STATE OF NORTH CAROLINA
UTILITIES COMMISSION
RALEIGH

DOCKET NO. E-100, SUB 179

In the Matter of:	)	
Duke Energy Progress, LLC, and	)	**DIRECT TESTIMONY OF**
Duke Energy Carolinas, LLC, 2022	)	**ARJUN MAKHIJANI, Ph.D.**
Biennial Integrated Resource Plans	)	**ON BEHALF OF THE**
and Carbon Plan	)	**ENVIRONMENTAL WORKING GROUP**

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I. INTRODUCTION

Q: PLEASE STATE YOUR NAME, BUSINESS ADDRESS, AND CURRENT POSITION.

A: My name is Dr. Arjun Makhijani. My business address is P.O. Box 5324, Takoma Park, MD 20913. I am the President of the Institute for Energy and Environmental Research.

Q: WHAT ARE YOUR PRIMARY RESPONSIBILITIES AS THE PRESIDENT OF THE INSTITUTE FOR ENERGY AND ENVIRONMENTAL RESEARCH?

A: In my role as the President of the Institute for Energy and Environmental Research, my responsibilities include being the principal researcher and writer on projects, being responsible for the fiscal soundness of the Institute and reporting to the Board about its finances and the substance of the work.

Q: PLEASE BRIEFLY DESCRIBE YOUR EDUCATIONAL AND PROFESSIONAL BACKGROUND.

A: I hold a Bachelor of Engineering (Electrical) from the University of Bombay, a Master of Science in Electrical Engineering from Washington State University, and a Ph.D. in Engineering specializing in nuclear fusion from the Electrical Engineering and Computer Sciences department of the University of California at Berkeley.

Over the past forty years, I have produced various studies and articles on nuclear fuel cycle-related issues, including nuclear energy, nuclear weapons production, testing, and nuclear waste (both power and weapons-related). My energy work goes back over fifty years. My most recent comprehensive work on renewable energy is *Prosperous, Renewable Maryland: Roadmap for a Healthy, Economical, and Equitable Energy Future*, which is based on hour-by-hour modeling of the Maryland electricity sector, as well as energy justice considerations in a transition to renewable energy. I am the principal author of the first study ever done on conservation potential in the U.S. economy (1971).

In the last decade, I have authored or co-authored numerous articles and reports relating to the transition to a decarbonized energy system, including on land use, energy justice, electrification of buildings that now use fossil fuels and the cost of distributed solar for new residential construction. I am a member of the Mitigation Work Group of the Maryland Commission on Climate Change and a member of the Advisory Council of the state-created non-profit agency, the Maryland Clean Energy Center.

I have served as a consultant on energy issues to utilities, including the Tennessee Valley Authority ("TVA"), the Edison Electric Institute, the Lawrence Berkeley National Laboratory, and several agencies of the United Nations. In 2007, I was elected a Fellow of the American Physical Society, an honor granted to at most one-half-of-one-percent of the Society's members. I am a co-author of Investment Planning in the Energy Sector, which was produced in the 1970s during one of my consulting contracts with Lawrence Berkeley National Laboratory.

Q: HAVE YOU PREVIOUSLY TESTIFIED BEFORE THE NORTH CAROLINA UTILITIES COMMISSION ("THE COMMISSION")?

A: No.

Q: HAVE YOU PREVIOUSLY PROVIDED TESTIMONY OR COMMENT AS AN EXPERT BEFORE ANY OTHER REGULATORY BODIES OR FORUMS?

A: Yes. I presented testimony before the California Public Utilities Commission's *En Banc* hearing as an energy expert for the Just Solutions Collective on the integration of affordability, decarbonization, and modernization of the electric grid.[1] I have provided comments and presented testimony on behalf of the Institute for Energy and Environmental Research before the Public Service Commission of Maryland.[2] I have also presented testimony before the United States Nuclear Regulatory Commission's Atomic Safety and Licensing Board. Further, I have

[1] Testimony on Integrating Equity and Affordability into Energy Transition in California. The California Public Utilities Commission Affordability Proceeding Phase 3 *En Banc* hearing (2022). Available online: https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/en-banc/makhijani-slides-w-alt-image-and-link-text.pdf.

[2] Presentation on Net Metering and Distributed Energy Resources, *In the Matter of the Investigation Into the Technical and Financial Barriers to the Deployment of Small Distributed Energy Resources*, the Public Service Commission of Maryland, Public Conference 40 (2015); Comments regarding report by Gabel Associates, Inc. on the advisability of establishing an opt-in electric affordability program for residential and small business customers. *In the Matter of the Advisability of Establishing an Opt-In Electric Affordability Program for Residential and Small Business Customers*, the Public Service Commission of Maryland, Public Conference 47 (2017); Comments regarding the Electric Universal Service Program Proposed Operations Plan for Fiscal Year 2019. *In the Matter of the Electric Universal Service Program*, the Public Service Commission of Maryland, Case No. 8903 (2018).

presented testimony on behalf of Southern Alliance for Clean Energy before the Georgia Public Service Commission.[3]

Q: ON WHOSE BEHALF ARE YOU TESTIFYING IN THIS PROCEEDING?

A: I am testifying on behalf of the Environmental Working Group.

Q: WHAT IS THE PURPOSE OF YOUR TESTIMONY IN THIS PROCEEDING?

A: The purpose of my testimony is: 1) to address the costs, risks, and reliability of the proposed new nuclear technology and nuclear generation in the Carbon Plan filed on May 16, 2022 by Duke Energy Carolinas, LLC ("DEC") and Duke Energy Progress, LLC ("DEP) (collectively, "Duke Energy"); 2) to address the cost and schedule challenges associated with Duke Energy's proposed reliance on Small Modular Reactors ("SMRs") and advanced nuclear reactors as well as certain technical risks, given the history of such reactor programs and proposals; 3) to address the need for the Commission to acknowledge the reality and history associated with nuclear power from both large and small reactors and the unlikeliness of fitting into a least-cost profile that achieves the carbon reduction goals of North Carolina House Bill 951 ("HB 951"); and 4) to point out the need for additional portfolios because Duke Energy's proposed portfolios were similar in most major respects, including the very large amount of new

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[3] Testimony on Georgia Power Company's Integrated Resource Plan, Georgia Public Service Commission Docket No. 24505-U (2007).

nuclear energy planned in all of them, and because they did not include technologies that could make decarbonization more efficient, cost-effective, and resilient.

Q: HOW IS THE REMAINDER OF YOUR TESTIMONY ORGANIZED?

A: The remainder of my testimony consists of two parts and two subparts which are organized consistent with the outline provided in ordering paragraph 1 of the Commission's *Order Scheduling Expert Witness Hearing, Requiring Filing of Testimony, and Establishing Discovery Guidelines* entered on July 29, 2022.

- Part II will address the topic that the Commission has identified in part as "Near-Term Development Activity—prudence of development work and need for long-lead time resources." Part II contains two subparts: subpart (A.) will address the costs, risks, and reliability of Duke Energy's proposed new nuclear technology and generation, and subpart (B.) will address the cost, schedule, and technical challenges associated with Duke Energy's proposed reliance on SMRs and advanced nuclear reactors.
- In light of the above, in Part III, I will discuss for the Commission's consideration a framework for a range of portfolios that will help meet the requirements of HB 951 to design the least cost plan and meet or exceed present grid reliability levels.

II. TOPIC: NEAR-TERM DEVELOPMENT ACTIVITY—PRUDENCE OF DEVELOPMENT WORK AND NEED FOR LONG-LEAD TIME RESOURCES

A. Costs, Risks, and Reliability of Duke Energy's Proposed New Nuclear Technology and Nuclear Generation

Q: CAN YOU PLEASE PROVIDE EXAMPLES OF HISTORICAL DELAYS AND COST OVERRUNS ASSOCIATED WITH DEVELOPING AND CONSTRUCTING NUCLEAR FACILITIES?

A: A "nuclear renaissance" was proclaimed in the 2000s and quickly fizzled out. Plans for 34 reactors were announced[4] and construction started on only four proposed reactors. Of those that did not materialize, six were proposed and cancelled by Duke Energy. In the case of Duke Energy's proposal for two reactors at the Shearon Harris site, the company signed a construction contract, but abandoned the licensing effort after that.[5] Additionally, Duke Energy abandoned plans to construct two reactors at the William States Lee III site in 2017, after the Nuclear Regulatory Commission ("NRC") had completed its licensing review.[6] In all, Duke Energy pursued plans for six new nuclear units within eight years; no nuclear capacity resulted from these efforts.

