ATTACHMENT A

REVIEW AND COMMENTS ON DUKE ENERGY CAROLINAS, LLC and DUKE ENERGY PROGRESS, LLC'S 2022 PROPOSED CARBON PLAN

NCUC Docket No. E-100, Sub. 179

PART I (pp. 1 - 40): **Arjun Makhijani, Ph.D.**

PART II (pp. 41 - 58): **Arjun Makhijani, Ph.D. & M.V. Ramana, Ph.D.**

July 15, 2022

PART I

I. Qualifications

I am the President of the Institute for Energy and Environmental Research (IEER) in Takoma Park, Maryland. I hold a Master of Science in Electrical Engineering from Washington State University and a Ph.D. in Engineering specializing in nuclear fusion from the University of California at Berkeley. Over the past twenty years, I have produced various studies and articles on nuclear fuel cycle-related issues, including weapons production, testing, and nuclear waste. 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 energy 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, 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. A copy of my CV is attached as **Exhibit 1.**

II. Assignment

I have been retained by the Environmental Working Group ("EWG") to review Duke Energy Carolinas, LLC ("DEC") and Duke Energy Progress, LLC's ("DEP") (collectively, "Duke Energy") proposed Carbon Plan filed on May 16, 2022, in the above referenced docket before the North Carolina Utilities Commission (the "Commission").

I have been asked to opine on whether the proposed Carbon Plan complies with the least cost planning for generation mandate of House Bill 951 ("HB 951") within the constraints of maintaining or improving reliability relative to the present system and decarbonizing it completely by 2050 using a variety of technologies, including those that represent technological breakthroughs.

III. Summary of Opinions

My analysis of Duke Energy's Carbon Plan portfolios led me to the following conclusions:

1. The four portfolios are so similar that there is little basis for making a "least cost" judgment. All four have essentially the same major resources in the form of nuclear power plants, solar photovoltaic generation, combustion turbine generation, combined cycle generation, pumped hydro storage, and onshore wind. All four have the same assumptions about efficiency, demand response, and transportation electrification. There is some difference in the amount of battery storage between portfolios. The largest difference is in offshore wind with the lowest amount being none (P3) compared to a maximum of 3,200 MW in the P2 portfolio; yet it represents less than 10% of generation requirements.

2. Although Duke Energy recognizes the complementary of wind and solar for renewable supply, all four portfolios are very unbalanced in this regard. Even the least unbalanced, the P2 portfolio, has wind generation far lower than solar generation. A balanced portfolio would likely reduce the amount of peaking generation required and related costs. The wind energy potential off North Carolina's shores is far more than what would be needed for a balanced wind-solar supply; there are also distributed wind energy resources that could complement solar energy. Thus, there are no resource limitations on wind energy that would prevent achieving a balance between wind and solar generation.
3. None of the Carbon Plan portfolios consider light duty fuel cells, such as those developed for cars, for use in place of combustion turbines, even though this may result in lower costs. Similarly, Duke Energy's Carbon Plan does not consider medium-duty fuel cells in place of combined cycle power plants, though they might be more economical. Only baseload fuel cells appear to have been considered; they were rejected.
4. Duke Energy's plans to procure about half its hydrogen requirements for combustion turbine and combined cycle generation in the year 2050 on a "green hydrogen market." This reliance on a putative "green hydrogen market" in all four portfolios are unrealistic and speculative; it introduces significant uncertainties as to cost and possibly even whether the 100% decarbonization target can be achieved in the year 2050.
5. The proposed Carbon Plan has an average reserve margin considerably more than the minimum 17% set for reliability. These excess reserve margins are largely due to the lumpy addition of resources, notably nuclear, in addition to lumpy retirements of coal resources and the current high reserve margin of Duke Energy Carolinas. Duke Energy's Carbon Plan did not consider a larger amount of shorter lead-time resources, on both the supply and demand sides, to reduce average excess capacity above the reserve requirement as a way of reducing costs considerably, besides reducing uncertainties.
6. Vehicle-to-Grid ("V2G") technology is adequately developed to be an included resource for the purposes of least cost analysis, increasing resilience, increasing

demand response significantly, displacing combustion turbine resources, and/or complementing or decreasing stationary battery storage requirements.

7. Duke Energy's proposed Carbon Plan, as it stands, will not enable the Commission or Duke Energy ratepayers to evaluate whether it is a least cost plan. Moreover, there are potentially lower cost elements and approaches (such as achieving a balance between solar and wind and adding short-lead-time resources to keep average reserve margin closer to 17%) that should be included in the development of far more distinct portfolios. Only then can a least cost option be chosen, within the constraints of HB 951 and other applicable law.
8. Duke Energy may have seriously underestimated demand due to electrification of transportation. This could undermine reliability and result in missed opportunities.
9. Duke Energy has not taken large-scale conversion of non-electric residential and commercial space and water heating to efficient electric systems. Besides underestimation of demand, such conversions could also lead to a higher cost of generation for approaches that use existing natural gas pipeline infrastructure. This is because fewer customers will be demanding less natural gas leaving remaining users, including companies using natural gas for electricity generation, to pay higher costs for the gas transportation infrastructure.
10. Duke Energy's proposed Carbon Plan would add about 10,000 MW of new nuclear (with only slight variation among the portfolios) increasing existing North Carolina nuclear capacity by about 130% from about 7,500 MW to 17,500 (in round numbers). This could introduce vulnerabilities that could reduce reliability. For instance, Duke Energy has mentioned but not quantitatively evaluated black-start requirements. As another example, it has not assessed vulnerabilities related to water requirements. Higher temperatures of intake water due to climate change could result in de-rating of Duke Energy's nuclear capacity at the very times of peak summer load when it would be needed. A recent (2021) global evaluation of nuclear power plants concluded that the rate of nuclear plant outages had increased by more than seven times in the decade of the 2010s relative to the 1990s due to a variety of impacts of climate change.

11. Duke Energy has used conventional criteria for reliability. This is necessary; but it is not sufficient to ensure resilience, for instance, for continuing to serve essential loads during outages. Duke Energy's Self-Optimized Grid ("SOG") provides a good basis for approaching resilience. The approach has not been developed quantitatively in the Carbon Plan, for instance, to evaluate how it might be combined with microgrids to increase resilience and to supply essential loads for specified periods of time in case of outages.
12. Duke Energy's portfolios have somewhat different cumulative carbon emissions due to different intermediate targets for CO2 emission reductions. Duke Energy estimates that Portfolio P1 CO2 emissions would be 69 million short tons less than for Portfolio P3, which had the highest emission. But Duke Energy has not considered the social cost of carbon of the variation in comparing the costs of its four portfolios. At $60 per metric ton, approximately the middle of the range of costs estimated by the Environmental Protection Agency, the added social cost of carbon imputed to Portfolio P3 would be $4.4 billion, wiping out three-fourths of the cost advantage of $5.9 billion imputed to this portfolio relative to P1. This makes the four Carbon Plan portfolios even closer than they are based on resources included.
13. The proposed use of natural gas-hydrogen mixtures in gas turbines (including those in combined cycle plants) may produce more nitrogen oxide pollution. Currently, significantly more pollution results from the use of just 10% hydrogen by volume (planned for 2038). Duke Energy has not evaluated the health and environmental justice implications of burning hydrogen in turbines. It has also not compared its portfolios, all of which have substantial burning of hydrogen, with the use of fuel cells, which would not produce such pollution. In fact, they would eliminate pollutants emitted presently from existing combustion turbine and combined cycle plants.
14. Using large amounts of hydrogen for use in power plants may involve the use of natural gas infrastructure that also supplies the residential and commercial sectors. Duke Energy has included this as a possible option. In that case, added indoor air pollution from the use of such mixtures would have adverse health and

environmental justice implications. Duke Energy has not addressed potential indoor air pollution increases that may result from implementation this option in its Carbon Plan and has not examined the environmental justice implications of such a possibility.

15. A set of three portfolios that are substantially different from the present set should be developed so that the cost, reliability, resilience, and pollution implications can be compared with the approach that Duke Energy has chosen. Such a set is recommended in this analysis. Duke Energy's P3 portfolio, which it estimates is least cost among the four described in the proposed Carbon Plan, could be retained for the purpose of comparison.

IV. The Carbon Plan is Not a Least Cost Plan

HB 951, the North Carolina law on reducing carbon dioxide emissions from the state's public utilities requires that the Commission develop a plan that "*at a minimum*, consider[s] power generation, transmission and distribution, *grid modernization*, storage, energy efficiency measures, demand-side management, and *the latest technological breakthroughs* to achieve the least cost path consistent with [Section 1] to achieve compliance with the authorized carbon reduction goals (the "Carbon Plan")".[1]

The four Portfolios in the "Carolinas Carbon Plan"[2] presented by Duke Energy to the Commission do not constitute a least cost plan. Further, while they take into account for some advanced technologies, like electrolytic hydrogen production, other technological breakthroughs, such as low-cost light duty fuel cells and vehicle-to-grid ("V2G") technology are ignored or marginally included even though they may well lower costs and make the system more reliable and resilient. The only sensitivity analysis that was done in relation to the resources did not affect the centrality of the nuclear-solar-CC-CT theme that runs through the four Carbon Plan portfolios.

[1] 2021-165 N.C. Sess. Law 1 (emphasis added).
[2] Duke Energy Company & Duke Energy Progress Verified Petition for Approval of Carbon Plan ¶ 13, Docket No. E-100 Sub 179 (N.C.U.C. filed May 16, 2022).

i. <u>The Duke Energy Carbon Plan Portfolios are Very Similar</u>

The four Portfolios in Duke Energy's Carbon Plan are very similar and do not contain enough variation of technologies and approaches to enable a cost comparison across the available approaches to achieve carbon neutrality by 2050. The Portfolios also contain higher cost elements, making any least cost claim dubious at best.

The table below, reproduced from Appendix E of Duke Energy's Carbon Plan, shows the generation resources in the year 2050.

Table E-71: Final Resource Additions by Portfolio [MW] for 2050

	Coal Retirements	Solar[1]	Onshore Wind	Battery[2]	CC	CT	Offshore Wind	New Nuclear[3]	PSH
P1	-9,300	19,900	1,800	7,400	2,400	6,800	800	9,900	1,700
P2	-9,300	18,200	1,700	5,900	2,400	6,400	3,200	9,900	1,700
P3	-9,300	19,000	1,800	6,400	2,400	7,500	0	10,200	1,700
P4	-9,300	18,100	1,800	6,100	2,400	6,800	800	10,200	1,700

Source: Duke Energy Carbon Plan 2022, Appendix E

The following features of these four Portfolios in the year 2050 are noteworthy and demonstrate that the differences are moderate, and for the most part, marginal:

- Combined cycle capacity is exactly the same.
- Pumped Storage Hydro ("PSH") is exactly the same.
- There are only marginal differences between the two major primary supply sources – solar and nuclear. The highest solar capacity ("P1") is only approximately 9% more than the lowest. The highest nuclear capacity is only about 3% greater than the lowest. Among other things, this takes no account of the vast uncertainties in cost and construction time of new nuclear designs, including SMRs and non-light water reactor designs that are not yet certified (see Part II).
- The proposed onshore wind is almost identical in all four portfolios (about 6% difference between the smallest and highest capacity).
- The efficiency assumptions are the same in every Portfolio, at "1% of *eligible* load"; Duke Energy states that this is "a very ambitious target" even though it is not even 1% of the entire load. It is modestly larger than the achievement between 2016 and 2019 of about 0.8% per year and higher than other utilities in

neighboring states.[3] However, Duke Energy has made only the tiniest gains in efficiency among low-income households–so small that they are hardly visible in the chart–even though almost one-third of North Carolina households have incomes less than 200% of the federal poverty level.[4] The State Energy Efficiency Scorecard compiled by the American Council for an Energy Efficient Economy shows that there is a much wider range of efficiency achievements across the country. For instance, 15 states achieved efficiency gas of more than 1% in 2020, with the highest being 2.34% (Massachusetts). The median gain was 0.63% across the states; North Carolina was below the median at 0.55%. This is not surprising since North Carolina's investment of resources as a fraction of electricity revenues (0.9%) was also below the median (1.3%).[5] Given that efficiency is often considered the lowest cost energy resource, there is no reasonable way to evaluate whether the Duke Energy Carbon Plan meets the least cost mandate without a wider range of efficiency assumptions, including more ambitious targets, and investments to reduce load and to better shape the load curve on the demand side that would offset more costly supply side investments.

- The assumptions about transportation electrification are also the same in all four portfolios. These assumptions fail to capture the uncertainty, the wide range of realistic outcomes given the variety of targets that have been adopted, and the

[3] DUKE ENERGY, CAROLINAS CARBON PLAN Appendix G at 5, 8 (May 16, 2022) (emphasis added) [hereinafter CAROLINAS CARBON PLAN].
[4] *Id.* at 8 Figure G-2. For the fraction of North Carolina households below 200% of the poverty level, *see Distribution of the Total Population by Federal Poverty Level (Above and Below 200% FPL)*, KAISER FAM. FOUN. (2019), https://www.kff.org/other/state-indicator/population-up-to-200-fpl/?currentTimeframe=0&sortModel=%7B%22colId%22:%22Location%22,%22sort%22:%22asc%22%7D.
[5] The 2020 data are shown for relative achievements in that year, and not for comparison with prior years since 2020 was the year the Covid-19 pandemic began, North Carolina was ranked 27th among the states for its overall efficiency efforts across the energy sector, which includes electricity, but also non-electric parts of the energy sector. North Carolina scored only 3 out of a possible 20 in the utilities sector, which includes electricity and natural gas. *2020 State Energy Efficiency Scorecard: North Carolina*, AM. COUNCIL FOR AN ENERGY-EFFICIENT ECON. (2020), https://www.aceee.org/sites/default/files/pdfs/ACEEE_ScrSht20_NorthCarolina.pdf. For comparison, Massachusetts had a utility sector score of 19.5 out of a possible 20. *2020 State Energy Efficiency Scorecard: Massachusetts*, AM. COUNCIL FOR AN ENERGY-EFFICIENT ECON. (2020), https://www.aceee.org/sites/default/files/pdfs/ACEEE_ScrSht20_Massachusetts.pdf.

opportunities to reduce costs by more varied investments, such as in V2G technology, that go beyond demand response to make electric vehicles a part of peaking dispatchable supply, as discussed in Part I, Section V. Suffice it to say here that there are major gaps in Duke Energy's portfolios in relation to technology that may lower costs and increase resilience at the same time.

- The combustion turbine capacity in the four portfolios is only moderately different, being 11% higher in the highest (P3) relative to the lowest capacity (P2) portfolio.

There are differences in battery capacity between the Portfolios, with the highest, P1, being about 25% greater than the lowest P2.

The one significant difference in primary energy supply is in offshore wind, with the lowest capacity being 0 in P3 and the highest 3,200 MW in P2. However, this represents well under 10% of overall primary generation requirements. Yet, P2 has the lowest battery storage requirement of all portfolios demonstrating, if only modestly, the complementarity of solar and wind resources as discussed below.

ii. Duke Energy's Sensitivity Analysis Did Not Change the Basic Similarity in the Portfolios

Duke Energy examined the impact of variation in natural gas prices on the resource mix in the four Carbon Plan portfolios. The results of the changes in portfolio capacities resulting from Duke Energy's portfolios are shown in the table below, which is reproduced from Appendix E of the Carbon Plan.

Table E-85: Final Resource Additions by Portfolio [MW] for 2050, Delta from Final Carbon Plan Portfolios

	Coal Retirements	Solar[1]	Onshore Wind	Battery[2]	CC	CT	Offshore Wind	New Nuclear[3]	PSH
P1A	0	-400	0	200	-1,600	1,100	0	0	0
P2A	0	-500	100	-600	-1,600	1,100	1,600	0	0
P3A	0	-300	0	100	-1,600	3,400	0	0	0
P4A	0	100	0	-200	-1,600	4,100	0	0	0

Source: Duke Energy's Carbon Plan, Appendix E, p. 86.

It is clear the main result was to rearrange the natural gas resources between combined cycle power plants and combustion turbine power plants. Offshore wind was affected in one portfolio, increasing by 50% in Portfolio P2, to 4,800 MW; while this is still too small for a balanced solar-wind portfolio, it is, nonetheless, an important indicative result. Specifically, among the other resources, the largest change was a reduction in battery capacity by about 10% was in P2, down from 5,900 MW, which was already the lowest of the four Carbon Plan portfolios. Combustion turbine resources are increased by much smaller amounts in P2 than the more nuclear heavy portfolios, P3 and P4. These results are instructive since P2 is the only sensitivity portfolio in which primary generation resources changed more than an insignificant amount towards more balance of wind with solar. It indicates what was shown in a detailed Maryland study (see Part I, Section IV, Subsection iii below), that better solar-wind balance can reduce storage requirements, and potentially also lower peaking capacity requirements.

