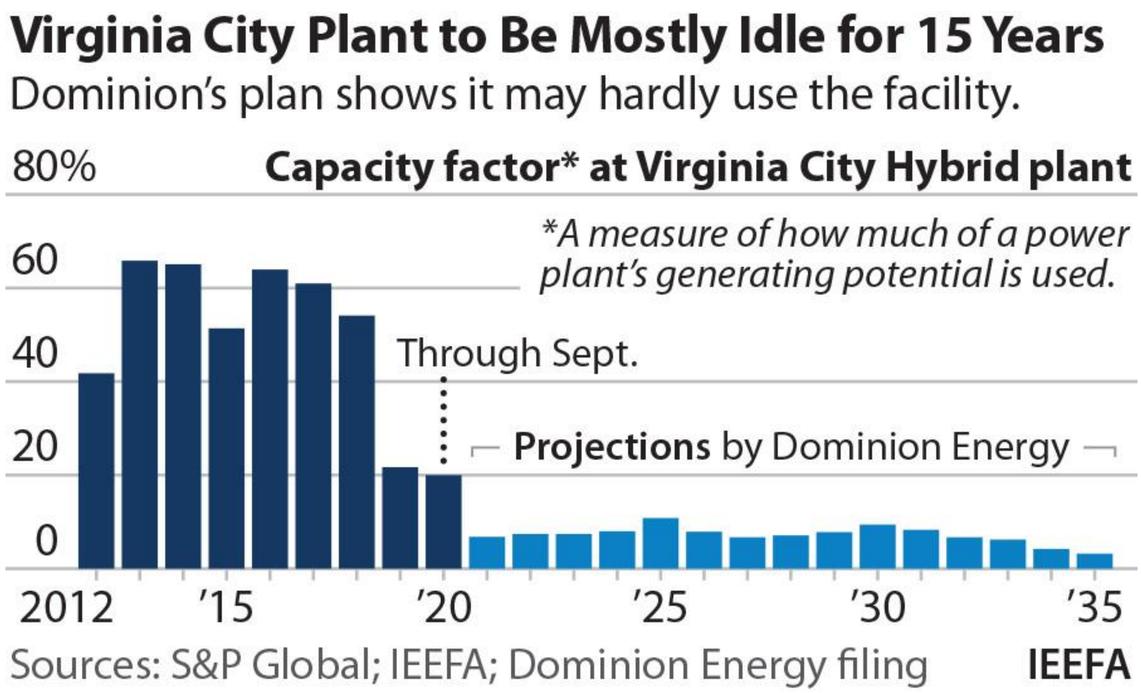

Figure 4: Virginia City Hybrid Energy Center Capacity Factor over Time & Projections.

The Virginia City Hybrid plant is just one example of this phenomenon. In September 2012, Dominion Power closed or converted eight company-owned, coal-fired power stations to biomass or natural gas plants, further illustrating this trend. One of these eight stations was the Bremo Power Station, which was converted from coal to natural gas for electricity generation (2, Dominion Virginia Power).

This can also been seen in Figure 5 as the coal and natural gas electricity generation shifted greatly in just 15 years. In 2005, natural gas generated just under 10,000 MWh while coal generated around 35,000 MWh. By 2020 that had switched, and coal was generating around 2,000 MWh, but natural gas generated over 60,000 MWh, increasing the electric generation of natural gas by 50,000 in only 15 years.

Figure 5 illustrates the major shift in electricity generation sources, with natural gas (green line) increasing as coal (yellow line) declines. In 2005, natural gas generation was below 10,000 MWh, while coal generation was approximately 35,000 MWh. This trend reversed in 2012 when natural gas surpassed coal, generating 25,000 MWh compared to coal's 15,000

MWh. This led to coal’s eventual downfall with production below 5,000 MWh. Meanwhile, natural gas experienced its own downfall in 2020, which will be covered later in this section.

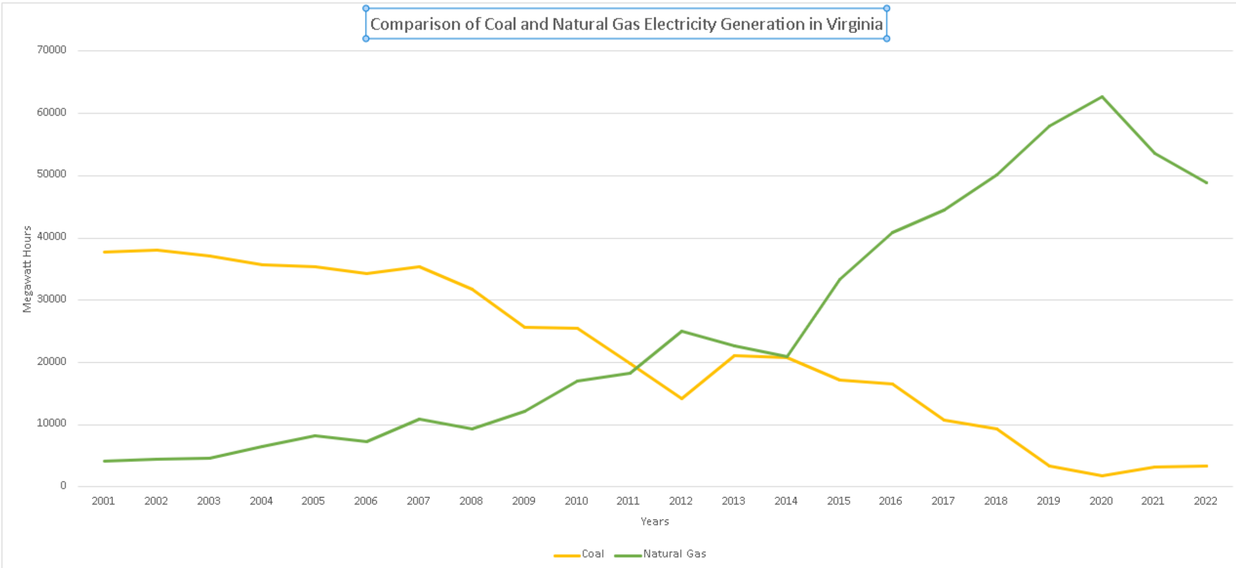

Figure 5: Comparison of Coal and Natural Gas Electricity Generation in Virginia (EIA)

From Figure 6, it is shown that Virginia relied heavily on natural gas for its electric generation in 2023, about 50% each month. Coal is barely visible in this graph and shown at the bottom by a thin blue line, however it is not noticeable in May and June as there was barely any electricity produced by coal in those months. This shows the continued decrease of coal used for electricity generation and it is plausible to think this will continue in the future as natural gas, nuclear, and renewables will provide generation. It's evident that coal generation markedly declined in comparison to other sources, contributing minimally to Virginia’s overall electricity generation. Additionally, it's noteworthy from the graph that coal failed to generate any electricity in certain months, such as May, June, and September.

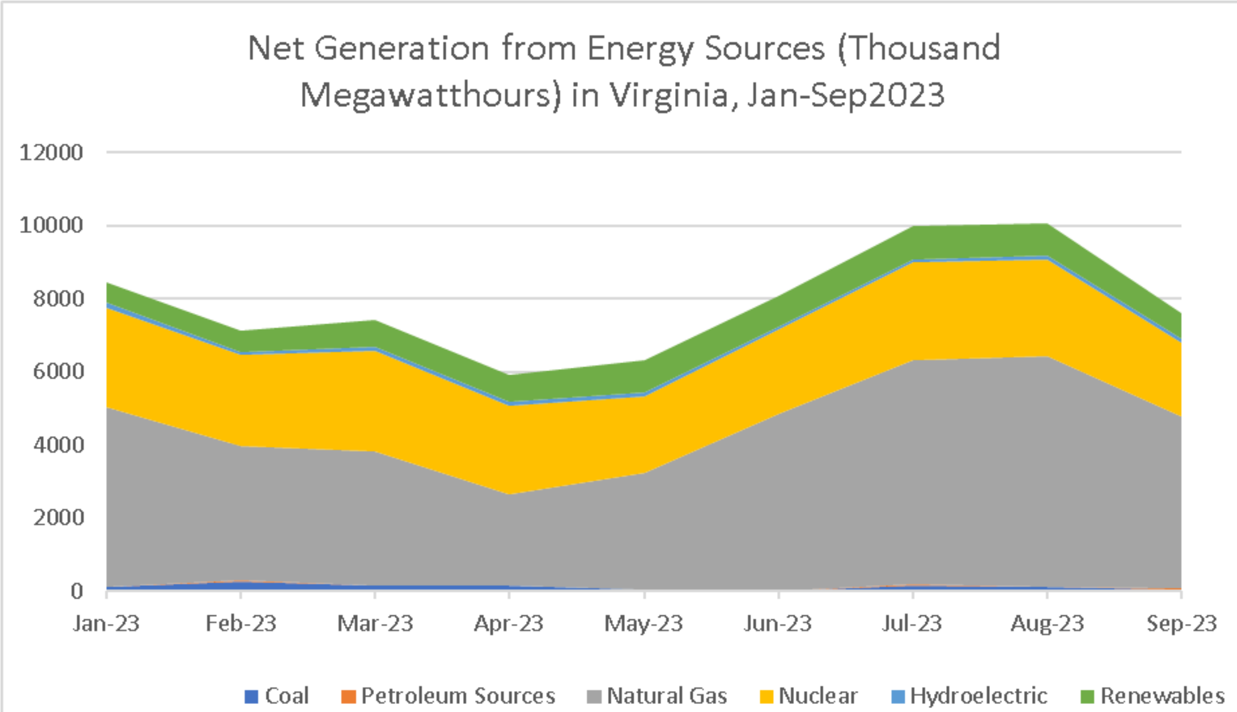

Figure 6: Net Generation (Thousand Megawatt Hours) in Virginia , Jan-Sep 2023 (EIA).

Natural Gas Generation

According to 2022 Virginia's Energy Plan, natural gas currently dominates the state's electricity generation, accounting for 57% of the total, with each plant producing 0.13 KWhs per cubic foot of natural gas (VDOE, 2022). Natural gas emerged as a substitute for coal in Virginia during the 2000s and 2010s (VDOE, 2022). However, under the energy plan it outlines a new transition, aiming to replace natural gas entirely with carbon-free sources like solar, wind, and nuclear by 2045. Furthermore, the Commonwealth has mandated, under the Virginia Clean Economy Act (VCEA), the retirement of natural gas plants operated by Appalachian Power and Dominion by 2045 and 2050, respectively (LIS, 2020).