Two of the four "nuclear renaissance" reactors that broke ground and proceeded with construction were Summer Units 2 and 3 in South

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[4] Larry Parker & Mark Holt, Nuclear Power: Outlook for New U.S. Reactors, Table 1 (Cong. Rsch. Serv., 2007), https://sgp.fas.org/crs/misc/RL33442.pdf.
[5] Mark Holt, Nuclear Energy Policy 6–9 (Cong. Rsch. Serv., 2014), https://sgp.fas.org/crs/misc/RL33558.pdf.
[6] World Nuclear News, *Duke Seeks to Cancel Plans for Lee AP1000s*, (Aug. 29, 2017), https://www.world-nuclear-news.org/NN-Duke-seeks-to-cancel-plans-for-Lee-AP1000s-2908175.html.

Carolina. Construction on both was abandoned after an expenditure of $9 billion.[7] The other two, Vogtle Units 3 and 4 in Georgia have faced serious cost overruns and delays. The initial cost estimate of $14 billion for both units has skyrocketed to more than $30 billion.[8] The planned starting dates for the Vogtle units of 2016 and 2017 have since gone by and the current estimate for a start-up date is 2023.[9]

The experience of the failed "nuclear renaissance"—when things were supposed to be more efficient and cost effective—has been considerably worse than the first round of major construction during which more than 120 announced nuclear units were cancelled.[10] In that round, a similar number of units, including those now owned by Duke Energy, were actually built and commissioned. This approximately 50-50 record is not good; but it did yield the largest fleet of nuclear power reactors in the world. Things have gone backwards since that time: if the two Vogtle units come online, as appears likely, the record of the "nuclear renaissance" would be considerably worse—a completion success rate of about six percent.

It has been no different with France, a leading western country in nuclear power generation. Its new reactor design, the 1,600-megawatt EPR,

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[7] Akela Lacy, *South Carolina Spent $9 Billion to Dig a Hole in the Ground and Then Fill it Back in*, The Intercept (Feb. 6, 2019), https://theintercept.com/2019/02/06/south-caroline-green-new-deal-south-carolina-nuclear-energy/.

[8] *See* David Schlissel, Southern Company's Troubled Vogtle Nuclear Project (Inst. for Energy Econs. and Fin. Analysis 2022), https://ieefa.org/wp-content/uploads/2022/01/Southern-Companys-Troubled-Vogtle-Nuclear-Project_January-2022.pdf.

[9] Kristi E. Swartz, *Plant Vogtle Hits New Delays; Costs Surge Near $30B*, E&E NEWS (Feb. 18, 2022), https://www.eenews.net/articles/plant-vogtle-hits-new-delays-costs-surge-near-30b/.

[10] Larry Parker & Mark Holt, Nuclear Power: Outlook for New U.S. Reactors, CRS-3 (Cong. Rsch. Serv., 2007), https://sgp.fas.org/crs/misc/RL33442.pdf.

was offered to Finland at a price of 3 billion euros and construction was supposed to be completed in 2009. The reactor finally began power production for the grid on a test basis in the first part of 2022; a mishap shut it down, and test production is set to be completed (after repairs) in December 2022.[11] In the meantime, the cost has almost quadrupled to 11 billion euros.[12]

The record in France itself is also not promising. Costs for the Flamanville Nuclear Power Plant EPR have ballooned from an estimated 3.3 billion euros to 12.7 billion euros and the scheduled commissioning has been delayed from an initial estimate of 2012 to 2023.[13]

Finally, it is essential to note that the nuclear industry in western countries, centered in the United States and France, does not have a promising record of learning from experience. On the contrary, costs in both countries increased as more reactors were built.[14]

Q: CAN YOU PLEASE DESCRIBE WHAT YOU MEAN BY A FAILED "NUCLEAR RENAISSANCE?"

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[11] World Nuclear News, *Olkiluoto 3 test production to continue until December*, (June 16, 2022), https://www.world-nuclear-news.org/Articles/Olkiluoto-3-test-production-to-continue-until-Dece.

[12] Schneider et al., The World Nuclear Industry Status Report 2019, p. 66 (Sep. 2019), https://www.worldnuclearreport.org/IMG/pdf/wnisr2019-v2-hr.pdf.

[13] Schneider et al., The World Nuclear Industry Report 2021, pp. 92-94 (Sep. 2021), https://www.worldnuclearreport.org/IMG/pdf/wnisr2021-lr.pdf.

[14] Jonathan G Koomey & Nathan E Hultman, A Reactor-Level Analysis of Busbar Costs for US Nuclear Plants, 1970–2005, 35 Energy Pol'y 5630 (2007); Arnulf Grubler, The French Pressurised Water Reactor Programme, Energy Technology Innovation: Learning from Historical Successes and Failures, p. 146 (Arnulf Grubler & Charlie Wilson eds., 2013).

A: In nearly two decades, no proposed new nuclear reactor has been completed or supplied power to the grid. The two Vogtle reactors in Georgia, the only ones still under construction, represent about six percent of the 34 announced reactors, presuming they are completed. It is worth repeating that six of the unrealized "nuclear renaissance" reactors were proposed by Duke Energy, which spent resources on them for licensing and contracting processes.

Q: FOR NUCLEAR POWER REACTORS THAT HAVE REACHED THE POINT OF OPERATION, HAVE ANY BEEN PREMATURELY RETIRED?

A: Yes. Several reactors have been retired before their license expiry.

Q: CAN YOU PLEASE DISCUSS WHY NUCLEAR POWER REACTORS HAVE BEEN RETIRED DESPITE BEING LICENSED TO OPERATE BEYOND THE TIME OF THEIR RETIREMENT?

A: High operating costs have been one of the main reasons the number of operating reactors dropped from 104 at the close of 2010 to 92 in July 2022. Losses from operating an uneconomical plant can be considerable.

For instance, in 2018, NextEra estimated that it would save customers nearly $300 million (present value) by prematurely shutting down the Duane Arnold reactor and generating wind power instead. Reactors have also been shut down for issues related to steam generator replacement. This was the case for two reactors in California (San Onofre) and one in Florida (Crystal River). The latter belongs to Duke Energy; it was shut down for refueling, steam generator replacement, and a power uprate. It was shut down permanently in 2013 due to problems and delays associated with the steam generator replacement.[15]

Q: CAN YOU PLEASE SUMMARIZE AND COMMENT ON THE FINAL RESOURCE ADDITIONS OF EACH PORTFOLIO FOR 2050 IN DUKE ENERGY'S CAROLINAS CARBON PLAN?

A: As indicated in Appendix E, Table E-71 of the Carolinas Carbon Plan, all four portfolios in the Carolinas Carbon Plan contain either 9,900 MW or 10,200 MW of new nuclear in 2050, which includes SMR and advanced nuclear with integrated storage reactor design options. The highest nuclear capacity is only about three percent greater than the lowest.

The combined combustion turbine and combined cycle gas-fired generation capacity is also similar, ranging from 8,800 MW to 9,900 MW across scenarios in 2050. The portfolios are also the same or similar in other major respects, such as the amount of onshore wind, the level of efficiency assumed, the amount of pumped hydro storage, and solar power capacity. Offshore wind capacity varies across portfolios from 0 to 3,200 MW; however, even the highest level would be a small fraction of generation

[15] Duke Energy News Release, *Crystal River Nuclear Plant to be retired; company evaluating sites for potential new gas-fueled generation*, (Feb. 5, 2013), https://news.duke-energy.com/releases/crystal-river-nuclear-plant-to-be-retired;-company-evaluating-sites-for-potential-new-gas-fueled-generation.

requirements in 2050. Battery capacity varies somewhat across portfolios, from a low of 5,900 MW to a high of 7,400 MW in the year 2050.

Q: IN YOUR OPINION, DOES DUKE ENERGY'S "NEW SUPPLY-SIDE RESOURCE CAPITAL COST SENSITIVITY ANALYSIS"[16] CONSIDER HISTORICAL COST ESCALATIONS AS DEMONSTRATED BY THE FAILED "NUCLEAR RENAISSANCE?"

