TVA's Clean Energy Future

Charting a course to decarbonization in the Tennessee Valley

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AUTHORS

Pat Knight
Jason Frost
Tyler Fitch
Elijah Sinclair
Jon Tabernero
Olivia Griot
Ben Havumaki
Jack Smith
Lucy Metz
Sabine Chavin

Synapse
Energy Economics, Inc.

485 Massachusetts Avenue, Suite 3
Cambridge, Massachusetts 02139

617.661.3248 | www.synapse-energy.com

CONTENTS

ACKNOWLEDGEMENTS I

EXECUTIVE SUMMARY 1

1. TVA'S ROLE IN THE CLEAN ENERGY TRANSITION 6
   1.1. Integrated resource planning: A roadmap for TVA's energy future 8
   1.2. Synapse's approach 10

2. ANALYSIS 11
   2.1. Methodology 11
   2.2. Modeled scenarios 12
   2.3. Results 15

3. RECOMMENDATIONS FOR FUTURE MODELING EFFORTS 35
   3.1. TVA should consider its decarbonization targets in resource planning 35
   3.2. TVA should increase cost-effective energy efficiency investments 35
   3.3. TVA must consider electrification trends and the IRA to prepare for economy-wide decarbonization and increased demand 36
   3.4. TVA planning processes should evaluate demand-side resources as options to mitigate grid investment and reduce total system costs 37
   3.5. TVA should evaluate renewables and conventional resources on equal footing 39
   3.6. TVA should improve reserve margin modeling and appropriately evaluate the reliability contributions of renewables 40
   3.7. TVA should account for non-electric benefits of a clean energy transition 41

4. CONCLUSION 42

APPENDIX A. KEY SCENARIO INPUTS 43

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- Appalachian Voices: Brianna Knisley and Rory McIlmoil
- Center for Biological Diversity: Gabriela Sarri-Tobar
- Energy Alabama: Daniel Tait
- Friends of the Earth: Herman Morris
- GridLab: Taylor McNair, Ric O'Connell, and Kyra Ngai
- RMI: Joseph Daniel and Aaron Schwartz
- Southern Alliance for Clean Energy: Maggie Shober
- Southern Environmental Law Center: Amanda Garcia
- Southern Renewable Energy Association: Simon Mahan

Consumers in TVA's service territory can save $255 billion by switching away from fossil fuels.

EXECUTIVE SUMMARY

Tennessee Valley Authority (TVA), the largest provider of public power in the United States, is uniquely positioned to lead the way in the clean energy transition for Tennessee Valley. The U.S. Congress created TVA, originally conceived as a flood-control solution, as a federally owned electric utility in the 1930s to electrify the Tennessee Valley and bring economic benefits to the region. Today, TVA has the chance to continue this legacy through the 21st century with a shift to clean energy.

This clean energy transition will involve a major shift away from TVA's conventional emphasis on aging fossil technology towards new technology, including storage, solar, wind, and demand-side resources. Changes in the electric sector will accompany a shift away from burning dirty and inefficient fossil fuels in homes, businesses, and vehicles. This future electric sector leverages efficient electric-powered technology to meet expanded heating and mobility needs for the same customers that TVA is already serving. By taking advantage of new federal legislation, particularly the *Inflation Reduction Act of 2022*, TVA is poised to lead a transition that can produce benefits for local consumers such as improved air and water quality, as well as job creation.

Our "100% Clean Energy" scenario shows that by completely switching away from fossil fuels in the electric sector by 2035, and by pursuing ambitious levels of electrification in the transportation, buildings, and industrial sectors, consumers in TVA's service territory can experience savings of $255 billion, compared to a status quo "TVA Baseline" scenario.

Synapse was hired by GridLab, in partnership with Center for Biological Diversity, to better understand what it would take to achieve this clean energy transition. Using state-of-the-art electric sector and economic computer models, we examined TVA's electric system at a detailed level from the early 2020s through 2050. By conducting scenario analysis of several different visions of the future, we compared a scenario that accelerates a clean energy future using storage to balance solar and wind without fossil fuels to a scenario that adheres to TVA's status quo approach. We found that a clean energy future that reduces greenhouse gas emissions not only meets energy and capacity needs and provides electricity reliably, but also generates a wealth of economic development, public health, and energy justice benefits to Tennessee Valley consumers (on the order of hundreds of billions of dollars).

Table 1 illustrates the magnitude of this change in the electric sector. We modeled a shift from a current TVA that is dependent on fossil fuels for 40 percent of electricity generation (the "TVA Baseline" scenario) to a TVA that phases out fossil fuels entirely by 2035 (the "100% Clean Energy" scenario). By 2050, this future reduces emissions from all sectors of the Tennessee Valley's economy by over 90 percent.[1] Table 2 shows the estimated economic impacts. When compared to a status quo TVA approach, this clean energy future produces savings of $255 billion for consumers. Moreover, electricity is served reliably despite the system having more than double the current demand for electricity and exclusive reliance on non-emitting energy resources such as wind, solar, and battery storage.

Table 1. Primary electric-sector findings

	2020	2035		2050	
	Actual	*TVA Baseline*	*100% Clean Energy*	*TVA Baseline*	*100% Clean Energy*
CO_2 emissions reduction					
Electric sector reductions (target)	51%	84% (n/a)	100% (100%)	99% (n/a)	100% (100%)
All sector	-	26%	55%	41%	92%
Share of generation (%)					
Coal	12%	0%	0%	0%	0%
Gas	31%	24%	0%	2%	0%
Nuclear	38%	39%	30%	35%	17%
Hydro and other	16%	17%	22%	18%	19%
Renewable	3%	20%	48%	46%	64%
Wind	3%	4%	19%	22%	32%
Utility-scale & distributed solar	0%	16%	28%	23%	32%
Battery storage & demand response	-	-	-	-	-
Load (TWh)	164	169	192	179	327
Operating capacity (GW)					
Coal	7	0	0	0	0
Gas	15	13	1	6	0
Nuclear	8	8	8	8	8
Hydro and other	7	7	6	6	6
Renewable	2	22	72	60	191
Wind	1	2	14	13	41
Utility-scale & distributed solar	0	15	35	37	101
Battery storage & demand response	1	5	23	11	49

Notes: Electric sector emission reductions are given relative to 2005. All Sector emission reductions are given relative to 2020. Battery storage is shown as having no generation due to having net negative energy requirements. "Other" includes biomass and other miscellaneous sources.

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[1] Throughout this report, "all sector emissions" include CO_2 emissions from the electric, motor vehicle, and building sectors, but not non-CO_2 GHG emissions, upstream emissions, or emissions from airplanes, agriculture, and other sectors of the economy.

Table 2. Single-year and cumulative net costs, 100% Clean Energy versus TVA Baseline (2021 $ billion)

	2035	2050	Cumulative
Electric system	-$1.2	-$4.6	-$53.9
Buildings	$0.0	$0.6	$9.2
Transportation	$8.1	$22.0	$277.2
Other	$0.1	$3.9	$23.0
Net savings	**$7.1**	**$21.8**	**$255.6**

Note: Positive numbers are savings while negative numbers are costs. "Electric system" includes wholesale energy costs, and programmatic and participant spending on energy efficiency and distributed generation resources. "Buildings" includes the costs and savings related to switching residential and commercial customers to efficient heat pumps and electrifying all remaining end uses, inclusive of avoided fossil fuel expenditures. "Transportation" includes the costs and savings related to consumers switching from conventional internal combustion engine vehicles to electric vehicles, including avoided fossil fuel expenditures, as well as the cost of building out charging infrastructure for EVs. "Other" includes fuel savings related to electrifying the industrial sector but does not include the costs of electrification itself. This list is non-exhaustive; see subsection "System costs" on page 23 for more.

Our analysis also found:

- **The 100% Clean Energy scenario produces economy-wide net savings of $255 billion over the study period throughout the Tennessee Valley.** Although wholesale electric sector system costs rise from about $5 billion today to $9 billion in 2050, these cost increases are more than offset by fuel savings outside the electric sector, including a reduction in transportation fossil fuel expenditures of $195 billion over 30 years. Electric sector cost increases are primarily driven by capacity additions needed to power newly electrified measures, and is not due to switching from fossil fuels to clean energy.

- **Through continued emphasis on energy efficiency, residential energy burdens fall from 7 percent today to 3 percent by 2050.** Residential energy burden is defined as the amount of money a household spends on energy, relative to its income. Through an emphasis on more efficient clean energy and away from less efficient and volatile fossil sources, households spend less on their energy needs in a clean energy future. This is in spite of a 13 percent increase in monthly electricity bills, which is more than offset by a marked decrease in household fossil fuel spending on gasoline and home heating fuels.

- **Both primary scenarios achieve (and sometimes exceed) their clean energy targets with no reliability issues.** With the level of temporal resolution we modeled (8 three-hour blocks per day in a typical week) we did not see any hours with unserved energy. In addition, the modeled scenarios met both summer and winter reserve requirements every year. We note that a full evaluation of reliability in an all-clean electric grid would require more detailed stochastic analysis.

- **The TVA Baseline scenario shows that electric-sector emissions in 2050 can be reduced by 99 percent with no increases in costs.** We observed electric system costs of about $5 billion in every year of the TVA Baseline case. This suggests that clean energy deployment is already a least-cost option for TVA, even without enforced decarbonization constraints.

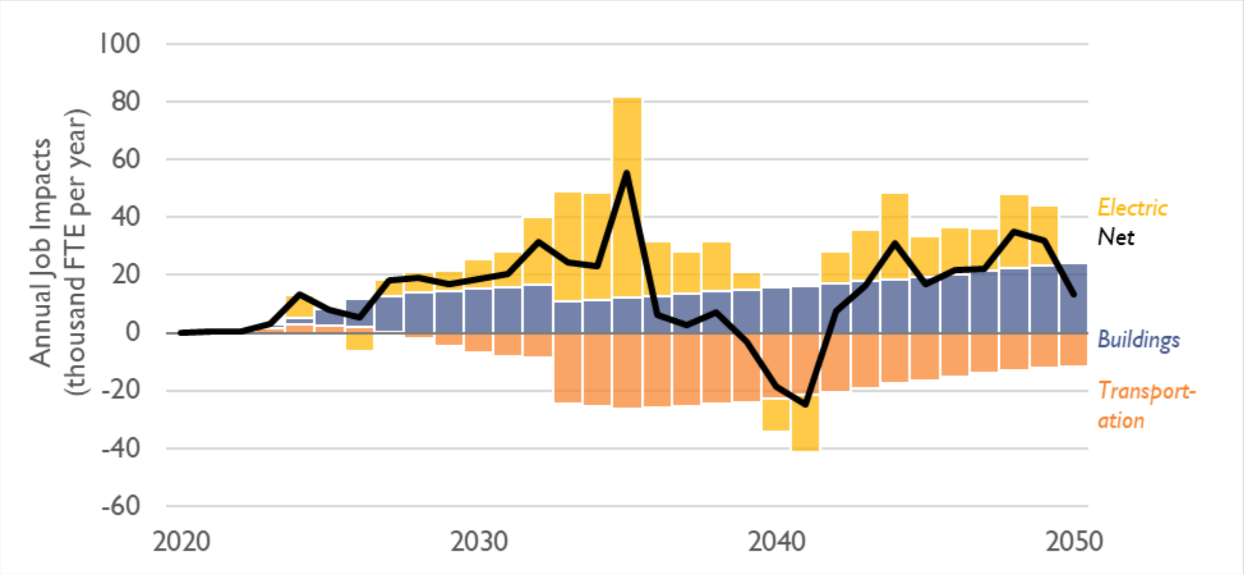
- **Ambitious building decarbonization in the 100% Clean Energy scenario adds no new net electricity demand.** Because many TVA customers currently heat with inefficient electric resistance heating, switching to more efficient heat pumps offsets any additional electricity demand created by switching from natural gas heating to heat-pump-driven electric heating. Instead, most load growth is due to transportation electrification and industrial electrification, each representing about half of the total increase in load by 2050. Moderate and reasonable increases in the deployment of conventional energy efficiency measures throughout the study period helps to defer load growth.

- **An emphasis on flexible demand resources can help minimize the construction of battery storage and utility-scale solar resources.** By better utilizing advanced demand response and distributed resources, TVA could avoid the construction of 2 GW of utility-scale solar and over 20 GW of battery storage. By analyzing increased levels of distributed resources in our "Ambitious DER" scenario, we found that TVA consumers could reduce wholesale electric sector costs by $1.5 billion in 2050 alone.

- **Both scenarios project a shift away from TVA-owned resources.** The TVA Baseline scenario models 45 TWh of wind power purchase agreements (PPA) with neighboring regions by 2050; the 100% Clean Energy scenario has 130 TWh of non-TVA wind PPAs (about one-third of TVA's total generation). This is largely due to the more favorable economics and better capacity factors of midwestern wind, even accounting for (a) TVA's new eligibility for federal clean energy tax credits under the IRA (2022) and (b) cost of transmission lines to neighboring regions to facilitate this wind. This is a marked shift away from TVA's approach to procuring power today, where only a small fraction of energy comes from out-of-Valley renewables.

- **A clean energy transition adds about 15,600 job-years to the economy in TVA's service territory.** Job additions are driven by the construction of new solar, storage, and heat pump resources, as well as savings on energy expenditures (see Figure 1).

Figure 1. Job impacts from the 100% Clean Energy scenario, relative to the TVA Baseline scenario



- **A clean energy transition creates vast amounts of public health and societal benefits.** The 100% Clean Energy scenario leads to $27 billion in nationwide public health benefits related to avoided heart attacks, respiratory illnesses, and premature death. It also provides $265 billion in cumulative societal benefits, based on the latest estimates of social cost of carbon from the U.S. Environmental Protection Agency (EPA). Both of these benefits are in addition to the benefits shown above in Table 2. Switching away from fossil fuels to clean energy sources eliminates the creation of coal ash and more than halves water consumption from power plants.

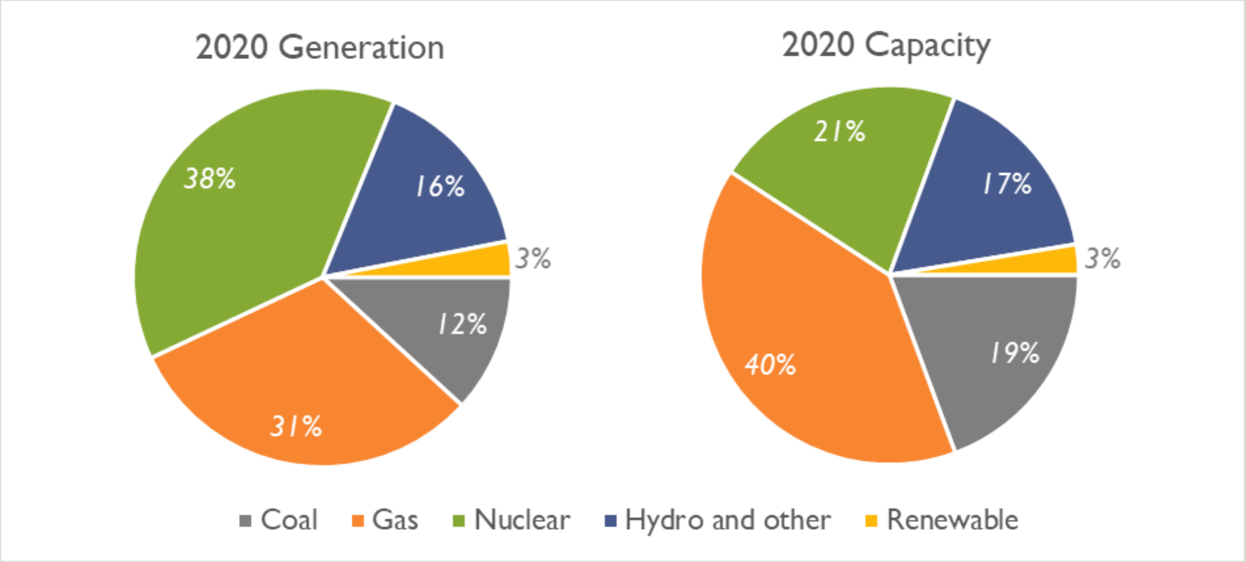
- **Land-use impacts in the Tennessee Valley can be minimized through an emphasis on distributed resources.** We found that to achieve the level of utility-scale solar in the 100% Clean Energy scenario, each county in TVA's service territory would need to build the equivalent of just 480 MW solar facilities, or roughly two large solar farms. Meanwhile, to achieve the level of distributed solar assumed in the 100% Clean Energy scenario, only 4 percent of rooftops in the Tennessee Valley would need to add solar. An increase in that portion of rooftop solar could minimize the utility-scale solar impacts on land use.