Figure 7 below presents a graphical projection by the Commonwealth in their 2022 Virginia Energy Plan which shows the general transition from fossil-based sources like coal and natural gas to strictly carbon-free sources. It's projected by 2045, solar and wind will account for three quarters of all generation in Virginia with nuclear accounting for the final quarter (VDOE, 2022).

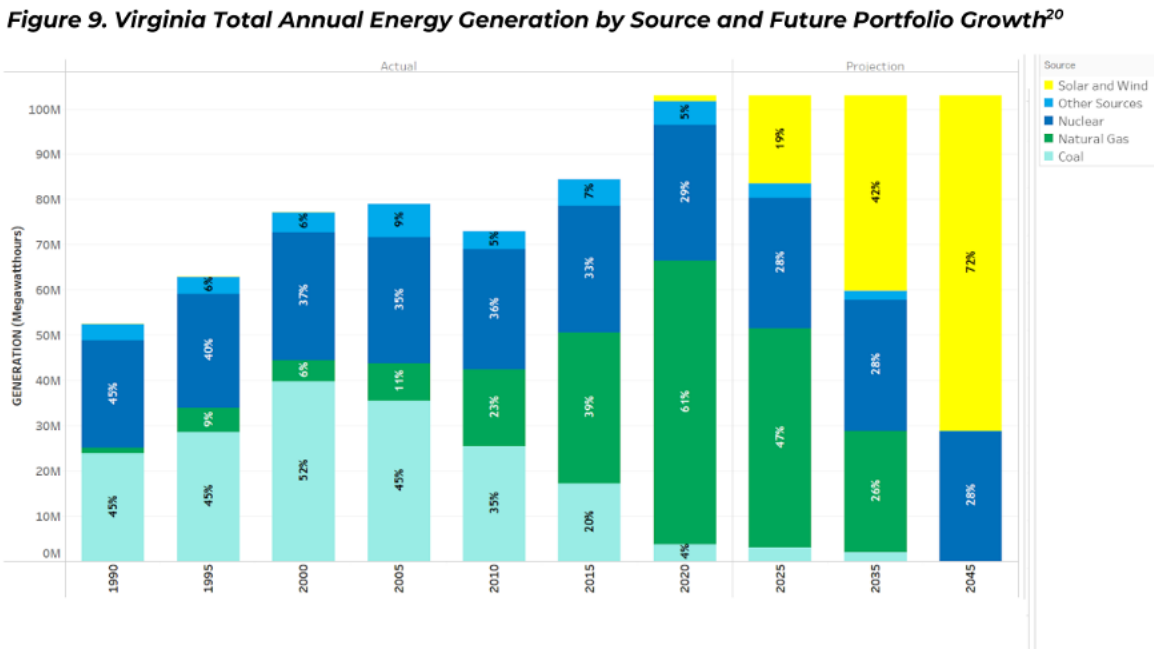

Figure 7: Virginia's Projected Generation Portfolio.

With Virginia's household electricity demand holding steady at around 35 MWh per year, there's a prime opportunity for non-carbon-emitting sources to supplant both coal and natural gas (EIA, 2009). This is facilitated by the ease of integrating renewable energy sources into existing power grids. However, even with an established grid, there will be a transition period during which consumers still require electricity. Consequently, Virginia is strategizing to phase out natural gas while ramping up the adoption of non-carbon-emitting sources. Although natural gas currently provides 57% of Virginia's electric power, this phase-out is crucial for advancing cleaner energy initiatives (VDOE, 2022).

Nuclear Energy Generation

Virginia currently operates two nuclear power plants. The first, North Anna Power Station supplies 17% of Virginia's total energy, while the second, Surrey Nuclear Power Station, supplies 14% (Energy, n.d.). Figure 10 displays the forecasted electricity demand until 2050 across different time periods. This graph indicates a projected increase in demand, necessitating a corresponding increase or even surpassing it in energy supply. This transition is further complicated by the shift from fossil-based to renewable-based electricity with issues like intermittency and having a consistent and reliable energy source. Nuclear energy is poised to play a pivotal role in this transition, providing a reliable and consistent supply of electricity essential to meeting a quarter of Virginia's demands (Virginia, 2020).

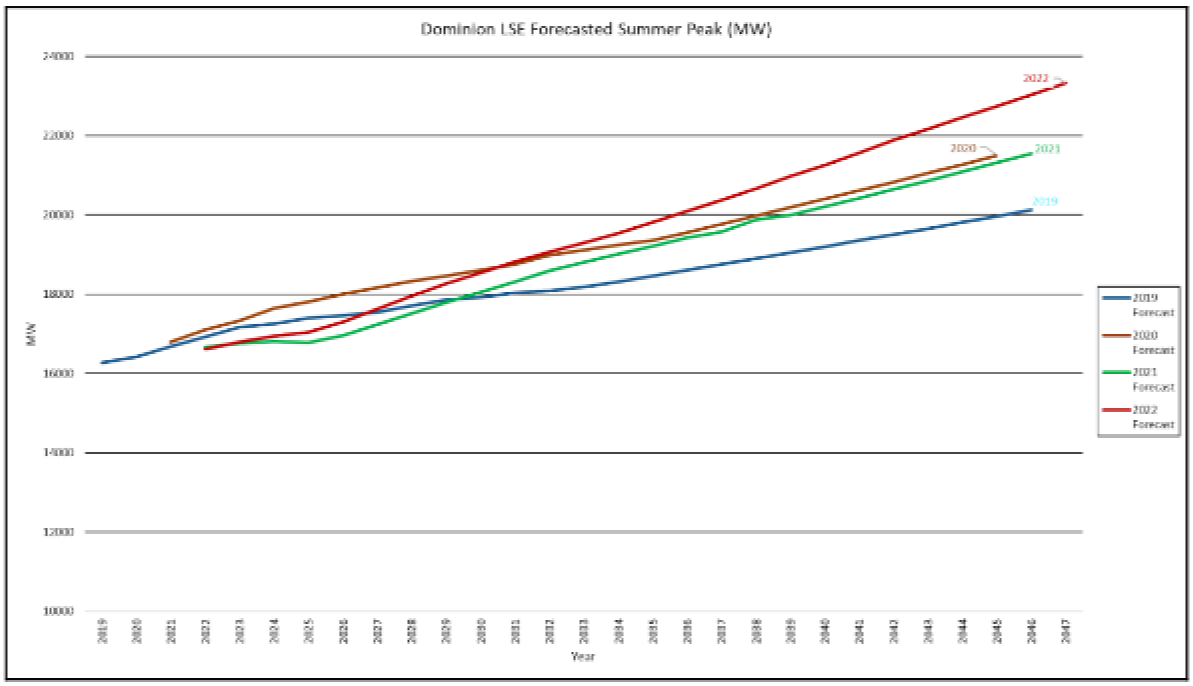

Figure 10: The Forecast Peak Electricity Demand Over Time in Virginia.

Nuclear power faces several challenges in the public domain, primarily stemming from misinformation and bias rooted in historical events. A survey conducted by Virginia Commerce revealed that 39% of US citizens do not support the latest advancements in nuclear electricity generation (Commerce, 2023). Additionally, another survey found that 49% of US citizens believe nuclear electricity generation produces more carbon emissions compared to renewable alternatives (Commerce, 2023). Furthermore, approximately 43% of US citizens questions the necessity of nuclear power in achieving climate goals (Commerce, 2023). Beyond public perception, nuclear power also grapples with significant financial hurdles, including hefty upfront construction costs and prolonged development phases lasting an average of 10 years per nuclear power plant (Park, 2018). These financial aspects may deter potential investors due to the time value of money.

A plausible approach to addressing this issue is the utilization of small-scale nuclear reactors (SMRs) for electricity generation. SMRs typically generate approximately 300 MW, which is roughly one-fourth of the output of a standard reactor (Plumer, 2023). While they may not match the generation capacity of full-size reactors, their smaller size allows for quicker development and construction, facilitating faster integration into the grid. This could expedite the retirement of natural gas plants and enable the achievement of carbon-free electricity sooner than anticipated. Additionally, the smaller scale of SMRs may appeal to individuals concerned about the risks associated with nuclear meltdowns.

An emerging technology known as sodium-cooled reactors is gaining traction, offering even smaller-scale nuclear energy solutions. Compared to traditional small-scale reactors, sodium-cooled reactors boast an even lower risk of meltdown incidents. With a capacity of about 15 MW, these reactors are versatile and suitable for various energy generation needs. Applications such as powering electric car charging stations could benefit from the deployment of sodium-cooled reactors (Plumer, 2023).

Solar Energy Generation

Solar energy stands as one of the most rapidly expanding and widely adopted modern renewable energy sources globally, including within the United States. The efficiency of a solar panel hinges on various factors, including temperature, climate conditions, sunlight intensity, and the orientation of the panels relative to the sun's angle. Without these optimal conditions, panels may not harness sufficient sunlight for electricity conversion. Nonetheless, despite these challenges, solar energy remains heralded as the future of sustainable power generation. Many state governments have committed to reducing carbon emissions by promoting the transition to renewable energy sources like solar.

The Commonwealth of Virginia is one of the leading states transitioning energy sources from traditional methods to modern renewable systems, especially solar energy for which it ranks 10th in the country for total installed solar capacity. Electricity generation from solar energy has increased by 38,197% from 4,996MWh in 2016 to 1,913,330MWh in 2022. Growing at a positive exponential rate, Virginia has up to 4,393MW installed total, with 525MW installed over 2022, and its growth projection over the next 5 years is 6,722MW (ranking 9th in the country).

The Commonwealth of Virginia stands out as a leading state in transitioning its energy sources from traditional methods to modern renewable systems, notably solar energy, where it currently ranks 10th in the country for total installed solar capacity. In the span of six years, electricity generation from solar energy in Virginia has seen an astonishing increase of 38,197%, soaring from 4,996 MWh in 2016 to 1,913,330 MWh in 2022. Experiencing a robust positive exponential growth, Virginia now boasts a total installed capacity of 4,393 MW, with an additional 525 MW installed just in 2022 alone. Looking ahead, the state anticipates further expansion, with a growth projection of 6,722 MW over the next five years, solidifying its position as the 9th-ranked state in the country in terms of solar energy development.