A: No. Duke Energy did a capital cost sensitivity for nuclear and estimated the present value of cumulative impacts at $4 billion for a proposed portfolio of about 10,000 MW. This does not reflect historical or recent cost escalations. The cost of just two Vogtle reactors under construction had cost overruns of more than $16 billion, about $7 billion per gigawatt of capacity. Duke Energy is proposing to build 10 gigawatts of capacity. Moreover, corporations also spent money on the "nuclear renaissance" projects that were cancelled, including six proposed by Duke Energy.

Had Duke Energy's sensitivity analysis reflected real-life experience, its estimate would have been well over an order of magnitude more than Duke Energy's calculations. Moreover, even the very low estimate of $4 billion was not examined for its impact on the mix of generation in their four proposed portfolios. Cost estimates of SMRs and

[16] Duke Energy, Carolinas Carbon Plan Chapter 3 at 14-15 (May 16, 2022) (hereinafter "Carolinas Carbon Plan").

advanced reactors also depend in part on mass manufacturing components more than larger present-day reactors.

A sensitivity analysis should take into account the possibility that there may not be sufficient orders for such reactors to establish the lower costs anticipated by the time Duke Energy orders its reactors.

Q: IN YOUR OPINION, DOES A COST GAP EXIST BETWEEN NUCLEAR AND RENEWABLE POWER?

A: Yes. Renewable energy, specifically wind and solar, has come down rapidly in cost in the last 10 to 15 years. Lazard, a Wall Street firm, publishes cost estimates of electricity generation from new power plants towards the end of each calendar year. In its 2021 edition, it showed unsubsidized levelized cost declines for generation from utility-scale solar power plants from $359 per megawatt-hour (MWh) in 2009 to $36/MWh in 2021.[17] The corresponding values for onshore wind were $135/MWh in 2009 to $38 per MWh in 2021.[18] Offshore wind costs have also declined, but the history is based on European experience, where many offshore wind farms have been built. In 2021, Lazard estimated the range of offshore wind electricity cost as between $66 and $100/MWh.[19]

In contrast, the estimated unsubsidized costs of nuclear electricity have risen from an estimated $123/MWh in 2009 to $167/MWh in 2021.[20]

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[17] Lazard's Levelized Cost of Energy Analysis—Version 15.0, 8 (Oct. 2021), https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf.
[18] *Id.*
[19] *Id.* at 17.
[20] *Id.* at 8.

The potential range of costs estimated for 2021is also large—between \$131/MWh and \$204/MWh in 2021.[21] Of course, this presumes the reactors are built and commissioned.

Solar is increasingly coupled with storage (as is the case in the Duke Energy portfolios as well). Hence the utility-scale solar-plus-storage cost is of interest. The costs of solar plus storage have also been declining rapidly. The National Renewable Energy Laboratory ("NREL") estimated that the unsubsidized levelized cost of utility-scale solar plus large-scale storage was \$88/MWh in 2020 and that it declined to \$77/MWh in 2021; this represents a decrease of over 12% in levelized cost in a single year.[22] The 2021 cost estimate of utility-scale solar with storage was less than half the estimated cost of nuclear; as noted, in contrast to solar, nuclear costs have tended to rise.

The above estimates are of unsubsidized costs. The practical economic realities will change as a result of the newly enacted Inflation Reduction Act with subsidies for nuclear, renewables, and storage. In the case of solar with storage, the installed cost of utility scale projects with the investment tax credit in 2021 was only about \$30/MWh.[23] If storage equal

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[21] *Id.* at 2.

[22] Vignesh Ramasamy et al., U.S. Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021, p. 47 (Nat'l Energy Renewable Lab'y, 2021), https://www.nrel.gov/docs/fy22osti/80694.pdf. The estimate does not include the investment tax credit: "In this year's report, we calculate LCOE assuming long-term steady-state financing assumptions, with no investment tax credit and with interest rates higher than current historically low levels." p. 44.

[23] Joachim Seel et al., Batteries Included: Top 10 Findings from Berkeley Lab Research on the Growth of Hybrid Power Plants in the United States, Lawrence Berkeley National Laboratory, p. 6 (2022), https://eta-publications.lbl.gov/sites/default/files/berkeley_lab-_battery_included_-_top_10_hybrid_research.pdf.

to the capacity of the solar installation were added, the "price adder" to the cost of electricity would be $20/MWh.[24] Nuclear costs will most likely remain well above this level even with a comparable subsidy, such as a 30% investment tax credit. Finally, the clear trendline for solar-plus storage costs is sharply downward, so that costs are likely to remain low even when subsidies expire by 2034. As noted, the trendline for nuclear is in the opposite direction.

Q: IN YOUR OPINION, WOULD NEW NUCLEAR DESIGNS, SUCH AS LIGHT WATER COOLED SMRS AND NON-LIGHT-WATER-COOLED ADVANCED REACTORS, HAVE DIFFICULTY COMPETING ON A COST BASIS WITH MORE ESTABLISHED RENEWABLE POWER GENERATION METHODS?

A: Yes. Several evaluations of the cost of electricity from SMRs have come up with high estimates. For example, in its 2019 Integrated Resource Plan ("IRP"), Idaho Power estimated a cost of $121 per megawatt hour for a NuScale plant operating at a 90% capacity factor.[25] More recently, Australia's Commonwealth Scientific and Industrial Research Organisation ("CSIRO") has estimated that the cost of generating electricity from an

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[24] *Id.* at p. 6, Figure 4.

[25] Integrated Resource Plan 2019, IDAHO POWER, Appendix C (2020), https://www.idahopower.com/energy-environment/energy/planning-and-electrical-projects/our-twentyyear-plan/.

SMR would be between A$136 and A$326 (Australian dollars) (about $95 to $228 in U.S. dollars) per megawatt hour.[26]

As I have noted already, costs of solar would remain well below the cost of nuclear even when storage equal to 100% of the solar capacity is added. While a full comparison of a high variable renewable portfolio with a high nuclear portfolio would be done on a system basis (as indicted in the portfolios I suggested for evaluation in my July statement[27] and also in this testimony), the margin between the high cost of nuclear and the low cost of renewables plus storage is so large that nuclear would have great difficulty competing with renewables.

Q: CAN YOU PLEASE EXPLAIN WHETHER SMRS ARE ECONOMICALLY SUITABLE FOR RESPONDING TO VARIABILITY.

A: SMRs are not economically viable even at 90% or 95% average capacity factor. If SMRs respond to the variability of wind and solar by adjusting power output downward when renewable output is high and upward when renewable output falls, their average capacity factor will fall. Thus, the most important component of cost—capital cost—will be spread out over a smaller number of megawatt hours, raising the per unit cost of electricity.

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[26] Paul Graham, et al., Commonwealth Scientific and Industrial Research Organization, p. 76 at Apx Table B.9 (July 2022), https://www.csiro.au/-/media/News-releases/2022/GenCost-2022/GenCost2021-22Final_20220708.pdf. An exchange rate of A$1 = USD$0.70 was used. It has varied from a little below to a little above that rate in recent weeks. A historical chart of the Australian dollar to U.S. dollar exchange rate is available at https://www.macrotrends.net/2551/australian-us-dollar-exchange-rate-historical-chart.
[27] Initial Comments of Environmental Working Group, Attachment A.

For instance, costs per megawatt-hour of SMR electricity would increase by about 25% if annual capacity factor falls from 95% to 75%.[28]

Q: CAN YOU PLEASE EXPLAIN THE PRIMARY DIFFERENCE BETWEEN LARGE NUCLEAR POWER PLANT REACTORS AND SMRS?

A: 1,000 MW is the usual reference size for large nuclear reactors though they can be a couple of hundred megawatts smaller; of course, there are also designs larger than 1,000 MW. Large reactors have generally been chosen because they offer economies of scale. SMRs are modular, i.e., standardized, reactors that are relatively small, usually meaning 300 MW or less per reactor. Of course, nuclear plants often have more than one unit; that would generally be the case for SMRs.

Q: IN YOUR OPINION, DO SMRS OFFER ECONOMIES OF SCALE?