This report closes with recommendations for future modeling efforts. We view this analysis as a guide for future analytical efforts, including those performed by TVA in the integrated resource planning (IRP) process that we expect to begin in 2023.

1. TVA'S ROLE IN THE CLEAN ENERGY TRANSITION

Tennessee Valley Authority (TVA) is a federally owned electric utility and the largest provider of public power in the United States. U.S. Congress created TVA in 1933 to, "provide for the agricultural and industrial development" of the Tennessee River Valley.[2] Today, 90 years since its founding, TVA remains a critical source of power and economic development in the region. TVA's electric generation fleet is the sixth-largest in the country, with over 66 GW of generation capacity under its control.[3] Figure 2 shows the generation and capacity for TVA's service territory in 2020.

Figure 2. Recent generation and capacity in TVA's service territory



Note: This figure includes generation and operational capacity from all resources within TVA's service territory, including those resources not necessarily owned by TVA. "Hydro and other" includes hydro, biomass, and miscellaneous resources. "Renewable" includes solar, wind, and battery storage resources.

After working to electrify the Tennessee Valley through the 20th century, TVA now has an opportunity to make a new transformation. Like many of its peer utilities, TVA has publicly committed to take advantage of cost-effective, zero-carbon resources and reduce its carbon emissions from power generation. TVA's carbon commitment targets a 70 percent reduction of carbon dioxide (CO_2) by 2030, 80 percent by 2035, and net-zero aspiration by 2050. President Biden's ambition to completely decarbonize the United States' electric generation by 2035 adds even more urgency to TVA's zero-

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[2] See https://www.tva.com/about-tva/our-history.

[3] For more information on TVA's climate goals, see its "Carbon Report" web page, available at https://www.tva.com/environment/environmental-stewardship/sustainability/carbon-report.

carbon commitment.[4] At a minimum, TVA's journey toward a zero-carbon grid will entail a transition away from TVA's legacy coal fleet and an ambitious deployment of zero-carbon technologies like solar, wind, and energy storage. Notably, TVA leadership has suggested that existing technology can get the utility to reduce carbon emissions by 80 percent by 2035, but that technology will need to evolve in order to achieve 100 percent decarbonization.[5]

TVA's decisions will impact future ratepayers as well as today's national decarbonization trends. As its aging coal fleet reaches the end of its useful life, TVA must decide whether to chart a course for clean energy development or continue with its legacy utilization of fossil resources. In January 2023, TVA indicated it would replace a retiring coal plant with a 1,450-MW gas generator.[6] Status quo decisions like this one will lock TVA into a future dependent on fossil fuels, and thereby burden the region with the associated detrimental impacts to consumer wallets, public health, and pollution.

As TVA and utilities across the country continue their transition toward less carbon-intensive energy sources, clean energy technologies are creating new options and pathways for serving the grid. Distributed energy resources promise to play a greater role than ever before. Rooftop solar and distributed energy storage technologies provide zero-carbon electricity directly at the point of use, which could avoid or defer capital-intensive investments in distribution and transmission infrastructure and also lead to increases in jobs within the Valley. Demand-side management programs also allow customers unprecedented control over their own usage so they can reduce their own bills while generating savings for the grid as a whole. Together, distributed energy resources provide a unique service to the grid and will be a critical source of flexibility as the power system integrates more variable renewable energy.[7]

As entrepreneurs, ratepayers, and policymakers contemplate transitioning from carbon-emitting technologies to clean energy across the entire Tennessee Valley economy, the electricity grid's role will be even more critical as a source of zero-carbon energy across an expanded set of sectors and end uses. Switching from fossil fuels to electricity across heating, transport, and heavy industry will also bring new benefits to the community. These benefits include less local pollution; less dependence on volatile fuel

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[4] The White House. April 22, 2021. *FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies*. Available at https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

[5] Tennessee Valley Authority (2021). TVA Charts Path to Clean Energy Future. Retrieved at: https://www.tva.com/newsroom/press-releases/tva-charts-path-to-clean-energy-future.

[6] "TVA Retiring Cumberland, Continues Transition to Clean Energy Future." Press Release. TVA. January 10, 2023. Available at https://www.tva.com/newsroom/press-releases/tva-retiring-cumberland-continues-transition-to-clean-energy-future; *A Clean Energy Portfolio Is Still the Best Option for TVA*. Synapse Energy Economics. January 2023. Available at https://www.synapse-energy.com/sites/default/files/Synapse%20Response%20to%20Concentric%20Report.pdf.

[7] Shen, B., Kahrl, F., & Satchwell, A. (2021). Facilitating Power Grid Decarbonization with Distributed Energy Resources: Lessons from the United States. Retrieved at: https://emp.lbl.gov/publications/facilitating-power-grid.

commodities; and local economic development in sectors that construct, install, and maintain new, electricity-powered equipment. This report describes cutting-edge modeling and analysis to envision an electrified Tennessee Valley and project its impacts on the economy and electric grid.

Economy-wide decarbonization and electrification inverts the conventional wisdom that electricity use will continue to grow at a low, stable rate. High-quality national decarbonization models project that, across the United States, total electricity demand could more than double between now and 2050.[8] Despite these authoritative projections, TVA's last long-term planning process (its 2019 integrated resource planning, or IRP, process--described below) did not include any meaningful consideration of electrification despite its potentially dramatic impact on how electricity is generated, transmitted, distributed and used. As TVA plans to decarbonize its energy supply, it must also plan for integrating increasing demand for zero-carbon electricity from other sectors.

Faced with a rapidly changing energy landscape, TVA should be developing a long-term plan for meeting the Tennessee Valley's energy needs reliably, affordably, and sustainably. TVA's planning choices will impact both TVA's own decarbonization pathway and the broader economy across the Tennessee Valley. Responsible energy planning should account not only for how TVA's energy portfolio serves the electric grid, but also its impacts on economic development and land and water resources. Ensuring that TVA is charting a pathway to decarbonization that is most beneficial for the Tennessee Valley requires even-handed consideration of each of these impacts.

1.1. Integrated resource planning: A roadmap for TVA's energy future

TVA updates its roadmap for energy resources every few years through the development of its IRP.[9] Integrated resource planning is the industry-standard method that utilities use to plan for the future: they assess future grid needs over the next 20 years; explore inventory supply- and demand-side resources available to meet those needs; and then make plans to build or procure energy resources to meet grid needs while also satisfying reliability, affordability, and environmental standards.

As a federally owned public entity, TVA's IRP process is unique. Most utilities submit draft IRPs to state regulators, who review the plan and make a judgment about whether the utility's plan is in the public interest and identify any needed revisions. In TVA's case, its IRPs proceed like many other federal agency decisions: TVA develops and issues a draft IRP and environmental impact statement (EIS), which initiates a period of public review, consultation, and comment. After the comment period, the presidentially

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[8] Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala,R.Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley,E. Leslie, K.Paustian, and A. Swan, (2021, October). Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final report, Princeton University. Retrieved at: https://www.dropbox.com/s/ptp92f65lgds5n2/Princeton%20NZA%20FINAL%20REPORT%20%2829Oct2021%29.pdf?dl=0.

[9] TVA's statute does not have a requirement that IRPs be conducted on a set schedule. Previous IRP processes have been conducted in 2019, 2015, and 2011.

appointed TVA Board of Directors revises and adopts the IRP.[10] In addition to the goal of providing low-cost, reliable, and clean electricity, TVA's IRPs have a goal of identifying an energy resource plan that performs well under a variety of future conditions, taking into account cost risk, environmental stewardship, operational flexibility, and Valley economics.[11]

The Inflation Reduction Act and the Tennessee Valley Authority

Signed into law in August 2022, the *Inflation Reduction Act* (IRA) includes an ambitious set of climate and clean energy provisions that promise to further transform the energy landscape. The historic law, representing $369 billion in funding, targets cutting U.S. greenhouse gas emissions roughly 40 percent by 2030.[12] While TVA's identity as a publicly owned entity has historically excluded it from taking advantage of tax credits on clean energy investments, specific provisions of the IRA will unlock access to clean energy incentives for TVA. The IRA will have wide-ranging impacts on the U.S. energy economy, including in the Tennessee Valley. Taking advantage of the IRA's provisions in the short term should be a priority for energy resource planning in the Tennessee Valley and across the country. The following IRA programs present big opportunities for TVA's energy future (Appendix 1 details how we included these tax credits and investment subsidies in our modeling):

- **Refundable clean energy tax credits:** technology-neutral clean energy investment tax credits (for which standalone storage is newly eligible) and production tax credits (for which solar is newly eligible) with a 10-year lifespan; TVA is now eligible for direct refunds, which will enable it to monetize these credits.
- **Incentives for building energy efficiency and electrification:** two new major rebate programs to support home energy retrofits, through which the seven states served by TVA have been allocated $1.2 billion of funding altogether;[13] the IRA expanded and extended existing tax credits for residential and commercial building improvements.[14]
- **Accelerating transmission buildout:** $2 billion in funding for national-interest electric transmission facilities and $760 million for studying transmission impacts; this will complement the "Building a Better Grid" initiative, a program funded by the Infrastructure Investment and Jobs Act (IIJA) that aims to catalyze nationwide development of high-capacity transmission lines.
- **Energy Infrastructure Reinvestment Program:** $5 billion to guarantee up to $250 billion in loans to replace retired infrastructure or enable operating infrastructure to reduce emissions, e.g., by refinancing undepreciated assets.[15]
- **Electric vehicle funding:** individuals and businesses purchasing new or used electric vehicles are eligible for electric vehicle rebates, including a $7,500 rebate for new electric cars under $55,000.

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[10] IRP Record of Decision: https://tva-azr-eastus-cdn-ep-tvawcm-prd.azureedge.net/cdn-tvawcma/docs/default-source/default-document-library/site-content/environment/environmental-stewardship/irp/irp_rod_published_9-17-19_in_fed_reg_201920104.pdf?sfvrsn=a53fe867_4.

[11] 2019 Integrated Resource Plan. Volume I – Final Resource Plan. TVA. June 2019. Available at https://tva-azr-eastus-cdn-ep-tvawcm-prd.azureedge.net/cdn-tvawcma/docs/default-source/default-document-library/site-content/environment/environmental-stewardship/irp/2019-documents/tva-2019-integrated-resource-plan-volume-i-final-resource-plan.pdf?sfvrsn=44251e0a_4. See also TVA's statutory requirement for least-cost planning: U.S. Code 16 (2021), § 831m-1. www.govinfo.gov/app/details/USCODE-2021-title16/USCODE-2021-title16-chap12A-sec831m-1.

[12] Jenkins, J.D., Mayfield, E.N., Farbes, J., Jones, R., Patankar, N., Xu, Q., Schivley, G., "Preliminary Report: The Climate and Energy Impacts of the Inflation Reduction Act of 2022 ," REPEAT Project, Princeton, NJ, August 2022.

[13] Energy.gov, (2022). Biden-Harris Administration Announces State and Tribe Allocations for Home Energy Rebate Programs. Available at: https://www.energy.gov/articles/biden-harris-administration-announces-state-and-tribe-allocations-home-energy-rebate.

[14] Ungar, L., and S. Nadel. (2022). Home Energy Upgrade Incentives: *Programs in the Inflation Reduction Act and Other Recent Federal Laws*. Washington, DC: American Council for an Energy-Efficient Economy. www.aceee.org/policy-brief/2022/09/home-energy-upgrade-incentives-programs-inflation-reduction-act-and-other.

[15] O'Boyle, M., Solomon, M. (2022, August 24). "Inflation Reduction Act Benefits: Billions in Just Transition Funding for Coal Communities." *Forbes*. Available at: https://www.forbes.com/sites/energyinnovation/2022/08/24/inflation-reduction-act-benefits-billions-in-just-transition-funding-for-coal-communities/?sh=6e22963d6ebd.

While IRPs were initially adopted by the electric utility industry as a response to nuclear cost over-runs and fossil supply constraints, today they are used to plan for a whole new set of transitions in the energy sector.[16] An IRP's long time horizon (typically 20 years or more) brings medium- and long-term carbon emissions goals into focus, and the integration of electricity demand and supply provide an opportunity to synchronize electricity supply with electrification across the economy. In the context of economy-wide decarbonization, IRPs provide an opportunity to look at the big picture and plot a path forward. TVA's most recent IRP was finalized in September 2019, with a direction to update the IRP no later than 2024. TVA's next IRP will be the first one since TVA's announcement of an 80 percent reduction in carbon emissions by 2035 and net-zero emissions by 2050, and the first since President Biden's executive order to decarbonize the electricity supply by 2035. TVA's next IRP represents a critical opportunity to chart a pathway toward achieving those goals while supporting economy-wide decarbonization and continuing to deliver affordable, reliable power to TVA ratepayers.

1.2. Synapse's approach

In this report, Synapse Energy Economics explores several pathways for TVA's energy future. Synapse's approach is anchored by the EnCompass capacity expansion and production cost modeling software, which allows Synapse to model the TVA electricity system in detail and ensure that resource pathways optimize costs and maintain system reliability.[17] Synapse has developed robust forecasts of electricity demand in the context of increasing electrification and used up-to-date, industry-standard cost forecasts for new resources to ensure that Synapse's results are consistent with real-world outcomes.

In turn, we have assessed the impact of optimized resource portfolios generated by EnCompass on topics that are meaningful to TVA ratepayers, including impacts to rates and bills, energy burden, local economic development, public health, land use, and water use. These additional dimensions provide a fuller picture of what the energy transition will mean for the Valley, and the tradeoffs that might exist between different resources and pathways. Importantly, our analysis highlights that TVA's energy pathway has wide-ranging impacts across the people and economy of the Tennessee Valley.

In 2023, TVA will release its own draft IRP that charts its own proposed pathways for providing clean, affordable, and reliable power in the public interest. As TVA and interested stakeholders deliberate on their vision for TVA's energy portfolio, this study can provide an initial, independent assessment of potential energy futures for the TVA and the Tennessee Valley.

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[16] For more information on IRP history and best practices, see *Best Practices in Electric Utility Integrated Resource Planning.* Synapse Energy Economics. June 2013. Available at https://www.synapse-energy.com/sites/default/files/SynapseReport.2013-06.RAP_.Best-Practices-in-IRP.13-038.pdf.

[17] We note that in May 2022, Synapse published a report *Clean Portfolio Replacement at Tennessee Valley Authority* (available at https://www.synapse-energy.com/sites/default/files/TVA_Clean_Portfolio_Modeling_21-097_0.pdf). This analysis, while similar conceptually, differs from that previous work in several ways. Notably, it is inclusive of the effects of the Inflation Reduction Act (which did not exist at the time of the prior report's printing, conducts analysis through 2050 (rather than 2042), and envisions a future Tennessee Valley with more ambitious levels of electrification and decarbonization.

2. ANALYSIS

Synapse's exploration of a clean energy future for TVA relied on the comparison of several scenarios. These scenarios present several visions of the future, with different assumed values for electricity demand and electrification, availability of clean energy and demand-side resources, modifications to TVA's approach to reserve margins, and requirements for electric sector emission reductions. Within each scenario, we evaluated the least-cost approach for TVA to reliably meet its customers' electricity needs, and then we estimated the impact on the electric sector and other sectors of the economy.