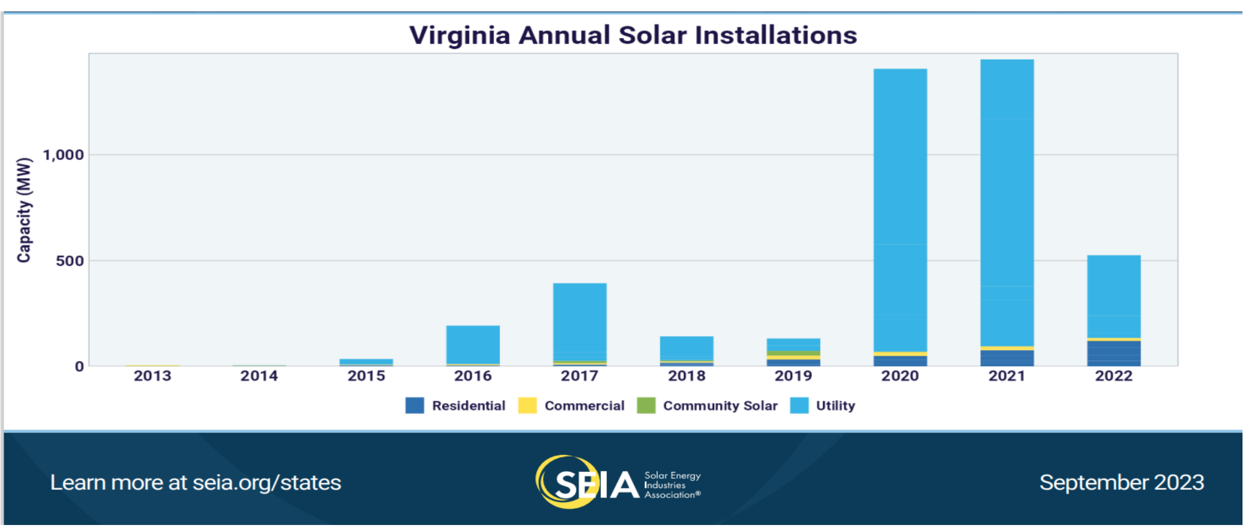

Figure 11: Virginia Annual Solar Installations

Figure 11 illustrates significant growth in solar panel installations throughout the previous decade, particularly in Virginia. Notably, the years 2020-2021 saw a remarkable tripling of capacity compared to the highest previous year in 2017. This surge in installations encompasses. Both utility-scale projects and residential capacity expansion, indicate a substantial increase in energy storage and transmission to meet the residential electricity demand. In Virginia, solar installations are predominately “Behind the Meter”, meaning energy generated from solar panels is consumed on-site, directly powering the residence. Consequently, electricity produced by residential solar panels does not feed into the grid, leading to data inaccuracies in solar generation reporting, as utility companies do not monitor or store this locally harnessed solar energy.

Referring to Figure 8 and homing in on the projected trends for solar and wind energy from 2025 to 2045, it becomes evident that the utilization of renewable sources undergoes a substantial transformation, rising from under 5% to approximately 72% between 2020 and 2045. This underscores the significant potential for growth within Virginia’s solar energy portfolio in the coming years and highlights a milestone towards achieving the objectives outlined in the Virginia Clean Economy Act (VCEA) by 2050.

The shift toward increased solar generation is in its early stages, as evidenced by the fact that only 6.16% of Virginia’s electricity comes from solar sources. This translates to approximately 519,386 homes being powered by solar energy. Large corporations like Meta, Amazon (which boasts its own corporate solar panels generating a total of 191 MW), and Microsoft are leading the way in embracing renewable infrastructure within the corporate sector.

Wind Energy Generation

Wind energy represents another significant renewable energy source. Currently, wind energy constitutes a small fraction of Virginia’s total electricity generation. Only three known mind turbines are operational within the state, one of which is the CASE Small Scale Wind turbine situated on JMU’s East Campus. However, this landscape is destined to change following the Commonwealth’s approval for further development of Dominion Energy’s offshore wind turbine farm (CVOW-Coastal Virginia Offshore Wind). Upon completion, this project is anticipated to become the largest operational offshore wind farm in the United States.

This project, with an estimated cost of up to $9.8 billion, is projected to be fully operational by 2027, delivering up to 8.8 million megawatt-hours of clean energy annually, enough to power approximately 660,000 homes in Virginia. It will consist of 176 megawatt-scale turbines, boasting a 42% capacity factor and a storage capacity of 14.7 megawatt-hours (Dominion Energy Virginia, 2023). The electricity generated by these wind turbines is expected to prevent up to 5 million tons of carbon dioxide emissions annually, which is equivalent to the environmental benefit of planting over 80 million trees (Dominion Energy Virginia, 2023). This project signifies a significant milestone in the transition from carbon-emitting energy sources to renewable alternatives, representing a substantial reduction in carbon emissions from energy generation within Virginia.

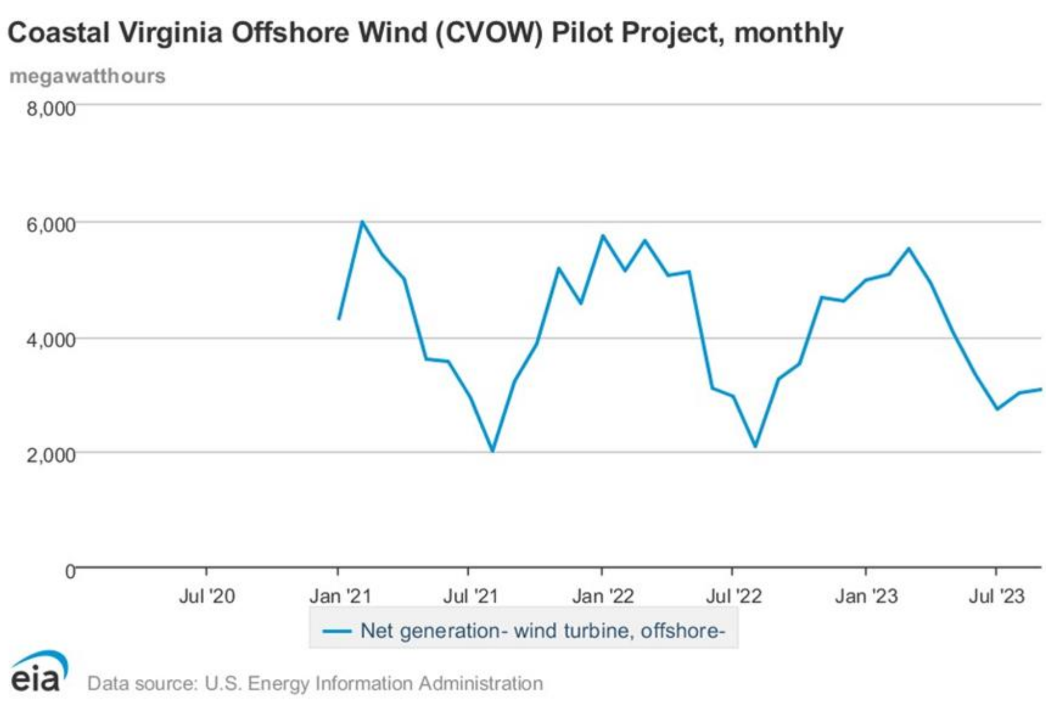

Figure 12: Coastal Virginia Offshore Wind (CVOW) Monthly Pilot Projection

As of September 2023, Virginia's wind energy generation remains at 3,000 MWh, a figure that has remained constant since September 2022. This electricity output is exclusively derived from two experimental pilot turbines, which were deployed to assess the wind potential in the project area.

Hydropower Generation

Hydroelectric, while recognized as a renewable energy source, is less prevalent in the Commonwealth compared to other renewable sources. It harnesses the kinetic energy of water to generate electricity through the force of water flow. However, its contribution to the overall electricity in Virginia is not as substantial as that of other renewable sources.

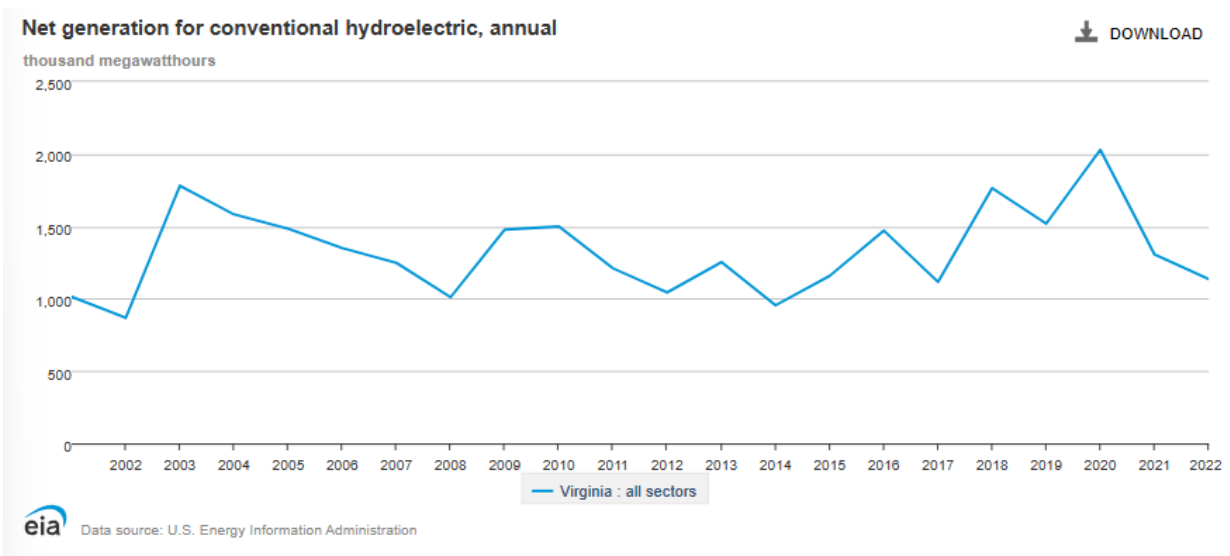

Figure #13 Annual Net Generation for Conventional Hydroelectric

Conventional hydroelectricity has been around in Virginia has been around for more than 20 years, peaking at 2,000 thousand megawatt-hours (2,000 GWh) in 2020 before beginning a decline. Little change has occurred in conventional hydroelectric generation over the span of 21 years, as evidenced by the strikingly similar net generation figures in 2001 and 2022. In 2001, the generation stood at 1,014 thousand megawatt-hours (1,014 GWh), only slightly lower than the 1,137 thousand megawatt-hours (1,137 GWh) recorded in 2022. There are no forthcoming projects aimed at increasing this level of generation, with hydroelectric plants focused solely on maintaining a steady output (EIA, 2022).