A: No. The term "economies of scale" means that, all else being equal, the cost per kilowatt of capacity of a larger reactor would be less than that of a smaller unit. The total cost of an SMR would be lower because the capacity and, hence, electricity generation per unit would be lower. The cost per unit of capacity matters because that is the main determinant of the cost of electricity from nuclear power.

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[28] M.V. Ramana, *Eyes Wide Shut: Problems with the Utah Associated Municipal Power Systems Proposal to Construct NuScale Small Modular Nuclear Reactors*, Oregon Phys. for Soc. Resp., p. 15 (2020), https://www.oregonpsr.org/small_modular_reactors_smrs.

The cost per kilowatt of nuclear reactor capacity tends to decrease with increasing size because the amount of steel, cement, other materials, and the number of welds (and the required labor), etc., do not increase linearly with size.

Loss of economies of scale would tend to make capital cost per kilowatt higher. For example, most of the early small reactors built in the United States shut down early because they could not compete economically.[29]

Q: ARE THERE WAYS TO COMPENSATE FOR THE POORER ECONOMICS OF SMALL REACTORS?

A: SMR proponents propose mass manufacturing and assembly-line style construction as one means of overcoming the loss of economies of scale. This, in turn, implies that there must be a considerable order book for SMRs to compensate, in whole or in part, for the loss of economies of scale. They also have simplified designs as a way to lower costs.

Q: HOW COULD MODULARITY AND FACTORY MANUFACTURING COMPENSATE FOR THE POORER ECONOMICS OF SMALL REACTORS?

A: Mass manufacturing is a standard way to lower costs for industrial products dating back to the famous Ford Model T assembly lines. A current example

[29] M.V. Ramana, *The forgotten history of small nuclear reactors*, Inst. of Electrical and Electronics Eng'rs Spectrum (Apr. 2015), https://spectrum.ieee.org/the-forgotten-history-of-small-nuclearreactors#toggle-gdpr.

of an expensive investment that is mass manufactured would be large passenger aircraft such as Boeing Dreamliners, Boeing 737s, and Airbus 350s. Much of the savings would arise from modularity and factory manufacturing.[30]

Proponents of SMRs acknowledge that a significant order book will be necessary for the projected economies of standardizing the design to be realized. The first units would therefore be more expensive. Industry proponents estimate that the order book would have to be in the dozens to one hundred reactors;[31] independent estimates put the order book requirement in the hundreds or reactors (at least) for an assembly approach to compensate for the loss of economies of scale.[32] Moreover, all this would need to happen on the schedule that Duke Energy envisions for adding reactors—for each substantially different design. Most importantly, it would need to happen on a schedule that is consonant with the decarbonization requirements of HB 951.[33]

In this context, it is important to note that in reality costs increased as more plants were built in the United States and France, the countries with

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[30] Giorgio Locatelli et al., Small Modular Reactors: A Comprehensive Overview of their Economics and Strategic Aspects, 73 Prog. Nucl. Energy 75 (2014).

[31] Arjun Makhijani, Light Water Designs of Small Modular Reactors: Facts and Analysis, Institute for Energy and Environmental Research, p. 5 (Sept. 2013), http://ieer.org/wp/wp-content/uploads/2013/08/SmallModularReactors.RevisedSept2013.pdf; Heba Hashem, Westinghouse: Taking care of business, Nuclear Energy Insider, (Feb. 12, 2014).

[32] *See* Alexander Glaser et al., Small Modular Reactors: A Window on Nuclear Energy (Princeton Univ., 2015), https://acee.princeton.edu/wp-content/uploads/2015/06/Andlinger-Nuclear-Distillate.pdf.

[33] *See* Arjun Makhijani, Light Water Designs of Small Modular Reactors: Facts and Analysis, Institute for Energy and Environmental Research, pp. 5-7 (Sept. 2013), http://ieer.org/wp/wp-content/uploads/2013/08/SmallModularReactors.RevisedSept2013.pdf.

the highest numbers of nuclear plants.[34] As a result, there is no guarantee that even with a substantial order book, costs will decline to the estimated levels.

After this monumental task, even if SMRs were to consistently achieve the same per-unit costs as the present large reactors, they would still be an economic failure, given the high costs of large reactors.[35]

Q: CAN YOU PROVIDE EXAMPLES OF SMRS DEPLOYED AT A COMMERCIAL SCALE IN THE UNITED STATES?

A: There are none.

Q: ARE THERE ANY SMRS THAT EXIST IN THE UNITED STATES?

A: No SMRs have been built in the United States.

Q: WHAT REACTOR DESIGNS HAS DUKE ENERGY IDENTIFIED AS VIABLE FOR CONTRIBUTING TO THE 70% CO_2 EMISSIONS REDUCTIONS TARGET SET OUT IN HB 951?

A: In Appendix L, Table L-5 of the Carolinas Carbon Plan,[36] Duke Energy identifies two SMRs and two advanced reactors that are scheduled to be built and in commercial operation by the end of 2029. These designs include:

- Natrium Reactor Liquid Sodium-cooled

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[34] Jonathan G Koomey & Nathan E Hultman, A Reactor-Level Analysis of Busbar Costs for US Nuclear Plants, 1970–2005, 35 Energy Pol'y 5630 (2007); Arnulf Grubler, The French Pressurised Water Reactor Programme, Energy Technology Innovation: Learning from Historical Successes and Failures, p. 146 (Arnulf Grubler & Charlie Wilson eds., 2013).
[35] Arjun Makhijani & M. V. Ramana, Can Small Modular Reactors Help Mitigate Climate Change?, 77 Bull. at. Sci. 207 (2021), https://www.tandfonline.com/doi/full/10.1080/00963402.2021.1941600.
[36] Duke Energy, Carolinas Carbon Plan Appendix L, Table L-5 at p. 10.

- Xe-100 Reactor Helium Gas-cooled High Temperature
- BWRX-300 Reactor Light Water-cooled ("BWR")
- VOYGR Reactor Light Water-cooled (PWR), i.e., NuScale's latest design.

Duke Energy plans to use only light-water-cooled designs for the 70% target in two of its portfolios.[37]

Q: HAVE ANY OF THE REACTOR DESIGNS IDENTIFIED BY DUKE ENERGY IN APPENDIX L, TABLE L-5 OF THE CAROLINAS CARBON PLAN BEEN APPROVED BY THE NRC?

A: No. Only one of the reactor designs, NuScale, has provisional certification for its 50 MW version; it may be granted full certification in the near future. However, the VOYGR NuScale reactor listed by Duke Energy is a 77 MW reactor, a capacity more than 50% above the capacity of the certified reactor. This larger capacity reactor will have to be certified in a separate process. The NRC website states that this version is in the pre-application stage.[38]

Q: HAVE ANY REACTOR DESIGNS IDENTIFIED BY DUKE ENERGY IN APPENDIX L, TABLE L-5 OF THE CAROLINAS CARBON PLAN BEEN CONSTRUCTED?

A: No.

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[37] Duke Energy, Carolinas Carbon Plan Appendix E, Table E-39 at p. 35 and E-69 at p. 77.

[38] U.S. United States Nuclear Regulatory Commission, Standard Design Approval (SDA) Application – NuScale US460 (last updated on July 12, 2022), https://www.nrc.gov/reactors/new-reactors/smr/nuscale-720-sda.html.

Q: WHAT IS THE EARLIEST DATE WHEN ANY REACTOR DESIGN IDENTIFIED BY DUKE ENERGY IN APPENDIX L, TABLE L-5 OF THE CAROLINAS CARBON PLAN WILL COME ONLINE?

A: According to Table L-5 in Appendix L, three of the listed designs are "expected" to be online in 2028. However, none of these designs have been certified. Two are non-light-water designs. The NuScale design has an expected online date of 2029. This has been greatly delayed. In 2008, NuScale officials expected an online date of 2015-2016; it took until 2016 for NuScale to even submit its application for certification—for the 50 MW design. However, NuScale's Idaho project, which would be the first for commercial production, is now going to be based on a 77 MW reactor, that has not been certified and is still in the pre-application stage. This is the version of the NuScale reactor that Duke Energy has included in its list. The historical record is not promising for commissioning on schedule.