2.1. Methodology

Our approach for analyzing the impacts of decarbonizing TVA and end uses in its service territory involved a number of tools (see Figure 3). At the heart of our analysis was the use of an electric-sector capacity expansion and production cost model, EnCompass. Developed by Anchor Power Solutions, EnCompass is a single, fully integrated power system platform that allows for utility-scale generation planning and operations analysis, and it is widely used by utilities across the country for IRP planning. Synapse populated the model using the EnCompass *National Database*, created by Horizons Energy, and supplemented this dataset with additional publicly available information to provide further detail on power plant characteristics, resource costs, and fuel prices. EnCompass was used to produce outputs related to generation, capacity, emissions, and system costs, based on least-cost optimization.

This analysis also relied on a number of other tools for developing metrics relevant to the transportation, buildings, and industrial sectors. Several of these metrics (such as avoided tailpipe emissions) are outputs in their own right; others become inputs into the EnCompass model or another analytical tool. Four such tools utilized in this project were Synapse's Electric Vehicle Regional Demand Impacts (EV-REDI) tool, Synapse's Building Decarbonization Calculator (BDC), U.S. EPA's Energy Savings and Impacts Scenario Tool (ESIST), developed by Synapse, and U.S. DOE's EVI-Pro Lite tool.[18]

Synapse used each of these tools to generate costs and cost deltas between scenarios. We combined data related to costs with job-per-million-dollar-spent factors generated from the IMPLAN model and other inputs to generate estimates of job changes over time.[19]

Many of these tools also generate changes to emissions of criteria pollutants that impact human health, including nitrogen oxide (NO_X), sulfur dioxide (SO_2), particulate matter ($PM_{2.5}$), volatile organic compounds (VOC), and ammonia (NH_3). Data on how emissions of these pollutants vary between

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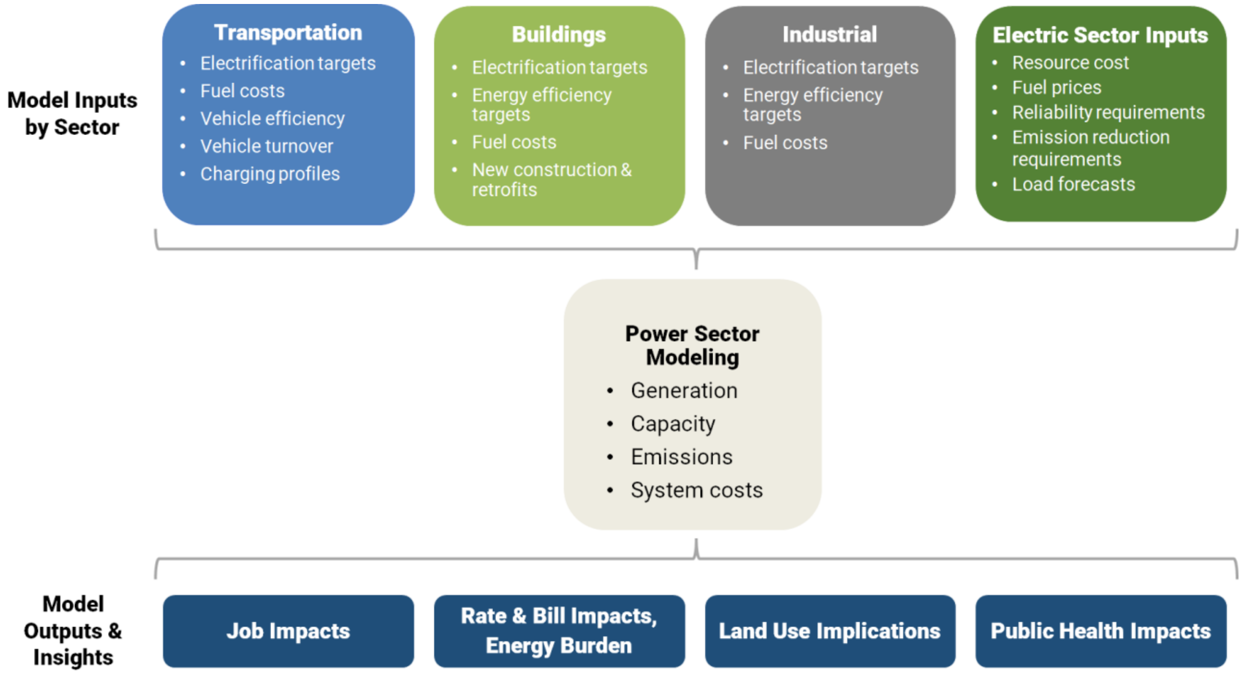
[18] For more information on EV-REDI and BDC, please see https://www.synapse-energy.com/tools/electric-vehicle-regional-emissions-demand-impacts-tool-ev-redi and https://www.synapse-energy.com/tools/building-decarbonization-calculator. For more information on ESIST, see https://www.epa.gov/statelocalenergy/energy-savings-and-impacts-scenario-tool-esist. For more information on EVI-Pro Lite, see https://afdc.energy.gov/evi-pro-lite.

[19] For more information on the IMPLAN model, see https://implan.com/.

scenarios was passed through U.S. EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) to estimate how emission dispersion varies, and how this change could impact public health.[20]

Figure 3. Diagram of modeling tools



2.2. Modeled scenarios

Table 3 describes the scenarios modeled in this study, and the primary differences among them. Our three scenarios were:

- TVA Baseline: Models a status-quo approach to a future TVA. This is a scenario that builds on the "Current Outlook" modeling conducted by TVA in its 2019 IRP, but allows TVA to procure cost-effective renewables enabled, in part, by the passage of the Inflation Reduction Act of 2022.
- 100% Clean Energy: Requires a transition to 100 percent clean energy by 2035 and expands electrification and demand-side resources.
- Ambitious DER: Envisions even further demand-side resource options.

All three scenarios modeled in this analysis utilize the same set of assumptions, with only five main differences. The first is the required electric sector emission reductions: the 100% Clean Energy scenario and Ambitious DER scenario require electric-sector emissions to be reduced by 80 percent by 2030 and

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[20] For more information on COBRA, see https://www.epa.gov/cobra.

100 percent by 2035 (relative to 2005 levels), whereas the TVA Baseline scenario has no such requirement. Second, the TVA Baseline case assumes low levels of energy efficiency and transformational electrification in line with the "Current" case of TVA's recent 2019 IRP.[21] Meanwhile, the 100% Clean Energy and Ambitious DER case assume that energy efficiency levels ramp up to those observed by leading neighboring states like Arkansas, reaching levels of 1.5 percent per year (as a percent of previous year retail electricity sales) by 2029. These two scenarios also assume high levels of electrification of the transportation, buildings, and industrial sectors. Specifically:

- For the transportation sector, we assumed that 100 percent of light-duty vehicle sales are electric vehicles (EV) by 2030. We also assumed that 60 percent of medium- and heavy-duty vehicle sales are EVs by 2030 and 100 percent of these vehicle sales are EVs by 2038. Vehicle sales trajectories follow a conventional S-curve for technological adoption; vehicle stock (and implied impacts on tailpipe emissions and electricity load) lag vehicle sales according to vehicle turnover. For more information on Synapse's methodology for modeling EVs, see https://www.synapse-energy.com/tools/electric-vehicle-regional-emissions-demand-impacts-tool-ev-redi. This analysis made no assumptions regarding the emissions impacts related to non-road vehicles (e.g., airplanes, boats, rail, etc.).

- For the residential and commercial buildings sector, we assumed that 100 percent of new sales of space heating, water heating, cooking, and drying equipment are electric by 2030. This is primarily achieved through the use of high-efficiency heat pumps. For more information on Synapse's methodology for modeling electrification in the building sector, see https://www.synapse-energy.com/tools/building-decarbonization-calculator. Importantly, because many customers in TVA's footprint currently heat their homes and business with inefficient electric resistance heating, a switch to more efficient heat pumps leads to a *reduction* in annual electricity requirements. When this phenomenon is coupled with the electrification impacts of switching fossil-fuel-powered end uses (such as natural gas-fired furnaces) out for heat pumps, we observe effectively no net change in annual electricity requirements.

- For the industrial sector, we assumed that 80 percent of end uses currently relying on fossil fuels are electrified by 2050, with the shift beginning in 2030. These adoptions follow the same S-curve for technological adoption described above. As of the time of this study, data on the amount of electricity required to decarbonize industrial end uses remains sparse. This analysis assumed that 230 TWh of wholesale electricity are required for every 1 quadrillion Btu of current fossil fuel end use.[22] This analysis also assumed that the amount of electricity required for direct use by industrial customers and other large customers remains constant throughout the study period.

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[21] See TVA's 2019 IRP at https://tva-azr-eastus-cdn-ep-tvawcm-prd.azureedge.net/cdn-tvawcma/docs/default-source/default-document-library/site-content/environment/environmental-stewardship/irp/2019-documents/tva-2019-integrated-resource-plan-volume-i-final-resource-plan.pdf?sfvrsn=44251e0a_4, Appendix E.

[22] This assumption is derived from data described in Energy Innovation's *NDC Pathway* scenario in their Energy Policy Simulator. More information is available at https://us.energypolicy.solutions/scenarios/home.

Third, the scenarios differ in terms of the assumed distributed energy resources. The TVA Baseline case assumes the same levels of distributed solar and distributed storage assumed in the "Base" case of TVA's 2019 IRP. The 100% Clean Energy scenario assumes levels in line with the "Medium" case, and the Ambitious DER scenario assumes levels in line with the "High" case. Fourth, the scenarios feature different levels of demand response and flexible load. All three scenarios include the amount of demand response assumed in the "Current" case of TVA's 2019 IRP. The Ambitious DER scenario also includes an additional quantity of "flexible load," meant to represent load-shifting of newly electrified end uses (see page 37 for more information).

Finally, the scenarios feature different reserve margin assumptions. The TVA Baseline scenario maintains TVA's current reserve margins throughout the study period. Meanwhile, the other two scenarios assume a change to winter reserve margins, such that TVA features a single year-round 17 percent reserve margin beginning in 2024.

Table 3. Differences between modeled scenarios

	TVA Baseline	100% Clean Energy	Ambitious DER
Required electric sector CO_2 emissions reductions	None	80% by 2030, 100% by 2035 *(relative to 2005)*	Same as 100% Clean Energy
Electrification and energy efficiency	Minimal electrification and energy efficiency according to 2019 TVA IRP	Ambitious electrification and energy efficiency aimed at economy-wide decarbonization by 2050	Same as 100% Clean Energy
Distributed energy	Follows "Base" case in 2019 IRP: DG PV: 1.2 GW (2030); 2.7 GW (2050) DG storage: None	Follows "Medium" case in 2019 IRP: DG PV: 1.7 GW (2030); 4.4 GW (2050) DG storage: 25 MW (2030); 270 MW (2050)	Follows "High" case in 2019 IRP: DG PV: 2.1 GW (2030); 6.3 GW (2050) DG storage: 180 MW (2030); 1.1 GW (2050)
Demand response and flexible load	Follows 2019 IRP: 1.9 GW conventional DR (2050)	Follows 2019 IRP: 1.9 GW conventional DR (2050)	1.9 GW conventional DR (2050) 32 GW flexible load (2050) (*Components of flexible load vary by duration and price paid*)
Changes to reserve margins	No changes to current TVA requirements (17% summer, 25% winter)	Assumes year-round 17% reserve margin beginning in 2024	Same as 100% Clean Energy

All other assumptions related to topology, modeling horizon, load forecasts, load shapes, resource costs and characteristics, transmission, and capacity contributions were the same in all scenarios. See Appendix A for more detail on assumptions.

2.3. Results

The following section describes the results of our scenario analysis, with a main focus on the TVA Baseline and 100% Clean Energy scenarios (page 37 provided detail on the Ambitious DER scenario).

CO_2 emissions

The TVA Baseline scenario, which features no CO_2 reduction requirements, nevertheless sees a marked decrease in electric sector CO_2 emissions. In the mid-2020s and early 2030s this is primarily driven by a decrease in coal generation linked to coal plant retirements. In the second half of the study period, this is largely driven by new wind and solar resources displacing generation from gas plants. By 2050, electric sector CO_2 emissions in the TVA Baseline scenario are 99 percent lower than 2005 emissions, indicating that this level of emissions reduction is achievable based on economics alone (see Figure 4).

The 100% Clean Energy scenario features a requirement for CO_2 reductions to fall by 80 percent by 2030 and 100 percent by 2035 and all later years, in line with TVA's own announced aspirational goals. This requirement proves to be binding in most year it is applied, with CO_2 emissions decreasing rapidly in the late 2020s through 2035. This is driven by new wind and solar resources entirely displacing existing coal and gas resources by 2035.

The two scenarios feature radically different trajectories for all-sector emissions in TVA's footprint (see Figure 5). By 2050, the TVA Baseline scenario reaches a 41 percent reduction in economy-wide emissions (relative to 2020 levels), reflecting the fact that while the electric sector is nearly decarbonized, emissions from other sectors have remained largely flat. In contrast, the 100% Clean Energy scenario reduces economy-wide emissions by 92 percent, demonstrating the results of an economy-wide decarbonization strategy.

Figure 4. Electric sector CO_2 emissions

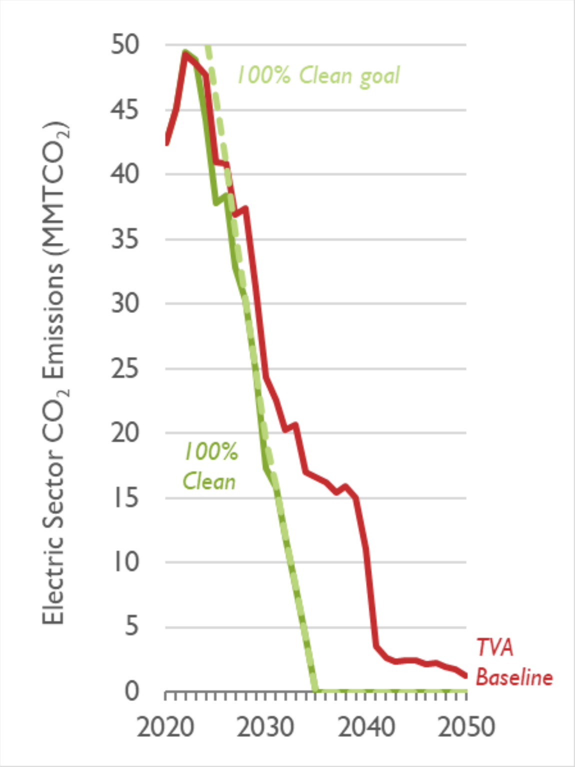
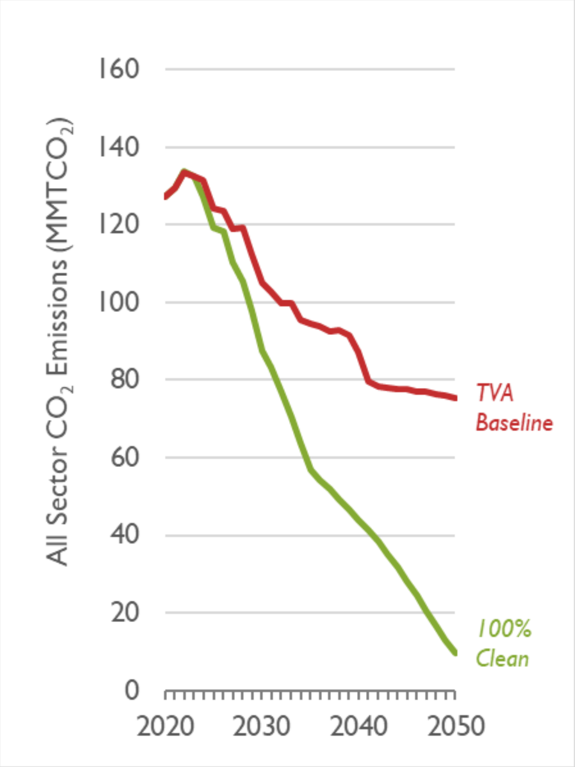


Figure 5. All sector CO_2 emissions



Annual load and generation

The TVA Baseline scenario is characterized by largely flat load over the study period, commensurate with a lack of planned electrification (see Figure 6). On the generation side, we observe coal generation decreasing during the mid-2020s, and falling to zero by 2035, in line with planned coal retirements. Generation from clean energy is relatively small until the mid-2030s, when new wind and solar plants are added to replace energy from retiring coal and gas plants. This clean energy continues to displace more and more existing fossil energy in every year. By the mid-2040s, over 95 percent of system generation is produced from non-fossil resources. By the end of the study period, about 12 percent of generation is dedicated to charging battery storage resources.