Duke Energy also did a capital cost sensitivity analysis but did not examine its impact on the composition of the portfolios in the Carbon Plan:

> Resource selection in the development of the Carbon Plan portfolios was driven largely by carbon reduction targets and annual limits on resource availability (development lead-times and annual interconnection limits). For this reason, high and low capital cost scenarios were run to evaluate potential changes to overall portfolio costs that could result from changes to the costs of supply-side resources. This cost sensitivity is of particular relevance in light of the potential for inflationary pressures on resource costs and further domestic and global supply-chain constraints currently impacting the installed costs for all technologies in the portfolios. *Portfolios were not re-optimized for this analysis*, nor were production costs re-calculated for this sensitivity in order to isolate the impact of potential changes to the installed cost of resources on total portfolio cost relative to baseline planning assumptions.[6]

Duke Energy did estimate the difference in the present value of cumulative capital cost impacts at about $4 billion for the new nuclear portfolio of about 10,000 MW and at about $6 billion to $8 billion for solar.[7] These Duke Energy assumptions would result in considerably higher cost increases for solar than nuclear, even though the history of capital costs indicates the contrary. Utility-scale solar costs per MWh have declined despite the imposition of tariffs on Chinese solar panels by both the Obama

[6] CAROLINAS CARBON PLAN, *supra* note 3, at Chapter 3 at 14 (emphasis added).
[7] *Id.* at 15 Figure 3-11. The variations on the lower cost side were small and are not discussed in this analysis.

and Trump administrations;[8] nuclear costs have risen.[9] In fact, nuclear costs have risen hugely for the one "nuclear renaissance" project still under construction, Vogtle units 3 and 4 in Georgia, despite the provision of subsidies by ratepayers in the form of payments for Construction Work in Progress and by the federal government in the form of a large loan guarantee (see Part II). Finally, it is also worthy of note that the cost increases experienced in the Vogtle project— about $7 billion per gigawatt— have been much greater than the cost delta taken into account in Duke Energy's analysis. At the rate of Vogtle Project cost escalations, which is the one relevant real-world value in the United States, the undiscounted cost increases for Duke Energy's Carbon Plan portfolios would be on the order of $70 billion total. The cost escalations of SMRs, which are still only paper reactors, indicate the same grim trajectory (see Part II). Had Duke Energy re-optimized its portfolios for a realistic capital cost sensitivity reflecting the experience of the "nuclear renaissance" of the last decade-and-a-half, it would certainly have drastically rearranged the Carbon Plan portfolios, the more so if solar-wind balance were incorporated.

iii. <u>Duke Energy's Carbon Plan Does Not Optimize the Complementarity of Solar and Wind Resources</u>

Duke Energy recognizes the value of wind as a complement to solar:

> However, deployment of wind resources can complement solar resources *by providing energy to the system during overnight hours or winter months* when solar energy is low or not available.[10]

And again:

> DEC peak demand (system peak demand net of UEE, NEM and other demand-side impacts of non-dispatchable supply-side solar and wind resources) is projected to occur in the summer while DEP peak demand is projected to occur in the winter. Solar output aligns more closely with afternoon summer peak demands compared to *winter peak demands*

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[8] For Obama administration tariffs *see* Diane Cardwell & Keith Bradsher, *U.S. Will Place Tariffs On Chinese Solar Panels*, N.Y. TIMES (Oct. 10, 2012), https://www.nytimes.com/2012/10/11/business/global/us-sets-tariffs-on-chinese-solar-panels.html. For Trump administration tariffs *see* Proclamation No. 9693, 83 Fed. Reg. 3,541 (Jan. 23, 2018).

[9] 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.

[10] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix E at 10 (emphasis added).

> *which occur in the early morning hours when solar output is low*. Thus, it is notable that DEC and DEP are both winter planning utilities since the annual peak demand net of non-dispatchable solar and wind is projected to occur in the winter for both Companies, which drives the timing need for new reliability resources capable of serving the winter morning peak.[11]

Despite this recognition, Duke Energy makes no attempt to optimize this diurnal and seasonal complementary of the two most plentiful renewable resources. The hour-by-hour analysis of the Maryland electricity sector done by IEER's Renewable Energy Project showed that approximately equal annual generation of solar and wind (onshore and offshore) balanced seasonal loads; this balance is an important factor in the overall design of a carbon-free electricity system with high penetration of variable renewable resources:

> Seasonally balanced wind and solar energy, complemented by hydrogen-fueled CHP [Combined Heat and Power], make it possible to meet about 87 percent of the total annual load without the mediation of storage or demand response. When flexibly operated hydropower is added, that rises to 89 percent.[12]

Similar to Duke Energy's Carbon Plan, the hydrogen would be produced with electricity that would otherwise be curtailed.

All of Duke Energy's portfolios are seriously unbalanced and fail to achieve complementary between solar and wind supply. The most deficient Portfolio in this regard is "P3," which, according to Duke Energy's analysis is the lowest in cost of the four.[13] Portfolio P2, the least unbalanced amongst the four, is also very unbalanced.[14]

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[11] *Id.* at 69 (emphasis added).

[12] The percentages are as a fraction of total annual load. More detailed results were as follows: the entire load was met by wind, solar, hydrogen CHP, and flexibly-operated existing hydropower (572 MW, without pumped storage) for about two-thirds of the hours in the year, rising to about 96%, with than battery storage capacity corresponding to less than 6 hours of average load. The rest was be met by demand response and electrolytic hydrogen used in light duty fuel cells for peaking. The electrolytic hydrogen was assumed to be produced at the peaking generation site with electricity that would otherwise be curtailed. ARJUN MAKHIJANI, PROSPEROUS, RENEWABLE MARYLAND: ROADMAP FOR A HEALTHY ECONOMICAL AND EQUITABLE ENERGY FUTURE 139 (Inst. For Energy and Env't Rsch., Nov. 2016), https://ieer.org/wp/wp-content/uploads/2016/11/RenewableMD-Roadmap-2016.pdf.

[13] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix E at 81 Table E-75.

[14] *See* the "Energy Mix" boxes. *Id.* at Chapter 3 at 8-1 Figures 3-6 through 3-9.

Taking cognizance of the restrictions and difficulties of siting large onshore wind farms, the main conclusion (leaving aside distributed wind) in this regard would be that offshore wind is not adequately represented in any Portfolio. The highest offshore wind capacity is in P2 – 3,200 MW, which would represent on the order of 10 to 12 TWh of electricity per year, well under 10% of the 2050 requirements. The waters off North Carolina are estimated to have an offshore wind potential of more than 600 TWh. Most of this potential is in waters less than 60 meters deep.[15] Duke Energy recognizes that offshore wind supply has a relatively high-capacity factor[16] and, as noted above, also recognizes that wind is a good complement for solar. Offshore wind costs have declined rapidly in recent years. The National Renewable Energy Laboratory database for electricity costs moderate cost projections for mid-range fixed bottom offshore costs and capacity factors are $48/MWh for 2035 and $40/MWh for 2050. The corresponding estimates for deep water, floating wind power plants are $55/MWh and $47/MWh respectively. These costs include transmission to bring the power ashore (from 45 kilometers offshore for fixed bottom turbines and 90 kilometers for floating turbines).[17]

Besides the cost imposed by the imbalance between solar and wind, the failure to have any Portfolio with offshore wind capacity balancing solar is rather odd so far as transmission costs are concerned. Duke Energy's estimates of transmission upgrades for offshore wind are $0.45/watt for the first 800 MW, $0.79/watt for the next 800 MW, and $0.22/watt for capacity in excess of that.[18] Thus, it would make sense for minimizing costs from a transmission as well as solar-wind balance point of view to have explored offshore wind (together with the modest onshore wind capacity in any of the four portfolios) that was balanced with solar capacity in at least one Portfolio. The potential is certainly there.

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[15] WALT MUSIAL ET AL., 2016 OFFSHORE WIND ENERGY RESOURCE ASSESSMENT FOR THE UNITED STATES 34 Figure 22 (Nat'l Renewable Energy Lab'y, Sept. 2016), https://www.nrel.gov/docs/fy16osti/66599.pdf.
[16] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix J at 2.
[17] *Annual Technology Baseline: Offshore Wind*, NAT'L RENEWABLE ENERGY LAB'Y (2021), https://atb.nrel.gov/electricity/2021/offshore_wind.
[18] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix E at 38-39 Table E-44.

iv. **Duke Energy's Plan for Hydrogen in 2050 Is Speculative and Unrealistic**

Duke Energy plans to produce a considerable amount of its hydrogen needs for CT and CC generation from electricity that would otherwise be curtailed:

> …the Companies calculated the curtailed energy from renewables and nuclear resources in 2050. The Companies then calculated if that curtailed or unutilized energy were used to produce green hydrogen through electrolysis, how much of the Companies' 2050 hydrogen consumption could theoretically be produced from excess carbon-free energy generated on the DEC and DEP systems.
>
> The Companies calculated that *all hydrogen needs, including blending starting in 2035 and new hydrogen needs through 2049*, could be produced annually from excess and unutilized carbon-free energy on the DEC and DEP systems. Additionally, on average across the final Carbon Plan portfolios, nearly 50% of the 2050 hydrogen consumed by the remaining CCs and CTs on the system, operating exclusively on hydrogen in 2050, was able to be produced from excess and unutilized carbon-free energy on the DEC and DEP systems in the final year of the Carbon Plan.[19]

This passage appears to indicate that Duke Energy would meet all its hydrogen needs until 2049 with electricity generated by the company itself, but that in 2050 the internally produced fraction would suddenly drop to about half that amount. Duke Energy's Appendix O, where hydrogen is discussed in more detail, is somewhat more ambiguous, but affirms that only about half of the hydrogen in 2050 would be produced with electricity generated by Duke Energy.[20] It seems improbable that Duke Energy would intend to suddenly increase its hydrogen purchases on the "green hydrogen market" from none to well over 100,000 metric tons in a single year,[21] though some statements indicate that. In any case, a very large amount of hydrogen would have to be procured externally from a green hydrogen market in 2050.

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[19] *Id.* at 102 (emphasis added).
[20] *Id.* at Appendix O at 3-4.
[21] Calculated from hydrogen generation in 2050, *id.* at Chapter 3 at 8-11 Tables 3-6 through 3-9, and Duke Energy's statement that "over 60% of the Companies' energy mix by 2050 is obtained from nuclear resources in all portfolios." *Id.* at 5.

Duke Energy "assume[s] hydrogen becomes a readily accessible fuel as a green hydrogen market develops."[22] It is risky and speculative to assume that a large hydrogen market would develop in North Carolina and be "readily accessible" to Duke Energy. There appears to be no Plan B in case it is not. An alternative approach that does not depend on a "green hydrogen market" coming into being and delivering large amounts of hydrogen to North Carolina should have been developed in at least one of the portfolios, so that the achievement of the decarbonization target of HB 951 does not depend on one risky assumption. That assumption is also economically speculative since it is very difficult or impossible to estimate what a "green hydrogen market" might look like, where the hydrogen would be produced, what infrastructure would be needed in North Carolina to deliver it to Duke Energy's power stations, and not least, with what other users and uses Duke Energy's power production plans would be competing for the hydrogen.

Appendix O, which focuses on hydrogen, refers to a variety of hydrogen studies; several of them include hydrogen derived from natural gas with carbon sequestration, or hydrogen derived from biomethane or landfill gas, in addition to hydrogen produced by electrolysis.[23] However, Duke Energy does not make reference to actually procuring the large amount of hydrogen needed from any specific source or sources in Appendix O.

No judgment about a least cost portfolio, or even about achievement of full decarbonization in 2050, can be made based on speculative statements about a putative "green hydrogen market" in North Carolina coming into being as an essential part of the Duke Energy Carbon Plan. Duke Energy acknowledges that there are uncertainties "in both price and execution" in its hydrogen plan for 2050.[24] But that acknowledgement resolves neither the cost nor decarbonization uncertainties introduced by Carbon Plan's reliance on a large procurement of hydrogen from a putative "green hydrogen market."

[22] *Id.* at Appendix E at 31.
[23] *Id.* at Appendix O at 4-5. For examples, see the hydrogen plans proposed in footnotes 1, 2, and 10.
[24] *Id.* at Appendix E at 102.

v. <u>Duke Energy's Carbon Plan Omits Potentially Lower Cost Options for Dispatchable Peaking and Intermediate Load Generation</u>

The Duke Energy Carbon Plan briefly considered fuel cells and ruled them out. The entire paragraph on fuel cells from the technology screening appendix is reproduced below:

> Although originally envisioned as a competitor to combustion turbines and central power plants, fuel cells are now mostly targeted to distributed power generation systems. The size of the distributed generation applications ranges from a few kilowatts ("kW") to potentially tens of megawatts ("MW"). Cost and performance issues have generally limited the application of fuel cells to niche markets and/or subsidized installations. While some research and development continue, this technology is not commercially viable/available for utility-scale application but will be reviewed in future Carbon Plan updates.[25]

Interestingly, this rejection of fuel cells is in the section on baseload technologies; this indicates that Duke Energy did not specifically evaluate the option of using low-cost light duty fuel cells, such as those developed for personal motor vehicles, or medium duty fuel cells, such as those developed for commercial trucks for use in place of combustion turbines and combined cycle plants – that is, for peaking and intermediate load applications.

The discussion of these two fuel cell types below is not meant to be a definitive cost analysis; rather it is meant to illustrate that, given hydrogen production, fuel cells may be a lower cost approach that CT or CC plants. Fuel cells would also eliminate air pollution attributable to CT and CC generation as further discussed in Part I, Section VIII.

Light duty automotive fuel cells could be installed for electricity generation at the same power stations as combustion turbines (existing or new). The cost of mass manufactured light duty fuel cells even with 2018 technology is about $60 per kW-electrical; light duty fuel cell cost is expected to decline to less than $50 per kWe by

[25] *Id.* at Appendix H at 4.

2025 with incremental technology improvements.[26] The Department of Energy's durability target for these fuel cells is 5,000 hours, roughly 8 to 10 years (possibly more in peaking generation mode, depending on the system). Utility scale inverters cost $50/kW;[27] costs of solar components have generally been declining. These costs are low enough that a least cost approach should compare the CT approach with the light duty fuel cell approach, taking account of direct costs as well as the difference in pollution.

Similarly medium duty automotive fuel cells are not considered in place of combustion turbines. They can be installed for electricity generation at the same power stations as combustion turbines. The project cost of mass manufactured fuel cells is at less than $100 per kW-electrical with a durability target of 25,000 hours;[28] this would give a lifetime of almost 6 years at 50% capacity factor; as with light duty fuel cells, $50/kW needs to be added for the inverter. Such a system could be considered as an alternative to combined cycle power plants. Other types of fuel cells with higher efficiency may also be suitable comparison technologies.

The main point is that with installed costs of $900/kW for a combustion turbine generation power plant and about $1,000/kW for combined cycle power plants,[29] the Carbon Plan should include fuel cells of varying costs, durability, and efficiencies in one or more portfolios so that a reasonable least cost comparison can be made, especially since electrolytic hydrogen would be the fuel in both cases. Moreover, as Duke Energy acknowledges, the cost of combustion turbines that use 100% hydrogen as a fuel is likely to be higher than that of natural gas burning CTs.[30]

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[26] BRIAN JAMES, 2018 COST PROJECTIONS OF PEM FUEL CELL SYSTEMS FOR AUTOMOBILES AND MEDIUM-DUTY VEHICLES 25 (U.S. Dep't of Energy, Apr. 25, 2018) [hereinafter 2018 COST PROJECTIONS], https://www.energy.gov/sites/prod/files/2018/04/f51/fcto_webinarslides_2018_costs_pem_fc_autos_trucks_042518.pdf.
[27] Vignesh Ramasamy et al., U.S. Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021, 58 (Nat'l Energy Renewable Lab'y, 2021), https://www.nrel.gov/docs/fy22osti/80694.pdf.
[28] 2018 COST PROJECTIONS, *supra* note 19, at 37.
[29] Nat'l Renewable Energy Lab'y Advanced Technology Database spreadsheet, 2021 at https://data.openei.org/files/4129/2021-ATB-Data_Master_new.xlsm
[30] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix E at 31.

vi. Duke Energy's Carbon Plan Has Average Reserve Margins Far Above the Required Amounts

There is no Portfolio with an average winter reserve margin that is not excessively over the required 17%. This is costly and wasteful. There are many years where reserve margins are greatly beyond minimum requirements both in the winter and summer and existing excess reserve margin in Duke Energy Carolinas, which is the larger of the two Duke Energy companies.[31] Duke Energy acknowledges this fact:

> In summary, planning to meet carbon reduction targets results in higher reserve margins due to the addition of increasing variable energy and energy limited carbon-free and lower carbon resources required to meet those targets. Thus, projected reserve margins for Portfolios 1-4 satisfy the minimum 17% reserve margin target and are *projected to be well above the target* in some years, with reserve margins trending back down as older gas fired generation is retired. Summer reserve margins are projected to be higher than winter reserves margins and to a significant degree for DEP.[32]

A significant excess cost can be imputed to average capacity margin far more than the minimum. Since lumpiness of capacity additions and retirements is a significant cause of such excess cost, options for reducing it should be considered. Specifically, greater reliance on short-lead time supply-side and demand-side technologies could enable maintenance of average reserve margin closer to the minimum requirement, thereby lowering costs. These lower costs of smaller reserve margins would need to be compared to the cost of the new portfolio of resources required and the avoided costs of resources that would not be needed. For instance, deeper aggregate demand response penetration, now recognized as a dispatchable resource by the Federal Energy Regulatory Commission, would also enable Duke Energy to keep reserve margins consistently closer to 17% the portfolios in Duke Energy's Carbon Plan.

[31] *Id.* at Appendix E at 19 Table E-18, 67, 68 Figure E-12, 69 Figure E-13.
[32] *Id.* at 72.

vii. Duke Energy's Carbon Plan Essentially Omits Vehicle-to-Grid Technology

In addition to the examples above, one of the biggest advanced technology omissions is the dismissal of vehicle-to-grid ("V2G") technology, which enables two-way transfer of power between electric vehicles and the electricity grid, as a significant element in even one Portfolio, using the following rationale:

> Finally, the ability to reliably harness bi-directional charging may unlock a multitude of dual use rolling assets. Today, vehicle-to-grid, vehicle-to-home and vehicle-to-X is in commercial infancy. At maturity, its potential to shape load, provide for power quality control and serve in back-up power situations is considerable.[33]

Despite the acknowledgement of large potential, this statement is essentially a dismissal of the technology: significant V2G resources were not incorporated into any portfolio. This is clearly a big gap in the assessment alternatives that would enable a least cost approach to a decarbonized grid.