Methodology

Model Description

This model illustrates Virginia's energy generation transition spanning from 2000 to 2050, encompassing coal, natural gas, nuclear, solar, wind, and hydroelectric sources. It factors in population data, energy generation costs, and historical energy generation data. Each energy generation sector calculates its total annual potential energy production, which is then aggregated to depict the combined generating capacity of all sources in Virginia. Several assumptions underlie this model. First, it assumes a significant surge in solar energy uptake from 2025 to 2050, becoming the dominant energy source during this period, driven by a decline in natural gas usage and its complete phase-out by 2040. This leads to the second assumption of natural gas being entirely phased out by 2040, with all fossil fuel energy generation ceasing around 2040-2045. Renewables and nuclear energy are expected to produce all of Virginia's energy generation by 2040 at the earliest. The third assumption involves the construction of a large offshore wind farm in 2027, comprising 176 turbines off Virginia's coast. Lastly, the model assumes specific fractions of income allocated to each energy generation source, based on the most probable scenarios due to the lack of available data.

Model Construction

The model is organized in sections that include natural gas, coal, nuclear, hydro, solar, wind, population, fraction income, total generation, historical generation, and graphs.

The analysis of Figure 14 begins with the "Ratio of Annual Demand to Generating Power," indicating the comparison between electricity demand and generated power. The "Effect of Demand to Supply on Funding" demonstrates how the demand-supply ratio influences funding allocation. The "Current Fraction of Income Allocated for Construction" indicates the portion of total income designated for energy generation construction. When multiplied, the

"Effect of Demand to Supply on Funding" and "Current Fraction Allocated for Construction" yield the "Money Allocated for Construction," representing the actual available funds for new energy generation construction. The "Income Allocated to Wind" is an estimated value set at 30% of the money allocated to constructing wind energy generation sources. Multiplying the "Money Allocated for Construction" by 0.30 provides the "Income Allocated to Wind." This allocation drives the "Addition to Turbines," signifying approved turbine development and construction. Subsequently, "Turbines Under Development" indicates turbines in the developmental phase with a time delay. "Turbines Coming Online" signifies completed turbine construction and commencement of energy production. After each turbine comes online, they are added to the "Number of Turbines," tracking the total at every moment. "Number of Turbines" is multiplied by 6 MW, the average MW per turbine, to find the "Potential Generating Capacity (Wind)," illustrating the total possible MW production if all turbines were running at full capacity, nonstop. "Total Annual Potential Energy Production (Wind)" is calculated by multiplying "Potential Generating Capacity (Wind)" by the number of hours in a year (8760) and the average capacity factor of a wind turbine (35%, 0.35). This variable will show the actual amount of MW*h/year produced. "Total Annual Potential Energy Production (Wind)" feeds back into "Ratio of Annual Demand to Generating Power", and the cycle restarts.

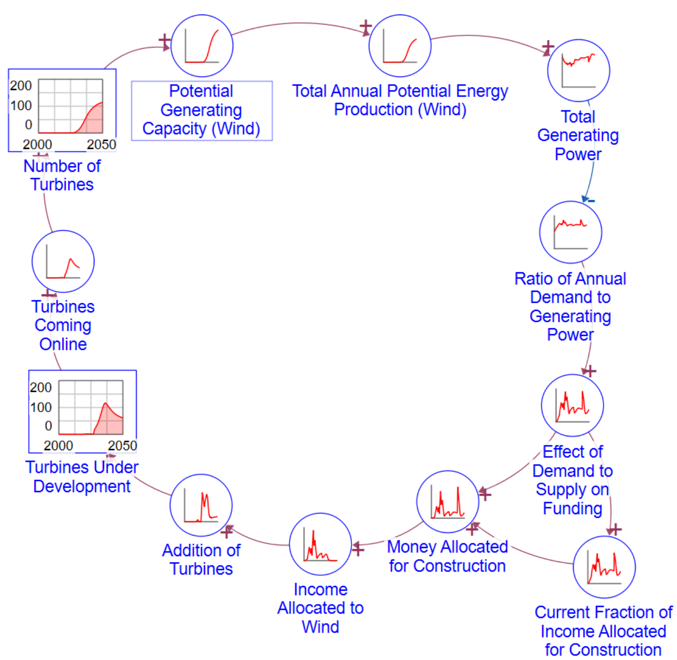

Figure 14: Reinforcing Loop for Wind

The analysis of Figure 15 begins with the "Ratio of Annual Demand to Generating Power," indicating the comparison between electricity demand and generated power. The "Effect of Demand to Supply on Funding" demonstrates how the demand-supply ratio influences funding allocation. The "Current Fraction of Income Allocated for Construction" indicates the portion of total income designated for energy generation construction. When multiplied, the "Effect of Demand to Supply on Funding" and "Current Fraction Allocated for Construction" yield the "Money Allocated for Construction," representing the actual available funds for new energy generation construction. The "Income Allocated to Solar" is an estimated value set at 40% of the money allocated to constructing solar energy generation sources. Multiplying the "Money Allocated for Construction" by 0.40 provides the "Income Allocated to Solar." This allocation drives the "New Solar Farm Planning," signifying approved solar farm development and construction. Subsequently, "Solar Farm Planning and Development" indicates solar farms in the developmental phase with a time delay. "Addition of Solar Farms" signifies completed solar farm construction and commencement of energy production. After each solar comes is constructed, they are added to the "Number of Solar Farms," tracking the total at every moment. "Number of Solar Farms" is multiplied by 39 MW, the average MW per solar farm, to find the "Potential MW" illustrating the total possible MW production if all solar farms were running at full capacity, nonstop. "Total Annual Potential Energy Production (Solar)" is calculated by multiplying "Potential MW" by the number of hours in a year (8760) and the average capacity factor of a wind turbine (30%, 0.30). This variable will show the actual amount of MW*h/year produced. "Total Annual Potential Energy Production (Solar)" feeds back into "Ratio of Annual Demand to Generating Power," and the cycle restarts.

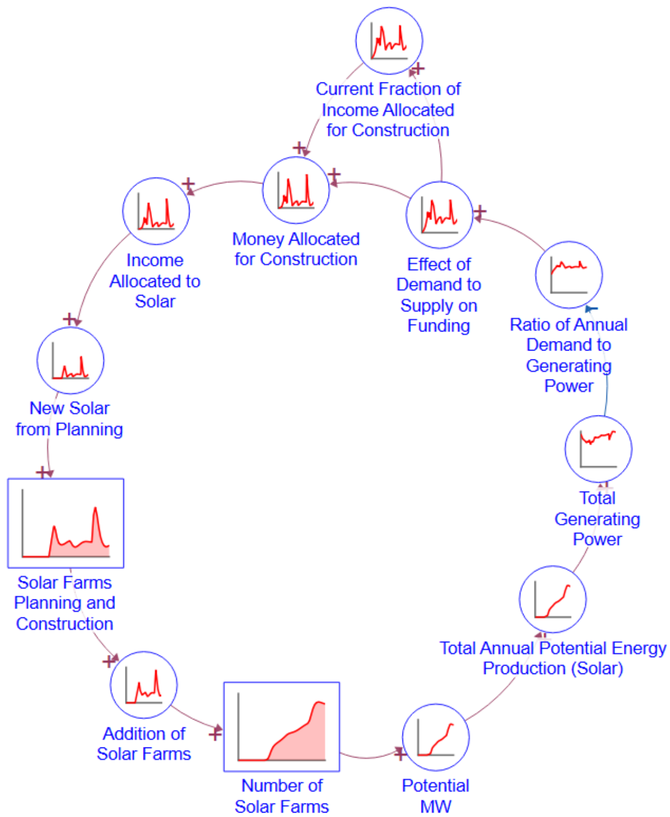

Figure 15: Reinforcing Loop for Solar

These two primary feedback loops stand out as the most crucial and influential components within the model. However, the model's scope extends beyond these loops, with various stocks and flows exerting additional influence. One significant external factor impacting both loops is the "Natural Gas Switch". Scheduled for 2040, this switch marks the end of natural gas usage, the final source of fossil fuel generation. The activation of this switch significantly impacts the behavior of each feedback loop.

Data Collection

To construct an accurate model, we relied on specific and general quantitative data sourced from reputable secondary sources. These data were pivotal in generating behavior over time graphs that effectively illustrate historical and projected energy trends, as well as fluctuations in variables up to the year 2050. Our primary sources of data were well-documented secondary sources, predominately from institutions like the Virginia Department of Energy and

Dominion Energy, owing to their significant role in energy generation in Virginia. The model and paper incorporated critical legislations, notably the 2022 Virginia Energy Plan and the 2022 Virginia Clean Economy Act, which catalyzed Virginia's transition to carbon-neutral energy sources. These legislative measures emphasized a shift towards increasing solar and wind energy while reducing reliance on coal and natural gas generation. This allowed us to validate our model during its development, ensuring as much alignment to the end goals outlined by the legislations. We meticulously documented the most significant variables and changes that affected the trajectory of renewable and fossil-based generation in Virginia.

Validation & Verification

Throughout the development of the model, our group continuously tested the equations to ensure that each stock and flow maintained the correct variables. By maintaining consistent variables, our group was able to model individual sectors and their relationships effectively. We relied on multiple reliable resources to confirm the nominal values inputted into the model, all of which are documented. To ensure correlation with the historical model of energy generation, we used reliable sites for quantitative generation data and systematically fluctuated the identified variables. This allowed us to assess the impacts of the 2022 Virginia Energy Plan on future energy generation. The results generated by our model align with the predictions in the Virginia Energy Plan, demonstrating the accuracy of our modeled results according to the standards we aimed to achieve.

Results

Simulation Results

Our simulation model aims to model the energy transition in Virginia, focusing on the implementation of various generation sources to align with the Virginia Clean Economy Act (VCEA) goal of reducing fossil fuel dependency by 2045. Our model depicts the gradual shift in energy until 2050. In 2000, coal dominates the sector but gradually was overtaken by natural gas. By 2010, natural gas overtakes coal as the dominate energy source, as depicted by Figure 16. Natural gas continues to generate until 2040 when it's destined to be completely phased out. Meanwhile, solar energy experiences rapid growth and is expected to meet natural gas generation by 2025. This surge is attributed to significant investment in solar farms, with approximately 40% of the budget allocated to solar production, and an absence of restrictions on solar panel installation. Concurrently, nuclear and hydropower generation remains stable, with a capped number of wind turbines in the state. Consequently, solar emerges as the predominant source of carbon-free energy in our model, poised to meet the 2050 target.