In contrast, the 100% Clean Energy scenario is characterized with relatively flat load through 2030, followed by rapidly increasing load in response to electrification (see Figure 7). By 2050, load (not inclusive of energy storage charging demands) is two times higher than present day. This increase in load is primarily met through increasing solar and wind generation, which arrives earlier (compared to the TVA Baseline scenario) in order to displace fossil fuels and meet the CO_2 reduction requirements modeled in this scenario. This solar and wind generation is balanced with substantial battery storage resources—by 2050, the charging requirements for these resources comprises 19 percent of system generation.

In the 100% Clean Energy scenario, the model relies solely on solar, wind, battery storage, hydro, and nuclear resources to successfully meet electricity demand for 16 modeled years.

Figure 6. TVA Baseline generation and load

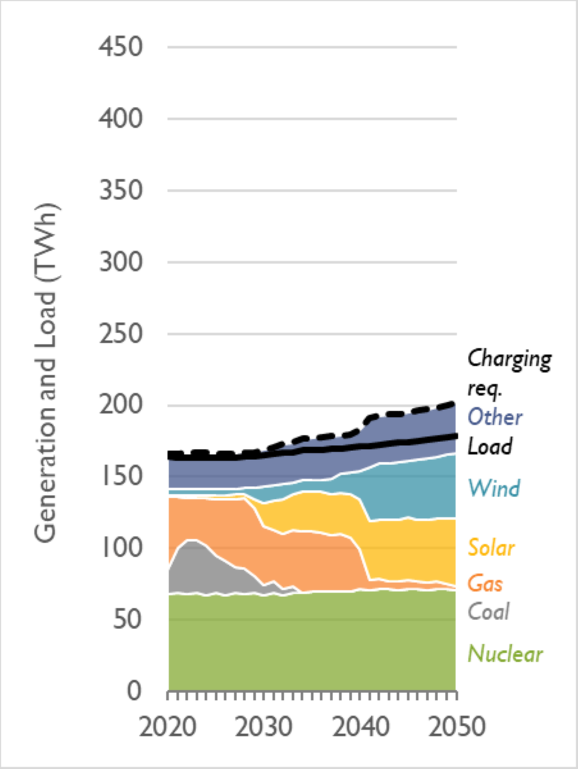
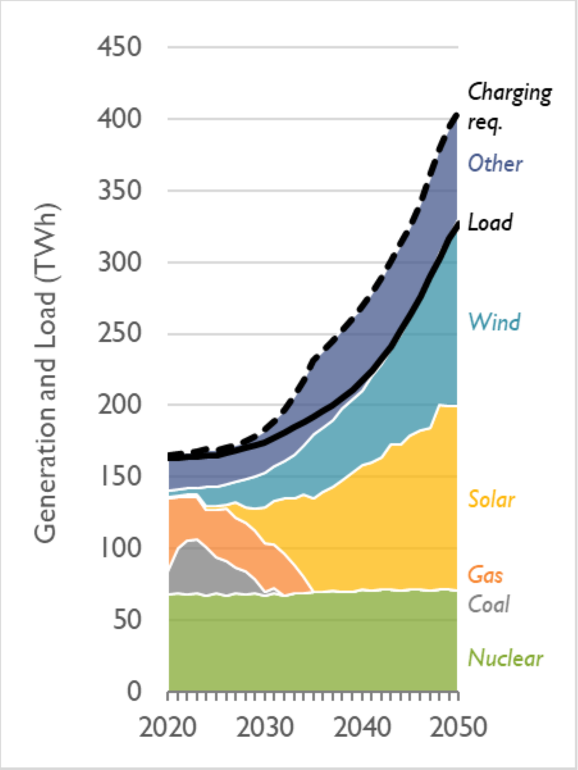


Figure 7. 100% Clean Energy generation and load



Capacity changes

In the TVA Baseline scenario, the period through the mid-2030s is marked by planned coal plant retirements, with some coal plants retiring one or two years ahead of schedule due to economic forces (see schedule of assumed coal retirement dates in Table 4). Additions of new clean energy are rare until the early 2030s, in part because of the assumed levels of low load growth. New clean energy is then added in several waves in the early 2030s, early 2040s, and late 2040s, typically occurring as renewable costs shift and these resources become more economic (see Figure 9). In the 2040s, these renewables begin to displace more and more generation from gas plants, causing those less-economic plants to retire as they are used less frequently. By 2050, 34 GW of solar is added, alongside 3 GW of distributed solar, 13 GW of wind, and 9 GW of battery storage.

The 100% Clean Energy scenario features a similar trend for coal retirements, but it has an accelerated trend for clean energy additions. Solar, wind, and battery storage are added rapidly beginning in the late 2020s, in response to this scenario's CO_2 reduction requirement (see Figure 8 and Figure 10). This same dynamic drives gas plant retirements, with all but 1 GW retired by 2035.

In all scenarios, we assumed a 5-GW maximum buildable amount independently for each new type of clean energy resource (wind, utility-scale solar, and utility-scale battery storage), meant to reflect limitations in in resource construction and supply chains. We found that

Table 4. Coal unit retirement assumptions

Unit Name	Nameplate Capacity (MW)	Assumed Retirement Date
Bull Run 1	870	December 2023
Cumberland 1	1239	December 2026
Cumberland 2	1231	December 2028
Kingston 1	132	December 2026
Kingston 2	132	December 2026
Kingston 3	132	December 2026
Kingston 4	132	December 2027
Kingston 5	174	December 2027
Kingston 6	174	December 2027
Kingston 7	174	December 2027
Kingston 8	174	December 2027
Kingston 9	174	December 2027
Gallatin 1	225	December 2031
Gallatin 2	225	December 2031
Gallatin 3	263	December 2031
Gallatin 4	263	December 2031
Shawnee 1	134	December 2033
Shawnee 2	134	December 2033
Shawnee 3	134	December 2033
Shawnee 4	134	December 2033
Shawnee 5	134	December 2033
Shawnee 6	134	December 2033
Shawnee 7	134	December 2033
Shawnee 8	134	December 2033
Shawnee 9	134	December 2033
Shawnee 10	124	December 2033
Paradise 3	971	Retired in 2020
Red Hills Generating Facility	440	December 2031

Notes: The assumed retirement dates of the Cumberland units are intended to reflect the uncertainty in TVA's retirement announcement known at the outset of this modeling project (i.e., the units would retire as early as 2026 and no later than 2030). The assumed retirement dates of the Kingston units also reflect the uncertainty of TVA's announcement (3 units as early as 2026, but no later than 2031, and the remaining 6 units as early as 2027, but no later than 2033). The Red Hills Generating Facility is a PPA which is assumed to expire in December 2031.

this assumed 5-GW cap is sometimes binding for wind in the 2040s. Wind capacity is added throughout the study period, reaching 41 GW in 2050. On average, 1.5 GW of wind is built per year. Just 6 percent of wind additions are in the TVA footprint, highlighting the advantages of procuring wind power from outside the Valley. This is in spite of accounting for the cost of new transmission lines outside the region (totaling $45 billion in the 100% Clean Energy scenario). Together, these new lines facilitate over 130 TWh of wind from outside of the Valley.

Solar capacity additions occur in every single year after 2025, with the 5-GW cap being frequently binding, and 4 GW built per year on average. Throughout the study period, 2 GW of battery storage is built per year for a total of 46 GW. One-quarter of this is 50-hour storage, which is almost all built after 2040.

Figure 8. Clean energy additions in the 100% Clean Energy scenario

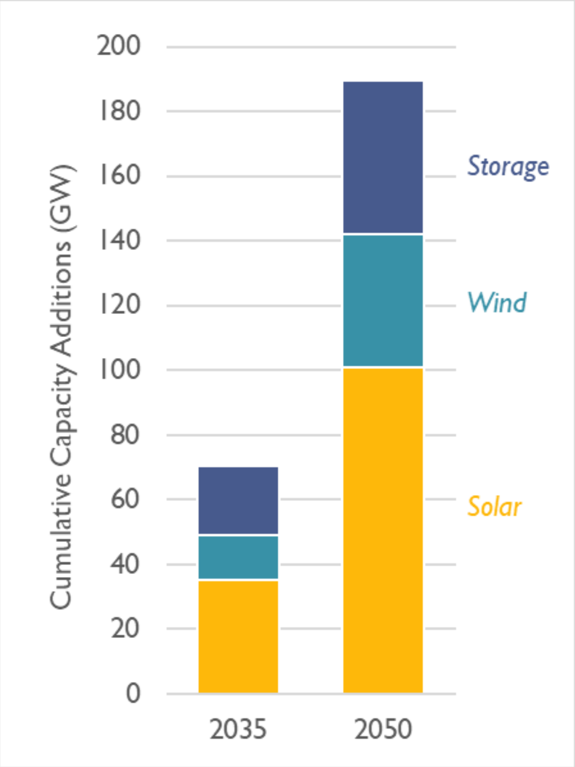


Figure 9. TVA Baseline additions and retirements

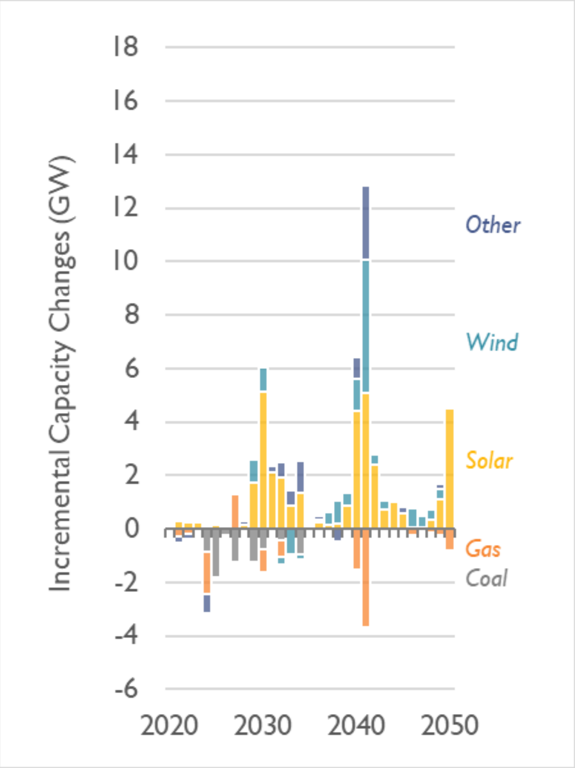
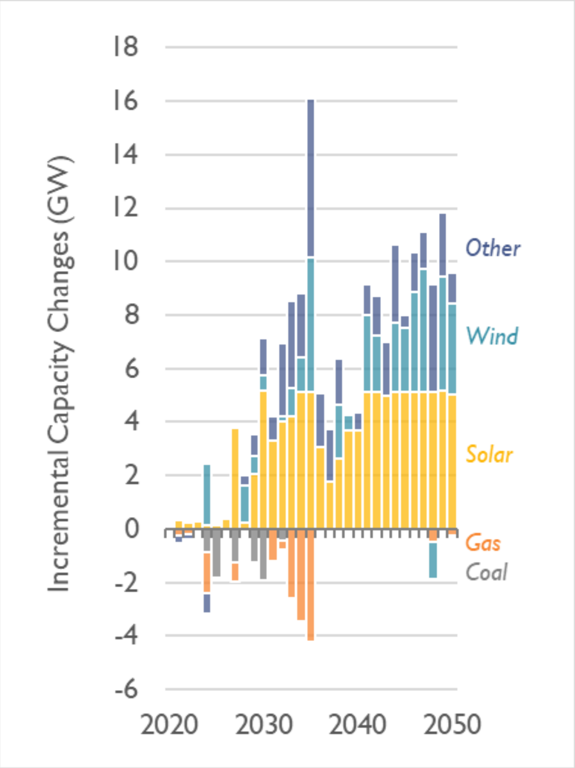


Figure 10. 100% Clean Energy additions and retirements



Firm capacity

The TVA Baseline assumes present-day TVA reserve margins remain static through 2050. In other words, this scenario assumes that today's 25 percent reserve margin for winter months and 17 percent reserve margin for summer months persists through the future.

In contrast, the 100% Clean Energy scenario assumes that TVA moves to a year-round reserve margin of 17 percent beginning in the winter of 2024/2025. In our view, TVA currently relies on an inflated winter reserve margin, as its own analysis suggests that it needs a greater energy reserve in the winter to meet potential winter demand issues. We believe that TVA's winter reserve margin is inflated because (1) winter heating is largely driven by inefficient electric resistance systems, which create large and immediate power draws and leave TVA susceptible to potential demand issues, and (2) TVA's thermal resources, like all thermal resources, are not 100 percent dependable in the winter. Winter conditions can cause supply issues related to fuel deliverability and further decrease the performance of coal and gas generators. To compensate, TVA requires a higher level of energy reserves in winter to meet potential winter demand.

Our 100% Clean Energy scenario shifts away from this paradigm. As we electrify demand-side resources, highly efficient electric heat pumps replace inefficient electric resistance heating, thereby reducing winter peak demand issues. Secondly, an increase in renewable resources increases grid reliability. Wind resources have high contributions in winter months, and solar often ramps up in the morning to meet midday peaks. Regardless, in order to be conservative, both scenarios assume the same set of today's assumptions for capacity contributions (see Appendix A for further detail about these assumptions).

We observe that both scenarios safely meet reserve margins in every year, for both seasons (see Figure 11 and Figure 12). In addition, we observe that the summer reserve margin constrains the model and drives resource additions from about 2025 through 2030 as coal plants retire. In the TVA Baseline scenario, from 2030 on, the winter reserve margin constrains the model. This occurs as solar becomes a dominant new type of resource addition and features only a very small winter capacity contribution of 1 percent, causing the model to build additional capacity (typically storage resources) to meet the firm capacity requirements.

Meanwhile, in the 100% Clean Energy scenario, after the mid-2030s both winter and summer requirements cease to constrain the model, meaning the importance of firm capacity (as the metric is designed today) fades. This occurs as the model builds more variable-dispatch wind and solar and more storage. During this period, the model is increasingly focused on complying with multi-day energy requirements, rather than a single seasonal peak. This highlights the increasing need to reconsider conventional approaches for planning for capacity requirements in light of an increasingly changing electricity system.