For example, the Ford-150 Lightning all-electric pick-up truck is already in production. It can serve as a back-up generator for the home, providing the appropriate transfer switch is installed. Ford has made the following statement about vehicle-to-home-capability:

> Your F-150® Lightning ™ automatically begins powering your home when connected to the 80-amp Ford Charging Station Pro.*
>
> *When home is properly equipped and home transfer switch disconnects home from the grid.[34]

The vehicle can also be used for "vehicle-to-X" mode, depending of course on what the specific "X" is.

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[33] *Id.* at Appendix G at 44.

[34] Ford estimates that the extended range battery can power the home for three days, and if electricity is "properly rationed" for up to 10 days. *Ford Intelligent Backup Power*, FORD MOTOR CO. (2022), https://www.ford.com/trucks/f150/f150-lightning/features/intelligent-backup-power/.

Vehicle-to-grid is the most important omission; it should be a significant part of at least one Portfolio. Duke Energy only mentions V2G as part of a pilot program.

V2G was invented in the 1990s. Pilot projects have already been done in several countries, in addition to a large number of studies.[35] Among the most interesting and relevant was the Parker Project that tested V2G in operating within a market-oriented grid. The demonstration involved evaluation of V2G for providing a variety of grid services at both the transmission system and distribution system levels. In the former case, the services provided by the V2G system were "[f]requency regulation," "[s]pinning reserves," "[c]ongestion management," "[b]lack start provision," and "[s]ecurity of [s]upply [p]rovision"; in the latter case the services provided were "Active power support" (which included "[c]ongestion management," "[l]oad shifting," "[p]eak shaving," and "[v]oltage control"), "[r]eactive power support," and "[r]enewable [e]nergy [s]upport."[36]

The economics of V2G were evaluated in the context of the actual electricity market (though on "relaxed terms"), as were the opportunities and barriers to V2G adoption. After two years of testing, including 13,000 hours of V2G operation with a single vehicle, and operation of 10 vehicles at a time, the conclusions were as quoted below:

1. It has been validated that the Parker portfolio of EVs (PSA, Mitsubishi and Nissan) together with DC V2G chargers (Enel X) support V2G and are ready to provide advanced services to the grid.
2. A field-test in Copenhagen has proven that it is possible to commercialize this technology though the provision of FCR [Frequency Containment Reserves].

[35] Sanchari Deb et al., *V2G Pilot Projects: Review and Lessons Learnt*, *in* DEVELOPING CHARGING INFRASTRUCTURE AND TECHNOLOGIES FOR ELECTRIC VEHICLES 252 (2022), https://www.irma-international.org/viewtitle/293776/?isxn=9781799868583.
[36] PETER BACH ANDERSEN ET AL., THE PARKER PROJECT: FINAL REPORT 87 Figure 65 (Jan. 31, 2019), https://parker-project.com/wp-content/uploads/2019/03/Parker_Final-report_v1.1_2019.pdf.

3. Further steps must be taken to allow for universal support of V2G and VGI services across all EV brands, standards, and markets.[37]

Revenues, under the relaxed market terms, average 1,860 euros per car per year, though they were variable and could be greater, lower, or even negative, depending on a variety of factors including electricity prices, taxes, and battery degradation.[38]

V2G has been tested and is closer to larger scale testing than technologies that Duke Energy has incorporated on a large scale, including nuclear reactor designs for which certification applications have not even been submitted, much less have they been built and operated under commercial conditions (see Part II) and gas turbines that would operate on 100% hydrogen fuel. V2G is developed enough to be included as a medium-term and long-term resource and possibly even as a resource in the next decade.

V2G technology could have a major role in a future decarbonized grid provided the suitable infrastructure is built and suitable regulations and market conditions are created. It has the potential to displace a large amount of conventional infrastructure, notably gas turbines. For instance, there are about 55,000 parking spots at major North Carolina airports (Charlotte Douglas International, Raleigh Durham International, Piedmont Triad, Greenville Spartanburg International, and Wilmington International).[39] If wired for V2G, the potential capacity of vehicles, at 8 kW and 40 kWh per spot,[40] the maximum capacity would be, in round numbers, over 400 MW and over 2,000 MWh. Other similar V2G resources such as school bus and transit bus depots, parking depots for delivery vehicles, etc.

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[37] *Id.* at 7. Frequency containment reserve is the capacity needed for the transmission system operator to maintain the frequency of electricity supply within specified margins.
[38] *Id.* at 5-6.
[39] Amy Passaretti, *ILM Daily Parking Rates Increase, Another Lot in the Works*, PORTCITY DAILY (Apr. 13, 2022), https://portcitydaily.com/local-news/2022/04/13/ilm-daily-parking-rates-increase-another-lot-in-the-works/; Renee Martin, *All You Need to Know About RDU Airport Parking*, WAY.COM (2021), https://www.way.com/blog/all-you-need-to-know-about-rdu-airport-parking/. Numbers for the Piedmont Triad and Greeneville Spartanburg airports were provided via telephonic communications.
[40] Assuming an 80-kWh battery that would not be discharged below 50% of maximum capacity and fast charging and discharging modes.

could also be developed to add significant capacity in locations that could each provide significant amounts of capacity and energy.

The market is also moving toward incorporating individual homes with electric vehicles into a V2G system. For example, the California utility, Pacific Gas & Electric has announced a plan for enrolling 1,000 residential customers and 200 business customers in a bidirectional electric vehicle charging experiment. Residential customers would be paid "at least $2,500 for enrolling, and up to an additional $2,175 depending on their participation"; businesses "will receive at least $2,500 for enrolling, and up to an additional $3,625 depending on their participation." A third element of this pilot would test V2G integration into microgrids on terms like those offered to businesses.[41] This aspect is directly relevant to the concept of the "Self-Optimizing Grid" that Duke Energy intends to develop, potentially increasing resilience and reliability significantly.[42]

The distributed approach to V2G opens a vast new range of possibilities. North Carolina had about 3.4 million registered vehicles in 2020.[43] Most or all these vehicles (and any growth in their number) are likely to be electric by 2050. A significant fraction is likely to be electric by 2040. With a suitable rate structure and physical grid infrastructure in distribution systems, they could play a role comparable to other major resources for creating a decarbonized and resilient electricity system by 2050.

Besides the evaluation of V2G against other electric system resources in the Duke Energy Carbon Plan, indirect benefits should also be evaluated. For instance, the V2G option could save hydrogen that would be used in gas turbines and provide the opportunity of offering it to industries like steel and cement.

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[41] *PG&E to Launch New Pilots Studying Electric Vehicle Bidirectional Charging Technology at Homes, Businesses and with Microgrids*, PAC. GAS & ELEC. CO. (May 5, 2022), https://investor.pgecorp.com/news-events/press-releases/press-release-details/2022/PGE-to-Launch-New-Pilots-Studying-Electric-Vehicle-Bidirectional-Charging-Technology-at-Homes-Businesses-and-with-Microgrids/default.aspx.
[42] *See generally* CAROLINAS CARBON PLAN, *supra* note 3, at Appendix G.
[43] Mathilde Carlier, *Automobile Registrations in the United States in 2020, by State*, SATISTA (Jan. 18, 2022), https://www.statista.com/statistics/196010/total-number-of-registered-automobiles-in-the-us-by-state/.

viii. Summary of Least Cost Critique

In sum, Duke Energy's proposed Carbon Plan, as it stands, will not enable the Commission or Duke Energy ratepayers to evaluate whether the plan presented is a least cost plan. The sensitivity analysis was incomplete in not including the impact of a realistic range of uncertainties in capital costs, notably for nuclear capacity. As discussed above, the sensitivity portfolios that Duke Energy did compute are also, in the main, marginally different; the main result was to exchange combined cycle and combustion turbine capacity. Given that the Portfolios are nearly identical in most major respects, the use of the expression "least cost" is misplaced since that term implies that there are distinct options that can be objectively examined, and a least cost option chosen, within the constraints of HB 951 and other applicable law. Duke Energy's plans for procurement of a large amount of hydrogen on a putative "green hydrogen market" in the year 2050 are speculative, with significant uncertainties as to supply, cost, and achievement of full decarbonization in 2050.

Further, there are elements that could significantly lower cost that are not included in Duke Energy's Carbon Plan even though, in some cases, like the complementarity between solar and wind, the merits are recognized within the Carbon Plan itself and, in that specific example, also indicated by Duke Energy's sensitivity analysis.

Finally, critical advanced new technologies that could make significant differences to cost, reliability, and resilience have been omitted from the proposed Carbon Plan in favor of four Portfolios that are, apart from two relatively small aspects, essentially the same.

V. Demand is Not Adequately Addressed

i. Electrification of Transportation

As noted, there is only a single assumption across all four Portfolios about the extent of electrification of transportation. The Portfolios in the Carbon Plan are based on the announced Biden administration target of transportation electrification that 50% of new sales should be EVs by 2030. Duke Energy has also appealed to similar targets by some automobile manufacturing companies. This results in an estimate that 5.5% of the vehicle fleet in the DEC region and 6.28% in the DEP region will be electric by 2035.[44]

The Duke Energy portfolios present a very narrow view of currently available major targets that should be considered, since the automotive market and automotive technologies are largely globalized. There are a variety of corporate and national plans and targets that are far more ambitious than the assumptions made by Duke Energy; even if not fully realized, these more ambitious plans would greatly alter the Duke Energy's projection for transportation demand.

For instance, Volvo intends to have 100% of its production be electric vehicles by 2030.[45] Volkswagen, one of the world's largest automobile companies has made an even more ambitious announcement "Volkswagen will have electrified its entire model portfolio by 2030 *at the latest*."[46] In late 2020, the government of the United Kingdom, a major automotive market, decided to ban the sale of gasoline and diesel vehicles by the year 2030.[47]

More recently, the trend to ambitious targets has intensified. The European Union has introduced draft legislation that would require all vehicle sales to be electric by 2035.[48] An implementation of this decision, along with the ambitious targets of major automobile companies like Volkswagen, will have global impact.

Much faster electrification of transportation would mean that the Duke Energy Carbon Plan significantly underestimates transportation-related electric load.

[44] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix F at 11 Table F-13.
[45] *Volvo Cars to be Fully Electric by 2030*, VOLVO (Mar. 2, 2021), https://www.media.volvocars.com/global/en-gb/media/pressreleases/277409/volvo-cars-to-be-fully-electric-by-2030.
[46] *The Volkswagen Group Launches the Most Comprehensive Electrification Initiative in the Automotive Industry with "Roadmap E,"* VOLKSWAGEN NEWS ROOM (Sept. 11, 2017), https://www.volkswagen-newsroom.com/en/press-releases/the-volkswagen-group-launches-the-most-comprehensive-electrification-initiative-in-the-automotive-industry-with-roadmap-e-1242 (emphasis added).
[47] Roger Harrabin, *Ban on New Petrol and Diesel Cars in UK From 2030 Under PM's Green Plan*, BBC NEWS (Nov. 18, 2020), https://www.bbc.com/news/science-environment-54981425.
[48] Rupert Neate, *EU's Electric Vehicle Drive Leaves Supercars at the Back of the Grid*, THE GUARDIAN (July 2, 2022, 3:00 PM), https://www.theguardian.com/business/2022/jul/02/eus-electric-vehicle-drive-leaves-supercars-at-the-back-of-the-grid.

Specifically, Duke Energy's estimate of transportation load in 2035 may underestimate demand by thousands of gigawatt-hours in that year.

Large underestimates of demand could lead to reliability problems, including peak demand growth that may be more rapid than envisioned. At the same time, it is possible that a slower pace along the lines of the Duke Energy Carbon Plan assumption may be realized. Post 2035, the impact of large uncertainties in transportation electricity demand would be magnified in the Duke Energy Carbon Plan, with its heavy reliance on relatively long lead time new nuclear plants, even if there are no delays in major nuclear projects, an unlikely scenario, given the long history of nuclear power in this regard.[49] These uncertainties point to the need for the Carbon Plan portfolios that have more emphasis on short lead time resources.

Underestimating transportation electrification could also lead to major missed opportunities for V2G infrastructure. As noted, V2G could play a major role in the electricity resource mix of a future with intensively electrified transportation.

ii. Duke Energy's Carbon Plan Does Not Include Substantial Electrification of Natural Gas Uses in Buildings

The Duke Energy electric load forecast does not include major new initiatives for conversion of fossil fuel space and water heating, clothes drying, and cooking in the residential and commercial sectors. Large-scale conversions of existing buildings and economic and health concerns leading to new buildings being all-electric could result load growth significantly above that projected in the Duke Energy Carbon Plan.[50] More than one-third of North Carolina homes were heated with an energy source other than electricity in 2019.[51]

At the same time Duke Energy acknowledges that there is a peak load issue related to heat pumps:

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[49] *See* Part II, Section III.
[50] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix F at 22 Tables F-18 and F-19. These two tables, for DEC and DEP respectively, show the various major components of load changes in the next 15 years.
[51] *North Carolina State Energy Profile*, U.S. ENERGY INFO. ADMIN. (Nov. 18, 2021), https://www.eia.gov/state/print.php?sid=NC.

> Residential winter peak loads for customers who use electric heat pumps can be three times the summer peak load due to the use of resistance heating elements. Accordingly, Duke Energy commissioned Tierra Consulting ("Tierra") to perform a study to evaluate opportunities for addressing winter peaks through TOU and Critical Peak Pricing ("CPP") rates, as well as bill certainty programs with peak reduction strategies."[52]

This failure to include major growth due to conversion of natural gas uses in buildings (especially space and water heating) could have several repercussions.

- First it would result in an underestimation of needed generation and storage.
- Second, a large-scale move away from natural gas in the buildings sector could result in an increase in the cost of transporting and delivering a unit of natural gas for power generation. The Duke Energy Carbon Plan includes significant reliance on natural gas use in its generation plan well into the 2040s. A potential increase in cost of natural gas for electricity generation could mean that none of the portfolios may meet a "least cost" criterion.
- Third, it would lead to an underestimation of opportunities for efficiency investments and demand response aggregation.

With adequate incentives and regulations (such as state appliance efficiency standards that are above federal standards), efficiency and demand response opportunities could be significantly greater than now envisioned in Duke Energy's proposed Carbon Plan (Appendix G). Appliance standards are important to overcome the strong tendency to minimize first cost, especially for rental housing where the tenant pays the utility bills, but the landlord makes the investment in the HVAC system. Standards are suitable way to solve this well-known "spilt incentive" problem. The fact that such standards will disproportionately benefit low- and moderate-income households should also be taken into account as a benefit since their utility bills would be lower (other things being equal), increasing chances of bill payments remaining current.

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[52] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix G at 23.

VI. Duke Energy's Carbon Plan Fails to Adequately Capture Reliability and Resilience

HB 951 requires the Utilities Commission to "[e]nsure any generation and resource changes maintain or improve upon the adequacy and reliability of the existing grid."[53]

Numerous factors in the Duke Energy Carbon Plan may cause reliability to deteriorate, including serious underestimation of demand, especially in the context of reliance on relatively long lead-time nuclear.

Heavy reliance on nuclear power (both new and existing) means that 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). 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.[54]

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 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.[55] This vulnerability is *not* about whether such an event might trigger an accident – that is a matter for the Nuclear Regulatory Commission 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 event. It is also relevant to black-start capacity requirements as the grid evolves, as further discussed below.

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[53] 2021-165 N.C. Sess. Law 2.

[54] *10-Year Anniversary of US's Most Widely Felt Earthquake*, U.S. GEOLOGICAL SURV. (Aug. 4, 2021), https://www.usgs.gov/news/featured-story/10-year-anniversary-uss-most-widely-felt-earthquake.

[55] *See generally* U.S. GEOLOGICAL SURV., 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.

Increasingly extreme weather events 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. Maintaining reliability and service in the future requires explicit resilience planning, including quantitative criteria that go beyond the Loss of Load Expectation (LOLE), Loss of Load Hours (LOLH), and Expected Unserved Energy (EUE) in Duke Energy's Carbon Plan. For instance, the maintenance of electricity supply to critical infrastructure and essential services including shelters and transportation energy infrastructure (which includes gasoline stations for a considerable time to come) needs to be explicitly factored into grid design and the balance of the resources in it.

A prolonged, decades-long reliance on existing nuclear capacity might also create reliability issues. While it might not, 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 (see Part II).

There are avenues for improving resilience. Duke Energy's Carbon Plan refers to the development of a "Self-Optimizing Grid" ("SOG) stating that "[t]he long-term vision is to serve 80% of customers by the SOG program."[56] The electric system would "be divided into circuit segments that are three miles in length, able to serve approximately 400 customers, or able to serve 2 MW of peak load."[57] The aim is to integrate distributed solar and battery resources into this Self-Optimizing Grid.

The Self-Optimizing Grid is a suitable framework for planning resilience. However, Duke Energy has not translated this concept into resilience requirements and specific design criteria for distributed solar generation, storage, and other distributed resources. For example, it has not specified the number of self-islanding microgrids that would be required to maintain continuity of essential services (including heating and cooling in shelters, food supply, elevators in tall apartment buildings, etc.). Microgrids are not discussed in Appendix E of Duke Energy's Carbon Plan on generating resources; they are only mentioned once in passing in Appendix Q on Reliability and

[56] *Id.* at Appendix G at 4.
[57] *Id.* at 44.