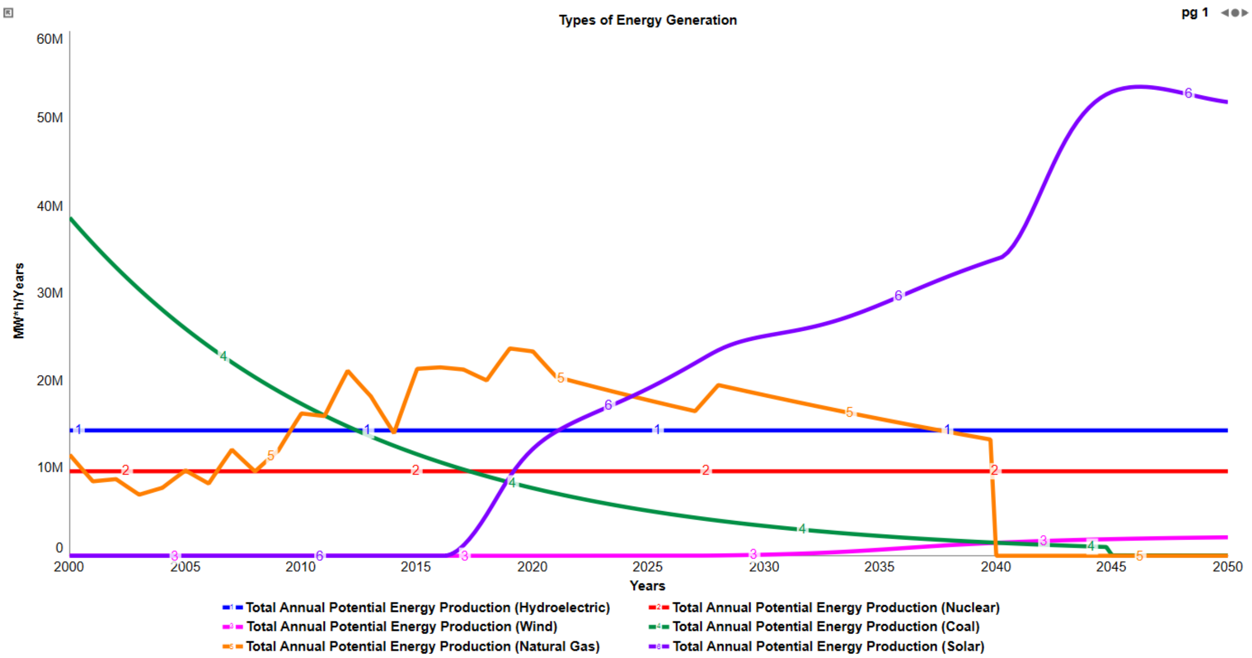

Figure 16: Total Annual Potential Energy Production from Generation Sources 2000-2050, from Systems Model

Our model also reveals that it accurately mirrors Virginia's current energy demand, highlighting that the state presently relies on imports for approximately 30% of its energy requirements. This relationship is depicted in Figure 17, where the total generating capacity remains below the blue line representing the annual demand, factoring in both total population and average MWh per person components as per our model.

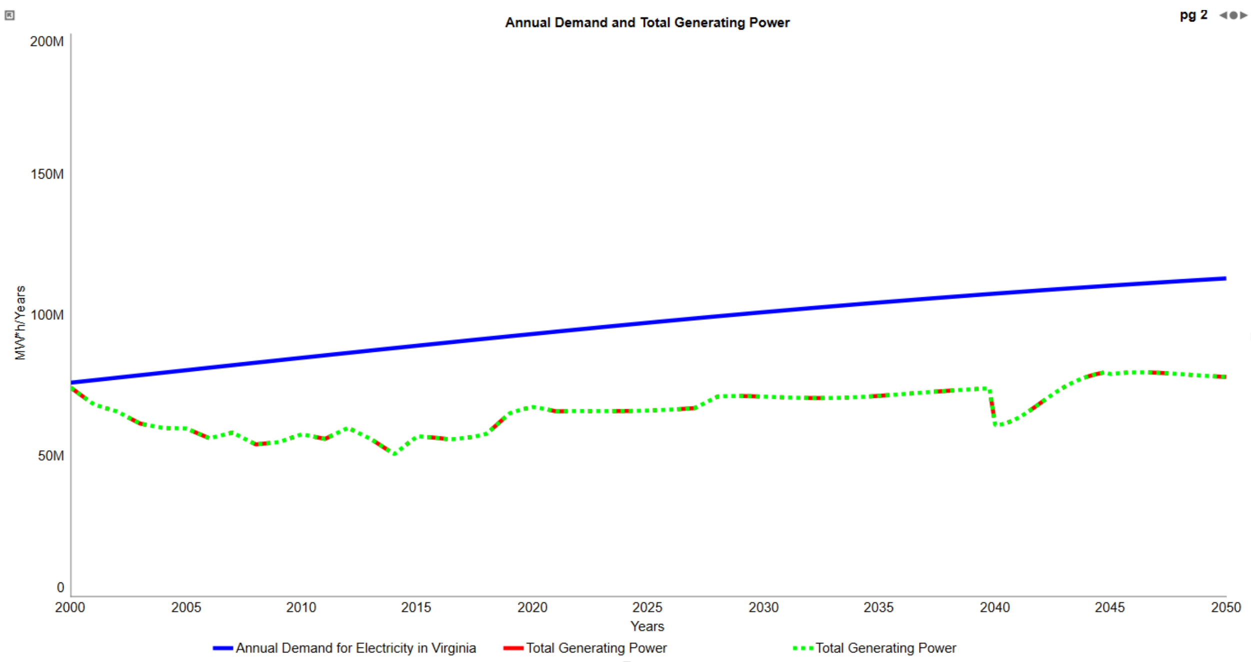

Figure 17: Annual Demand and Total Generating Power

Policy Analysis

In our model, there's a programmed switch that deactivates all-natural gas generation by 2040, aligning with the goals of the Virginia Clean Economy Act (VCEA) as per our base model. This action significantly redirects resources towards solar and wind power generation, resulting in a gradual increase in solar power output over the subsequent 5 years, as depicted in Figure 18. Conversely, if we allow the model to continue without shutting off natural gas, it shows a gradual decline in overall energy production. Figure 18 illustrates this decline with the yellow line gradually descending, followed by a slower more gradual increase in solar power, lacking the sharp decline observed previously from natural gas.

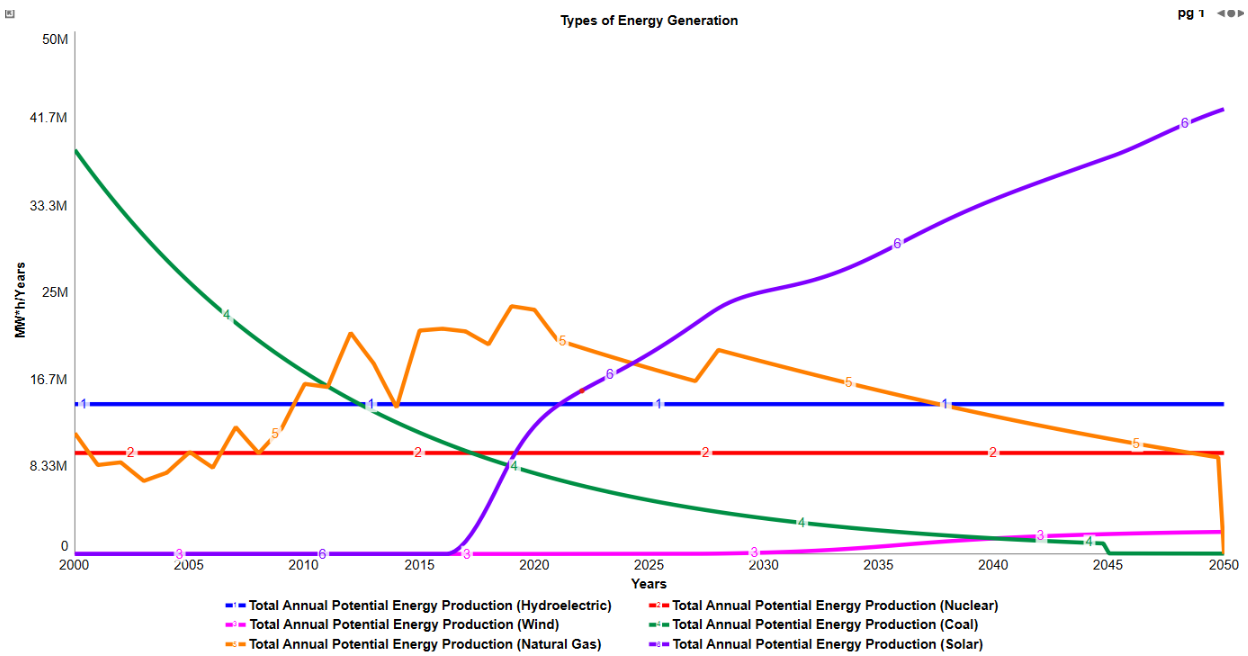

Figure 18: Types of Energy Generating with Natural Gas not Switched Off.

In our model, we've incorporated the count of wind turbines, notably influenced by the offshore wind farm off the coast of Virginia. Presently, our base model features just 176 turbines under construction. To enhance our model's accuracy, we've introduced a policy that allows for adjustments in turbine numbers. This includes scenarios where additional turbines could be constructed within the existing offshore farm or if new wind farms are established across Virginia. Such modifications prompt a deeper exploration into the potential shifts in energy generation from various sources.

Another policy concerns the distribution of income between solar and wind energy. Currently, our base model allocates 40% of the income to solar projects and 30% to wind initiatives. These policies serve to analyze the impact of financial changes on total energy generation. For instance, adjusting the income distribution to favor solar could potentially expedite Virginia's ability to meet energy demands.

The final policy integrated into our model addresses the cost per solar farm. Considering the government programs, rebates, and possible technological advancements, the cost of establishing solar farms may fluctuate in the foreseeable future. Our model is designed to reflect such variations and assess their implications. For instance, if the cost of solar farms were to decrease, our model can forecast the potential acceleration in production or the feasibility of constructing additional farms by 2050.

Sensitivity Analysis

The policy governing the maximum number of wind turbines stands out as one of the pivotal aspects of our model, dictating the capacity for available turbines. Through a sensitivity analysis, we examined the impact of varying turbine numbers on potential energy production, as illustrated in Figure 4. Our analysis encompassed values ranging from 50 turbines to 352, double the original count. The results revealed a substantial shift in wind energy production, nearly doubling to approximately 4 million MW/year with a full complement of 352 turbines, compared to the current 176 in our model. Furthermore, we observed a slight ripple effect on solar energy production: as wind turbine construction and wind energy output increase, there is a corresponding decrease in solar production, and vice versa.