Figure 11. Winter firm capacity and reserve margins

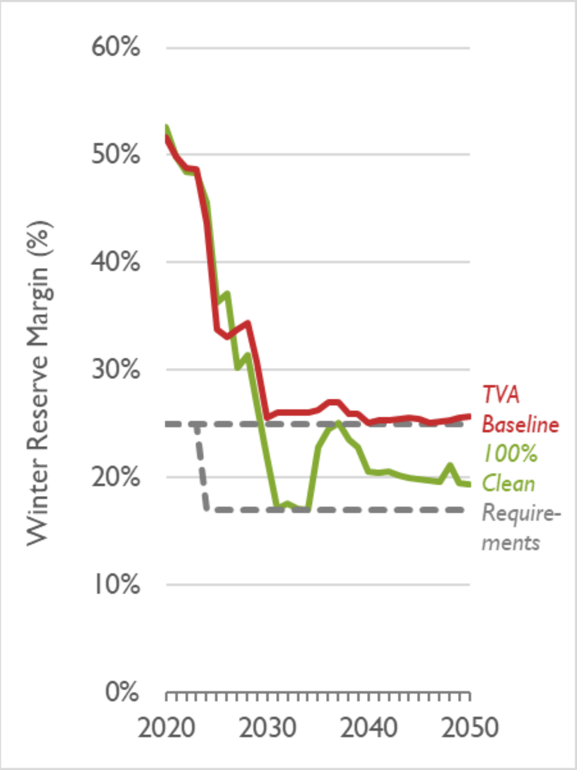
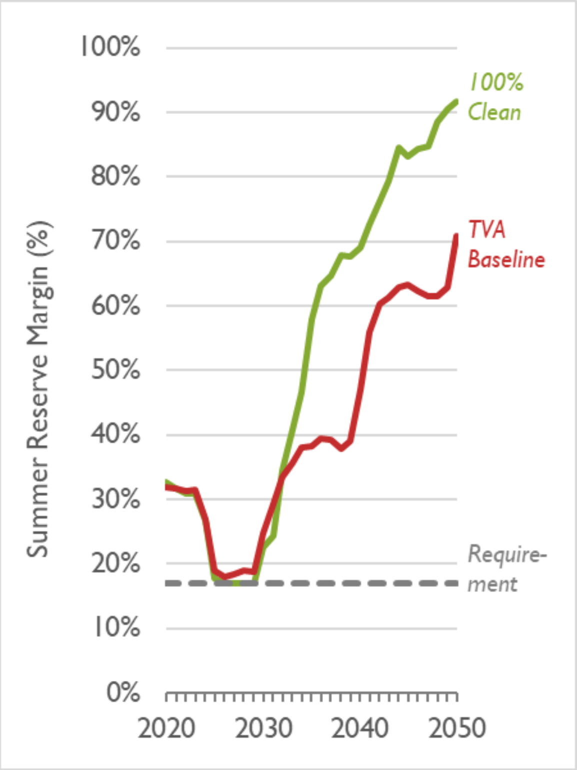


Figure 12. Summer firm capacity and reserve margins



Our analysis suggests the least-cost approach for TVA to both meet customer demand and decarbonize avoids the construction of new fossil resources. Contrary to this, TVA recently approved a proposal to replace the retiring Cumberland plant with a new, 1,450-MW gas plant. Coincidentally, our TVA Baseline scenario, a scenario which represents a future in which TVA does not adhere to its decarbonization targets, builds 2,100 MW of new gas in the 2026–2027 timeframe. While this does not explicitly represent the Cumberland replacement (or replacements of any other retiring coal facilities) this fossil addition acts as an interesting proxy for TVA's proposal. This scenario, which slows the deployment of clean energy resources in lieu of new gas-fired capacity, results in overall higher economy-wide costs, and delays critical years of new clean energy deployment.

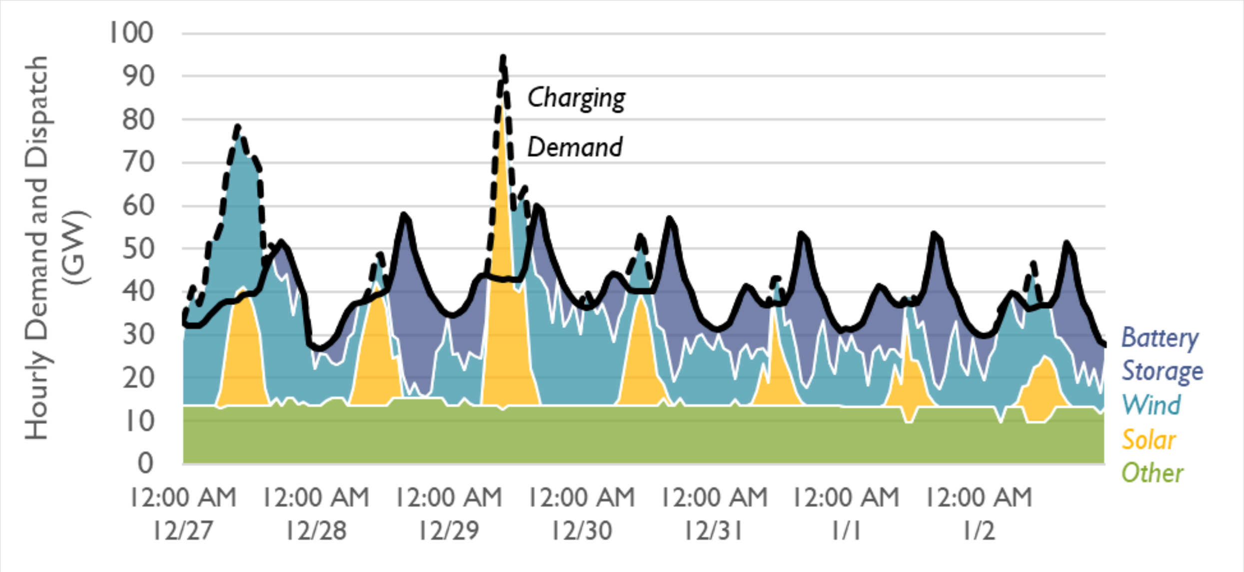
Reliability

For long-term economic planning, Synapse used a capacity expansion modeling approach that condenses each modeled month into a single week and models time in 3-hour slices. This approach accurately models dynamic grid conditions while managing total runtime and computing resource needs. For all modeled capacity expansion runs, modeled portfolios met total load across the entire time period, 2020–2050, with no unserved energy or loss of load events.

To confirm the reliability of the modeled portfolios, Synapse conducted more granular analysis of the performance of modeled scenarios in 2050 over 8,760 hours. While the modeled portfolios met planning reserve margin requirements in all periods, the 2050 supplemental analyses identified a limited number of potential loss-of-load events in the 100% Clean Energy scenario in 0.02 percent of all load-hours. To provide additional resource adequacy, Synapse added an additional 1.5 GW of long-duration energy storage resources, which were sufficient to avoid any unserved energy identified by the supplemental modeling. This report reflects these supplemental storage resources in cost and capacity results throughout. Figure 13 shows hourly dispatch of renewables, energy storage, and other resources in a severe winter week in 2050 with high demand and low renewable generation. Energy storage resources charge during high-renewables periods and discharge to meet load in every hour of the week. Notably, energy storage resources also rely on stored energy accumulated before this week, which is replenished in later weeks with less net load.

Synapse modeling showed that a combination of zero-emissions resources can provide affordable and reliable service, but conventional reserve margin approaches alone might not be well suited to the reliability challenges of the future. Future IRPs should include a comprehensive view of system reliability, including correlated outages, weather patterns, and regional capacity sharing.

Figure 13. Hourly generation by resource, 100% Clean Energy Scenario, December 27, 2050–January 3, 2051



Notes: "Other" includes generation from nuclear, hydro, demand response, and other miscellaneous resources.

System costs

Wholesale electric system revenue requirements for both scenarios remain similar until the late 2030s at about $5 billion. (Costs are higher in the early 2020s due to assumed high gas prices in the near term.)

The TVA Baseline scenario features mostly stable electric system costs. This is despite a shift away from generation sourced from fossil fuels and towards a future that relies on non-emitting sources for almost 100 percent of electricity generation by 2050. After an initial period of high gas prices, costs per MWh remain relatively flat at about $30 per MWh, and gradually decline as more clean energy is added.

In contrast, the 100% Clean Energy scenario features electric system costs that gradually trend upward to about $9 billion per year by 2050, or 73 percent higher than costs in the TVA Baseline scenario. These higher costs are driven by increased electrification, which necessarily requires the construction and operation of new grid resources. Importantly, these increases are *not* born out in cost-per-MWh terms, with this scenario's cost of providing electricity on a per-MWh basis being similar to or even lower than the TVA Baseline scenario. This is not unexpected given the relative similarity of new resource types being added to the grid in both scenarios.

Critically, "revenue requirements" defined here are only inclusive of fuel, variable, and fixed costs, as well as property taxes, book depreciation, allowed return, and other miscellaneous costs. They do not include other costs or savings related to decarbonization, many of which contribute to lower expenditures outside the electricity sector.

Figure 14. Wholesale electric system revenue requirements

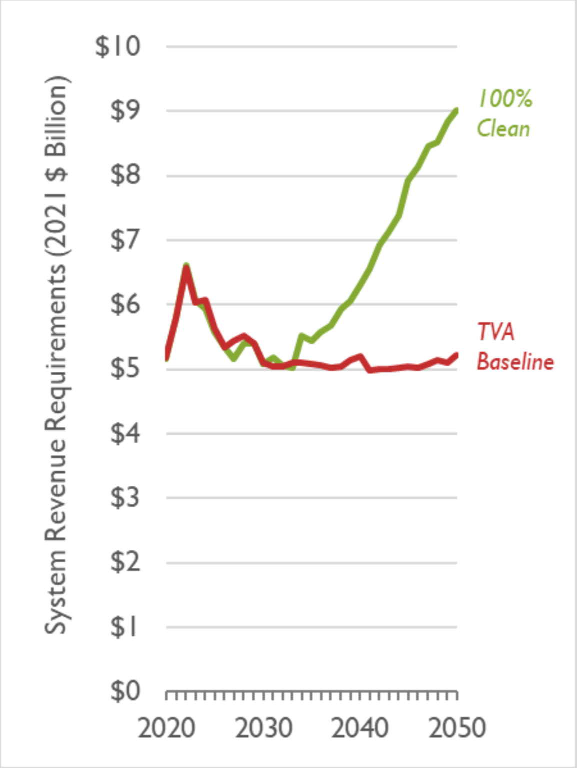
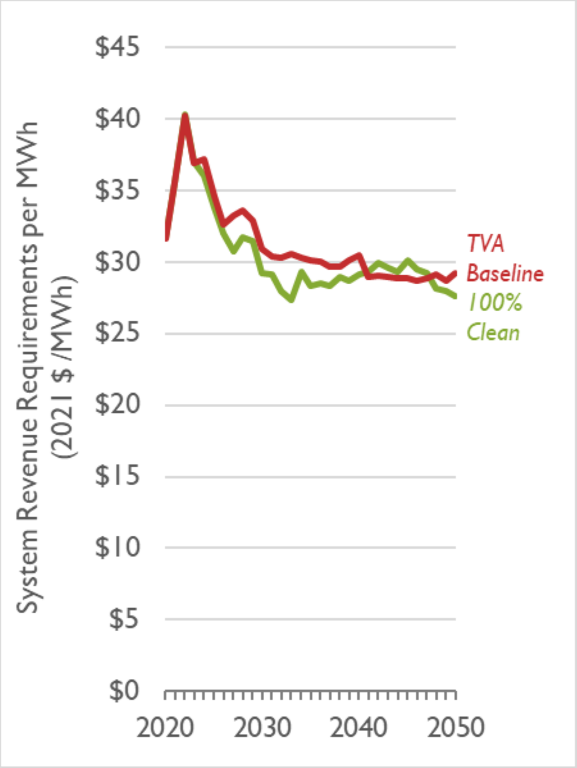


Figure 15. Wholesale electric system revenue requirements per MWh



While electricity system costs are projected to rise in the 100% Clean Energy scenario, these cost increases must be assessed within the context of the wider economy. Table 5 displays the cost differences between the 100% Clean Energy and TVA Baseline cases, with particular focus on 2035, 2050, and all differences accumulating over study period.

Table 5. Single-year and cumulative net costs, 100% Clean Energy versus TVA Baseline (2021 $ billion)

	2035	2050	Cumulative
Electric system	-$1.2	-$4.6	-$53.9
Buildings	$0.0	$0.6	$9.2
Transportation	$8.1	$22.0	$277.2
Other	$0.1	$3.9	$23.0
Net savings	**$7.1**	**$21.8**	**$255.6**

Note: Positive numbers are savings while negative numbers are costs. "Electric system" includes wholesale energy costs, and programmatic and participant spending on energy efficiency and distributed generation resources. "Buildings" includes the costs and savings related to switching residential and commercial to efficient heat pumps and electrifying all remaining end uses, inclusive of avoided fossil fuel expenditures. "Transportation" includes the costs and savings related to consumers switching from conventional internal combustion engine vehicles to EVs, including avoided fossil fuel expenditures, as well as the cost of building out charging infrastructure for EVs. "Other" includes fuel savings related to electrifying the industrial sector but does not include the costs of electrification itself.

We observe that while electric system costs are substantial, these are more than offset by savings from the clean energy transition outside the electric sector. For example, non-electric fuel savings tally almost $240 billion over the study period. These savings are over seven times larger than the additional costs resulting from ambitious electrification and clean energy deployment. These non-electric fuel savings are largely related to a reduced reliance on fossil fuels for heating and transportation, with lower motor gasoline and diesel demand driving about 80 percent of these savings.

Other aspects of the clean energy transition impose their own costs or produce their own rewards. For example:

- An increased reliance on demand-side resources, including energy efficiency and distributed generation, adds about $21 billion in cumulative costs.[23] However, these resources avoid increased reliance on utility-scale resources, playing a critical role in decreasing land-use impacts and diversifying TVA's resource portfolio.
- Outside of motor gasoline and diesel savings, the switch to EVs is projected to save $82 billion cumulatively. This is because, while EVs are assumed to be more expensive than internal combustion engine (ICE) vehicles initially (not including tax credits), starting in about 2035 EVs are assumed to be lower in upfront cost. Most EVs are deployed after 2035, leading to decreased costs overall. In addition, throughout the study period, EVs are assumed to have lower operating and maintenance costs than ICE vehicles, producing further savings. Finally, we assumed that almost 470,000 EV chargers are

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[23] This is inclusive of both participant and programmatic costs for both energy efficiency and distributed generation.

built by 2050 to accommodate the millions of new EVs in TVA's service territory. Using the National Renewable Energy Laboratory's (NREL) EVI-Pro Lite model, we estimated the cost of these chargers to be about $3.4 billion, cumulatively. However, these costs are more than offset by cheaper vehicles and lower operating and maintenance costs, leading to lower motor vehicle costs overall.

- We estimated that building electrification poses a small increase in costs, largely due to heat pumps being assumed to be more expensive than conventional HVAC equipment. This takes into consideration tax credits for heat pumps through the early 2030s as a result of the IRA but assumes that these tax credits disappear and that heat pump equipment remains more expensive than conventional HVAC equipment throughout the remainder of the study period.

When all of these factors are taken into account, the electric system costs of a clean energy transition are dwarfed by the potential economy-wide savings. TVA's service territory stands to save over $255 billion over the study period if it were to follow a trajectory like that shown in the 100% Clean Energy scenario. While our net cost calculation did not account for other transition costs such as the cost of new transmission or distribution within TVA and the cost (and savings) of industrial electrification, these unaccounted-for costs would need to exceed $255 billion in order for the 100% Clean Energy scenario to be uneconomic.

Finally, the net savings shown here do not include savings due to improved public health or savings associated with the social cost of carbon (see page 30).

Rate impacts, bill impacts, and energy burden

In a clean energy future, electricity customers will likely experience a change in electricity rates and bills due to several factors:

- Many customers will consume more electricity as they shift away from fossil fuels for heating or transportation purposes, and increasingly rely on electricity for all energy purposes. This increase in electricity consumption may be lessened by the presence of energy efficiency measures or more efficient electric appliances.

- Both clean energy requirements and increased electricity demand due to electrification will contribute to an increased buildout of clean energy resources. This will increase the cost of running the electricity system relative to a scenario where no such resources are needed due to flat electricity consumption). However, increased consumption of electricity does not necessarily mean customers' electricity rates will increase in tandem. Electricity rates even have the potential to decrease if electrification results in a switch to less expensive resources or better utilization of electricity infrastructure.