Resilience Considerations;[58] there is one reference to microgrids in Appendix G that is more substantial but still lacks any quantitative detail linking it to the Carbon Plan:

> The SOG design guidelines not only help to ensure the long-term availability of reliable electricity at the least reasonable cost for their Carolinas customers, but prepares the region for the next generation of electric services likely to include neighborhood-level microgrids supported by community solar, battery storage and other DER.[59]

Besides maintaining continuous service to essential and emergency response loads, black-start capability is a significant issue, especially as resources with large inertia, notably nuclear, increase. Duke Energy specifically acknowledges that it has not analyzed black-start requirements in the context of the emerging electricity system:

> In the event of a major outage (be it from weather, cyberattack or otherwise), quickly and safely returning power supply is a major feature of power system resilience. As the resource mix in the Carolinas changes, new challenges can emerge for re-energizing the power system after a blackout. This process of restoring system power, known as "black-start," relies on a carefully planned and coordinated strategy for re-energizing transmission pathways and bringing loads and generation back online in a balanced manner. New, variable generating resources such as solar can complicate this process by increasing the volatility of the system net load during restoration should these resources restart and re-energize automatically. New planning and processes to handle these risks will be necessary. Distributed resources also create new opportunities for resilience as microgrids powered by distributed renewables and storage could maintain islands of power during blackout events - keeping critical loads such as hospitals online and aiding in restoration.
>
> While *none of these conditions are explicitly modeled as scenarios in this initial Carbon Plan*, *they are important considerations* that will help inform the design and operation of the grid both during and after the transition to net-zero.[60]

Interestingly, while this discussion mentions the challenges of solar in the context of power system resilience, it does not mention the significant vulnerability that will be introduced with about 10,000 MW of new nuclear, in addition to existing nuclear, being the mainstay of the Duke Energy power system (see Part II). It is important to re-

[58] *Id.* at Appendix Q at 17.
[59] *Id.* at Appendix G at 45.
[60] *Id.* at Appendix Q at 17 (emphasis added).

emphasize in this context that Duke Energy's Carbon Plan has four Portfolios that are modest variations on a single nuclear-solar-CC-CT theme. Addressing black-start requirements among other resilience and reliability considerations would require a quantitative analysis of the number of self-islanding microgrids that would be built within the context of the Self-Optimizing Grid, the distributed solar and storage capacity that would be needed to meeting essential loads during islanding, and, among other similar considerations, the period of islanding against which distributed resource needs are calculated.

Because HB 951 requires the final Carbon plan to develop a least cost framework that maintains or improves reliability, the cost of the portfolios in Duke Energy's Carbon Plan cannot be evaluated and compared without black-start capability being addressed quantitatively. Detailed consideration of black-start capability may change the mix of resources indicated as "least cost." For instance, given the complementarity of solar and wind, the consideration of distributed wind resources, recently evaluated by the National Renewable Energy Laboratory,[61] should be part of the assessment of resilience, especially in the context of the Self-Optimizing Grid. That is also indicated by the Duke Energy sensitivity analysis, as discussed above. As another example, it may favor development of V2G infrastructure in certain regions as a substitute for, or a complement to, added battery capacity.

The issue of water resources is also not addressed in the context of reliability. The new nuclear generation capacity will increase Duke Energy's existing nuclear capacity in North Carolina by about 130%, from almost 7,500 MW to about 17,500 MW (rounded).[62] This will vastly increase cooling water requirements. As temperatures in the summer become hotter, there may be restraints on thermal generation – which, in the context of Duke Energy's Carbon Plan will be primarily nuclear generation.

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[61] Specifically, this study also shows that distributed wind and solar are moderately complementary in most of North Carolina. KEVIN MCCABE ET AL., DISTRIBUTED WIND ENERGY FUTURES STUDY 5 Figure 2 (Nat'l Renewable Energy Lab'y, May 2022), https://www.nrel.gov/docs/fy22osti/82519.pdf.

[62] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix L at 2 Table L-1. Duke Energy's existing nuclear capacity in the Carolinas is 10,773 MW, of which about 70% is in North Carolina. Duke Energy's proposed Carbon Plan would add about 10,000 MW to the North Carolina total (minimum 9,900 MW; maximum 10,200 MW). *Id.* at Appendix E at 77 Table E-71.

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.[63] The problem of de-rating due to high water temperature will tend to arise during the summer peak demand season, creating pressure on the grid during that critical period. Recent analysis of empirical data on nuclear plant performance globally 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 an "excessive presence of jellyfish, which have been shown to flourish in warmer waters under the effect of climate change."[64] 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 and wind power plants need 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.

Since the nuclear capacity is almost the same across the four portfolios, this vulnerability regarding water applies to the entire proposed Carbon Plan. The frequency and extent of de-rating due to higher water temperatures with specific reference to expected increases in extreme temperatures is critical in any plan that contains thermal generation (low carbon or not), but it is an indispensable requirement for assessment reliability of supply in a high thermal generation, low carbon future. Water considerations indicate the need for a wider array of Portfolios in terms of the mix of low-carbon primary energy resources, storage, and non-wires resources such as demand response and efficiency. Design of the system so that the individual resource

[63] *Heatwave Hits French Power Production*, THE GUARDIAN (Aug. 12, 2003), https://www.theguardian.com/world/2003/aug/12/france.nuclear.

[64] Ali Ahmad, *Increase in Frequency of Nuclear Power Outages Due to Changing Climate*, 6 NATURE ENERGY 755, 756 (July 2021). This paper provides a global assessment. Evidently, a North Carolina specific analysis is needed to develop a decarbonization path that will be as reliable or more reliable that the present system.

components complement one another is essential. Among other things, the resource mix should be evaluated against growing climate and water resource challenges.

VII. Duke Energy's Carbon Plan Does Not Take Into Account the Social Cost of Carbon in Comparing Portfolio Costs

Since all four portfolios in Duke Energy's Carbon Plan are substantially the same, their carbon mitigation trajectories are also substantially the same. But they do differ in terms of cumulative CO2 emissions because the portfolios have different dates for achievement of the 2030 target of 70% CO2 emission reductions. Only one portfolio actually achieves this by 2030 (P1); the others reach the target in 2032 (P2) and 2034 (P3 and P4). The cumulative difference in CO2 is estimated in the Carbon Plan as follows:

> The differences in interim target timelines and resources added to achieve those targets results in greater reductions early for Portfolios 1 and 2, that are generally sustained over the planning horizon, before all portfolios converge to zero CO2 emissions by 2050. Due to this difference, Portfolio 1 emits 69 million short tons less and Portfolio 2 emits 32 million short tons less over the planning horizon on a combined DEC and DEP systems basis, relative to Portfolio 3. Portfolios [sic] 3 and Portfolio 4 essentially emit the same over the planning horizon, with a steady and consistent emissions reduction trajectory over the planning horizon.[65]

But the higher emission Portfolios are estimated to have lower costs.

> As discussed in the CO2 reduction analysis, Portfolios 1 and 2 achieve the interim CO2 reduction targets at an accelerated pace relative to Portfolios 3 and 4. As a tradeoff for the extended timeline to achieve the interim CO2 reduction target, Portfolios 3 and 4 result in a combined system PVRR that is $3.3 to $5.9 billion less. The extended timeline allows for the use of new nuclear to meet the reduction target, providing high-capacity factor, carbon-free energy. New nuclear is economically selected in the mid-2030s in all portfolios but allowing time for this resource to contribute to the interim reduction target allows for the avoidance of more costly resources in the near term. Furthermore, the additional years allowed to achieve the interim target permits the Companies to take advantage of cost declines of resources such as solar and batteries and maintain lower annual solar integration, increasing the executability of the portfolios at the

[65] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix E at 80-81.

> same time. Overall, the lowest cost portfolio is Portfolio 3, but the inclusion of offshore wind in Portfolio 4, only slightly increases the cost of the portfolio while, importantly, providing resource diversity to mitigate technology cost and timing risk. The costliest plan is Portfolio 1, but this portfolio achieves the interim CO2 reduction target the soonest, while emitting the least cumulative system CO2 emissions over the planning horizon.

However, these lower costs for P3 and P4 are, in the CO2 emissions context, largely illusory, because they seem to be achieved mainly by pushing back the CO2 emission target for 2030. The supposed cost advantage is greatly reduced, disappears entirely, or is even reversed, if a social cost of carbon is imputed to the added emissions in the P3 and P4 Portfolios.[66]

The EPA has published a variety of estimates of the social cost of carbon, ranging from $14 to $270 per metric ton in 2021 dollars.[67] Using $60 as a typical value, the P3 and P4 Portfolios would have, in round numbers, about $4.4 billion more in social cost of carbon relative to P1, wiping most of estimated cost advantage. The range of imputed added carbon emission costs is huge: almost $970 million to over $18.7 billion higher for P3 and P4 relative to P1.

In sum, taking the social cost of carbon into account, indicates that there is, as a first approximation, essentially no cost advantage for any of the portfolios in the Duke Energy Carbon Plan; in the worst case, should climate impacts be at the higher end estimated by the EPA, the P3 and P4 portfolios in the proposed Carbon Plan would be considerably worse than the P1 and P2 portfolios.

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[66] N.C. Exec. Order 246 (Jan. 7, 2022) (encouraging consideration of the social cost of carbon in Section 6).

[67] The EPA's values are in 2007 dollars. They have been multiplied here by a factor of 1.227 convert to 2021 dollars, reflecting the Gross Domestic Product price deflator between 2007 and 2021. A typical value from the EPA table would be $50 per metric ton in 2007 dollars, which is, in round numbers, about $60 per metric ton in 2021 dollars. *The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Concentrations*, U.S. ENV'T PROT. AGENCY (Jan. 19, 2017), https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html. The deflator was calculated from Federal Reserve data. *Gross Domestic Product: Implicit Price Deflator*, FED. RSRV. ECON. DATA (June 29, 2022), https://fred.stlouisfed.org/series/GDPDEF/.

VIII. Duke Energy's Carbon Plan Fails to Address Potential Nitrogen Oxide Emissions and Related Air Pollution

The use of hydrogen has vastly different air pollution consequences depending on whether it is burned or used in fuel cells. The only by product of fuel cell generation is water. In contrast, both the CT and CC generation systems involve burning, which creates air pollution. In Duke Energy's Carbon Plan, what is burned would evolve from burning natural gas to a mix of natural gas and hydrogen, with increasing fractions of the latter till it reaches 100% hydrogen by 2050.

With present-day turbines, there is a rather low limit to the proportion of hydrogen that can be added without significantly increasing nitrogen oxide emissions. This has been described by General Electric (GE), one of the largest manufacturers of turbines, as follows:

> The overall trend shows that at lower percentages of hydrogen the increase in NOx emissions are minimal, but at 50% hydrogen (by volume), NOx emissions could increase by as much as 35%. *Extrapolating this data, gas turbine NOx emissions could potentially double if operating at or near 100% hydrogen.* For power plants currently in development, one potential mitigation for increased NOx emissions is a larger or more efficient SCR (selective catalytic reduction) system. For existing power plants, there may be some ability to accept some increases in NOx emissions based on existing NOx emissions, existing SCR capabilities (if installed), and the plant's air permit limits. Other mitigations could include derating the power plant to maintain operation within the existing air permit's NOx emission limits.[68]

There is in fact a several percent increase in nitrogen oxide emissions even with just 10% hydrogen mixed with natural gas.[69] GE has a program to redesign turbines to lower nitrogen oxide emissions. Modifying existing gas turbines presents significant

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[68] GENERAL ELECTRIC, HYDROGEN FOR POWER GENERATION: EXPERIENCE, REQUIREMENTS, AND IMPLICATIONS FOR USE IN GAS TURBINES 14 (Mar. 2022), https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/future-of-energy/hydrogen-for-power-gen-gea34805.pdf (emphasis added).

[69] *Id.*; *see also* CAROLINAS CARBON PLAN, *supra* note 3, at Appendix E at 43. The Carbon Plan envisions the use of 10% hydrogen mix (by volume) in 2038 and 15% in 2041.

challenges; among other things, the materials in them may crack due to embrittlement by hydrogen.[70]

Duke Energy has not addressed the problem of nitrogen oxide emissions. Specifically, it has not evaluated the environmental justice implications of any increased pollution (at both CC and CT plants) that may result, even though Executive Order 246 requires consideration of the environmental justice aspects of the energy transition.[71] It is possible that redesign of turbines could keep nitrogen oxide pollution similar to present levels. Duke Energy has assumed somewhat higher costs for the turbines.[72] But in any case, air pollution associated with CT and CC generation would continue at the present rates. Fuel cells would eliminate that pollution and environmental injustice associated with it.

Among, other options, Duke Energy should compare the air pollution implications of using fuel cells in place of gas turbine and combined cycle power plants in the same locations.

Duke Energy has also not evaluated the indoor air pollution impacts of mixing hydrogen with natural gas in pipelines supply power plants and the residential and commercial sectors, even though such mixing is likely to increase indoor air pollution. This may well occur in Duke Energy Carbon Plan because of the extensive use of hydrogen in all four portfolios and the likely centralized production it implies. Duke Energy's Carbon Plan includes the option of on-site hydrogen production or dedicated hydrogen production facilities, but it keeps open the possibility of putting hydrogen "into existing pipelines."[73]

Indoor air pollution, including nitrogen oxide pollution, is already an issue in homes that use natural gas for cooking.[74] The indoor air pollution increases that may

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[70] GENERAL ELECTRIC, *supra* note 64, at 15.
[71] N.C. Exec. Order No. 246 (Jan. 7, 2022) ("North Carolina's Transformation to a Clean, Equitable Economy").
[72] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix E at 31.
[73] *Id.* at Appendix O at 3.
[74] *See, e.g.*, Eric D. Lebel et al., *Methane and NO_x Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes*, 56 ENV'T SCI. & TECH. 2529 (2022).

accompany putting hydrogen into natural gas pipelines, including environmental justice and health implications and associated health costs, must be factored into all four Duke Energy Portfolios and compared with production of hydrogen at power plant sites for use in fuel cells in place of combustion turbines and combined cycle plants as the decarbonized fraction of electricity supply grows.

Both outdoor and indoor air pollution impacts are required to be considered by HB 951. Article 951(d)(1)(a) requires the Commission to assure "that no customer or class of customers is unreasonably harmed…." Increase in indoor air pollution in the residential sector and certain parts of the commercial sector, such as restaurants that use natural gas for cooking, would likely harm these sectors disproportionately. In view of the explicit requirement of HB 951, putting hydrogen in existing pipelines does not appear to be in keeping with the spirit Article 951(d)(1)(a), at least so long as there are alternatives—and, as noted, Duke Energy has recognized that such alternatives exist.

IX. Recommendations to Duke Energy's Carbon Plan: Well Differentiated Carbon Plan Portfolios

As is eminently clear from the above analysis, the four portfolios in Duke Energy's Carbon Plan are only moderate to minor variations on a single theme with nuclear, solar, combustion turbine, combined cycle, and battery storage as the principal elements in the zero-carbon design. Duke Energy's sensitivity analysis did not fundamentally change this picture, except to indicate that solar-wind balance could improve the cost picture and reduce storage requirements. Most of the generation would be provided by existing and new nuclear plants in all four portfolios. None of these is likely to be least cost when a more varied mix of resources is considered. All four portfolios have significant reliability vulnerabilities, and all have large gaps in the consideration of demand. In other words, the Duke Energy Carbon Plan is conceptually unsatisfactory and does not meet the requirements of HB 951 to design a least cost plan that meets or exceeds present reliability levels. This is especially problematic in the context of increasing weather extremes that would likely stress primary supply that depends largely on thermal generation.

A more varied set of portfolios that consider the cost, reliability, and resilience of the coming decades is required to allow a good comparison and a determination of a least cost approach. My recommendation is for a different set of Portfolios that would allow a comparison with the approach that Duke Energy has laid out in its proposed Carbon Plan. One of Duke Energy's portfolios would be retained so that a comparison of cost, reliability, resilience, pollution, and adaptability to a changing climate can be assessed. Decreasing schedule and financial uncertainties and increasing resilience (in dimensions beyond loss-of-load-expectation and related metrics) should be important criteria in designing such a set of portfolios. Only a set of portfolios that substantially represents the large range of present and advanced technologies can allow a reasonable determination of a least cost approach within the decarbonization and reliability constraints.

1. **Duke Energy P3 – High Nuclear, No Offshore Wind**: The Duke Energy P3 Portfolio can be retained since Duke Energy has assessed it as the least cost option. Additionally, P3 has essentially all features of the other three, except offshore wind.
2. **Proposed P5** – **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). Given the increase in solar resources, offshore wind capacity would be accelerated. Existing nuclear resources would be retained but no new nuclear capacity would be built. The planned amount of new CT and CC resources in P2 would be retained but light and medium duty fuel cells would be used in place of rotating resources using electrolytic hydrogen only. In other words, no new resources using natural gas for part of all its fuel requirements should be built. Considerably faster transportation electrification would be included in light of plans by major manufacturers and countries that are major markets. A significant amount of V2G capacity would be included. 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. It would not be put into existing natural gas pipelines.