Duke Energy should carefully evaluate this record of delays and changes in preparing the schedule for the dates at which it proposes to add SMRs and advanced reactors to its portfolio.

Q: CAN YOU DISCUSS THE POTENTIAL DEPLOYMENT ISSUES WITH EACH REACTOR DESIGN IDENTIFIED BY DUKE ENERGY IN APPENDIX L, TABLE L-5 OF THE CAROLINAS CARBON PLAN?

A:

- The BWRX-300 Reactor Light Water-cooled by GE Hitachi is a relatively new SMR; its conceptual design only started in 2017.[39] The BWRX-300 is based on GE-HITACHI's Economical Simplified Boiling Water Reactor design, which was never constructed anywhere in the world and has a checkered certification history; the design was changed nine times before the 10th version was certified. The BWRX-300 has not been licensed for construction, has not been submitted for formal certification to any national safety regulator, and therefore, has never been constructed anywhere in the word. It would be prudent to anticipate significant delays in the "expected" 2028 commissioning date announced for the first reactor.
- As noted, certification of the 77 MW VOYGR Reactor Light-Water-cooled design by NuScale is in the pre-application stage and has faced significant deployment delays.
- The certification of the Natrium Reactor Liquid Sodium-cooled by TerraPower and GE Hitachi was in the pre-application phase as of mid-August 2022.[40] It should be noted that the proposed fuel is High Assay Low-Enriched Uranium ("HALEU"), which has

[39] Int'l Atomic Energy Agency, Advances in Small Modular Reactor Technology Developments: A Supplement T: Advanced Reactors Information System (ARIS) 2020 Ed. 93 (2020), https://aris.iaea.org/Publications/SMR_Book_2020.pdf.
[40] U.S. Nuclear Regulatory Commission, Natrium — Project Overview (last updated on August 15, 2022), https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/natrium.html.

uranium enrichments between 5% and 20%.[41] HALEU fuel is not used for any commercial reactor in the United States and is not currently commercially produced in the United States. Unlike SMR designs that would use fuel of up to 5% enrichment, the current practice, HALEU implies security and certification considerations related to the enrichment of the fuel. Specifically, enrichment greater than 10% may raise proliferation concerns because other countries, including non-nuclear weapon states, may want to follow the United States' example.[42]

- Pre-application stage certification activities for the Gas-cooled High Temperature Xe-100 reactor by X-energy started in 2018. The reactor was still in the pre-application stage as of June 30, 2022.[43] The Xe-100 appears likely to also use HALEU. The Office of Nuclear Energy is the supporting the manufacture of HALEU graphite fuel pebbles by X-Energy,[44] which is developing the Xe-100 reactor. The pre-application White Paper on the fuel that the NRC is reviewing states that the Xe-100 would use low-enriched

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[41] Office of Nuclear Energy, *What is High-Assay Low-Enriched Uranium (HALEU)?*, https://www.energy.gov/ne/articles/what-high-assay-low-enriched-uranium-haleu.

[42] For a discussion on security issues associated with various levels of reactor fuel enrichment, *see* Edwin Lyman, "Advanced" Isn't Always Better: Assessing the Safety, Security and Environmental Impacts of Non-Light Water Reactors, Union of Concerned Scientists (March 2021), https://www.ucsusa.org/sites/default/files/2021-05/ucs-rpt-AR-3.21-web_Mayrev.pdf.

[43] U.S. Nuclear Regulatory Commission, Xe-100 — Project Overview, (last updated on June 30, 2022), https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/xe-100.html.

[44] Office of Nuclear Energy, X-energy's TRISO-X Fuel Fabrication Facility to Produce Fuel for Advanced Nuclear Reactors, Department of Energy pp. 4, 17 (April 8, 2022), https://www.energy.gov/ne/articles/x-energys-triso-x-fuel-fabrication-facility-produce-fuel-advanced-nuclear-reactors.

uranium ("LEU") fuel; however, the same document defines LEU as "<20%" enrichment.[45] This is unusual, since it is normal practice to distinguish between the LEU now used in commercial reactors, which is up to 5% enrichment, and LEU which has enrichments between 5% and 20%, and call it HALEU, due to its greater proliferation implications. Finally, the International Atomic Energy Agency, in its 2020 edition on SMRs states that the Xe-100 reactor would use 15.5% enriched fuel.[46] It therefore appears that the Xe-100 reactor will be using HALEU fuel and that its licensing process may face the same additional fuel review as the Natrium reactor on this account.

Q: IN YOUR OPINION, ARE DUKE ENERGY'S PORTFOLIOS SPECULATIVE GIVEN ITS RELIANCE ON SMRS BEING DEPLOYED AS EARLY AS 2032?

A: Yes. The history of SMRs is replete with substantial delays and changes. Certification processes are prolonged. Neither of the proposed light-water designs is certified. While the light-water designs are based on the same principles as current commercial reactors, their designs have been modified

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[45] X-Energy, LLC, Submission of X Energy, LLC (X-energy) Xe-100 Topical Report: TRISO-X Pebble Fuel Qualification Methodology, Revision 2, Enclosure 3: X Energy, LLC Xe-100 Topical Report: TRISO-X Pebble Fuel Qualification Methodology, (Non-Proprietary), pdf. p. 24 (Sept. 2, 2021), https://www.nrc.gov/docs/ML2124/ML21246A289.pdf.

[46] International Atomic Energy Agency, Advances in Small Modular Reactor Technology Developments: A Supplement to IAEA Advanced Reactors Information System (ARIS), 2020 Ed. p. 175 (Sept. 2020), https://aris.iaea.org/Publications/SMR_Book_2020.pdf.

in part to reduce costs. Thus, the first reactors may face more than the usual amount of teething troubles; this would delay subsequent reactors.

Q: CAN YOU DISCUSS THE POTENTIAL OPERATIONAL RISKS ASSOCIATED WITH THE RAPID DEPLOYMENT OF NUCLEAR TECHNOLOGY?

A: David Lochbaum, a nuclear engineer with extensive experience in the nuclear industry, in Non-Governmental Organizations, and in the NRC, has shown that reactor operational risks follow a "bathtub curve" – high in the early years due to factors such as material imperfections and mistakes in assembly, low in the middle years, and rising again with age due to age-related degradation.[47]

For instance, Three Mile Island Unit 2 was just over a year old when the infamous 1979 accident occurred. Chernobyl Unit 4 was also relatively new – construction was completed in 1983; the accident occurred in 1986.

An analysis of early risks, relative to the average, would therefore be a prudent part of planning if the Commission approves the exploration of new designs, especially in view of the rapid rate at which new reactor designs would be commissioned.

New designs or modifications of existing designs raise the risk of such early operational difficulties. For instance, the NuScale reactors will have their steam generators inside the reactor vessel. In contrast, existing

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[47] David Lochbaum, *Nuclear power in the future: risks of a lifetime*, Bulletin of the Atomic Scientists (Feb. 24 2016), https://thebulletin.org/2016/02/nuclear-power-in-the-future-risks-of-a-lifetime/.

commercial pressurized water reactors ("PWRs") have their steam generators outside the reactor vessel but within the secondary containment where they can be repaired or replaced. Problems with steam generators, which have had to be prematurely replaced in existing PWRs, would be more complex with the steam generator inside the reactor vessel.

Q: IS IT YOUR POSITION THAT DUKE ENERGY'S PORTFOLIOS PRESENT SIGNIFICANT SCHEDULE AND COST RISKS GIVEN ITS RELIANCE ON SMRS AND ADVANCED REACTORS BEING DEPLOYED AS EARLY AS 2032 AND THEN EACH YEAR AFTER THAT?

A: Yes. I have outlined the serious and varied risks associated with reliance on either light water SMRs on a schedule that is very optimistic, given the many delays that even light-water SMRs have experienced. It is essential, given this experience, not to take the announced dates of commercial operation of first-of-a-kind reactors at face value; instead, a careful evaluation of the overall history and the specific history of each reactor is called for to assess the cost and schedule risks. This is necessary for light-water-cooled SMRs and even more necessary for the two non-light-water designs that Duke Energy has selected. As I have noted, none of these designs have even been certified. Duke Energy's timeline and schedule[48] make no allowance for delays in the commissioning dates of the four first-

[48] Duke Energy, Carolinas Carbon Plan Appendix L, Figures L-3 and L-4 at pp. 12-13.

of-a-kind reactors, not to mention making allowances for those reactors to operate for some time to work out and resolve any teething troubles.