- It will be important for TVA and local power companies to closely evaluate the drivers of these costs and allocate the costs accordingly in order to avoid cost-shifting among customers.

For this study, we evaluated the increase in system costs (relative to today) in each scenario. We then allocated the increase in costs to the residential, commercial, and industrial sectors in line with each sectors' increase in electricity consumption. In the 100% Clean Energy scenario, we observe that residential and commercial customers experience an increase in electricity consumption of about 60 percent per customer, whereas industrial customers experience an increase in electricity consumption of about 175 percent per customer.[24] Importantly, the cost of increases in electricity consumption are offset by decreases in the end-use consumption of fossil fuels, and all costs related to this (see Table 5, above).

As a result of costs and usage increasing at nearly the same rate, we observe that overall electricity rates remain relatively consistent across time and between the two scenarios. Table 6 demonstrates the modeled electricity rates in 2020, 2035, and 2050. On a simplified, dollar-per-kWh basis, we observe that electricity rates in the 100% Clean Energy scenario either remain flat or slightly decrease over time. We note that this is in line with TVA's priority to reduce electricity rates.

Table 6. Modeled electricity rates, bills, and energy burden

	2020	2035		2050	
	Actual	*TVA Baseline*	*100% Clean Energy*	*TVA Baseline*	*100% Clean Energy*
Electricity rates (2021 cents/kWh)					
Residential	11.4	10.7	9.0	9.7	8.0
Commercial	10.9	10.6	9.8	10.4	7.7
Industrial	4.4	4.3	4.4	4.2	3.3
Monthly electric bill (2021 $/customer)					
Residential	$131	$131	$141	$129	$149
Energy burden (% of household income)					
Residential	7%	7%	5%	6%	3%

Notes: "Actual" electricity rates for 2020 are based on data reported to EIA Form 861 (available at https://www.eia.gov/electricity/data/eia861/) for TVA and all local power companies in TVA's service territory. For the purposes of this analysis, rates are analyzed in a highly simplified way—in reality, rates and rate structures for customers across TVA's service territory may differ widely, with some customers utilizing rates that include fixed costs, demand costs, or other more complex rate approaches.

However, Table 6 shows that for residential customers, 2050 monthly bills in the 100% Clean Energy scenario increase by 13 percent.[25] Although the electricity system is used more efficiently, and costs are allocated according to increases in electricity consumption, an overall increase in electricity consumption leads to increased bills.

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[24] In this analysis, we assumed that residential and commercial customer counts also increase at the same pace as electrification. We assumed that the number of industrial customers remains constant.

[25] Rate increases for residential customers could be tempered by local power companies deploying rate structures that align consumption with grid needs (e.g., time-of-use rates). Electricity bills are not calculated for customers in the commercial and industrial sectors due to the fact that electricity consumption by customers in these sectors can differ substantially.

Critically, electricity bills are just one part of the equation. At the same time, as residential customers begin to pay more for their higher electricity consumption, they also reduce their spending on fossil fuels. Avoiding spending on inefficient fossil fuels for home heating, water heating, and transportation leads to an overall reduction in household energy costs. Energy burden is a common metric used to assess how much typical households spend on their energy costs as a share of their household income. Per U.S. Census' American Community Survey (ACS), the typical household in TVA's service territory has a median income of about $56,100 per year.[26] If we assume this median household income remains unchanged through 2050, Table 6 shows that energy burdens decrease over time in the 100% Clean Energy scenario, from about 7 percent today to merely 3 percent in 2050.[27] This halving in energy burden is in large part due to a switch away from inefficient spending on fossil fuels, including motor gasoline. Furthermore, a reduction on fossil fuel use (and associated spending) will lead to more money staying in the Tennessee Valley rather than going to companies involved in fossil fuel extraction outside the Valley. We quantify these impacts, as well as other job impacts, in the following section.

Job impacts

A transition to clean energy is poised to create thousands of jobs in the Tennessee Valley, echoing one of the original purposes of TVA. Using data from the IMPLAN model, we estimated the annual impacts on jobs resulting from the 100% Clean Energy scenario, relative to the TVA Baseline scenario.[28] Figure 16 shows that over the study period, TVA's service territory stands to gain an average of 15,600 full-time-equivalent (FTE) jobs in each year. Job impact estimates include those related to initial construction; ongoing fueling, operation, and maintenance (O&M); and respending.

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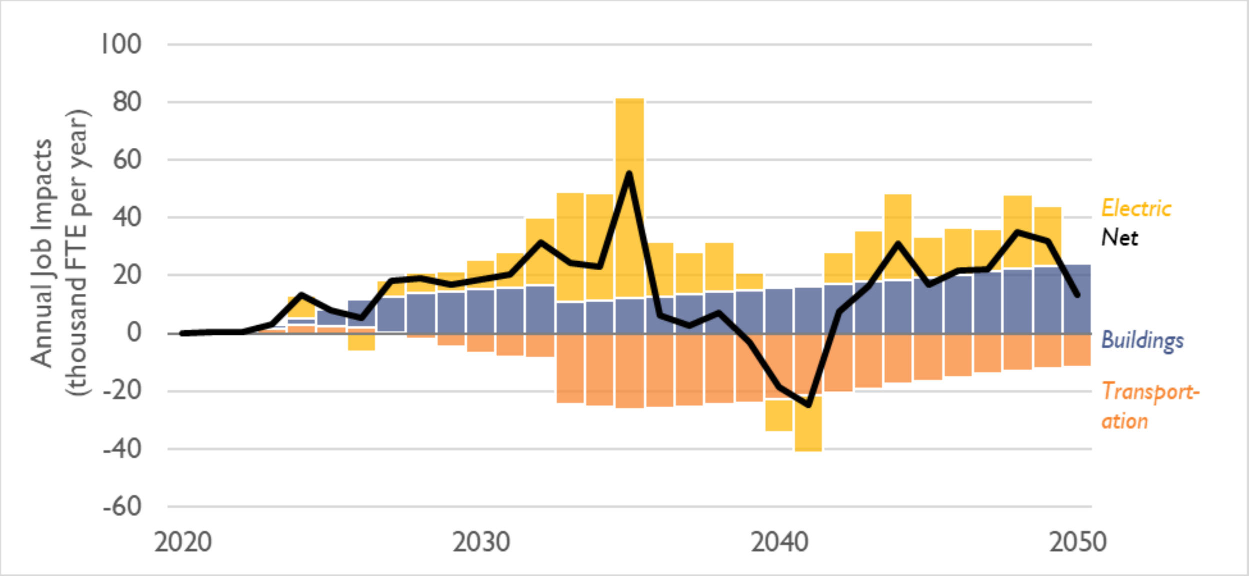
[26] County-level household income data from the 2020 5-Year ACS estimate is available at https://data.census.gov/cedsci/table?t=Income%20%28Households,%20Families,%20Individuals%29&g=0100000US%240500000&tid=ACSST5Y2020.S2503.

[27] This calculation of energy burden is inclusive of electricity expenditures, fossil fuel expenditures, and energy efficiency and distributed generation participation costs. Per energy burden convention, it is not inclusive of expenditures on new end-use equipment, such as new (or avoided) HVAC equipment or vehicles.

[28] For more information on the IMPLAN model, see https://implan.com/.

Figure 16. Job impacts from the 100% Clean Energy scenario, relative to the TVA Baseline scenario



We calculated job impacts based on two primary inputs: the amount of money spent on a particular activity in a given year, and the jobs associated with spending money on that activity (a "job factor"). Each modeled sector sees different drivers for job impacts. In the electric sector, we projected an additional 14,700 full-time positions on average in each year. Large increases in employment in individual years are linked to in-region construction of solar, battery storage, and energy efficiency resources, as well as transmission construction needed to facilitate out-of-region wind purchases.[29] The IRA also plays a role in lowering the cost of many renewable resources, thereby creating jobs at a higher rate per million dollars spent by TVA residents. Still, a small number of jobs are lost due to a transition away from fossil fuels—these jobs are few in number, in part because modern gas plants employ relatively few people, and because large, older coal plants are assumed to retire in both scenarios. Jobs also decrease as a result of increased spending—consumers are likely to spend more money on electricity in a clean energy future (and less on other fuels), reducing their opportunities to use that money for other purposes and stimulate job growth. These job decreases are included in the "Electric" component of Figure 16.

In the buildings sector, we observe an additional 15,800 job-years per year. This is because we assumed that heat pumps are more labor-intensive to install than conventional HVAC systems (in other words, for every $1,000 spent on a heating system, more of that money will go to on-site labor for a heat pump installation, relative to a conventional fossil-fuel-powered furnace). Our calculations account for the total cost of a heat pump installation. For example, our employment results reflect the increased labor associated with installing higher capacity electric panels for houses that transition to electric heating. Avoided fuels are also a large job generator—every dollar not spent on purchasing natural gas or other

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[29] Several years that appear to have zero or negative job additions under the electric sector are due to the TVA Baseline scenario having similar or slightly larger job additions than the 100% Clean Energy scenario.

fossil fuels for heating means more money in the pockets of consumers, who then stimulate job growth with increased spending in the wider economy.

The transportation sector is the only sector where our analysis found consistent job losses. This is due to two reasons: first, EVs require fewer expenditures on maintenance and operation compared to conventional gasoline- and diesel-powered vehicles, leading to a decrease in jobs. Second, relying on the latest data from Argonne National Laboratory, we estimated that the typical EV will be cheaper than the typical ICE vehicle starting around 2030 (not accounting the impacts of tax credits in the IRA).[30] Most EVs sold in the study period are sold after this date, leading to an overall reduction in the amount of money spent on new vehicles in the 100% Clean Energy scenario. This reduced spending on vehicles, combined with an assumption that a greater share of EV parts are made outside of TVA than are conventional vehicle parts, leads to an overall reduction in transportation-sector jobs. This is in spite of reduced spending on motor gasoline and diesel, which results in more money for consumers. As with the buildings sector, much of this money is then re-spent in the wider economy, creating new jobs. This trend is amplified by tax credits available under the IRA, which are assumed to put more money in consumers' pockets through 2032.

According to data from the Bureau of Labor Statistics, TVA's service territory has about 4.7 million jobs.[31] An increase in full-time employment of 15,600 positions represents an increase of about 0.3 percent.

Caveats to job impacts

The above job impacts are predicated on an assumed methodology and set of inputs.

- All job factors used in this analysis are static snapshots of Tennessee's economy as it existed in the recent past.[32] These may change in the future, with corresponding impacts on jobs. For example, should Tennessee and other parts of the Tennessee Valley become hubs of EV manufacturing (as is planned by TVA and others, for example), net impacts to jobs could be even more positive than are currently calculated.[33]

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[30] Burnham, A. et al. *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains*. Argonne National Laboratory. April 2021. Available at https://publications.anl.gov/anlpubs/2021/05/167399.pdf.

[31] U.S. Bureau of Labor Statistics. *Local Area Unemployment Statistics*. Accessed December 2022. Available at https://data.bls.gov/timeseries/LASST470000000000005?amp%253bdata_tool=XGtable&output_view=data&include_graphs=true.

[32] IMPLAN is typically run for individual states. For this analysis, we assume that job factors in Tennessee are representative of job factors in the wider TVA service territory.

[33] "Ford aims to create 5,700 jobs with new factory, battery plant near Memphis" *The Tennessean*. September 27, 2021. Available at https://www.tennessean.com/story/money/business/development/2021/09/27/ford-electric-vehicles-memphis-regional-megasite-new-jobs/5884664001/; "TVA Accelerates Nation's Decarbonization Efforts, Fuels a Clean Energy Economy." Press Release. TVA. May 11, 2022. Available at https://www.tva.com/newsroom/press-releases/tva-accelerates-nation-s-decarbonization-efforts-fuels-a-clean-energy-economy.

- Our analysis included calculations of direct, indirect, and induced jobs. In other words, our analysis included job impacts at the resources or facilities themselves, upstream impacts related to development of components for the resources or facilities, and other ripple effects in the economy related to respending energy bill savings and other effects.

- Our analysis focused on impacts in TVA's service territory only. It did not account for positive or negative impacts that accrue outside of TVA. For example, construction jobs associated with building out-of-region wind that provides electricity to TVA were not included.

- Our analysis did not account for industrial job impacts due to a lack of available cost information and job vectors. Because this activity is likely to require a large amount of local capital investment, we expect that it would produce net positive jobs.

Other impacts

A transition to clean energy in TVA's service territory has many other benefits beyond the purely economic. This section describes benefits related to public health, social cost of carbon, water use, and coal ash. This section also includes a discussion of potential land-use impacts related to a clean energy transition.

Public health and social cost of greenhouse gases

Burning fossil fuels produces hazardous air pollution. The combustion of fossil fuels (including coal, gas, gasoline, diesel, among others) and biomass results in the formation of pollutants like SO_2, NO_X, PM, VOCs, and NH_3. These pollutants are released into the atmosphere from a power plant's smokestack, a car's tailpipe, or a home or business' chimney. These pollutants may then be dispersed over a wide area, or stay locally. Eventually, they may find their way into a person's respiratory system where they may cause health impacts related to asthma, heart conditions, or even premature death.

Using the COBRA created by U.S. Environmental Protection Agency, we calculated the health impacts of phasing out fossil fuels in the 100% Clean Energy scenario, relative to the TVA Baseline scenario.[34] Table 7 summarizes these results. We see that over the entire study period, phasing out fossil fuels leads to over $27 billion in public health benefits realized nationwide. About 90 percent of benefits are due to reductions in criteria air pollutants outside the electric sector (e.g., from cleaner cars, buildings, and industry). Within the electric sector, both the 100% Clean Energy and TVA Baseline scenarios are very similar in terms of criteria pollutant emissions—both feature coal retirements that occur on about the same schedule, and both scenarios reach zero emissions at some point in the study period. In other words, even without substantial electrification, by switching to clean energy TVA can reduce its impact on the health of those living in its service territory. But by planning for a high electrification future, these public health benefits stand to be much greater.

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[34] More information on COBRA can be found at https://www.epa.gov/cobra.

Table 7. Public health benefits related to phasing out fossil fuels

	2035	2050	Cumulative (2020–2050)
Benefits (2021 $ B)	$0.6	$2.4	$26.6

Next, Table 8 summarizes the benefits related to the social cost of carbon. The social cost of greenhouse gas is a "damages" calculation that describes the amount of harm avoided from reducing the emissions of greenhouse gases, as these gases contribute to catastrophic climate change. We found that over the study period an accelerated clean energy future avoids over $265 billion in damages related to greenhouse gas emissions.

Table 8. Social cost of greenhouse gas benefits related to phasing out fossil fuels

	2035	2050	Cumulative (2020–2050)
Benefits (2021 $ B)	$9.8	$21.1	$265.2

Water use

As a result of fossil plant retirements, water use in TVA's service territory drops by about one-third. In particular, water withdrawals fall from about 3.2 trillion gallons in 2020 to about 2 trillion gallons in the early 2030s, when the last coal plants retire.[35] Water withdrawals hold at about 2 trillion gallons through 2050, as a result of nuclear plant operation. Meanwhile, water consumption (i.e., water that is withdrawn and not returned to the water source) falls by about one-half: after fossil and coal generation cease in 2035, we estimate an ongoing annual water consumption of about 11 billion gallons from the nuclear plants in every year from 2035 to 2050.

Coal ash

According to data from EIA, almost 90 percent of ash produced in TVA's service territory comes from just two coal plants: Cumberland and Red Hills Generating Station (a plant located in Choctaw County, Mississippi, with which TVA has a PPA). About 80 percent of this coal ash is used for productive purposes; the plants dispose of the other 20 percent. The modeling assumed that Cumberland retires in 2026 and the Red Hills PPA ends in 2031. As a result, by 2032, coal ash production for all of TVA's service territory falls by 90 percent, relative to today. Some ash production continues (at rate of about 9 thousand tons per year) from biomass facilities until these plants retire. By 2035, the requirement for TVA to procure electricity only from non-emitting facilities causes the production of coal ash to cease entirely.