3. **Proposed P6 – Balanced Solar and Wind with High Resilience**: This would be like P5 above but 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 appropriate higher incentives and standards put in place to achieve the higher levels. There would be much more investment in the equity aspects of efficiency investments than in the Duke Energy Carbon Plan. 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 integrated with the Self-Optimizing Grid. Demand response would be significantly deeper than in Duke Energy's P3 portfolio and generalized to offer contracts to all loads that can reasonably be shifted within a 24-hour period (though with the expectation of various participation levels, depending on the load). As in P5, hydrogen for power production in fuel cells would be produced using electricity that would otherwise be curtailed; however, in P6 all production would be at the power station sites, so that hydrogen pipelines from dedicated hubs would not be needed. Pipeline leaks would thereby be avoided.
4. **Proposed P7 – High Resilience with Existing Nuclear Retired**. This would be like P6 except in the following respects. Among other things, this portfolio would minimize or entirely avoid the contingency of unexpected problems and costs such as those that France is facing (see Part II). This proposed portfolio would assume that existing nuclear plants are retired at license expiry or when significant new financial resources to support their continued operation are required from ratepayers. Since the latter point in time is not foreseeable, the former would be assumed. The P7 Portfolio would plan for an accelerated

deployment of renewable, efficiency, and aggregated demand response resources prior to nuclear plant license expiry dates. By the mid-2040s, solar, wind, and hydro (including existing and planned pumped hydro) would be the only primary energy supply resources, complemented by deep demand response (DR) with DR-loads reassigned within a 24-hour period. Suitable rate structures and incentives DR resources would be needed. More hydrogen would be produced than in P5 and P6 due to the larger solar and wind capacity; in addition to peaking, it would be used in large fuel-cell-based combined heat and power plants and other similar uses. All the hydrogen needed for electricity generation would be produced with Duke Energy generated electricity that would otherwise be curtailed. It would also be used in large industrial fuel cell combined heat and power plants. It should be noted that in the P5, P6, and P7 scenarios, the "peak" times for the electricity grid will not necessarily be the times of highest load; rather they will be relative peaks – that is when demand is most out of balance with variable supply and available battery and pumped hydro resources. The option of developing medium- and large-scale solar with dual agricultural use, for instance for grazing (known as agrivoltaics), could also be included. Other than the V2G and agrivoltaics, this general approach to a 100% decarbonized electricity system by 2050 was modeled and evaluated in the Maryland context in *Prosperous, Renewable Maryland*: *Roadmap for a Healthy, Economical, and Equitable Energy Future*.[75] In this Maryland portfolio developed by IEER, there was sufficient surplus renewable generation to enable production of all the hydrogen requirements for peaking generation, as well as substantial hydrogen production for combined heat and power and industry. Unlike the four Carbon Plan portfolios, no reliance on a green hydrogen market was necessary even for full decarbonization of the electricity sector. Agrivoltaics for Maryland were separately evaluated later in a different study.[76]

[75] *See generally* MAKHIJANI, *supra* note 12.
[76] *See generally* ARJUN MAKHIJANI, EXPLORING FARMING AND SOLAR SYNERGIES: AN ANALYSIS USING MARYLAND DATA (Inst. For Energy and Env't Rsch., Feb. 2021), https://ieer.org/wp/wp-content/uploads/2021/02/Agrivoltaics-report-Arjun-Makhijani-final-2021-02-08.pdf.

Based on the considerations outlined above, the following features could be evaluated as variants within P6 and P7:

- Seasonal thermal storage in insulated cells in the ground (like Drakes Landing Solar Community in Alberta) using solar and wind that would otherwise be curtailed, as part of microgrid design. This would reduce battery storage in required microgrids to meet essential loads during a predefined outage period. This small community of 52 homes in a very cold climate has met 90% to 100% of its winter heating needs using heat produced by solar thermal systems in the summer, storing it in boreholes in the ground, recovering it for use in the winter. It does not have an air-conditioning component.[77] In the suggested North Carolina application, the solar thermal component would not be needed; rather, a heat pump device would be used to store heat in the fall and coldness in the spring for recovery in the winter and summer respectively. Some storage would also occur in the winter and summer as well, during periods of excess supply. This approach may be especially compatible with Duke Energy's proposed Self-Optimizing Grid. It can be evaluated as a basic component of SOG to increase resilience and to make maximum use of distributed renewable generation.
- Use of front-of-the-meter distributed wind as described by the National Renewable Energy Laboratory[78] as part of the units of the Self-Optimizing Grid along with distributed solar and storage.
- More intensive use of V2G to replace a significant part of large-scale stationary battery resources.

[77] *See generally* LUCIO MESQUITA ET AL., DRAKE LANDING SOLAR COMMUNITY: 10 YEARS OF OPERATION (Int'l Solar Energy Soc'y, 2017), http://www.dlsc.ca/reports/swc2017-0033-Mesquita.pdf. Other details about this community can be found at its website at http://www.dlsc.ca/.

[78] KEVIN MCCABE ET AL., DISTRIBUTED WIND ENERGY FUTURES STUDY (Nat'l Renewable Energy Lab'y, May 2022), https://www.nrel.gov/docs/fy22osti/82519.pdf.

PART II

I. Qualifications

Part I, Section I*, supra*, which states Dr. Makhijani's qualifications, is incorporated herein by reference. Further, a copy of Dr. Makhijani's CV is attached as **Exhibit 1**. The following is a statement by Dr. Ramana regarding his qualifications.

I am the Simons Chair for the Disarmament, Global and Human Security program at the School of Public Policy and Global Affairs for the University of British Columbia in Vancouver, Canada. I hold a Master of Science in Physics from the Indian Institute of Technology, located in Kanpur, India, and a Ph.D. in Physics from Boston University. Over the last 20 years, I have produced numerous studies, peer-reviewed papers, and online forum articles on topics related to nuclear energy, small modular reactors, and renewable energy alternatives. My most recent work involving nuclear energy includes authoring chapters in books *Hiding in Plain Sight: Uncovering Nuclear Histories* and *The Technological and Economic Future of Nuclear Power*.

I have also served as a Professional Specialist at the Science and Global Security Program at Princeton University, researching issues related to nuclear power, nuclear proliferation, and climate change; and served as a Lecturer at the Woodrow Wilson School of Public and International Affairs at Princeton University, designing and teaching courses related to energy, environment and development, and nuclear power. A copy of Dr. Ramana's CV is attached as **Exhibit 2**.

II. Assignment

We have been retained by EWG to evaluate the four portfolios in the proposed Carbon Plan filed on May 16, 2022, by Duke Energy Carolinas, LLC ("DEC") and Duke Energy Progress, LLC ("DEP") (collectively, "Duke Energy") in the above-referenced docket before the North Carolina Utilities Commission ("Commission") to jointly opine on the role of new and existing nuclear power plants in the four portfolios in Duke Energy's Carbon Plan. The assignment includes examining the risk, economic, and reliability considerations associated with the nuclear element of the four portfolios within the context of least cost planning for achieving the carbon reduction goals of HB 951, including full decarbonization by the year 2050.

III. Summary of Opinions

All portfolios in Duke Energy's proposed Carbon Plan involve a very heavy reliance on nuclear energy and envision the construction of new nuclear reactors. The type of nuclear plants that are envisioned for construction are described as "advanced nuclear," in particular "small modular reactors" ("SMRs"). In the long run, nuclear power is projected to constitute "over 60% of the Companies' energy mix by 2050 . . . in all portfolios."[79]

The high costs associated with nuclear power from all kinds of reactors—large or small—implies that such pathways are unlikely to fit into a least-cost profile. Frequent and large overruns in costs of nuclear power projects, combined with a history of underestimation of costs, make it likely that the economic impact of nuclear deployment will be significantly greater than projected. The pattern of delays in nuclear deployment also means that Duke Energy is unlikely to meet its emission reduction targets on schedule. Duke Energy has not included in its proposed plan any analysis of the huge cost overruns and major delays in commissioning nuclear power plants in the last four decades, nor has it analyzed the impact of cancellations of reactor projects—both planned and under construction—that have been common in the United States for the last four decades. Given that all four portfolios envision almost the same, very large amount of nuclear, and that the portfolios do not include analysis of the risk of nuclear facility cost overruns, delays, and/or cancellations, there is no way to adequately assess the costs and risks of Duke Energy's Carbon Plan as part of a path to decarbonization.

Further, Duke Energy has taken no account of the potential that existing nuclear plants may develop significant operational, reliability, or cost issues as they age. The current severe predicament of the French nuclear power system provides a stark example of the need to factor in such an eventuality.

If Duke Energy's Carbon Plan is overly optimistic about light water reactor designs of small modular reactors, it is entirely fanciful about the prospects of the sodium-cooled and high-temperature gas reactors becoming economical, timely, and

[79] CAROLINAS CARBON PLAN, *supra* note 3, at Chapter 3 at 5.

reliable parts of a decarbonized portfolio. The main, common problem is that Duke Energy has not connected the large new nuclear capacity in all four portfolios in the Carbon Plan with the reality and history of these designs and the lack of demonstration that the outstanding operational, reliability, and cost problems of these non-light water reactor designs have been satisfactorily resolved.

IV. Nuclear Power is Not Economically Competitive: The Economics of Nuclear Power and Other Low Carbon Alternatives

Poor economics has been a persistent problem for nuclear energy. In 2003, an influential study put out by the Massachusetts Institute of Technology expressed the challenge baldly: "Today, nuclear power is not an economically competitive choice."[80] Since then, the situation has only become worse. In the 2021 edition of its annual cost report, Lazard, the Wall Street asset management and investment firm, estimated that the levelized cost of electricity from new nuclear plants will be between $131 and $204 per megawatt hour ("MWh"), whereas the corresponding cost from newly constructed utility-scale solar and onshore wind plants are between $26 and $50 per MWh; offshore wind is estimated to produce electricity at somewhere between $66 and $100 per MWh.[81] The cost gap between nuclear power and renewables is large and growing larger. While nuclear costs have increased with time, the levelized cost of electricity for solar and wind have declined rapidly and is expected to continue declining over the coming decades. Of course, there are other factors to be considered when there are greater fractions of variable renewables; these are addressed *supra* in Part I, notably in the three portfolios that have been suggested for inclusion in a least cost analysis.

Even operating costs for nuclear power plants are high, and many reactors have been shut down because they are unprofitable.[82] The degree of loss involved in

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[80] STEPHEN ANSOLABEHERE ET AL., *The Future of Nuclear Power* 3 (2003), http://web.mit.edu/nuclearpower/.
[81] 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.
[82] STEVE CLEMMER ET AL., THE NUCLEAR POWER DILEMMA: DECLINING PROFITS, PLANT CLOSURES, AND THE THREAT OF RISING CARBON EMISSIONS (Union of Concerned Scientist, 2018), https://www.ucsusa.org/resources/nuclear-power-dilemma; Matthew Bandyk, *UBS analysts: Long-term contracted nuclear plants also at risk of shutdown,* S&P GLOB. (June 24, 2016), https://www.spglobal.com/marketintelligence/en/news-insights/trending/baejqqkda_ijmhgbnpqkrq2; Matthew L. Wald, *Nuclear Plants, Old and Uncompetitive, are Closing Earlier than Expected,* N.Y. TIMES

operating an unprofitable nuclear plant can be considerable. In 2018, when NextEra decided to shut down the Duane Arnold nuclear reactor, it estimated that replacing nuclear with wind power would "save customers nearly $300 million in energy costs, on a net present value basis."[83]

These high operating costs are the reason that several old reactors have been retired, even though they were still licensed to operate for many more years. There were 104 nuclear reactors in operation at the end of 2010 in the United States.[84] As of July 2022, that figure has dropped to 92 reactors.[85] The figure would have been even lower but for the fact that many states have chosen to subsidize their unprofitable nuclear plants.[86]

The United States is not an exception. The United Kingdom's fleet has dropped from 19 reactors at the end of 2010 to 11 reactors as of July 2022; Sweden's fleet has reduced from 10 to 6 reactors.[87] Most remarkably and notably, France—a country that is highly reliant on nuclear power for its electricity supply—is having significant problems with its nuclear reactors. Apart from pandemic related matters, the current series of problems began with the discovery of stress corrosion cracking in the pipes of the emergency core cooling system of some reactors towards the end of 2021.[88] Winter electricity prices soared to €500/MWh (about $500/MWh at the July 11, 2022, exchange

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(June 14, 2013), http://www.nytimes.com/2013/06/15/business/energy-environment/aging-nuclear-plants-are-closing-but-for-economic-reasons.html.

[83] Aaron Larson, *Duane Arnold Nuclear Plant Will Close in 2020*, POWER MAG. (July 29, 2018), https://www.powermag.com/duane-arnold-nuclear-plant-will-close-in-2020/.

[84] INT'L ATOMIC ENERGY AGENCY, NUCLEAR POWER REACTORS IN THE WORLD: 2011 EDITION at 11 Table 1 (2011), https://www.iaea.org/publications/8752/nuclear-power-reactors-in-the-world.

[85] *The Database on Nuclear Power Reactors*, INT'L ATOMIC ENERGY AGENCY (2022), https://pris.iaea.org/pris/.

[86] Cassandra Jeffery & M. V. Ramana, *Big Money, Nuclear Subsidies, and Systemic Corruption*, BULL. OF THE ATOMIC SCIENTISTS (Feb. 12, 2021), https://thebulletin.org/2021/02/big-money-nuclear-subsidies-and-systemic-corruption/; Catherine Clifford, *Why Illinois Paid $694 Million to Keep Nuclear Plants Open*, CNBC (Nov. 20, 2021), https://www.cnbc.com/2021/11/20/illinois-nuclear-power-subsidy-of-694-million-imperfect-compromise.html.

[87] *The Database on Nuclear Power Reactors*, INT'L ATOMIC ENERGY AGENCY (2022), https://pris.iaea.org/pris/.

[88] Autorité de Sûreté Nucléaire, Phénomène de corrosion sous contrainte détecté sur les réacteurs 1 et 2 de Civaux, B2 de Chooz et 1 de Penly, January 31, 2022 at https://www.asn.fr/l-asn-informe/actualites/phenomene-de-corrosion-sous-contrainte-detecte-sur-certains-reacteurs.

rate). President Macron of France ordered the French utility EDF (which, like Duke Energy, is winter-peaking) to sell its electricity at prices capped at just €46/MWh.[89]

Less that 30 GW of the 61.4 GW capacity of the French nuclear power fleet was online at the end of April 2022. While this is a time when many reactors are taken offline for refueling and maintenance, the operating capacity was 10 to 15 GW—or 25 to 33 %—less than what is normally available, according to Thomas Veyrenc, the Executive Director of France's Transmission System Operator. The French nuclear regulator, Autorité de Sûreté Nucléaire, believes it will take years to fix the above-referenced issues.[90]

This example is relevant to Duke Energy's proposed Carbon Plan. Among other things, the Carbon Plan projects a very similar reliance on nuclear power to that of France. Duke Energy maintains that its existing reactors will operate reliably beyond the currently licensed 60 years for another 20 years:

> All of Duke Energy's nuclear plants are currently licensed for 60 years and can safely and reliably run for many years after that. A 20-year extension is possible due to the excellent maintenance performed over the life of the plant, and the large investments made, and committed to be made, for major modifications and upgrades to each plant. When a license renewal is approved by the NRC, each plant is committed to maintain an extensive aging management program to keep the plant systems in top condition. Many other U.S. utilities have already committed, or plan to commit, to requesting SLRs extending the life of their plants to 80 years.[91]

Duke Energy may be able to operate these reactors as assumed with investments and maintenance. And it may not. Essentially all of France's nuclear power reactors are less than 60 years old. It would be prudent to consider alternatives to reliance on existing reactors in at least one portfolio (like the P7 portfolio suggested in Part I).

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[89] Liz Alderman, *French Nuclear Power Crisis Frustrates Europe's Push to Quit Russian Energy*, N.Y. TIMES (June 18, 2022), https://www.nytimes.com/2022/06/18/business/france-nuclear-power-russia.html
[90] Perrine Mouterde, "Nucléaire : un nombre record de réacteurs à l'arrêt," Le Monde, May 18, 2022, at https://www.lemonde.fr/planete/article/2022/05/18/nucleaire-un-nombre-record-de-reacteurs-a-l-arret_6126572_3244.html.
[91] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix L at 4.

V. The Riskiness of Nuclear Power and the Failed "Nuclear Renaissance"

The Massachusetts Institute of Technology study referenced above in Part II Section IV was published just before the energy sector was said to be on the verge of a nuclear renaissance.[92] That proposed renaissance was propelled by the Energy Policy Act of 2005 that offered various guarantees and incentives to nuclear power.[93] As a 2008 Congressional Budget Office ("CBO") report explained, "Loan guarantees and insurance against delays reduce the financial risk of investing in advanced nuclear power plants by transferring risk to the public" and even added a cautionary note: "economic theory suggests that such incentives cause recipients to invest in excessively risky projects because they do not bear all the cost of a project's failure."[94]

Utility companies did invest in excessively risky projects. Altogether, they proposed constructing more than 30 reactors.[95] This follows an even longer history of cancelled nuclear orders. In 2007, the U.S. Congressional Research Service reported that "more than 120 reactor orders were ultimately cancelled" in the United States.[96] The list of projects that were announced but never constructed includes two AP1000 reactors proposed to be built in Levy County, Florida, two AP1000 reactors at the Harris site in North Carolina, and two AP1000 reactors proposed to be built at the William States Lee site in South Carolina. All six projects were announced by Duke Energy. None of them were constructed. In the case of the Levy County project, Duke Energy

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[92] *See, e.g.*, Gail H. Marcus & Alan E. Levin, *New designs for the nuclear renaissance* 55 PHYS. TODAY 54 (2002); NUKEM, *Nuclear renaissance: U. S. A: Coping with the new NPP sticker shock*, NUKEM MARKET REPORT, 2008, at 1–43; SHARON SQUASSONI, NUCLEAR RENAISSANCE: IS IT COMING? SHOULD IT? (Oct. 2008), https://carnegieendowment.org/files/nuclear_renaissance1.pdf; SHARON SQUASSONI, NUCLEAR ENERGY: REBIRTH OR RESUSCITATION? (Carnegie Endowment, 2009); Peter A. Bradford, *Honey, I Shrunk the Renaissance: Nuclear Revival, Climate Change, and Reality*, ELECTRICITY POL'Y (Oct. 11, 2010), https://www.electricitypolicy.com/index.php?option=com_content&view=article&id=2553:honey-i-shrunk-&catid=99:article&Itemid=710; MARK COOPER, RENAISSANCE IN REVERSE: COMPETITION PUSHES AGING U.S. NUCLEAR REACTORS TO THE BRINK OF ECONOMIC ABANDONMENT (July 2013), http://will.illinois.edu/nfs/RenaissanceinReverse7.18.2013.pdf.