Q: CAN YOU DISCUSS HOW RELIANCE ON BOTH NEW AND EXISTING NUCLEAR POWER CAN DESTABILIZE SIGNIFICANT PARTS OF THE DUKE ENERGY ELECTRICITY SYSTEM?

A: Numerous factors in Duke Energy's proposed Carbon Plan create risks of a deterioration of reliability. Reliance on relatively long lead-time new nuclear is one of them. In addition, Duke Energy would be adding about 10,000 MW to its already substantial North Carolina portfolio of 7,500 MW; this creates additional risks.

Specifically, nuclear power plants need grid electricity to operate safely and produce power. Plants only have enough emergency power supply to keep them in safe shutdown mode. A loss of grid power over a wide area with high concentrations of nuclear power plants could destabilize significant parts of the Duke Energy electricity system (and perhaps beyond) because a large amount of electric generating capacity would be taken offline—capacity which requires grid power to be restored for power generation to resume.

Q: CAN YOU PROVIDE EXAMPLES OF EVENTS THAT CAN IMPACT DUKE ENERGY'S ELECTRICITY SYSTEM IF THERE IS RELIANCE ON BOTH NEW AND EXISTING NUCLEAR POWER?

A: For instance, an earthquake on August 23, 2011, shut down the North Anna nuclear plant in Virginia for months. The ground-shaking was felt over a wide swath of eastern North America from Georgia to Maine and Quebec; it was felt all over North and South Carolina – that is the entire Duke Energy DEC and DEP region. A similar event (or an even larger one, comparable to the 1886 Charleston Earthquake), could paralyze the electricity system for a significant time. Duke Energy's proposed Carbon Plan has not analyzed such an eventuality, even though the United States Geological Survey recognizes the significant earthquake potential in the Southeastern United States.[49] This vulnerability is not about whether such an event might trigger an accident – that is a matter for the NRC to consider. It is about the increased exposure of the electricity system to a widespread nuclear plant shutdown (for instance for inspections and/or potential repairs) in case of an earthquake comparable to or greater than the 2011 Virginia event.

As another example, extreme weather events are intensifying; they could cause outages in large sections of the grid. Hurricane Ida in 2021 provided an example of all transmission lines into a major city, New Orleans, failing simultaneously. This creates risks since nuclear power plants need grid energy to restart supplying power.

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[49] U.S. Geological Survey, Improved Earthquake Monitoring in the Central and
Eastern United States in Support of Seismic Assessments for critical facilities, Open-File Report 2011-1101 (2011), https://pubs.usgs.gov/of/2011/1101/pdf/OF11-1101.pdf.

A prolonged, decades-long reliance on existing nuclear capacity may also create reliability issues. It would be prudent to examine such an eventuality, given the recent events in France that have led to high prices and large unplanned outages. Specifically, the discovery of stress corrosion cracking in reactors in late 2021 led to far less capacity being available than normal. France's energy regulator has stated that it will take years to fix the problem.

As another example, adding about 10,000 MW to the existing 7,500 MW of nuclear in North Carolina would create large new demands on water resources, increasing vulnerability in times of heat waves—when capacity is most needed. High summer water temperatures have already caused occasional de-rating of nuclear plants. For instance, some French nuclear power plants were de-rated during the 2003 heat wave, significantly reducing available capacity. The problem of derating due to high water temperature will tend to arise during the summer peak demand season, creating pressure on the grid during that critical period. A recent analysis of empirical data on nuclear plant performance showed that the rate of nuclear power plant outages due to climate change was more than seven times greater in the decade of the 2010s compared to the 1990s. The negative impacts were due to factors as varied as droughts, hurricanes, and, as noted in a recent article in the journal *Nature Energy*, an "excessive presence of jellyfish, which have been shown to flourish in warmer waters under the effect of climate change."[50] The quantity of water required and the vulnerabilities that that would create for the grid is a critical factor for assessing any decarbonization plan.

It should be noted that solar photovoltaic and wind power plants need essentially no water for their operation. The opportunity costs imposed on competing uses and resources, like fish, which would also be impacted by the heating of water resources, also need to be addressed in the context of a warming climate and least cost planning.

Q: IN YOUR OPINION, WHAT ROLE SHOULD ADVANCED NUCLEAR ENERGY PLAY IN TRANSITIONING FROM CARBON-INTENSIVE GENERATION SUCH AS COAL OR NATURAL GAS?

A: Based on a variety of factors, no reliance should be placed on SMRs and non-light-water advanced nuclear energy technologies to achieve the decarbonization goals of HB 951. They are costly; their schedules are likely to be delayed relative to the dates in Duke Energy's portfolios; and the risks and uncertainties involved are far too large to even put reliable upper limits on costs and delays. The history of the failed nuclear renaissance is most relevant here. After more than 15 years, not a single reactor of the dozens announced has produced any electricity to date, despite modular designs and simplified licensing that combined the construction and operating

[50] Ali Ahmad, *Increase in Frequency of Nuclear Power Outages Due to Changing Climate*, 6 Nature Energy pp. 755, 756 (July 2021).

licenses—two separate processes in the twentieth century—into a single license.

Moreover, renewable energy and storage are available at a much lower cost. Other non-nuclear advanced technologies are available to meet all the needs of replacing fossil fuel generation without resorting to costly and untried new nuclear technologies with known risk factors that are substantial.

The non-light water reactors that Duke Energy has selected face added risks. There are no operational commercial reactors in the United States, small or large, that use the proposed design approaches in the Xe-100 and Natrium reactors. The latter is a sodium-cooled design whose concept goes back to the earliest days of nuclear power. Tens of billions of dollars have been spent worldwide to commercialize this design; yet, neither consistently reliable operation across reactors or time periods or economics of production has yet been achieved. In addition, the Natrium design would add molten salt storage, which has not been used in association with nuclear reactors.

Gas-cooled, graphite-moderated reactors have also had a troubled history both in the United States and Germany. While the design is not vulnerable to meltdowns, it is susceptible to fires and incursions of water.

Past commercial experience is not promising; all four commercial reactors built in the United States and Germany were shut down early.[51]

There is therefore ample reason to be even more prudent when proposing to rely on non-light-water SMR designs by a date certain to meet the HB 951 2050 target while achieving reasonable costs.

Q: IS IT YOUR POSITION THAT NEAR-TERM DEVELOPMENT ACTIVITIES RELATED TO ADVANCED NUCLEAR REACTOR TECHNOLOGY ON DUKE ENERGY'S PART ARE NOT PRUDENT AT THIS TIME?

A: They are not prudent investments at this time. Given the risks, status, hurdles, and history, no expenditures are justified at this time. DEP and DEC witness Regis Repko states that "initial development work is needed both to gather information to provide a more refined cost estimate to the Commission in future proceedings, as well as to allow the Companies to be positioned to implement such resources on a timeline consistent with the Companies' modeled portfolios."[52] Duke Energy should have looked at its six-reactor failed nuclear renaissance experience before proposing a high risk, high capacity new nuclear portfolio of reactors that do not even have certification. Their prospects are poor and much lower cost alternatives are available.

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[51] M. V. Ramana, *The checkered operational history of high-temperature gas-cooled reactors*, Bulletin of the Atomic Scientists, Vol. 72, No. 3 (2016).

[52] Docket No. E-100, Sub 179, Direct Testimony of Regis Repko et al. for Duke Energy Progress, LLC and Duke Energy Carolinas, LLC, pp. 8-9 (Aug. 19, 2022).

In light of this, expenditure of ratepayer funds is not justified at this time. Should one or more new nuclear technologies progress in an unexpected positive direction in terms of certification, cost, and scheduling in the next few years, the issue of new nuclear technologies can be revisited at that time with due focus on the more promising reactor types.

B. Technical Challenges and Operational Problems Associated with Duke Energy's Proposed Reliance on SMRs and Advanced Nuclear Reactors

Q: CAN YOU DISCUSS THE POTENTIAL OPERATIONAL RISKS ASSOCIATED WITH DUKE ENERGY'S PROPOSED SMRS AND ADVANCED NUCLEAR REACTORS?