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[35] We note that there are some differences in the reported historical values for water use and coal ash in this report, relative to the historical values reported in the 2019 TVA IRP. All values reported in this analysis are based on publicly available data from EIA. Values in the 2019 TVA IRP may include water use and coal ash data for some plants that do not have data reported to EIA.

Land use

TVA's service territory encompasses an area of roughly 60 million acres, of which 293,000 acres are directly managed by TVA.[36] This does not include additional land area that currently hosts TVA's fossil-fired and nuclear power plants. In the 100% Clean Energy scenario, we estimated an increase in the demand for land needed to host the required solar, wind, and storage generating plants. Table 9 describes the distribution of capacity for the scenario, by resource type and region.

Table 9. Geographical distribution of renewable capacity, 100% Clean Energy scenario

	2035	2050
Wind	**14.0**	**41.2**
In TVA	*1.8*	*2.3*
Outside TVA	*12.2*	*38.9*
Solar	**35.0**	**101.0**
In TVA, distributed	*2.4*	*4.4*
In TVA, utility-scale	*32.6*	*96.6*
Outside TVA, utility-scale	*0.0*	*0.0*

Figure 17 compares the size of TVA's service territory to that of a number of existing land uses, alongside the land-use requirements of in-Valley resources, in a clean energy future.[37] We note the following:

- In-region wind land use is very small, relative to TVA's service territory.[38] This is due to the fact that the 100% Clean Energy scenario estimates only a small amount of in-region wind to be cost-effective, coupled with the fact that wind turbines need only impact a small amount of land immediately around the turbine footprint. The remainder of the land under the span of the turbine blades (and between turbines) can remain productive for other uses, such as livestock raising or agricultural. Land impacts associated with out-of-region wind are not shown. These would likely be 17 times larger than those shown for in-region wind but would be located in areas of the Midwest that already have a long history of installing wind turbines alongside existing agricultural uses.

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[36] More information on TVA's managed area is available at https://www.tva.com/environment/environmental-stewardship/land-management/reservoir-land-management-plans.

[37] The design of this figure was inspired by Figure 30 in Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022. *Examining Supply-Side Options to Achieve100% Clean Electricity by 2035*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf

[38] Land-use requirements for onshore wind are based on *Land-Use Requirements of Modern Wind Power Plants in the United States*. National Renewable Energy Laboratory. 2009. Available at https://www.nrel.gov/docs/fy09osti/45834.pdf, with an assumed factor of with an assumed factor of 333 MW_{AC} buildable per acre. This value includes direct land use impacts only (e.g., from turbine pylons and access roads).

- At 4 GW in 2050, distributed solar is projected to occupy just 4 percent of the estimated residential, commercial, and industrial rooftops available in TVA's service territory.[39] In other words, if only 4 percent of the rooftops in TVA's service territory were the site of future solar installations that would be enough to accommodate the distributed solar assumed in the 100% Clean Energy scenario. In the Ambitious DER scenario (described more below on page 37) an increased level of distributed solar (6 GW) would occupy 6 percent of rooftops.

- The land requirements for utility-scale solar are the largest future land use associated with clean energy production, with about 540,000 acres being needed for utility-scale solar in 2050 in the 100% Clean Energy scenario, or about 1 percent of the entire service territory area of TVA.[40] If the 540,000 acres of utility-scale solar were allocated equally across the almost 200 counties served by TVA, each county would require 2,700 acres dedicated to solar (or about 1 percent of each county). This would also translate to about 480 MW built in each county, about 18 MW built in each county in each year from 2024 to 2050, or about two projects on the scale of the Muscle Shoals solar project in Muscle Shoals, AL built in each county over the study period. This land area impact could be mitigated by shifting a greater share of this to rooftop solar, or by prioritizing landfills, brownfields, or other locations of less-than-prime agriculture or biological diversity value. TVA could also study the areas in its service territory that are likely to harbor lower quantities of embedded CO_2 in forests and other biomes, in order to prioritize the types of land most suitable for future solar development.

- Land-use impacts for battery storage are not shown. Siting storage tends to be less controversial than solar, wind, or conventional resources because of the relatively low impact these facilities have on their surroundings (i.e., in terms of environment or aesthetics) and the less stringent siting requirements for these facilities compared to other resources (i.e., they need not occupy one large area or be located in an area with particular physical characteristics (e.g., locations that are particularly sunny or windy).

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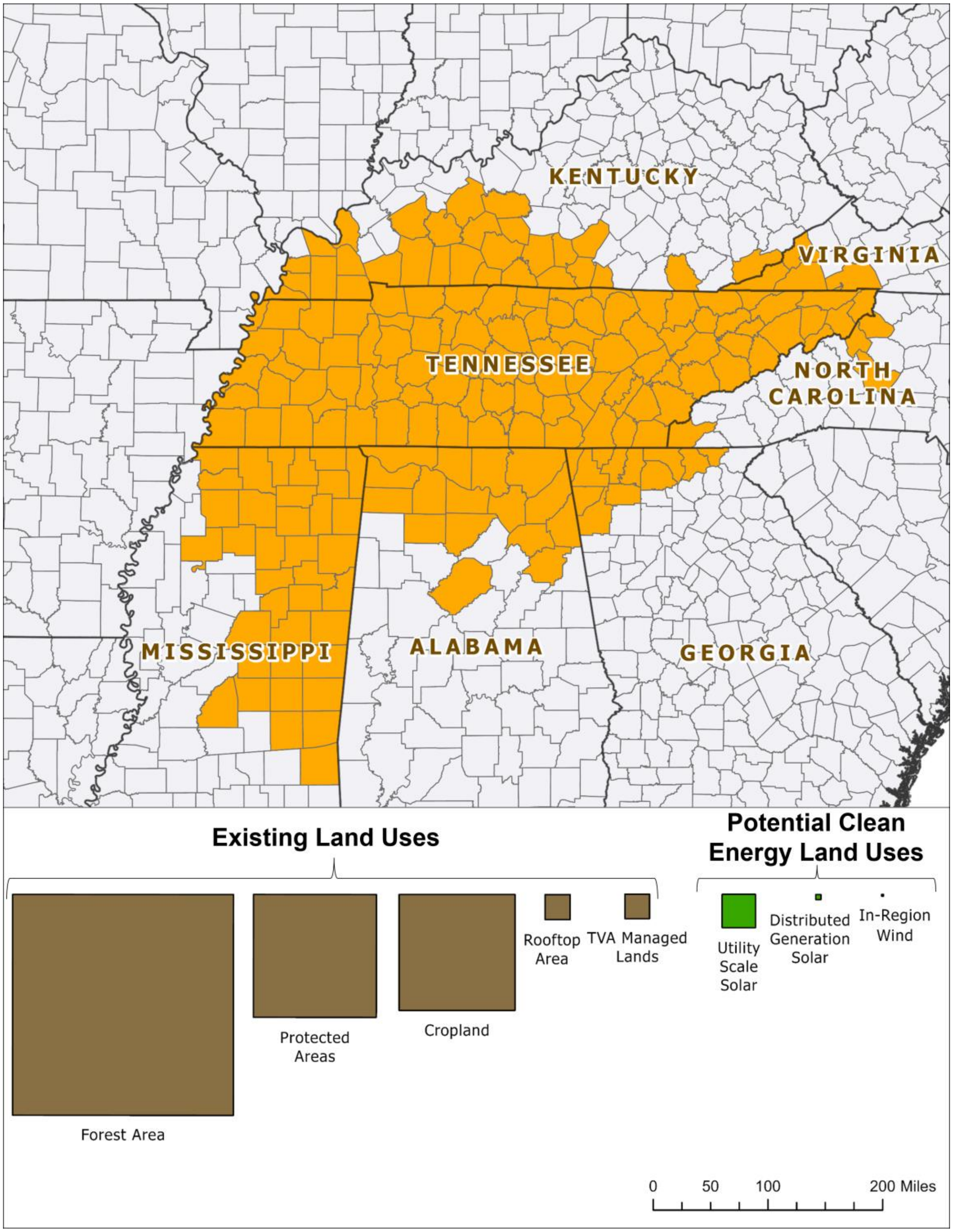
[39] Land-use requirements for distributed solar are based on *Rooftop Solar Photovoltaic Technical Potential in the United States*. National Renewable Energy Laboratory. 2016. Available at https://www.nrel.gov/docs/fy16osti/65298.pdf, with an assumed factor of with an assumed factor of 85 MW_{AC} buildable per acre.

[40] Land-use requirements for utility-scale solar are based on M. Bolinger and G. Bolinger, "Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density," in *IEEE Journal of Photovoltaics*, vol. 12, no. 2, pp. 589-594, March 2022, doi: 10.1109/JPHOTOV.2021.3136805. See Figure 3 and Section IV, with an assumed factor of 69 MW_{AC} buildable per acre.

Figure 17. Map of land-use requirements in the 100% Clean Energy scenario, compared with land-use requirements for existing uses



Note: Counties in yellow are counties where at least some electricity is supplied by TVA.

3. RECOMMENDATIONS FOR FUTURE MODELING EFFORTS

The 100% Clean Energy scenario modeled in this analysis is just one possible future of many. Historically, TVA's planning has not encompassed futures that are consistent with its newly stated clean energy and carbon-reduction aspirations. As this analysis shows, the transition to a clean energy future poses some challenges and results in an electric system that is very different than TVA's current system. But the benefits of such a transition stand large, indicating that TVA should make the effort to investigate this transition in its forthcoming modeling processes.

This chapter includes a sampling of questions that stakeholders may wish to ask about TVA's future modeling efforts, as well as an overview of the important issues related to clean energy planning that TVA and others should consider in these future modeling efforts.

3.1. TVA should consider its decarbonization targets in resource planning

First, any future modeling efforts by TVA should at least be inclusive of TVA's own goal of reducing greenhouse gas emissions by 70 percent by 2030, 80 percent by 2035, and reaching net zero carbon emissions by 2050.[41] These targets are in alignment with science-based goals aimed at averting the impacts of catastrophic climate change and current federal policy as set forth in the Biden Administration's executive orders. TVA planning should account for the fact that some options available to it today are at odds with its medium- and long-term goals. Building fossil plants have expected operating lifetimes of more than 25 years (such as the proposed 1,450-MW gas place replacement for the Cumberland coal plant) in the mid-2020s may preclude achievement of TVA's midcentury emission goals. As our analysis showed, even more ambitious levels of carbon reductions are possible, and with net benefits to consumers in TVA's service territory.

3.2. TVA should increase cost-effective energy efficiency investments

TVA has historically planned for only a very small amount of energy efficiency. This analysis considered a future where TVA looks to neighboring states and increases the level of energy efficiency deployed. TVA has historically been resistant to plan for increased levels of energy efficiency, with its consultants citing issues related to costs and potential pertaining to states that have been leading the charge on energy efficiency for years, rather than a region such as TVA that is still only in the nascent stages of energy efficiency deployment.[42]

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[41] For more information on TVA's climate goals, see its "Carbon Report" web page, available at https://www.tva.com/environment/environmental-stewardship/sustainability/carbon-report.

[42] Concentric Energy Advisors. *Assessment of the Draft Environmental Impact Study and Response to Certain Reports*. 2022. Available at: https://tva-azr-eastus-cdn-ep-tvawcm-prd.azureedge.net/cdn-tvawcma/docs/default-

3.3. TVA must consider electrification trends and the IRA to prepare for economy-wide decarbonization and increased demand

TVA's past modeling effort in its 2019 IRP contemplated very low levels of electrification. Next time, TVA should consider more ambitious levels of transportation and building electrification that at least reflect the adoption likely to occur with the incentives proscribed in the IRA. These include a $7,500 personal tax credit for many light-duty vehicles consumers are likely to buy, tax credits for medium- and heavy-duty vehicles that range from $7,500 to $40,000, tax credits for charging infrastructure, and tax credits for installing efficient heat pump equipment. These tax credits are likely to accelerate the current market trends that even without the IRA point to a much more ambitious level of electrification than assumed by TVA in past modeling.

In addition to modeling the likely effects of the IRA, TVA should model levels of electrification in the non-electric sectors that are consistent with its own carbon reduction goals for the electric sector. In other words, it would be most realistic for TVA to assume a zero-carbon emissions future in the electric sector happens alongside a future in which other sectors of the Tennessee Valley decarbonize (and are likely electrified).

Future electrification analyses should also examine the load shapes likely to result from this new electrification. For example, our analysis found that, on an annual basis, full electrification of the Tennessee Valley's residential and commercial sectors through efficient heat pumps is likely to produce net energy *savings* compared to a business-as-usual alternative. In other words, TVA could rely on deployment of heat pumps as an energy efficiency measure that reduces reliance on electric resistance heating, making winter peaks easier to manage.[43] This approach would yield near-term benefits, in addition to longer-term benefits related to emission reductions and associated impacts. Likewise, future modeling efforts should contemplate a range of load shapes related to vehicle electrification. As explored in the section below titled *Takeaways from the Ambitious DER scenario*, flexible loads can help to reduce electricity demand during periods of grid stress. Future technologies, such as vehicle-to-grid integration, may even go a step further by allowing EVs to act as mobile batteries that provide additional grid resources on the parts of the grid where they are most needed.

Finally, given the relatively large size of industrial energy consumption (and associated emissions) in the Tennessee Valley, we recommend that more work be done to better understand the likely trajectory that electrification might take for this sector. In this analysis, we utilized a set of assumptions that envision relatively rapid electrification to better understand impacts on the electric grid. We recommend that future modeling efforts take a closer look at individual industries or facilities and

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source/environment/cumberland-fossil-plant-retirement-final-eis4eeac6f0-b6bf-4843-9881-75d19ccf8ede.pdf?sfvrsn=d61f6b6f_7.

[43] We note that future TVA analyses of electrification impacts could rely on NREL's ResStock and ComStock models (see https://www.nrel.gov/buildings/resstock.html and https://www.nrel.gov/buildings/comstock.html), which can provide even more granular data on county-level energy use.

develop a finer-grained plan of how these industries might pursue electrification, and what the associated impacts and costs are likely to be.

3.4. TVA planning processes should evaluate demand-side resources as options to mitigate grid investment and reduce total system costs

TVA's 2019 IRP envisions several different trajectories for distributed storage and solar. We recognize that the distributed solar trajectory described by TVA as "moderate" (which was used in the 100% Clean Energy scenario) is rather ambitious: 1.7 GW by 2030, and projected out to 4.4 GW by 2050 by Synapse. On the other hand, TVA could model the assumed distributed storage trajectories more realistically: the trajectory described by TVA as "moderate" (and assumed in the 100% Clean Energy scenario) has 25 MW by 2030, which has been projected out to 270 MW by 2050 by Synapse. A 2022 NREL study observes that in 2020, 960 MW of behind-the-meter storage was installed nationwide, and that this number was projected to be about 7,300 MW by 2025.[44] If 1 percent of this were installed in TVA's service territory (about equal to the TVA service territory's fraction of the nation's population) this implies 73 MW by 2025, or the level of behind-the-meter storage that TVA does not project existing until 2036. We recommend that TVA continue to review the literature on these quickly advancing technologies and model appropriate levels of distributed solar and storage in future efforts.

Takeaways from the Ambitious DER scenario

In addition to the 100% Clean Energy scenario, we modeled an "Ambitious DER" scenario to understand the possible future benefits of increased emphasis on demand-side resources. The inputs to this scenario closely resembled those used in the 100% Clean Energy scenario, with two primary differences:[45]

- **More distributed solar and distributed storage:** This scenario follows the "High" case described in TVA's 2019 IRP, rather than the "Medium" case assumed in the 100% Clean Energy scenario. This leads to an additional 1.9 GW of distributed solar and an additional 0.8 GW of distributed storage by 2050.
- **Inclusion of "flexible load" resources:** This scenario contemplates a future where newly electrified end uses are capable of flexible load-shifting. In other words, we assumed that some fraction of new end uses are able to defer load for some number of hours until it is more economically efficient for that load to be served by available generation.