[93] *See* CONG. BUDGET OFF., NUCLEAR POWER'S ROLE IN GENERATING ELECTRICITY (May 2008), https://www.cbo.gov/sites/default/files/110th-congress-2007-2008/reports/05-02-nuclear.pdf.

[94] *Id.* at 22.

[95] MARK HOLT, NUCLEAR ENERGY POLICY 6–9 (Cong. Rsch. Serv., 2014), https://sgp.fas.org/crs/misc/RL33558.pdf.

[96] LARRY PARKER & MARK HOLT, NUCLEAR POWER: OUTLOOK FOR NEW U.S. REACTORS 3 (Cong. Rsch. Serv., 2007), https://sgp.fas.org/crs/misc/RL33442.pdf.

applied to the Nuclear Regulatory Commission ("NRC") for a construction licence in July 2008 but announced that the contract was terminated in August 2013.[97] For the Harris project, Duke Energy applied to the NRC for a construction licence in February 2008 and signed a construction contract in January 2009, but they announced that it was suspending the licensing effort in May 2013.[98] The NRC did complete its review of the application for the William States Lee project in 2016, but in 2017, Duke Energy cancelled its plans to construct these reactors.[99] That is a total delay of about eight years from construction contract to a decision that resulted in no addition of nuclear capacity.

That hoped-for renaissance fizzled out in a few years, and by 2012, John Rowe, former chairman and CEO of Exelon Corporation, then the largest nuclear operator in the United States, candidly admitted, "Let me state unequivocably [sic] that I've never met a nuclear plant I didn't like…Having said that, let me also state unequivocably [sic] that new ones don't make any sense right now."[100] The path that led the Exelon CEO to make that statement should be reviewed for the lessons it may hold. These delays and cost increases have occurred despite the fact that the project has benefitted from advance mandatory payments made by ratepayers on their electricity bills, known as Construction Work in Progress, as part of project finance,[101] in addition to a federal government loan guarantee of "up to $12 billion."[102]

Only two projects, involving two AP1000 reactors each, went forward to the stage of construction. Of these, the project to build units 3 and 4 at the Vogtle site in Georgia was originally estimated to cost $14 billion when construction started.[103] That projection

[97] *Id.* at 8.
[98] *Id.* at 9.
[99] *Duke Seeks to Cancel Plans for Lee AP1000s*, World Nuclear News (Aug. 29, 2017), https://www.world-nuclear-news.org/NN-Duke-seeks-to-cancel-plans-for-Lee-AP1000s-2908175.html.
[100] Jeff McMahon, *Exelon's "Nuclear Guy": No New Nukes*, Forbes (May 29, 2012), https://www.forbes.com/sites/jeffmcmahon/2012/03/29/exelons-nuclear-guy-no-new-nukes/?sh=123f84233c5d.
[101] *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.
[102] *Vogtle*, U.S. Dep't of Energy (2022), https://www.energy.gov/lpo/vogtle.
[103] Steve Hargreaves, *First New Nuclear Reactors OK'd in Over 30 years* CNNMoney (Feb. 9, 2012), http://money.cnn.com/2012/02/09/news/economy/nuclear_reactors/index.htm.

has now increased to over $30 billion.[104] Initial projection for startup of the two units was 2016 and 2017. The current schedule hopes to start the reactors in 2023.[105] The other nuclear project in South Carolina was abandoned after $9 billion was spent on it.[106] That project's failure led Westinghouse, the company directly or indirectly responsible for the design of the majority of the world's nuclear reactors, to file for bankruptcy protection.[107] In France, the Flamanville project is now estimated to cost 12.7 billion euros,[108] much higher than the 3.3 billion euros forecast when construction started.[109]

These cost and time increases are just the most recent examples of the long-standing pattern of such escalations at nuclear power plants.[110] One study examined 180 nuclear projects and a mere five met anticipated cost and time targets. The remaining 175 took on average 64% more time than projected and had final costs that exceeded the initial budget on average by 117%.[111] This history is important in evaluating Duke Energy's proposed nuclear plans and the impact it may have on cost and decarbonization schedules, since all four Carbon Plan portfolios contain almost the same amount of new nuclear capacity.

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[104] *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.

[105] 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/.

[106] 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/.

[107] Diane Cardwell & Jonathan Soble, *Westinghouse Files for Bankruptcy, in Blow to Nuclear Power*, N.Y. TIMES (Mar. 29, 2017), https://www.nytimes.com/2017/03/29/business/westinghouse-toshiba-nuclear-bankruptcy.html; Tom Hals & Emily Flitter, *How Two Cutting Edge U.S. Nuclear Projects Bankrupted Westinghouse* REUTERS (May 2, 2017), https://www.reuters.com/article/us-toshiba-accounting-westinghouse-nucle-idUSKBN17Y0CQ.

[108] *Update on the Flamanville EPR*, THE EDF GRP. (Jan. 1, 2022), https://www.edf.fr/en/the-edf-group/dedicated-sections/journalists/all-press-releases/update-on-the-flamanville-epr.

[109] THE EDF GRP., ANNUAL REPORT 2005 (2005), https://www.edf.fr/sites/default/files/contrib/finance/Annual%20Report%20VA/2005/Report/ra2005_corporate_full_va.pdf.

[110] *See* Benjamin K. Sovacool et al., *An International Comparative Assessment of Construction Cost Overruns for Electricity Infrastructure*, 3 Energy Rsch. & Soc. Sci. 152 (Sept. 2014); M. V. RAMANA, THE POWER OF PROMISE: EXAMINING NUCLEAR ENERGY IN INDIA (2012); Nathan E Hultman & Jonathan G Koomey, *The Risk of Surprise in Energy Technology Costs*, 2 ENV'T RSCH. LETTERS 1; Nathan E Hultman et al., *What History Can Teach Us about the Future Costs of U.S. Nuclear Power*, 7 ENV'L SCI. & TECH. 2087 (2007).

[111] Benjamin K. Sovacool et al., *Risk, Innovation, Electricity Infrastructure and Construction Cost Overruns: Testing Six Hypotheses*, 74 Energy 906 (Sept. 2014).

As the abovementioned statistic of a 117% average escalation in cost indicates, the experience with Vogtle units 3 and 4 is in line with historical experience. Nuclear reactor projects that are on time and on budget are very rare, while a doubling of initially estimated costs has been typical. Duke Energy's capital cost sensitivity analysis is clearly deficient in underestimating potential cost escalations, as discussed in Part I, Section IV, Subsection ii. It is also deficient in not addressing the impact that major delays could have on achieving the ultimate decarbonization target for 2050 mandated by HB 951 and on the intermediate targets that must be met to achieve the 2050 result. A sound sensitivity analysis should evaluate the impact of typical historical cost escalations and delays and re-optimize the portfolios for the lessons that could be learned.

VI. Small Modular Reactors: An Economically Impracticable Alternative

The high costs described above are for large nuclear power plants. Large reactors have generally been chosen because they offer economies of scale. SMRs, as the name suggests, produce relatively small amounts of electricity in comparison. But this feature is a significant disadvantage when it comes to economics. All else being equal, a reactor that produces three times as much power as a small modular reactor does not need three times as much steel or three times as many welds. In contrast, when the power output of the reactor decreases, it generates less revenue for the owning utility, the cost of constructing the reactor is not proportionately smaller. SMRs will, therefore, cost more than large reactors for each megawatt of generation capacity.[112] Economies of scale as they apply to industrial plants have been understood for a long time.[113]

[112] Stephen Thomas & M. V. Ramana, *A Hopeless Pursuit? National Efforts to Promote Small Modular Nuclear Reactors and Revive Nuclear Power*, 11 WIREs ENERGY ENV'T. 429 (2022); Arjun Makhijani & M. V. Ramana, *Can Small Modular Reactors Help Mitigate Climate Change?,* 77 BULL. AT. SCI. 207 (2021); Arjun Makhijani & M. V. Ramana, *Why Small Modular Nuclear Reactors Won't Help Counter the Climate Crisis*, ENV'T WORKING GRP. (2021), https://www.ewg.org/news-insights/news/why-small-modular-nuclear-reactors-wont-help-counter-climate-crisis.

[113] John Haldi & David Whitcomb, *Economies of Scale in Industrial Plants*, 75 J. POLIT. ECON. 373 (1967); Robin Cantor & James Hewlett, *The Economics of Nuclear Power: Further Evidence on Learning, Economies of Scale, and Regulatory Effects*, 10 RES. ENERGY 315=(1988); Anthony C. Krautmann & John L. Solow, *Economies of Scale in Nuclear Power Generation*, 55 SOUTH. ECON. J. 70–85 (1988); H. I. BOWERS ET AL., TRENDS IN NUCLEAR POWER PLANT CAPITAL-INVESTMENT COST ESTIMATES - 1976 TO 1982

Unless the problem of lost economies of scale is fully overcome, the higher cost per unit of capacity will make electricity from small reactors more expensive than large reactors. In the 1950s, the U.S. Atomic Energy Commission funded the construction of several small power reactors that were declared to be "suitable both for use in rural areas and for foreign export."[114] Most of the early small reactors built in the United States shut down early because they could not compete economically.[115]

SMR proponents argue that savings from modularity and factory manufacturing would compensate for the poorer economics of small reactors, and as these plants are built in large numbers, costs will go down.[116] But in both the United States and France, the countries with the highest number of nuclear plants, costs increased as more plants were built.[117] Even under optimistic assumptions about positive rates of learning, these reactors would have to be manufactured by the hundreds, if not the thousands, for an assembly approach to compensate for the loss of economies of scale.[118] After this monumental task, even if small modular reactors 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.[119]

Several evaluations of the cost of electricity from SMRs have come up with fairly high estimates. In its 2019 Integrated Resource Plan ("IRP"), Idaho Power estimated a

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(Off. of Sci. and Tech. Info., 1983), https://www.osti.gov/biblio/5752316-trends-nuclear-power-plant-capital-investment-cost-estimates.

[114] WENDY ALLEN, NUCLEAR REACTORS FOR GENERATING ELECTRICITY: U.S. DEVELOPMENT FROM 1946 TO 1963 (Rand, 1977), https://www.rand.org/pubs/reports/R2116.html.

[115] 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-nuclear-reactors#toggle-gdpr.

[116] Giorgio Locatelli et al., *Small Modular Reactors: A Comprehensive Overview of their Economics and Strategic Aspects*, 73 PROG. NUCL. ENERGY 75 (2014).

[117] 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*, *in* ENERGY TECHNOLOGY INNOVATION: LEARNING FROM HISTORICAL SUCCESSES AND FAILURES 146 (Arnulf Grubler & Charlie Wilson eds., 2013).

[118] *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.

[119] Arjun Makhijani & M. V. Ramana, *Can Small Modular Reactors Help Mitigate Climate Change?,* 77 BULL. AT. SCI. 207 (2021). The very small reactors, sometimes called "micro-reactors," CAROLINAS CARBON PLAN, *supra* note 3, at Appendix L at Table L-5, would face far greater challenges in regard to economies of scale and are therefore not discussed here. The Makhijani and Ramana 2021 article discusses some of the important problems and hurdles that would likely be faced by the two molten salt micro-reactor designs in Table L-5 were they to be pursued by Duke Energy.

cost of $121 per megawatt hour for a NuScale plant operating at a 90% capacity factor.[120] More recently, Australia's Commonwealth Scientific and Industrial Research Organisation ("CSIRO") has estimated that the cost of generating electricity from an SMR would be between A$136 and A$326 (Australian dollars) (about $92 to $220 in U.S. dollars) per megawatt hour.[121]

Recent experience with modular nuclear construction leaves no room for optimism regarding cost or schedule. Modular construction was a central aspect of the design of the AP1000 pressurized water reactor, yet the AP1000 reactors built in the United States have experienced significant construction cost overruns and schedule delays. As a former member of the Georgia Public Service Commission told the *Wall Street Journal*, "Modular construction has not worked out to be the solution that the utilities promised."[122]

Some SMR proponents suggest that nuclear power might provide a suitable complement to wind or photovoltaic power.[123] But nuclear reactors, whether small or large, are not economically suitable for responding to variability because they have high fixed (capital) costs and low variable (fuel) costs. This is why nuclear power plants have been used as a baseload electricity source; it spreads out the fixed costs over the largest number of kilowatt-hours, making each one cheaper. Responding to variability will mean operation at partial load for much of the time, raising costs per unit of electricity. For instance, the cost per unit of electricity from a NuScale SMR would rise by about 20 percent if the capacity factor is reduced from 95% to 75%.[124]

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[120] INTEGRATED RESOURCE PLAN 2019, IDAHO POWER, Appendix C (2020), https://www.idahopower.com/energy-environment/energy/planning-and-electrical-projects/our-twenty-year-plan/.

[121] *Renewables Remain Cheapest, but Cost Reductions on Hold*, COMMONWEALTH SCI. AND INDUS. RSCH. ORG. (July 11, 2022), https://www.csiro.au/en/news/news-releases/2022/gencost-2022.

[122] Rebecca Smith, *Prefab Nuclear Plants Prove Just as Expensive*, WALL ST. J. (July 27, 2015), http://www.wsj.com/articles/pre-fab-nuclear-plants-prove-just-as-expensive-1438040802.

[123] Jay Surina & Mike McGough, *The NuScale Value Proposition: Simple, Safe, Economic* (2015); D.T. Ingersoll et al., *Can Nuclear Power and Renewables be Friends?*, *in* PROCEEDINGS OF ICAPP 2015 (2015).

[124] *See* M. V. RAMANA, EYES WIDE SHUT: PROBLEMS WITH THE UTAH ASSOCIATED MUNICIPAL POWER SYSTEMS PROPOSAL TO CONSTRUCT NUSCALE SMALL MODULAR NUCLEAR REACTORS (Phys. for Soc. Resp., 2020), https://www.oregonpsr.org/small_modular_reactors_smrs.

Duke Energy proposes to rely on the load-following capabilities of some new reactor designs in its Carbon Plan:

> Advanced nuclear describes the next generation of reactor technologies that have significant potential to perform as zero-emitting load-following resources ("ZELFR"), which will be *critically important* as Duke Energy continues to develop more renewable resources in the Carolinas to achieve the energy transition and the CO2 emissions reductions target set by HB 951.[125]

Given the already poor economic prospects for SMRs, the load-following cost penalty would inflict additional costs on North Carolina ratepayers; these costs are not evident in the Duke Energy Carbon Plan because all four portfolios contain almost the same amount of nuclear capacity. This illustrates, in yet another way, the importance of developing more varied portfolios in the Carbon Plan, so that that a real least cost approach may become evident, within the constraints of decarbonization and reliability.

VII. Duke Energy's Carbon Plan Proposes Four Reactor Designs that are Not Ready for Use: Prospects for Small Modular Reactor Designs

Duke Energy lists four reactor designs that it describes as "four new advanced nuclear plants scheduled to be built and in commercial operation by the end of this decade: two SMRs and two advanced reactors."[126] These include two light water reactors—the NuScale Pressurized Water Reactor and the BWRX-300 Boiling Water Reactor—and the Natrium sodium cooled fast reactor and the X-energy high temperature gas cooled reactor. Below, we briefly describe their status and potential problems with each.

The design of the SMR chosen by Duke Energy is not specified in the Carbon Plan but is described as a "285 MW Small Modular Reactor."[127] The specified output most closely matches GE Hitachi's BWRX-300. This design was developed by GE-Hitachi (GE-Hitachi Nuclear Energy in the United States and Hitachi-GE Nuclear Energy in Japan) and has a thermal power output of 870 MW(t) and an electrical capacity of

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[125] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix L at 5.
[126] *Id.* at Appendix L at 9.
[127] *Id.* at Chapter 3 at 10.

270 to 290 MW(e).[128] This is a relatively new SMR; its conceptual design only started in 2017.[129] In 2018, GE-Hitachi Nuclear Energy (GEH) was awarded $1.9 million by the US Department of Energy ("DOE") for research and development.[130]

The BWRX-300 is based on GE-Hitachi's Economical Simplified Boiling Water Reactor ("ESBWR") design, which was submitted for licensing to the NRC in 2005.[131] That design was changed nine times; the NRC finally approved revision 10 of the ESBWR design that was submitted in 2014.[132] This was after GE-Hitachi "agreed to pay the US government $2.7 million to settle allegations that it made false claims to both the [NRC] and the [DOE]" about the safety of its steam dryer.[133] The ESBWR design was never constructed anywhere in the world.

The BWRX-300, too, has never been constructed anywhere in the world. Indeed, it has not even been licensed for construction, and the design has not even been submitted for formal certification to any national safety regulator.[134] The preliminary nature of the design and the history of problems with the ESBWR suggest that the BWRX-300 is unlikely to be ready for operation by 2032. For the same reasons, it is not possible to reliably estimate the cost of constructing a BWRX-300.