A: The new nuclear technologies as a set pose a significant risk given the fact that they are new, have never been built for commercial operation, and therefore, have never operated commercially. I have already alluded to the concept of the "bathtub curve," which demonstrates that there are more problems in the early and late parts of the operating life of reactors.

An analysis of early risks, relative to the average, would therefore be a prudent part of planning if the Commission approves the exploration of new designs at some point, especially in view of the rapid rate at which new reactor designs are proposed to be commissioned.

There are also specific risks associated with the different designs, especially the advanced reactors. Sodium leaks have historically plagued many sodium-cooled reactors. The Monju sodium-cooled nuclear reactor is an example of the "bathtub curve" as applied to this case. It was shut down due to a sodium leak and fire in 1995, having been completed in 1994. It remained shut until 2010, when it was reopened and suffered another accident, leading to permanent shut down.[53]

The poor operating history of graphite moderator reactors should also be evaluated. Four reactors of this type were all shut down with operating lifetimes between just 7 and 10 years. The Peach Bottom reactor in the United States started having operational problems in just over a year after commissioning.[54]

New waste types may also pose issues. As noted, graphite poses a risk of fires. Its storage will present different issues than those of light-water reactor spent fuel. Disposal will also present challenges specific to the fuel type in addition to the issues generally connected with long-lived radionuclides in high-level radioactive waste. A portion of the graphite will become carbon-14 during reactor operation. This is a radioactive isotope of carbon; when oxidized it becomes radioactive carbon dioxide that dissolves in water and is emitted to the air, thereby posing the risk of making food and water radioactive. For instance, in the 1990s an EPA scientific subcommittee of the Radiation Advisory Committee concluded that demonstrating that the disposal of light-water reactor spent fuel in an

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[53] For the 1995 sodium leak accident *see* Thomas B. Cochran et al., Fast Breeder Reactor Programs: History and Status, Int'l Panel on Fissile Materials, p. 54 (2010), http://ipfmlibrary.org/rr08.pdf; For the permanent shut down, *see* World Nuclear News, *Japanese government says Monju will be scrapped*, (Dec. 22, 2016), https://www.world-nuclear-news.org/NP-Japanese-government-says-Monju-will-be-scrapped-2212164.html.

[54] M. V. Ramana, *The checkered operational history of high-temperature gas-cooled reactors*, Bulletin of the Atomic Scientists, Vol. 72, No. 3 (2016).

unsaturated repository zone, such as the proposed Yucca Mountain repository, would meet the release limit on carbon-14 in the prevailing regulation (40 CFR 191, Table 1) could pose significant challenges.[55]

Q: CAN YOU DISCUSS SOME OF THE ISSUES THE TWO MOLTEN SALT MICRO-REACTOR DESIGNS IDENTIFIED IN APPENDIX L, TABLE L-5 OF THE CAROLINAS CARBON PLAN WOULD LIKELY FACE IF DUKE ENERGY PURSUES THEM?

A: Experience with molten salt reactors is very limited. Two have been built in the United States; neither was designed to generate power. The first was an aircraft reactor experiment; it operated for 100 hours. The second was a pilot reactor of just 8 megawatts thermal—the Molten Salt Reactor Experiment—built and operated at Oak Ridge National Laboratory; the heat generated by the reactor was dissipated into the air (by design); no electricity was generated. This molten fluoride fuel reactor had a short, four-year operational period from 1966 to 1969 (inclusive) during which it experienced several problems. As my colleague Dr. M.V. Ramana and I noted in our 2021 article for the Bulletin of the Atomic Scientists, "Over the four years, its operations were interrupted 225 times due to various problems, including sudden, usually unscheduled, shutdowns (called

[55] Environmental Protection Agency, An SAB Report: Review of Gaseous Release of Carbon-14: Review by the Radiation Advisory Committee, of the Release of Carbon-14 in Gaseous Form from High-Level Waste Disposal, p. 2 (1993), https://www.nrc.gov/docs/ML0413/ML041330429.pdf. Disclosure: I was a member of the EPA subcommittee that reviewed the issue.

"scrams") and fuel draining down the freeze valve (a component often touted as a safety feature in molten-salt reactor designs) . . . ."[56]

Molten salt waste containing fission products may also pose significantly more difficult problems of long-term high-level waste than the ceramic fuel pellets used in light water reactors. While the specific post-closure issues with the proposed reactors will likely differ somewhat from the ones in Duke Energy's table and may be less complex in the absence of uranium-233 (which is a post-closure issue for the Oak Ridge reactor), it is still worth noting that post closure costs of this reactor, whose size is in between the two micro-reactors in Table L-5, run into hundreds of millions of dollars.[57]

Q: CAN YOU PROVIDE EXAMPLES OF THE AMOUNT OF DEVELOPMENT THAT MUST FIRST OCCUR TO HAVE DUKE ENERGY'S PROPOSED SMRS ONLINE IN 2032?

A: The proposed reactors have to be certified, the combined construction and operating licenses have to be obtained, and the first reactors listed in Appendix L, Table L-5 of the Carolinas Carbon Plan have to be built on time at something resembling the costs assumed by Duke Energy. Even so, for Duke Energy to bring the first SMR reactor online for commercial operation in mid-2032, it would have to get a construction and operating

[56] Arjun Makhijani & M. V. Ramana, *Can Small Modular Reactors Help Mitigate Climate Change?*, 77 Bull. at. Sci. 207 (2021).
[57] *Id.*

license in 2026, begin initial construction in early 2028, and carry out full-scale construction activities starting in mid-2029, according to Duke Energy's own schedule.[58] This is approximately coincident with the currently projected completion of SMRs identified in Appendix L, Table L-5 with no allowance for delays and no allowances for a learning curve on the initial reactors to overcome the early part of the "bathtub curve."

Q: CAN YOU PROVIDE EXAMPLES OF FACTORS THAT MAY DELAY COMPLIANCE WITH THE EMISSIONS REDUCTIONS TARGET SET OUT IN HB 951 IF ALL PORTFOLIOS PROPOSED BY DUKE ENERGY RELY ON SMR CAPACITY?

A: There could be a variety of delays – in certification of the reactors (since none of the specific reactors identified in Appendix L, Table L-5 of the Carolinas Carbon Plan are certified), for instance. Another risk is that the companies proposing to build the first projects may abandon them. For instance, the TVA pulled out of the mPower, Babcock & Wilcox project in 2017, after six years and considerable expenditures. The projects may face substantial cost escalations, as has already occurred with the NuScale project proposed to be built in Idaho. That project was announced as a 720 MW project in 2015 but was downsized to 462 MW in 2021.[59] Even so, as of October 2021, 28 subscribers had signed contracts to purchase only 101

[58] Duke Energy, Carolinas Carbon Plan Appendix L, Figures L-3 and L-4 at pp. 12-13.
[59] NuclearNewsWire, *UAMPS Downsizes NuScale SMR Plans*, Nuclear News, (July 21, 2021) at https://www.ans.org/news/article-3087/uamps-downsizes-nuscale-smr-plans/.

MW, or just 22% of the *reduced* capacity; 2 utilities had signed Letters of Intent ("LOI") to explore purchasing another 38% of the reduced capacity; other utilities were exploring LOIs as of October 2021.[60] The October 2021 contractual subscription of 101 MW was down from the "approximately 244 MW" of "[p]articipation" that was claimed in May 2019 by the Utah Associated Municipal Power Systems.[61] Further cost increases may cause parties to pull out or reduce their subscriptions; they may also result in a failure to get firm subscriptions for much or most of the power. These eventualities may even result in project abandonment.

The extension of the investment tax credit under the Inflation Reduction Act and the low cost of solar plus storage increases the likelihood that nuclear projects will be abandoned due to the yawning cost gaps. Such setbacks could also make it difficult to consider follow-on projects, such as those proposed by Duke Energy, as reasonable and prudent investments.

Q: SHOULD COMPLIANCE WITH THE REQUIREMENTS OF HB 951 REST ON THE SUCCESSFUL DEVELOPMENT AND CONSTRUCTION OF NEW NUCLEAR FACILITIES?