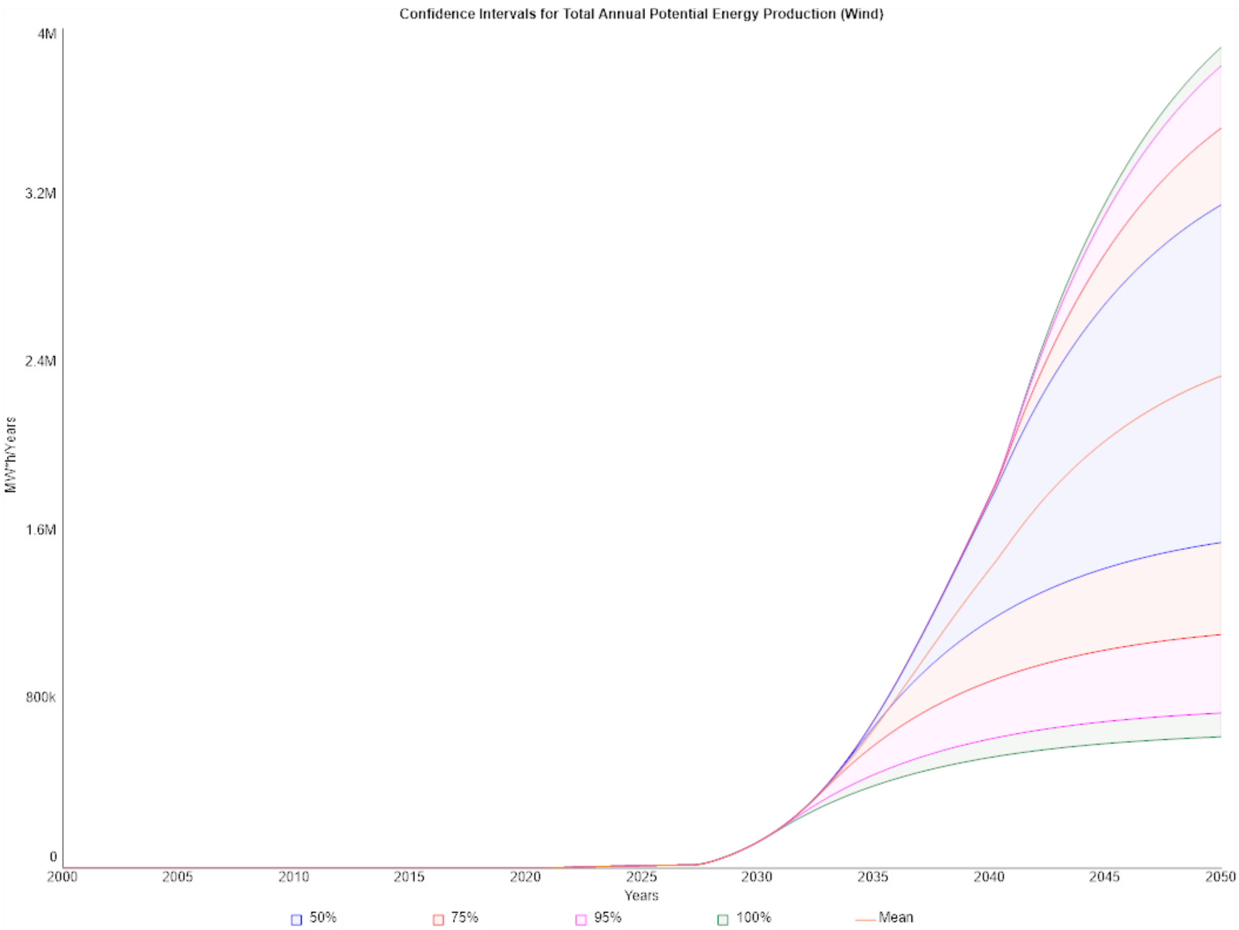

Figure 19: Confidence Intervals for Total Annual Potential Energy Production (Wind)

Sensitivity analysis was conducted on the policies governing the initial fractional income allocation for wind and solar energy. These policies dictate the financial resources directed towards the construction and operation of solar and wind facilities, thereby influencing the total annual potential energy production. In this analysis, the range of income allocated to solar was examined, with the lowest allocation set at 0 and the highest at 1. Our baseline model initially assigned 0.4 or 40% of income, to solar projects.

The analysis was iterated over 50 runs, starting from 0% income allocation in the first run and gradually increasing to 100% by the 50th run. Figure 20 illustrates that run #1-10 exhibited substantially lower outcomes compared to subsequent runs. By run #10, approximately 20% of the income was allocated to solar projects. Interestingly, the total solar production did not experience significant fluctuations even with an increase from 20% to 100% income allocated in runs #10-50.

These findings suggest that to ensure reliable solar construction, a minimum of 20% of the income must be allocated to it. Beyond this threshold, the marginal impact decreases considerably. Therefore, allocating the entire 40% may not be necessary, and the resources could potentially be reallocated elsewhere.

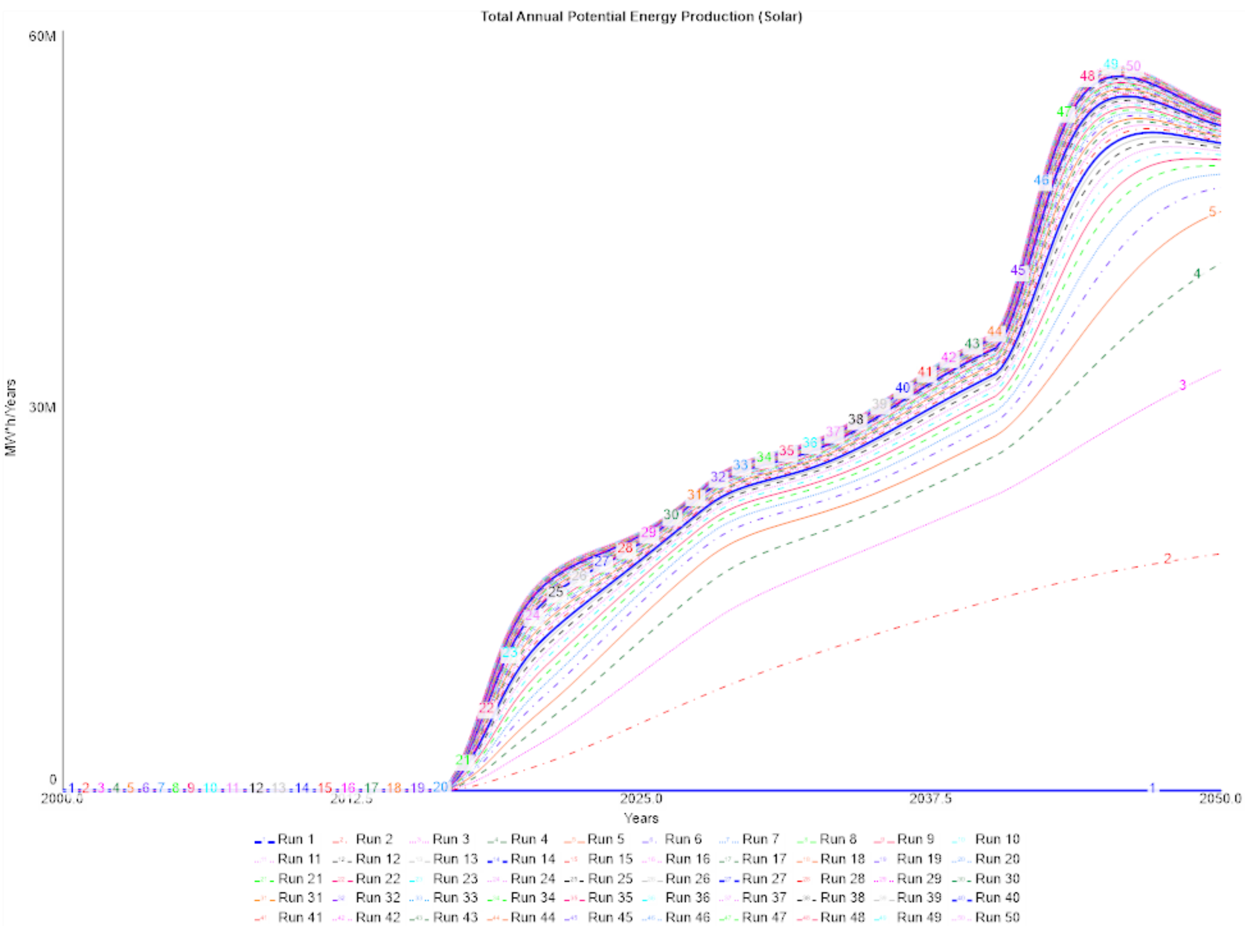

Figure 20: 50 Runs for Total Annual Potential Energy Production (Solar)

Similarly, when conducting sensitivity analysis on wind using identical fractional income values, the results closely resemble those observed for solar, as depicted in Figure 21. Once again, runs #1-10 exhibit significant disparities in energy production. Notably, allocating less than 20% of the income to wind results in a substantial decrease in wind energy output.

In both wind and solar scenarios, alternative energy sources compensate for deficiencies. For instance, if we consider run #3 for wind, where wind energy receives minimal income and consequently exhibits low production, solar energy steps in. This prompts an increase in the fractional income allocated to solar, leading to a corresponding rise in its total annual potential energy production.