The NuScale SMR is arguably the design that is most developed in the United States, since it is the only one that is fairly advanced in its safety review by the NRC. The design began as the outcome of the Multi-Application Small Light Water Reactor

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128 INT'L ATOMIC ENERGY AGENCY, ADVANCES IN SMALL MODULAR REACTOR TECHNOLOGY DEVELOPMENTS: A SUPPLEMENT TO: ADVANCED REACTORS INFORMATION SYSTEM (ARIS) 2020 EDITION 93 (2020).
129 *Id.* at 96.
130 *GEH Receives Federal Funds for BWRX300 Development*, WORLD NUCLEAR NEWS (July 17, 2018), https://www.world-nuclear-news.org/NN-GEH-receives-federal-funds-for-BWRX-300-development-1707184.html.
131 David B. Matthews, *Acceptance of the General Electric Company Application for Final Design Approval and Standard Design Certification for the Economic Simplified Boiling Water Reactor (ESBWR) Design*, (2005), https://www.nrc.gov/docs/ML0532/ML053200311.pdf.
132 *GE-Hitachi ESBWR Design Control Document Tier, Revision 10.*, U.S. NUCLEAR REGULATORY COMM'N (2014), https://www.nrc.gov/docs/ML1410/ML14104A929.html.
133 *GEH to Pay $2.7 Million to US in ESBWR False Claims Case*, NUCLEAR INTELLIGENCE WEEKLY, (Jan. 24, 2014).
134 It is undergoing pre-application review at the NRC and a pre-licensing vendor design review at the CNSC. *See New Reactors: GEH BWRX-300*, U.S. NUCLEAR REGULATORY COMM'N (2022), https://www.nrc.gov/reactors/new-reactors/smr/bwrx-300.html; *Canadian Pre-Licensing Review Starts for BWRX-300*, WORLD NUCLEAR NEWS (May 22, 2019), https://world-nuclear-news.org/Articles/Canadian-pre-licensing-review-starts-for-BWRX-300.

project that was funded by the DOE to "develop the conceptual design for a safe and economic plant and to test the design feasibility."[135] It resulted in a design for a plant with a net electrical output of 35 megawatts.

Subsequently, the design output of the reactor was increased to 40 MW in 2009, and these modules were, according to NuScale, "expected to cost about $4,000 per kW . . . translating to $160 million apiece."[136] By the time NuScale submitted its design certification application on December 31, 2016, the power output was increased again and NuScale described its design as capable of producing "50 megawatts of electricity. A NuScale power plant can house up to 12 of these modules for a total facility output of 600 megawatts (gross)."[137] A year and a half after the application had been submitted to the NRC, NuScale announced that it had modified the design again and that it was now capable of producing 60 MW of electricity.[138] Finally, in November 2020, NuScale again increased its design output to 77 MW of electricity.[139] It is this revised design that is in the early stages of being evaluated by the NRC.[140]

The potential deployment of NuScale has been delayed significantly. In 2008, NuScale officials announced that "a NuScale plant could be producing electricity by 2015-16."[141] By 2010, NuScale was hoping "to have its first reactor online in 2018."[142] As of July 2022, NuScale projects that its first module will begin generating energy in

[135] S. M. MODRO ET AL., MULTI-APPLICATION SMALL LIGHT WATER REACTOR FINAL REPORT (2003), https://www.osti.gov/biblio/839135.
[136] Small-Scale Nuclear Co. Hunts For Funds., POWER FINANCE & RISK, April 3, 2009.
[137] *NuScale Submits First Ever Small Modular Reactor Design Certification Application (DCA)*, NUSCALE NEWSROOM (Jan. 12, 2017), http://newsroom.nuscalepower.com/press-release/company/nuscale-submits-first-ever-small-modular-reactor-design-certification-application.
[138] *Breakthrough for NuScalePower: Increase in Its SMR Output Delivers Customers 20 Percent More Power*, NUSCALE NEWSROOM (June 6, 2018), https://newsroom.nuscalepower.com/press-releases/news-details/2018/Breakthrough-for-NuScale-Power-Increase-in-Its-SMR-Output-Delivers-Customers-20-Percent-More-Power/default.aspx.
[139] Sonal Patel, *NuScale Boosts SMR Module Capacity; UAMPS Mulls Downsizing Nuclear Project*, POWER MAG. (Nov. 11, 2020), https://www.powermag.com/nuscale-boosts-smr-module-capacity-uamps-mulls-downsizing-nuclear-project/.
[140] *Standard Design Approval (SDA) Application – NuScale US 460,* U.S. NUCLEAR REGULATORY COMM'N (2021), https://www.nrc.gov/reactors/new-reactors/smr/nuscale-720-sda.html.
[141] *See* Paul Lorenzini & Jose N. Reyes, *Power Plant Design - Compact and Bijou: A New Approach to Design*, 53 NUCLEAR ENG'G INT'L 14 (2008).
[142] Wayne Barbe, *NuScale Sees Large Upside in Small Nuclear Units*, SNL ENERGY POWER DAILY (2010).

mid-2029 and the remaining modules will come online by 2030.[143] Thus, if the current schedule is met, it would represent a delay of 13 to 14 years over the original potential date.

Even that much delayed date is highly uncertain because the NRC's Advisory Committee on Reactor Safeguards has identified serious safety concerns that will have to be addressed before any utility applies for permission to construct an SMR.[144] These concerns include a critical component: the steam generator. Steam generators have routinely been replaced prematurely in pressurized water reactors. The NuScale design is also a pressurized water reactor design. However, there is one major difference: in the NuScale design, the steam generator is inside the reactor vessel rather than outside, as it is in present day designs. This could be especially problematic if steam generators have to be replaced prematurely in a NuScale reactor. In fact, it may not be possible to replace them at all. In Appendix L to Duke Energy's Carbon Plan, Duke Energy refers to the NuScale design as having "[r]eceived design certification approval from the NRC in August 2020."[145] It makes no mention of the safety reservations or the steam generator vulnerabilities that could pose cost and reliability problems if this design is adopted. The difficulties and hurdles in the NuScale certification process should also give pause regarding prospects for certification of reactors that have not even submitted applications to the U.S. NRC.

Design changes have also been a frequent source of delay in licensing estimates throughout the history of nuclear power. In the case of the AP1000 reactors constructed in Sanmen, China, because of design changes carried out after construction had started, "Westinghouse had to rip out equipment that had already been installed and

[143] NuScale Power, *United States*, CURRENT PROJECTS (2022), https://www.nuscalepower.com/Projects/Current-Projects/United-States.
[144] NRC, *supra* note 59; Michael McAuliffe, *NRC raises questions about NuScale design, delays interim review milestone*, 61 NUCLEONICS WEEK, 2020; Advisory Committee on Reactor Safeguards, *NuScale Area of Focus - Helical Tube Steam Generator Design*, (2020), https://www.nrc.gov/docs/ML2009/ML20091G387.pdf; Advisory Committee on Reactor Safeguards, *NuScale Area of Focus - Probabilistic Risk Assessment and Emergency Core Cooling System Valve Performance*, (2020), https://www.nrc.gov/docs/ML2014/ML20149K596.pdf.
[145] CAROLINAS CARBON PLAN, *supra* note 3, at Appendix L at 8.

start again or undertake lengthy re-examinations of engineering work."[146] Likewise, in the case of the AP1000 reactors constructed in Georgia and South Carolina, a major source of delay and cost overruns was blamed on Westinghouse because "'several thousand' technical and design changes [were] made after work had already started on various components."[147]

NuScale has also followed a familiar pattern of cost escalations. The estimated cost of the Utah Association of Municipal Power Systems project went from approximately $3 billion in 2014 to $6.1 billion in 2020—this was to build twelve units of the NuScale SMR that were to generate 600 megawatts of power.[148] The cost was so high that NuScale had to change its offering to a smaller number of units that would produce only 462 megawatts at a cost of $5.32 billion.[149] In other words, the cost per kilowatt of generation capacity is around $11,500 (US dollars). That figure is around 80% more than the per kilowatt cost of the Vogtle project at the time its construction started. Since then, the estimated cost of the much delayed project has more than doubled.

Given the lack of full certification, the resolution of pending safety concerns, and the history of new construction illustrated by the reactors proposed in the "nuclear renaissance," it would be prudent to assume that if and when a NuScale SMR is built, its final costs may well exceed even the high current official estimates.

The other two "advanced" reactor designs use unusual fuel designs (like uranium coated in silicon carbide), moderators (like graphite), and coolants (helium and liquid sodium). Both reactor design types have had significant problems in the past.

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[146] Brian Spegele, *Troubled Chinese Nuclear Project Illustrates Toshiba's Challenges*, WALL ST. J. (Dec. 29, 2016), https://www.wsj.com/articles/troubled-chinese-nuclear-project-illustrates-toshibas-challenges-1483051382.
[147] Tom Hals & Emily Flitter, *How Two Cutting Edge U.S. Nuclear Projects Bankrupted Westinghouse* REUTERS (May 2, 2017), https://www.reuters.com/article/us-toshiba-accounting-westinghouse-nucle-idUSKBN17Y0CQ.
[148] Mike McGough, *Testimony at the House of Representatives Subcommittee on Energy* (2014), https://docs.house.gov/meetings/SY/SY20/20141211/102803/HHRG-113-SY20-20141211-SD007.pdf; Adrian Cho, *Several U.S. Utilities Back Out of Deal to Build Novel Nuclear Power Plant*, SCI. (Nov. 4, 2020), https://www.sciencemag.org/news/2020/11/several-us-utilities-back-out-deal-build-novel-nuclear-power-plant.
[149] Douglas O. Hunter, *Why the World is Watching Utah's Carbon Free Power Project*, THE SALT LAKE TRIBUNE (Nov. 23, 2021), https://www.sltrib.com/opinion/commentary/2021/11/23/douglas-o-hunter-why/.

Of the two advanced reactor designs, there is more experience with sodium-cooled reactors. Countries around the world have together spent tens of billions of dollars since 1950 on this design, yet these vast expenditures across the world, including the United States, France, and Japan, have not resulted in a commercially viable design. Prototypes and demonstration plants have generally had high construction costs, experienced operational problems, and frequently suffered early closure.[150] Leaks of sodium coolant are a pervasive problem. Leaks have occurred in sodium-cooled reactors in Russia, France, India, the United States, and Japan, and there may be metallurgical reasons for why such leaks occur persistently.[151] Sodium catches fire on contact with air—a problem that, for instance, prematurely shut down Japan's Monju reactor.[152] None of these problems of sodium-cooled reactors are discussed in Appendix L of Duke Energy's Carbon Plan.[153]

High Temperature Gas-cooled Reactors also have a long, troubled history. Four commercial units of this type were built over the decades in Germany and the United States. All underwent a variety of small failures and unplanned events, including fuel failures and ingress of water or oil. As a result, these reactors were all shut down early, with operational lifetimes of only 7 and 10 years for the US Peach Bottom and Fort St. Vrain reactors, respectively, and 1 and 20 years for the German THTR and AVR Jülich reactors, respectively.[154]

Proponents argue that high-temperature gas-cooled reactors are not capable of melting down. However, there are serious accident risks associated with air and water ingress accidents, and there is considerable uncertainty about the behavior of these

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150 *History and Status of Fast Breeder Reactor Programs Worldwide*, INT'L PANEL ON FISSILE MATERIALS (Feb. 17, 2010), https://fissilematerials.org/blog/2010/02/history_and_status_of_fas.html.
151 *See* J. Guidez et al., *Lesson Learned From Sodium-Cooled Fast Reactor Operation and Their Ramification for the Reactors With Respect to Enhanced Safety and Reliability*, 164 NUCLEAR TECH. 207 (2008); S. Rajendran Pillai & M. V. Ramana, *Breeder Reactors: A Possible Connection Between Metal Corrosion and Sodium Leaks*, 70 BULL. AT. SCI. 49 (2014).
152 ARJUN MAKHIJANI, *Traveling Wave Reactors: Sodium-cooled Gold at the End of a Nuclear Rainbow?*, (2013), https://ieer.org/wp/wp-content/uploads/2013/09/TravelingWaveReactor-Sept20131.pdf; *History and Status of Fast Breeder Reactor Programs Worldwide*, INT'L PANEL ON FISSILE MATERIALS (Feb. 17, 2010), https://fissilematerials.org/blog/2010/02/history_and_status_of_fas.html.
153 CAROLINAS CARBON PLAN, *supra* note 3, at Appendix L.
154 *See* M. V. Ramana, *The Checkered Operational History of High Temperature Gas Cooled Reactors*, 72 BULL. AT. SCI. 171 (2016).

reactors under accident conditions.[155] Further, graphite is susceptible to fires, as occurred at the United Kingdom's Windscale graphite-moderated gas-cooled reactor in 1957, which released radioactive isotopes into the atmosphere, including 1800 terabecquerel (TBq) of iodine 131 and 180 TBq of cesium 137.[156]

As with the problems and difficulties that sodium-cooled reactors have experienced, Appendix L of Duke Energy's Carbon Plan does not discuss the serious issues with high-temperature gas cooled reactors.

VIII. Conclusion

The high cost and low reliability of nuclear power as compared to other low carbon energy alternatives should eliminate new nuclear energy generation from inclusion in any least cost path toward carbon reduction goals. Nuclear reactors are particularly ill-suited to serve as a complement to wind or photovoltaic power generation. High fixed (capital) costs and low variable (fuel) costs drive energy unit costs higher if operated as a variable complement to other energy generation. Finally, all the available evidence, historical experience, and theoretical reasons indicate that small modular reactors are very likely to accentuate the economic problems of nuclear power.

Arjun Makhijani, Ph.D.

M.V. Ramana

M.V. Ramana, Ph.D.

[155] *See* Matthias Englert et al., *Accident Scenarios Involving Pebble Bed High Temperature Reactors*, 25 SCI. GLOB. SECUR. 42 (2017); Rainer Moormann, *Phenomenology of Graphite Burning in Air Ingress Accidents of HTRs*, 2011 SCI. TECHNOL. NUCL. INSTALL. 1 (2011); RAINER MOORMANN, A SAFETY RE-EVALUATION OF THE AVR PEBBLE BED REACTOR OPERATION AND ITS CONSEQUENCES FOR FUTURE HTR CONCEPTS (2008).

[156] *See* J. A Garland & R. Wakeford, *Atmospheric Emissions from the Windscale Accident of October 1957*, 41 ATMOS. ENVIRON. 3904 (2007).

EXHIBIT 1

INSTITUTE FOR ENERGY AND ENVIRONMENTAL RESEARCH
Democratizing science to protect health and the environment

Curriculum Vita of Arjun Makhijani

Arjun Makhijani is President of the Institute for Energy and Environmental Research in Takoma Park, Maryland. He earned his Ph.D. from the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley in 1972, specializing in nuclear fusion.

Dr. Makhijani is the author and co-author of numerous reports and books on energy and environment related issues. He has done extensive work on nuclear and renewable energy as well as on the health and environmental impacts of nuclear weapons production and testing. He is also author or co-author of reports and analyses of radionuclides emissions from nuclear weapons facilities, radiological conditions at nuclear production and testing sites, worker exposures, and the risks of radiation exposure. His recent work on renewable energy, *Prosperous, Renewable Maryland*, includes hour-by-hour modeling of the Maryland electricity sector and energy justice in a transition to renewable energy. He is principal editor and co-author of *Nuclear Wastelands: A Global Guide to Nuclear Weapons Production and Its Health and Environmental Effects*, (MIT Press, 1995 and 2000). He published articles in journals and other media as varied as *The Bulletin of the Atomic Scientists, Environment*, *The Physics of Fluids*, and the *Washington Post*.

Since 2004, he has served on a team to provide scientific support to the Advisory Board on Radiation and Worker Health. He has served as a consultant on energy issues to utilities, including the Tennessee Valley Authority, the Edison Electric Institute, the Lawrence Berkeley Laboratory, and several agencies of the United Nations.

In 2007, he was elected Fellow of the American Physical Society, an honor granted each year to at most half-a-percent of the Society's members. He was named a Ploughshares Hero, by the Ploughshares Fund (2006); was awarded the Jane Bagley Lehman Award of the Tides Foundation in 2008 and the Josephine Butler Nuclear Free Future Award in 2001; and in 1989 he received The John Bartlow Martin Award for Public Interest Magazine Journalism of the Medill School of Journalism, Northwestern University, with Robert Alvarez.

Dr. Makhijani has testified before Congress, and has appeared on ABC World News Tonight, the CBS Evening News, CBS 60 Minutes, NPR, CNN, and BBC, among others. He has served as a consultant on energy issues to utilities, including the Tennessee Valley Authority, the Edison Electric Institute, the Lawrence Berkeley Laboratory, and several agencies of the United Nations.

Education

- Ph.D. University of California, Berkeley, 1972, from the Department of Electrical Engineering. Area of specialization: plasma physics as applied to controlled nuclear fusion. Dissertation topic: multiple mirror confinement of plasmas. Minor fields of doctoral study: statistics and physics.
- M.S. (Electrical Engineering) Washington State University, Pullman, Washington, 1967. Thesis topic: electromagnetic wave propagation in the ionosphere.
- Bachelor of Engineering (Electrical), University of Bombay, Bombay, India, 1965.

Current Employment

- 1987-present: President, Institute for Energy and Environmental Research, Takoma Park, Maryland. (part-time in 1987).