A: No. It is far too risky and costly when there are other options available. Furthermore, if there is unexpected progress in terms of cost and expedited

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[60] PUET Committee, Carbon-Free Technologies: Opportunities and Challenges, Utah Associated Municipal Power Systems (UAMPS), pdf p. 17, (Oct. 21, 2021), https://ieefa.org/wp-content/uploads/2022/02/October-2021-UAMPS-presentation.pdf.

[61] Leadership in Nuclear Energy Commission Meeting, Presentation by Doug Hunter, (May 16, 2019), https://line.idaho.gov/wp-content/uploads/2019/05/2019-0516-UAMPS-slides.pdf.

schedules in the next few years in one or more of Duke Energy's identified reactor types, the issue could be more appropriately revisited at that time.

Q: IN YOUR OPINION, HAS DUKE ENERGY THOROUGHLY PRESENTED TO THE COMMISSION THE POTENTIAL TECHNICAL CHALLENGES AND OPERATIONAL PROBLEMS ASSOCIATED WITH ITS PROPOSED SMRS AND ADVANCED NUCLEAR REACTORS IN ITS CAROLINAS CARBON PLAN?

A: No.

III. RECOMMENDATIONS

Q: WHAT ARE YOUR RECOMMENDATIONS FOR THE COMMISSION CONCERNING MODIFICATIONS TO DUKE ENERGY'S RELIANCE ON EXISTING NUCLEAR GENERATION AND ADVANCED NUCLEAR TECHNOLOGY?

A: Given the reality of Duke Energy's heavy reliance on both existing nuclear generation and advanced nuclear technology in its proposed Carolinas Carbon Plan, my recommendations for the Commission are as follows:

No more than one portfolio should include new nuclear. If such a portfolio is included, the obstacles and risks should be explicitly discussed, including the issues that Duke Energy has not covered or covered only in passing. My opinion, especially in view of the Inflation Reduction Act (which was enacted after my written submission in this docket in July

2022[62]), is that it would be far better to examine a diversity of portfolios without any one of them containing new nuclear power plants. Existing nuclear plants can be maintained in one or more of them. The following list contains four portfolios of the type and variety that should be developed in detail; two of them retain existing nuclear; two do not.

1. **EWG Portfolio 1: Balanced Solar and Wind with Existing Resources**.

   A Portfolio in which onshore and offshore wind generation combine to approximately equal annual solar generation, both of which would be significantly larger than in the Duke Energy P2 Portfolio (with wind having to increase more than solar). Balanced wind and solar generation provide seasonal balance to better meet summer and winter loads with lower stress on non-generation resources. Existing nuclear resources would be retained. New hydrogen generation resources would be included, but instead of CT and CC resources, light and medium duty fuel cells would be evaluated. No new natural gas resources would be built. Considerably faster transportation electrification would be included in light of plans by major manufacturers and countries that are major markets for vehicles. Vehicle-to-Grid ("V2G") technology would be included. While Duke Energy did not include V2G in its proposed portfolios, deeming it to be in its "commercial infancy,"[63] it is

[62] Initial Comments of Environmental Working Group, Attachment A.
[63] Duke Energy, Carolinas Carbon Plan Appendix G at p. 44.

noteworthy that the company has since applied to the Commission to team up with Ford to implement V2G in North Carolina on a pilot basis. In its application to the Commission for ratepayer funds for this program, Duke Energy stated that it would start with a small pilot, initially enrolling 35 to 100 vehicles.[64] Based on this experience, it envisions taking the V2G pilot to a "commercialized" pilot stage, which, over five years would enroll thousands of F-150 Lightning leaseholders, and reduce their lease costs by directly paying Ford when it leases the vehicles.[65] Duke Energy would use the batteries in the vehicles to supply power to the grid to shift demand and estimates that the commercial pilot would result in a positive benefit-cost ratios for all three tests it applied – the "Utility Cost Test" ("UCT"), the Total Resource Cost ("TRC") test, and the Ratepayer Impact Measure ("RIM") test. Duke Energy estimates the benefit-cost ratios to be 1.24, 2.56, and 1.24 respectively.[66] Duke Energy may also enroll customers with solar energy, stationary battery storage, and combine that with V2G, with a maximum capacity of 20 kilowatts per installation.[67] If the results are positive, Duke Energy has gone even farther, stating that the "Company may seek to develop full-scale commercialized offerings *during the duration of this Pilot*, if interim measured results lead the Company to

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[64] Application for Approval of Vehicle-To-Grid Pilot Program, Docket No. E-7, Sub 1275, filed Aug. 16, 2022. at p. 3.
[65] *Id.* at p. 2 and Attachment A, p. 7.
[66] *Id.* at Attachment B, p. 8.
[67] *Id.* at Exhibit 1, p. 2.

do so."[68] That would put V2G, which is existing advanced technology, very far ahead any of the proposed new nuclear reactors. As noted, none of Duke Energy's proposed nuclear reactor designs have been certified, much less built. In fact, Duke Energy estimates that the V2G demand response market could ultimately be in the range of 15% to 25% of EVs.[69] When EVs become the most common type of vehicle, and rooftop solar and stationary batteries are much more common, this demand response approach could provide thousands of megawatts of demand response power of the very kind that is most compatible with variable renewable energy. Hydrogen would be produced with electricity that would otherwise be curtailed and used for peaking power generation loads not otherwise met by battery storage, V2G, and demand response shifting. Hydrogen would not be put into existing natural gas pipelines; rather it would be produced electrolytically on site (preferred) or transported in dedicated pipelines if necessary.

2. **EWG Portfolio 2: Balanced Solar and Wind with High Resilience**. This would be similar to EWG Portfolio 1 with the following differences. Efficiency for existing loads (i.e., not including electrification of transportation or heating conversions from gas, propane, and fuel oil) would increase by 2% per year to 2030, 1.5% per year from 2031 to 2035, and 1% per year from 2036-to 2050, with the

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[68] *Id.* at p. 2 (emphasis added).
[69] *Id.* at Exhibit 1, p. 3.

appropriate higher incentives and standards put in place to achieve the higher levels. There would be much more investment in efficiency in low-and moderate-income households. Explicit quantitative resilience criteria would be defined, including service of essential loads for a pre-specified period and the number of people who would be so served in emergencies. A significant fraction, or possibly all, of units of the Self-Optimizing Grid (400 customers or 2 megawatts peak load) would be designed as microgrids with the goal of serving essential loads within the neighborhoods for a pre-determined number of days. V2G would be more intensively represented and integrated with the Self-Optimizing Grid. Demand response would be significantly deeper than in Duke Energy's P3 portfolio; it would be generalized to offer contracts to all loads that can reasonably be shifted within a 24-hour period (though with the expectation of varied participation levels at specific times, depending on the load). All hydrogen production would be at the power station sites. Pipeline leaks would thereby be avoided.

3. **EWG Portfolio 3: Fully renewable with high resilience with existing nuclear retired**.

This would be like EWG Portfolio 2 but existing nuclear would be retired at the current license expiry dates between 2030 and the mid-2040s. Deployment of renewable energy, storage, efficiency, V2G, and aggregated demand response resources would be accelerated and expanded to meet requirements consistent with nuclear plant retirement dates. More hydrogen would be produced than in EWG Portfolio 2 and EWG Portfolio 3 for use in large fuel-cell-based combined heat and power plants and for heavy industries like cement plants. All the hydrogen needed for electricity generation would be produced with Duke Energy generated electricity that would otherwise be curtailed. The option of developing medium and large-scale solar with dual agricultural use, for instance for grazing (known as agrivoltaics), would also be included.

4. **EWG Portfolio 4: Fully renewable with high resilience, existing nuclear retired, distributed wind, and thermal storage for heating**. This would be similar to EWG Portfolio 3 with the following differences. There would be significant inclusion of front-of-the-meter distributed wind in Self-Optimized Grid resources as well as other distributed electricity production. Seasonal thermal storage would be implemented as part of many self-optimized grid units, other microgrids, including public purpose microgrids, and new commercial and residential developments as appropriate. Seasonal thermal storage can provide energy supply diversity in the summer and winter seasons by complementing other types of storage; it would also further tap into solar and wind that might be otherwise curtailed—a supply that would be expected to be more plentiful in fully renewable portfolios.

Q: DOES THIS CONCLUDE YOUR TESTIMONY?

A: Yes.