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[44] Cook, Jeffrey J., Kaifeng Xu, Sushmita Jena, Minahil Sana Qasim, and Jenna Harmon. 2022. *Check the Storage Stack: Comparing Behind-the-Meter Energy Storage State Policy Stacks in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-83045. https://www.nrel.gov/docs/fy22osti/83045.pdf.

[45] For more detail about the assumptions used in these scenarios, see Table 3 on page 13.

The increased levels of storage and distributed storage lead to reduced levels of utility-scale versions of the same resources. But it is the inclusion of the flexible load resources that leads to the largest differences in results.

In our analysis, we assumed flexible load potential and parameters using a 2020 study from NREL.[46] Using this study, we estimated the share of newly electrified end uses that could have flexible load attributes. Specifically, we assumed that about half of the modeled flexible load is associated with EV charging, where load can be shifted by up to eight hours. One-third of the flexible load is associated with space heating and cooling, where load can be shifted by up to 1 hour. The remaining flexible load associated with transportation, industrial end uses, and non-space heating and cooling end uses in residential and commercial buildings is shiftable by between 1 and 8 hours. This scenario assumes the dispatch costs of this resource is $0/MWh, and that there are no incremental capital costs associated with implementing this flexible load. We assumed that all flexible load has only a 50 percent capacity contribution. This means that while there is 32 GW of flexible load available to be dispatched at any one time, only 16 GW may contribute to the capacity requirement. Finally, we assumed that this flexible load resource phases on over the study period consistent with the deployment of newly electrified end uses.

With these parameters, we found that flexible load acts as nearly a one-to-one replacement for the energy service from batteries, and a two-for-one replacement for the capacity contribution that batteries otherwise supply. In other words, we found that the model replaces about 16 GW of 8-hour battery storage that it otherwise builds in the 100% Clean Energy scenario. By 2050, this flexible load resource dispatches about 45 TWh, enabling the model to shift energy from periods when excess generation is occurring to periods when load is higher and generation is lower. We observed electric system savings of about $1.5 billion in 2050, relative to the 100% Clean Energy scenario. This implies dispatch payments on the order of about $30 per MWh or about $50 per kW-year. In this analysis, we decided not to assign a dispatch cost to the flexible load resource. However, in a future electric system that is highly responsive to load, grid operators would likely pay demand-side users to shift or otherwise reduce load at certain hours. Our analysis suggests that the flexible load resources reduce a substantial amount of battery storage that would otherwise be necessary to meet reliability. These savings, when translated into per-MWh figures, suggest that the “cost” of flexible load dispatch is close to $30/MWh. Further detailed analysis is required to evaluate the potential of this resource in the Tennessee Valley and the effective dispatch cost.

We recommend that TVA consider the impact of flexible load resources such as the ones described above in future modeling endeavors, as they appear to be able to substantially decrease capital-intensive resource construction and associated cost and supply chain impacts.

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[46] Sun, Y. et al. Electrification Futures Study: Methodological Approaches for Assessing Long-Term Power System Impacts of End-Use Electrification. National Renewable Energy Laboratory (NREL). 2020. Available at https://www.nrel.gov/docs/fy20osti/73336.pdf.

3.5. TVA should evaluate renewables and conventional resources on equal footing

Any future modeling of the TVA service territory should place clean energy resources on equal footing with conventional resources. This includes using the latest, up-to-date information on current renewable energy costs as well as projections of future energy costs, such as those in industry-standard analyses like the *Annual Technology Baseline* published by NREL. TVA should modify these costs as necessary to reflect recent developments, such as newly passed tax credits or impacts to a resource's supply chain. TVA should apply these same considerations equally to both clean energy resources and conventional resources—for example, analyses should account for the latest data on fuel price projections and supply chain issues, some of which may lead to higher costs for these resources. These analyses should also consider realistic firm capacity contributions from existing and new fossil plants—if conventional fossil fuel plants do not have firm fuel sources, or have proven to be unreliable during recent extreme weather events, their firm capacity contributions should be decreased accordingly.

Our analysis found that when using the latest information on resource costs, inclusive of IRA impacts, the least-cost approach is invariably a switch from conventional fossil-fired resources to a future more dependent on solar, wind, and storage—even without a carbon emissions reduction requirement. This deployment is not without its challenges: our 100% Clean Energy scenario would require $45 billion of new capital investment on new inter-regional transmission lines in order to facilitate 39 GW of low-cost, high-capacity factor wind in TVA's neighboring territories.[47] However, even with these added costs, our modeling identified increased investment in these resources as key to a low-cost future for TVA.

Future modeling should also contemplate greater interconnection between TVA and neighboring regions. Prior TVA analyses have included resources in these regions, but with out-of-date information on current costs and tax credits, as well as unrealistic assumptions lacking future cost declines. Our analysis finds that when these resources are modeled with up-to-date cost information, our model seeks to build out-of-region wind resources, analyzing the high-capacity factor, low-cost, zero-emissions wind to be a perfect complement to in-region solar and storage resources. In its future modeling efforts, TVA would be well-served to look at other potential benefits of greater regional interaction among TVA and its neighboring balancing authorities. Higher levels of regional integration could help address issues related to resource curtailments or capacity shortfalls due to weather issues. We found that in the 100% Clean Energy scenario, curtailments in 2050 total almost 100 TWh, or about one-fifth of all generation. This level of curtailment is consistent with those observed in other deep decarbonization projections but could be lessened through greater regional integration or an increased reliance on flexible load resources (see section above titled *Takeaways from the Ambitious DER scenario*).

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[47] All assumptions related to inter-regional transmission line costs are based on data from Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022. *Examining Supply-Side Options to Achieve100% Clean Electricity by 2035*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf. We note that the level of transmission build modeled between TVA and neighboring regions in our analysis resembles the level of transmission build modeled in this NREL analysis. All transmission lines are assumed to be 500 kv AC.

Enhancing these interconnections has additional reliability benefits. During Winter Storm Elliot in December 2022, the neighboring MISO region scheduled more than 1 GW of electricity imports for a multi-day period.[48]

3.6. TVA should improve reserve margin modeling and appropriately evaluate the reliability contributions of renewables

TVA currently relies on a firm capacity construct that uses different seasonal values for summer and winter, and assumes that each resource type contributes a static portion of its capacity in each seasonal period. In our analysis, we observed that a switch to increased levels of low-cost, zero-emissions wind, solar, and storage render the current resource adequacy framing irrelevant. Rather than facing constraints at single high-demand hours, future reliability issues are likely to develop over the course of several days, when the grid is facing periods of high demand but relatively lower levels of renewable generation. As a result, future reserve margin and firm capacity requirements will likely need to be revised or overhauled entirely to reflect this new changing paradigm. For the purposes of this report, we continued to assume TVA's current approach to reserve margins and firm capacity, although we recommend that future analyses evaluate other strategies.

As described above in the *Reliability* section of *2.3 Results*, our own 8,760 hourly analysis of 2050 identified that with the assumed load and renewable load shapes, the model only faced one very short period of unserved energy (constituting 75 GWh, or about 0.02 percent of all load hours). We presume that there will be numerous tools to avoid potential unserved energy in 2050, including battery storage, flexible load resources, and regional integration. This type of analysis requires detailed, unit-specific stochastic reliability modeling beyond the scope of this analysis. While our analysis is technically rigorous and evaluates appropriate operating standards, because of the uncertainty out to 2050, further reliability analysis is required to evaluate other potential reliability issues.

Regardless of this fact, uncertainty of the technical limitations of operating a 100 percent clean energy system in 2050 should not be reason to limit today's deployment of critical solar, wind, and storage resources, particularly when wind and solar currently constitute less than 5 percent of TVA's operational capacity. Future IRPs should include a comprehensive view of system reliability, including correlated outages, weather patterns, and regional capacity sharing.[49]

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[48] *Overview of Winter Storm Elliott December 23, Maximum Generation Event*. MISO Reliability Subcommittee. January 17, 2023. Available at https://cdn.misoenergy.org/20230117%20RSC%20Item%2005%20Winter%20Storm%20Elliott%20Preliminary%20Report627535.pdf. Page 6.

[49] For more information on future alternatives to resource adequacy, we recommend *Redefining Resource Adequacy for Modern Power Systems*. ESIG. 2021. Available at https://www.esig.energy/wp-content/uploads/2022/12/ESIG-Redefining-Resource-Adequacy-2021-b.pdf.

3.7. TVA should account for non-electric benefits of a clean energy transition

As with this analysis, TVA’s 2019 IRP includes estimates for impacts related to waste, water use, jobs, and land use. We recommend that future modeling endeavors go further and also quantify impacts related to public health, the social cost of carbon, and fuel savings outside of the electric sector; our analysis shows these are likely to be substantial in a future featuring levels of electrification consistent with TVA’s electric-sector carbon-reduction goals.

4. CONCLUSION

Our 100% Clean Energy scenario shows that by completely switching away from fossil fuels in the electric sector in 2035, and by pursuing ambitious levels of electrification in the transportation, buildings, and industrial sectors, consumers in TVA's service territory can save $255 billion compared to a status quo "TVA Baseline" scenario. By pursuing a clean energy future, TVA can realize numerous benefits related to energy burden, job impacts, and public health while providing clean, reliable electricity to residents of the Tennessee Valley.

Appendix A. KEY SCENARIO INPUTS

Table 10 describes the primary assumptions used in the three scenarios analyzed in this study.

Table 10. Primary input assumptions for analyzed scenarios

		TVA Baseline	100% Clean Energy	Ambitious DER
Modeling Parameters	Topology	All of TVA's balancing area, including plants not owned by TVA and end uses not currently met via electricity from TVA	Same as "TVA Baseline"	Same as "TVA Baseline"
	Modeling horizon	2020-2050	Same as "TVA Baseline"	Same as "TVA Baseline"
	Temporal detail	Typical weeks (12 per year), 8 intervals per day	Same as "TVA Baseline"	Same as "TVA Baseline"
	Optimization period	Full-period optimization ("perfect foresight")	Same as "TVA Baseline"	Same as "TVA Baseline"
Load	Conventional end uses	Follows 2019 TVA IRP trajectory	Same as "TVA Baseline"	Same as "TVA Baseline"
	Energy efficiency	Follows 2019 TVA IRP trajectory	Ramps up to 1.5% annual savings as a % of sales	Same as "100% Clean Energy"
	LDV electrification	Follows 2019 IRP "1 Current" trajectory *(about 7 TWh by 2050.)*	Assumes that 99% of LDVs sold in 2030 are EVs *(About 50 TWh by 2050)*	Same as "100% Clean Energy"
	MDV/HDV electrification	Follows 2019 TVA IRP trajectory (none assumed)	Assumes that 60% of MDVs/HDVs sold in 2030 are EVs *(About 40 TWh by 2050)*	Same as "100% Clean Energy"
	Building electrification	Follows 2019 TVA IRP trajectory (none assumed)	Assumes that 100% of new equipment sold in 2030 are heat pumps *(By 2050 results in near-zero net-negative load addition due to baseboard heating replacement)*	Same as "100% Clean Energy"
	Industrial electrification	Follows 2019 TVA IRP trajectory (none assumed)	Non-electric demand electrifies according to MDV/HDV pathway (as this sector is similarly challenging to electrify). Based on 228 TWh/Quad assumption from EI's EPS analysis. *(About 112 TWh by 2050.)*	Same as "100% Clean Energy"
New conventional resources *(costs and tax credits, when allowed)*	Conventional gas	Allowed beginning in 2025, prices based on NREL's 2022 ATB	Same as "TVA Baseline"	Same as "TVA Baseline"
	Gas with CCS	Allowed beginning in 2025, prices based on NREL's 2022 ATB; includes 45Q tax credits	Same as "TVA Baseline"	Same as "TVA Baseline"
	Coal with CCS	Not currently modeled	Same as "TVA Baseline"	Same as "TVA Baseline"
	Adv. nuclear reactors / SMRs	Not currently modeled	Same as "TVA Baseline"	Same as "TVA Baseline"

		TVA Baseline	100% Clean Energy	Ambitious DER
New utility-scale clean energy resources *(costs and tax credits, when allowed)*	Utility-scale solar	Allowed beginning in 2024, prices based on NREL's 2022 ATB; includes options for both in-region PPAs and utility-owned solar; includes options for both PTC ($25/MWh) and ITC (30%); limited to 5 GW per year.	Same as “TVA Baseline”	Same as “TVA Baseline”
	Onshore wind	Allowed beginning in 2024, prices based on NREL's 2022 ATB; includes options for in-region PPAs, out-of-region PPAs, and utility-owned wind; includes PTC ($25/MWh); limited to 5 GW per year.	Same as “TVA Baseline”	Same as “TVA Baseline”
	Utility-scale battery storage	4- and 8-hour storage allowed beginning in 2024, prices based on NREL's 2022 ATB; Long-duration (50-hour) storage allowed beginning in 2030 according to 2021 LDES Council paper's "Conservative" central estimate: $2500/kW in 2025 declining to $1000/kW in 2040; includes ITC (30%); limited to 5 GW per year.	Same as “TVA Baseline”	Same as “TVA Baseline”
New distributed clean energy resources *(costs and tax credits, when allowed)*	Distributed solar	Follows "Base" case in 2019 IRP *(1.2 GW by 2030 and 2.7 GW by 2050)*	Follows “Medium" case in 2019 IRP *(1.7 GW by 2030 and 4.4 GW by 2050)*	Follows "High" case in 2019 IRP *(2.1 GW by 2030 and 6.3 GW by 2050)*
	Distributed battery storage	Follows "Base" case in 2019 IRP *(no additions)*	Follows “Medium" case in 2019 IRP *(25 MW by 2030 and 270 MW by 2050)*	Follows "High" case in 2019 IRP *(180 MW by 2030 and 1.1 GW by 2050)*
	Conventional demand response	Follows 2019 IRP: 1.9 GW by 2050	Same as “TVA Baseline”	Same as “TVA Baseline”
	Flexible load	None	Same as “TVA Baseline”	32 GW of flexible load by 2050, based on 2020 NREL potential study *(Components of flexible load vary by duration and price paid)*
Fuel costs	Gas	NYMEX in short term, AEO 2022 Reference case in mid- to long-term	Same as “TVA Baseline”	Same as “TVA Baseline”
	Coal	AEO 2022 Reference case	Same as “TVA Baseline”	Same as “TVA Baseline”

		TVA Baseline	100% Clean Energy	Ambitious DER
Existing fossil and nuclear and allowed retirements	Coal and gas	All plants currently listed as having an announced retirement retire no later than that date; plants are allowed to retire endogenously beginning in 2025	Same as "TVA Baseline"	Same as "TVA Baseline"
	Nuclear	Plants assumed to receive license extensions; IRA tax credits are assumed to prevent nuclear plants from retiring	Same as "TVA Baseline"	Same as "TVA Baseline"
Transmission	Within TVA	No internal constraints assumed; modeling TVA as a single electric region	Same as "TVA Baseline"	Same as "TVA Baseline"
	With regions adjacent to TVA	None assumed, except for PPAs *(From 2019-2021, average annual interchange was -1 TWh, or about 0.6% of total load)*	Same as "TVA Baseline"	Same as "TVA Baseline"
Reserve margins	Seasonal assumptions	17% summer (April-October), 25% winter (November-March)	17% year-round	Same as "100% Clean Energy"
Capacity contributions (ELCC)	Solar	1% winter, 50% summer (fixed systems) 1% winter, 68% summer (tracking systems)	Same as "TVA Baseline"	Same as "TVA Baseline"
	Wind	31% winter, 14% summer	Same as "TVA Baseline"	Same as "TVA Baseline"
	Other (nuclear, coal, gas, hydro, battery storage)	100% winter, 100% summer	Same as "TVA Baseline"	Same as "TVA Baseline"
	Flexible load	None present	None present	50% year-round