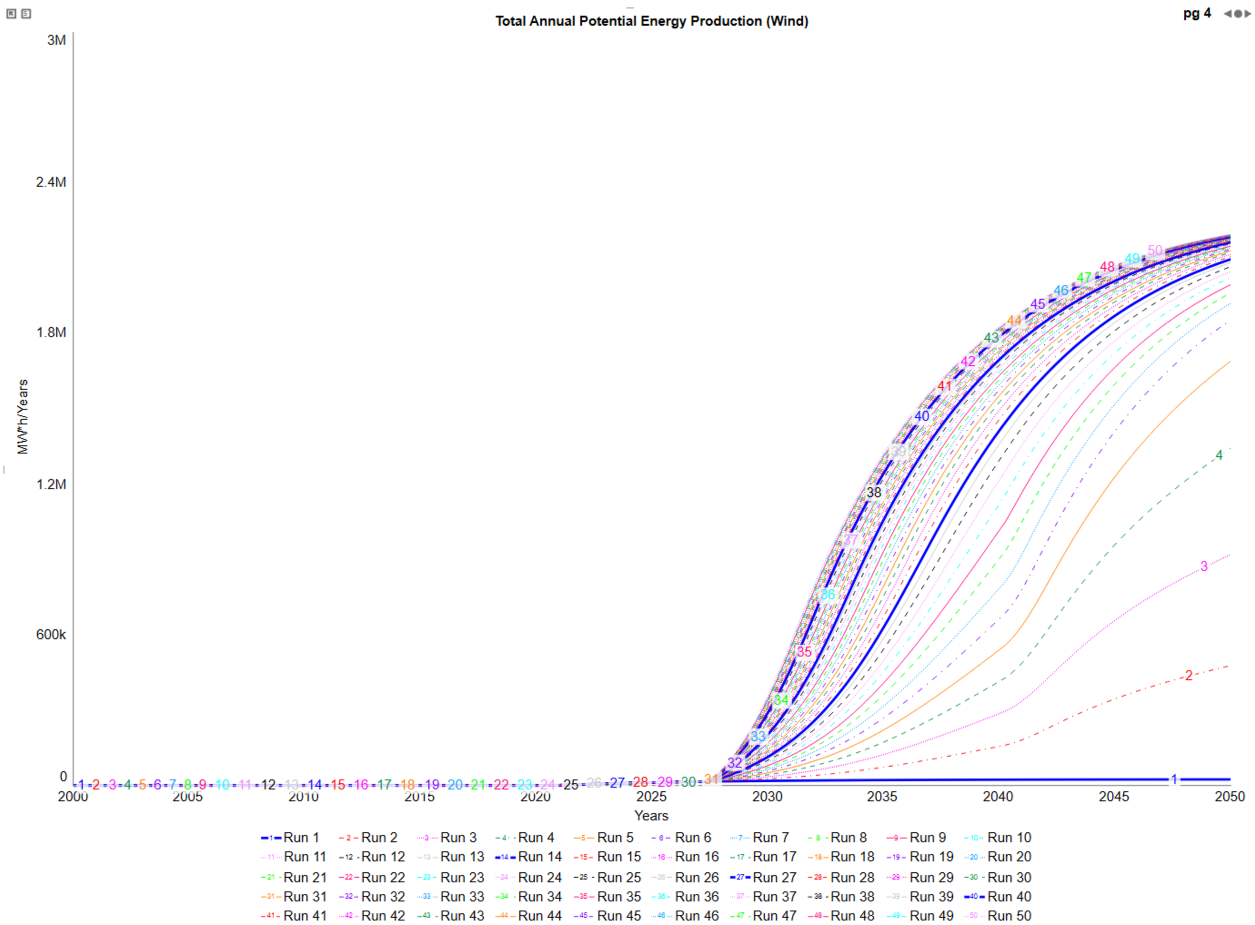

Figure 21: 50 Runs for Total Annual Potential Energy Production (Wind)

The final policy examined through sensitivity analysis was the cost per solar farm and its impact on the total number of solar farms. Initially, our base model set the cost per solar farm at #3.56 million dollars.

During the sensitivity analysis, 25 runs were conducted. The cost per solar farm varied across these runs, with the lowest cost observed in run #1 at $1 million dollars, and the highest in run #25 at $10 million dollars. Figure 22 illustrates the relationship between the cost per solar farm and the total number of solar farms.

It's evident that as the cost of a single solar farm fluctuates across the runs, the number of solar farms follows suit. Lowering the cost results in an increase in the total number of solar farms, and conversely, raising the cost leads to a decrease in the number of solar farms. Additionally, the figure highlights that lower costs facilitate more rapid construction of solar farms.

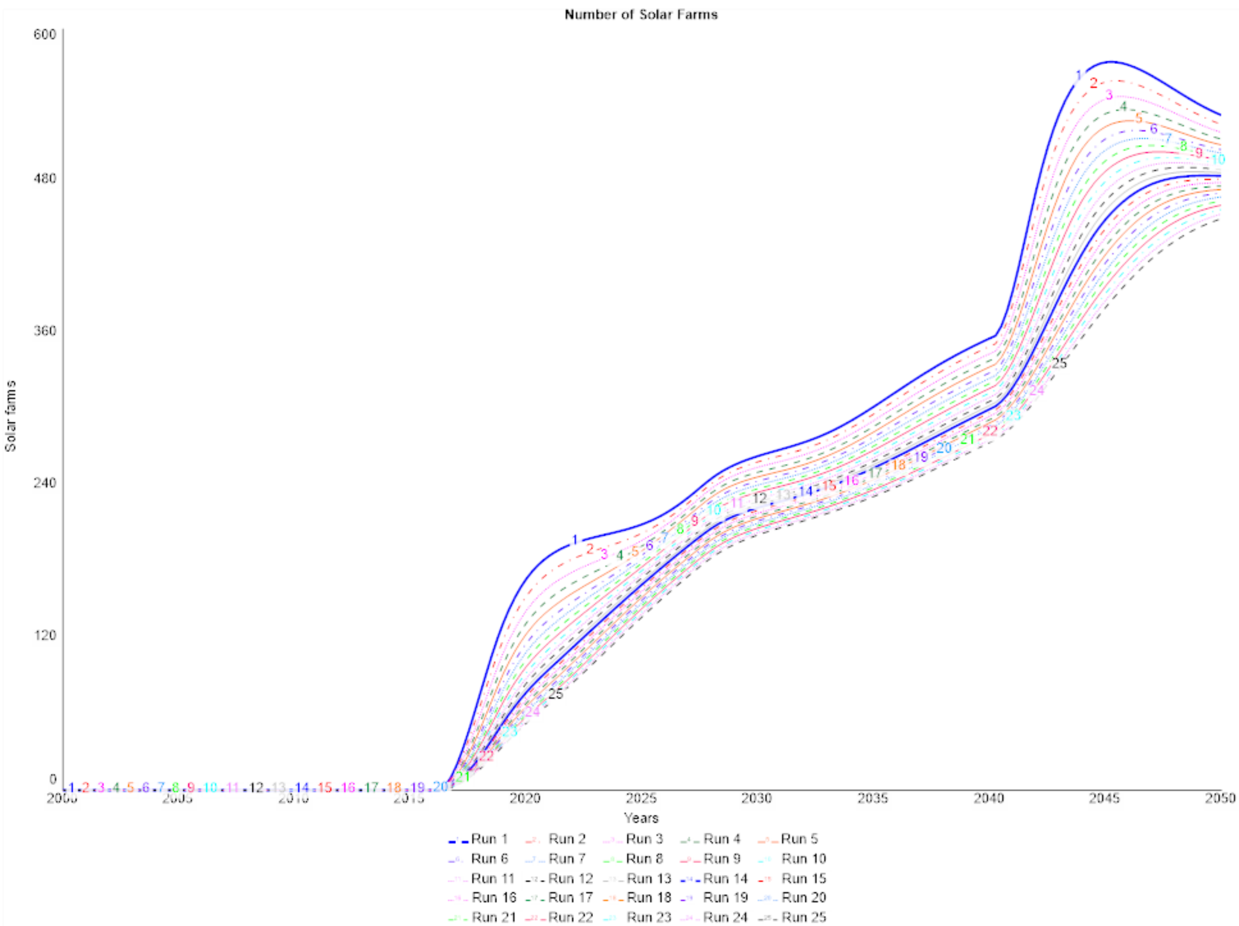

Figure 22: 25 runs for Number of Solar Farms

Scenarios

There are a couple scenarios that our model can explore and interpret. One such scenario involves technological breakthroughs among renewables. In this scenario, either wind energy or solar energy experiences a significant breakthrough that greatly enhances technology efficiency or dramatically reduces costs. This scenario is plausible and can be reflected in the model by adjusting the parameters such as the capacity factor of solar and wind. By increasing efficiency or reducing construction costs, renewables become more competitive, accelerating the transition away from fossil fuels, particularly natural gas. As a result, Virginia could potentially meet its energy demand from renewables much earlier than anticipated.

The other scenario presents a contrasting perspective, where a delay in renewable construction occurs, making natural gas a more appealing option. This delay could prolong the reliance on natural gas for energy generation, potentially extending beyond the timeframe currently predicted by our model. This scenario can be simulated in the model by increasing the construction time for renewables. Such delays could arise due to future policies or increased resistance against renewable energy projects. It’s important to acknowledge that both scenarios represent plausible possibilities in our future energy landscape.

Our model has the capability to simulate these extremes, along with various other situations and scenarios that may emerge. By exploring these possibilities, we gain insights into the potential trajectories of our energy transition and the factors that may influence it.

Discussion

Interpretation of Results

With our focus being on Energy Generation in the state of Virginia over time, our system adapts to the many policies and plans that are implemented in the Virginia Clean Economy Act (VECA) to reduce carbon emissions shift investment focus on more sustainable energy resources and make Natural Gas obsolete. Our model shows a steady linear incline in demand, and it also shows generation being less than demand. In Figure 17 which illustrates a spike in total generating power temporarily due to one of our policy switches that activates at that time and disables Natural Gas Energy Production. The model places a strong emphasis on the development of solar energy for the future of renewable energy generation in the state of Virginia. This preference stems from the abundant potential for solar farms to be established on land, surpassing the feasibility of offshore wind turbines or even land-based wind turbine farms.

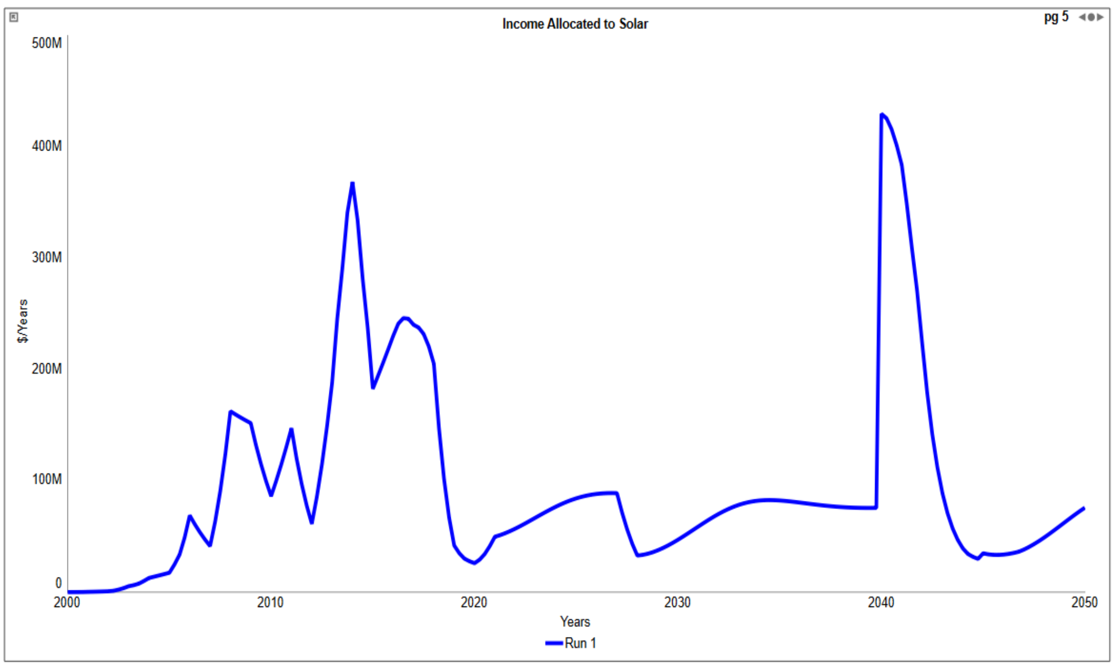

Figure 23: Income Allocated to Solar in the Future

Following the production of natural gas energy, there is a remarkable exponential growth in solar energy generation in the subsequent years. This surge is fueled by a significant increase in income allocated to solar projects, which skyrockets from $75.7 million in 2039 to a staggering $430 million in 2040, as evidenced by the compelling data depicted in Figure 23 and Figure 24.

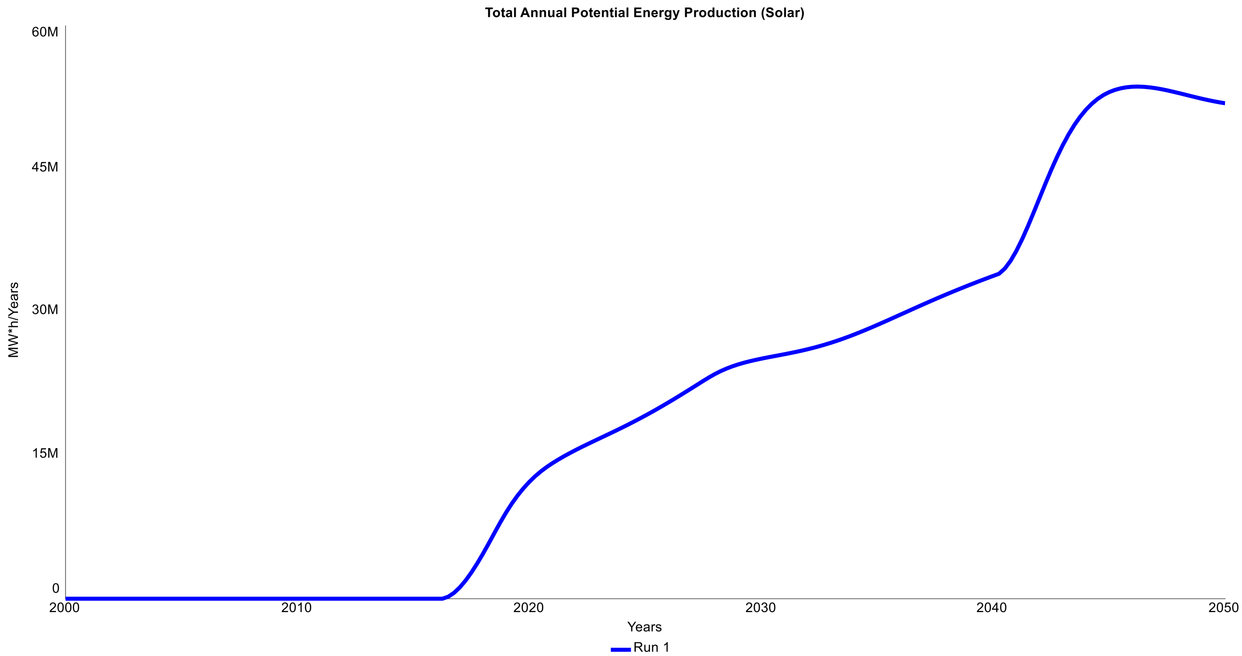

Figure 24: Total Annual Energy Production for Solar

The abundance of money that is being pumped into solar energy development across the state is increasing energy generation from solar sources from 33.8 MWh in 2040 to 53.6 MWh in 2046. This will fill the void of the riddance of natural gas generation and with time, a couple of years, the total annual energy production from solar will eventually raise the total energy generated in the state of Virginia and will become closer to the growing demand of energy.

Practical Implications

In 2024, we're witnessing a promising shift towards renewable energy sources, though they haven't completely eclipsed traditional methods in the energy sector just yet. Nevertheless, there's a clear momentum building towards a more sustainable future. This transition is backed by practical investments and funding that make the switch feasible. While traditional energy generation methods continue to have a foothold until roughly 2040, there's a significant redirection of funds from supporting natural gas towards the development of renewable sources such as wind and solar power. It's a gradual but deliberate process, marking a pivotal moment in our journey towards a more sustainable future.

Limitations

While our model provides valuable insights, it's important to acknowledge its limitations, especially regarding uncertainties in the data used for future estimates. We rely on references and parameters to ensure accuracy, but variations in data sources may lead to slight discrepancies. However, these discrepancies are unlikely to significantly impact our data and graphs. Our extensive research ensures that even minor fluctuations in numbers won't obscure the bigger picture or its applicability to our problem statement.

Conclusions

Summary of Findings

In conclusion, for Virginia to achieve its 100% zero-carbon goal, there needs to be a smooth transition from the current fossil fuel electricity generation to non-carbon-emitting electricity generation like renewables and nuclear. This process includes gradually increasing renewable and maintaining nuclear, while simultaneously decreasing reliance on fossil fuels, predominately natural gas. Based on our report and in conjunction with the 2022 Virginia Energy Plan, Virginia’s ambitious goal to achieve 100% carbon-neutral energy will be a substantial feat that’ll require precise timing and coordination to achieve.

To attain 100% carbon-neutral electricity by 2045, Virginia must gradually phase out its natural gas plants and decommission existing coal facilities while simultaneously expanding renewable infrastructure, particularly solar and wind energy. However, completely retiring natural gas plants by 2045 poses challenges due to their significant presence in Virginia, as indicated by our model. Additionally, limitations in wind turbine numbers mean Virginia will tap into its wind potential earlier than solar leading to a plateau in wind energy ahead of solar. Another hurdle is the allocation of land for solar farms, as Virginia will require substantial land for the influx of solar installations and storage infrastructure. This challenge does not extend to wind turbines, as only offshore wind farms are considered in our model.

Figure 25 below presents the output of our model, showcasing Virginia's energy portfolio in 2000 alongside projections for 2025 and 2050. The latter marks the target year for Virginia's aim of achieving 200% zero-carbon electricity generation.

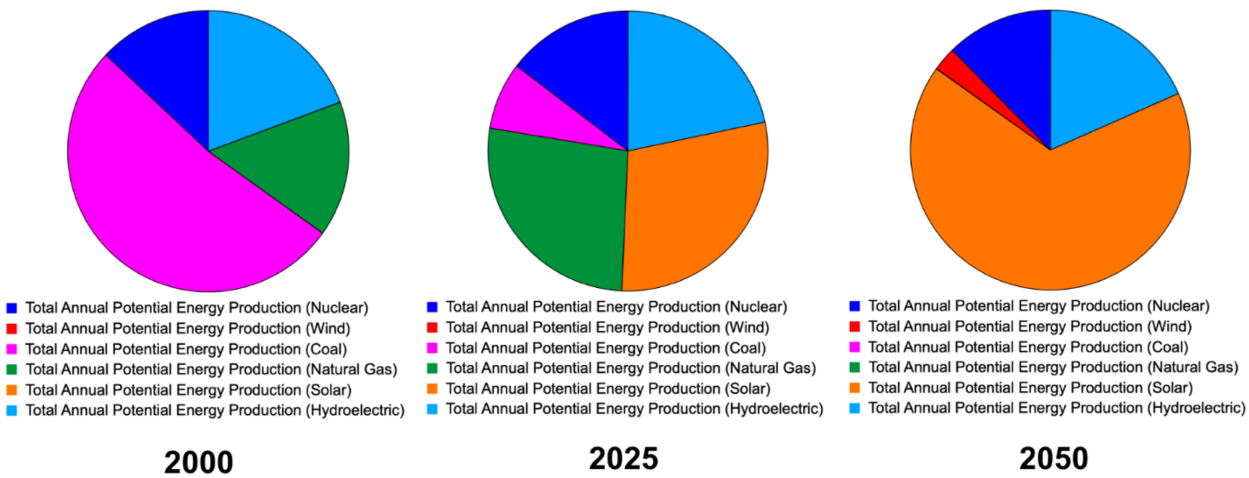

Figure 25: Energy generation from causal loop diagram

Contributions to the Field

While it's impossible to create a perfect model that considers every conceivable change and variable affecting energy generation in Virginia, we believe our model will serve as an excellent educational tool. It will benefit students, professors, researchers, and government/company officials in the energy field who seek to explore the complexity of this issue and understand the process Virginia will undergo to achieve its ambitious goal of 100% carbon-neutral energy generation by 2050. From an educational standpoint, students and professors can use our baseline model as a foundation, refining it to incorporate additional variables that impact energy generation. This iterative process can lead to the development of a more accurate and precise model. Coincidently, more behavior over time graphs can be generated, depicting the trajectory of generation sources and variable changes with greater factual evidence and reduced uncertainty.

Recommendations for Future Research

For future research, we would like students and professors to further investigate additional variables influencing energy generation in Virginia. Enhancing the model the model to incorporate these variables in more detail will facilitate the generation of more precise graphs with reduced uncertainty. Furthermore, research should focus on the Commonwealth's long-term plans for expanding their renewable energy infrastructure beyond 2050. This includes examining the rate at which Virginia intends to decommission existing fossil-based energy infrastructure to achieve its 100% carbon-neutral goal by 2045 (as outlined by the 2022 Virginia Energy Plan and Virginia Clean Economy Act), while maximizing energy generation within the state. Another crucial area for investigation is how Virginia plans to address disparities between energy demand and actual generation within its borders. By developing a model to illustrate potential solutions, further awareness and exploration can be spurred towards achieving energy independence for Virginia.

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