Other Long-term Employment

- 2014: 2018: Associate, SC&A, Inc., one of the principal members of an SC&A team providing technical support to the Advisory Board on Radiation and Worker Health regarding the reconstruction of worker radiation doses under the Energy Employees Occupational Illness Compensation Program Act (under contract to the Centers for Disease Control and Prevention, U.S. Department of Health and Human Services)
- 1984-88: Associate Professor, Capitol College, Laurel, Maryland (part-time in 1988).
- 1983-84: Assistant Professor, Capitol College, Laurel, Maryland.
- 1977-79: Visiting Professor, National Institute of Bank Management, Bombay, India. Principal responsibility: evaluation of the Institute's extensive pilot rural development program.
- 1975-87: Independent consultant (see page 3 for details)
- 1972-74: Project Specialist, Ford Foundation Energy Policy Project. Responsibilities included research and writing on the technical and economic aspects of energy conservation and supply in the U.S.; analysis of Third World rural energy problems; preparation of requests for proposals; evaluation of proposals; and the management of grants made by the Project to other institutions.
- 1969-70: Assistant Electrical Engineer, Kaiser Engineers, Oakland California. Responsibilities included the design and checking of the electrical aspects of mineral industries such as cement plants, and plants for processing mineral ores such as lead and uranium ores. Pioneered the use of the desk-top computer at Kaiser Engineers for performing electrical design calculations.

Professional Societies

- Institute of Electrical and Electronics Engineers and its Power Engineering Society
- American Physical Society (Elected a Fellow in 2007)
- Health Physics Society
- American Association for the Advancement of Science

Awards and Honors

- The John Bartlow Martin Award for Public Interest Magazine Journalism of the Medill School of Journalism, Northwestern University, 1989, with Robert Alvarez
- The Josephine Butler Nuclear Free Future Award, 2001
- Ploughshares Hero, Ploughshares Fund, 2006

- Elected a Fellow of the American Physical Society, 2007, "*For his tireless efforts to provide the public with accurate and understandable information on energy and environmental issues*"
- Jane Bagley Lehman Award of the Tides Foundation, 2007/2000

Advisory Groups and Committees

- December 2021-present: Member of the Panel of Independent Global Experts on Nuclear Issues appointed by the Pacific Islands Forum.
- 2015-present: Member, Mitigation Working Group of the Maryland Commission on Climate Change
- 2013-present: Member, Advisory Council, Maryland Clean Energy Center, 2013-2015
- 1992-1994: Committee Member, Radiation Advisory Committee, Science Advisory Board, U.S. Environmental Protection Agency
- 2006: Invited Faculty Member, Center for Health and the Global Environment, Harvard Medical School: Annual Congressional Course, Environmental Change: The Science and Human Health Impacts, April 18-19, 2006, Lecture Topic: An Update on Nuclear Power - Is it Safe?

Consulting Experience, 1975-1987

Consultant on a wide variety of issues relating to technical and economic analyses of alternative energy sources; electric utility rates and investment planning; energy conservation; analysis of energy use in agriculture; US energy policy; energy policy for the Third World; evaluations of portions of the nuclear fuel cycle.

Partial list of institutions to which Arjun Makhijani was a consultant in the 1975-87 period:

- Tennessee Valley Authority
- Lower Colorado River Authority
- Federation of Rocky Mountain States
- Environmental Policy Institute
- Lawrence Berkeley Laboratory
- Food and Agriculture Organization of the United Nations
- International Labour Office of the United Nations
- United Nations Environment Programme
- United Nations Center on Transnational Corporations
- The Ford Foundation
- Economic and Social Commission for Asia and the Pacific
- United Nations Development Programme

Languages

- English, French, Hindi, Sindhi, and Marathi

Publications -- Reports, Books, and Articles (Partial list)

(Newsletter articles, most newspaper articles, excerpts from publications reprinted in books and magazines or adapted therein, and other similar publications are not listed below. Numerous reports authored or co-authored since 2004 and prepared for the Advisory Board on Radiation and Worker Health not listed below.)

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EXHIBIT 2

CURRICULUM VITAE

M. V. Ramana
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Liu Institute for Global Issues
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EMPLOYMENT

Simons Chair in Disarmament, Global and Human Security, Liu Institute for Global Issues, School of Public Policy and Global Affairs, University of British Columbia	January 2017 onwards
Professional Specialist, Program in Science and Global Security, Princeton University Researching issues related to nuclear power, nuclear proliferation and climate change	July 2012 – December 2016
Associate Research Scholar, Program in Science and Global Security, Princeton University Researching issues related to nuclear power, nuclear proliferation and climate change	November 2009 – June 2012
Lecturer, Woodrow Wilson School of Public and International Affairs Designed and taught courses related to energy, environment and development, and nuclear power for Masters students and Freshmen	March 2010 – May 2012, Fall 2013, Fall 2014, Spring 2016
Visiting Research Scholar, Program in Science, Technology, and Environmental Policy, Woodrow Wilson School of Public and International Affairs, Princeton University Researching issues related to nuclear power and climate change	May 2009 – November 2009
Senior Fellow, Centre for Interdisciplinary Studies in Environment and Development, Bangalore	April 2007 – April 2009
Fellow, Centre for Interdisciplinary Studies in Environment and Development, Bangalore	April 2004 – April 2007

Researched economic and environmental aspects of India's nuclear energy program

Research Staff, Program on Science and Global Security, Princeton University	September 2001 – March 2004

Researched global nuclear disarmament and India's nuclear weapons and energy programs

Lecturer, Woodrow Wilson School of Public and International Affairs, Princeton University	September 2001 – February 2002

Lectured and conducted precepts for a course on Methods in Science, Technology, and Environmental Policy

Lecturer, Yale Center for International and Area Studies, Yale University	August 2001 – December 2001

Designed and taught course on Science, Technology, and Development in India

Research Associate, Center for Energy and Environmental Studies, Princeton University — September 1998 – August 2001

Conducted research on technical aspects of nuclear disarmament and India's nuclear weapons and energy programs; influence of scientists on nuclear policy

Lecturer, Woodrow Wilson School of Public and International Affairs, Princeton University — February 1999 – July 1999

Gave lectures and conducted precepts for a course on Science, Technology, and Public Policy

Post-doctoral Fellow, Security Studies Program, Massachusetts Institute of Technology — August 1996 – August 1998

Conducted research on technical aspects of nuclear weapons and disarmament, Indian ballistic missiles, and India's nuclear policy

Post-doctoral Fellow, Physics Department, University of Toronto — September 1994 - July 1996

Conducted theoretical research on tests of particle physics models at accelerator experiments

Research Fellow, Physics Department, Boston University — June 1989 – August 1994

Conducted research on phenomenological aspects of electroweak symmetry breaking

EDUCATION

Boston University, Ph.D., Physics, September 1994 — Thesis Advisor: Kenneth D. Lane

Thesis Title: "Phenomenological Aspects of Electroweak Symmetry Breaking"

Indian Institute of Technology, Kanpur, M.Sc. Physics, May 1988

HONORS, AWARDS, PROFESSIONAL SERVICE

Member, International Nuclear Risk Assessment Group, since 2018

Member, Canadian Pugwash Group, since 2018

Member, Team of Editors, *Journal of Peace and Nuclear Disarmament*, since 2017

Member, Editorial Board, *Science and Global Security*, since 2017

Distinguished Lecturer, Sigma Xi Society, 2017-18

Leo Szilard Award, American Physical Society, 2014

Member, International Panel on Fissile Materials, since 2005

Member, Science and Security Board of the Bulletin of Atomic Scientists, 2008-2014

Member, Editorial Board, *Energy Research and Social Science*, since 2015

Robert Jay Lifton Fellowship, John Jay College of Criminal Justice, City University of New York, 2005

Guggenheim Fellowship, 2003

Member, Selection Committee, Global Security and Cooperation Program, Social Sciences Research Council, 2000-01

MacArthur Foundation Research and Writing Grant, 1999

SSRC-MacArthur Fellowship for International Research on Peace and Security, 1999

SSRC-MacArthur Post-doctoral Fellowship on Peace and Security in a Changing World, 1996

National Talent Search Scholarship, 1981 -1988

Reviewed papers for several journals including *Bulletin of the Atomic Scientists, Climate Policy*, *Energy Policy*, *Journal of Environment and Development*, *Environmental Politics, Journal of Risk Research, Energy Strategy Reviews, Economic and Political Weekly*, and *Energy for Sustainable Development.*

PUBLICATIONS

Refereed Publications

Journal Articles

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PROFESSIONAL MEETINGS

- Invited Participant, Conference on Canada and the Treaty on the Prohibition of Nuclear Weapons, Convened by Canadians for a Nuclear Weapons Convention, Ottawa, November 29-30, 2021

- "Nuclear Power and Climate Change; The Case for Skepticism," Presentation at Conference on Nuclear Energy and Climate Strategy, The University of North Carolina at Chapel Hill, November 18 -19, 2021

- "Hype about Small Modular Reactors," Presentation at 2021 Fall Meeting of the International Risk Assessment Group (online), September 18, 2021

- "The nuclear industry's record of public engagement" presentation at online workshop on Understanding the Societal Challenges Facing Nuclear Power, National Academies of Sciences, Engineering, and Medicine, September 1, 2021

- "NuScale Small Modular Reactor," Presentation at 2020 Fall Meeting of the International Risk Assessment Group (online), September 18-19, 2020

- Invited participant, Expert Meeting to facilitate the participation of African and Asian States in the Fissile material Cut-off Treaty (FMCT) consultative process, Bangkok, Thailand, December 17-18, 2019

- "Small Modular Nuclear Reactors: Claims and Challenges," Workshop on Nuclear Power in Canada: Strategy Session, Canadian Environmental Law Association, October 25, 2019

- "The Nuclear Arms Race in South Asia: Capabilities and Dangers," Presentation at Conference on "Speeding Towards the Abyss: Contemporary Arms Racing and Global Security", Centre for International Policy Studies and Canadian Pugwash Group, University of Ottawa, September 26, 2019.

- "Military Conflicts Under the Nuclear Umbrella: India, Pakistan and Kashmir," Canadian Peace Research Association Conference, Vancouver, June 5, 2019

- "Puzzling over nuclear energy," Workshop on The Future of Nuclear Studies, University of British Columbia, June 3, 2019

- "Fissile Material Production Estimates for India," Presentation at Meeting of the International Panel on Fissile Materials, Princeton, May 5, 2019

- "India and Hiroshima/Nagasaki," Workshop on Global Hiroshima and Nagasaki, *SciencesPo*, November 13, 2018

- "Nuclear energy: Is decline inevitable?," Presentation as part of a panel on "The role of nuclear in the global energy transition: up, down, or out?" at the American Political Science Association Annual Meeting, Boston, September 1, 2018

- "Challenges in Assessing and Regulating Risk: The Case of the AP1000 Nuclear Reactor," Presentation at the Thirtieth International Summer Symposium on Science and World Affairs, Vancouver, July 6, 2018

- "Fissile Material Production in India," Presentation at Meeting of the International Panel on Fissile Materials, Seoul, South Korea, April 14, 2018

- "Challenges of Small Modular Reactors," Presentation at Panel on "Emerging Technologies for Small-scale Grids", Singapore International Energy Week, Singapore, October 27, 2017

- "Nuclear Energy and Nuclear Disarmament: Can the two co-exist?," Presentation at the Gathering in the Shadows of a Nuclear Winter Conference, South Asian Network for Secularism and Democracy and Institute for the Humanities, Simon Fraser University, Vancouver, September 9, 2017

- "Global and Regional Economics of Nuclear and Renewable Energy," Presentation at Workshop on The Future of Nuclear Energy in the Middle East, International Panel on Fissile Materials and American University of Beirut, Beirut, March 15, 2017

- "Nuclear Energy in Saudi Arabia: Necessary? Economically Competitive?," Presentation at NPEC Public Policy Fellowship Retreat, Nonproliferation Policy Education Center, Washington, D.C., March 4, 2017

- "Linkages Between Nuclear Energy and Nuclear Weapons," Presentation (over Skype) at Workshop on The Nuclear-Climate Nexus and Sustainable Peace, International Peace Bureau World Congress, Berlin, October 1, 2016

- "Emerging Reactor and Fuel Cycle Technologies, Including Associated Safety, Security, and Safeguards Risks," Presentation at Workshop on Managing Risks Associated with Global Nuclear Energy Expansion: Emerging Challenges and Cooperative Solutions, George Washington University, Washington, D. C., May 5, 2016

- "Reprocessing and Breeder Reactors: The Case of India," Presentation at Meeting of the International Panel on Fissile Materials, American Association for the Advancement of Science, Washington, D. C., March 14-15, 2016

- "Ethical Concerns Regarding Nuclear Energy: Weapons, Accidents, Wastes, Costs, and Democracy," Workshop on Ethics and Governance of Energy Technologies, Eindhoven University of Technology, Netherlands, January 15, 2016

- Co-convenor, Working Group on "Civilian Nuclear Energy, Energy Resources, and International Cooperation," 61st Pugwash Conference on Science & World Affairs, Nagasaki, Japan, November 1-5, 2015

- "Small Modular Reactors in the United States," Workshop on Nuclear Power And Small Modular Reactors In Indonesia: Potential And Challenges, Indonesian Institute of Energy Economics, Jakarta, June 25, 2015

- "The Challenges of Nuclear Safety," International Workshop on Emerging Energy Scenarios in the Middle East, Munib and Angela Masri Institute of Energy and Natural Resources,American University, Beirut, May 22, 2015

- "Accident Risks for High Temperature Reactors," 1st International Conference on Nuclear Risks, Vienna, April 16-17, 2015

- "Taking Sides on the 'Double Movement'," Polanyi Conference on Science and Social Responsibility, University of Toronto, November 15, 2014

- "Nuclear Power in Today's Energy and Environmental Discourse," Workshop on New Studies in Ecology and Environment, New Delhi, India, August 23, 2014

- "Liability" and "Waste Management," two talks at Workshop on Nuclear Power in East Asia: The Costs and Benefits, Australian National University, Canberra, Australia, August 12-14, 2014

- "The State of the SMR Market," Third Trilateral Meeting, Carnegie Mellon University, Pittsburgh, May 8-9, 2014

- "Arguing from the Periphery," American Physical Society Annual Meeting, Savannah, GA, April 6, 2014

- "Resource Requirements and Proliferation Risks Associated with Small Modular Reactors," Panel on Opportunities and Challenges for Nuclear Small Modular Reactors, American Association for the Advancement of Science Annual Meeting, Chicago, February 15, 2014

- "Global Context for Nuclear Power," Conference on Nuclear Technology, Nuclear Energy and a ME WMD-free Zone, Doha, Qatar, October 27, 2013
- "The Impact of Fukushima and Chernobyl on India's Anti-Nuclear Movements," Conference on Traveling Norms and the Politics of Contention, Zurich, Switzerland, October 25, 2013
- "Small Modular Reactors: Uranium Resource Requirements, Waste Generation and Proliferation Risk Assessment," Presentation at the 21st International Conference on Nuclear Engineering, Chengdu, China, July 29-August 2, 2013
- "Fukushima Nuclear Accident: Shortcomings of Safety Regulation and Lessons Learned," Panel Discussion at the Carnegie International Nuclear Policy Conference, Washington, D.C., April 8, 2013
- "Whither Nuclear Power?" Panel Discussion at the Carnegie International Nuclear Policy Conference, Washington, D.C., April 8, 2013
- "'One in infinity': Assessing Nuclear Risks in India," Presentation at the Panel on "India at Risk: Capacity, Institutions and Expertise", Society for Risk Analysis 2012 Annual Meeting, San Francisco, December 12, 2012
- "How about Domestic Emission Inequities? The Case of India," Presentation at the International Conference on Inequality and Sustainability, Stockholm Environmental Institute & Center for International Environment and Resource Policy, Boston, November 9, 2012
- "Proliferation Risks Associated with Small Modular Reactors," Presentation at the "Summer Symposium on Science and World Affairs", Organized by the Union of Concerned Scientists, Princeton, July 9, 2012
- "India and Nuclear Transparency," Presentation at the Workshop on "Transparency", Organized by the International Panel on Fissile Materials, Princeton, March 31, 2012
- "Nuclear Safety and Security in India," Presentation at the Panel Discussion on Nuclear Policy of Key Countries, Seoul National University, Seoul, South Korea, March 22, 2012
- "Indian Fallout: Public Protest and Organizational Strategies in the Aftermath of the Fukushima Accidents," Presentation at Panel Discussion on Nuclear Energy After Fukushima: Japan and Beyond, Association of Asian Studies Conference, Toronto, March 18, 2012
- "Nuclear Power in India: Implications of Fukushima," Presentation at the Panel on Nuclear Power: One Year after Fukushima, Amecian Physical Society Meeting, Boston, March 1, 2012
- "India's Nuclear Plans: Can they be Realized?," Presentation at the Workshop on "Reprocessing", Organized by the International Panel on Fissile Materials, Tokyo, January 20, 2012
- "Prospects for India's Breeder Program," Presentation at the Workshop on "Nuclear Fuel Cycle Issues in Asia", Organized by the International Panel on Fissile Materials, Tokyo, March 19, 2010
- "Inherently Ambiguous? The Limits of Nuclear Accident Scenarios and Safety Analyses," Meeting on "Knowledge Society Debates", Organized by the STEPS Centre, University of Sussex, National Institute of Advanced Studies, Bangalore, January 8, 2009
- "Some Challenges for Nuclear Power in Developing Countries," Presentation at Conference on "New Generation Nuclear: From policy to implementation," Organized by Chatham House, London, November 17-18, 2008
- "Nuclear Power in India: Perspectives and Challenges," Presentation at Conference on "The nuclear energy revival: regional perspectives and governance challenges," Organized by Centre for

International Governance Innovation & Canadian Centre for Treaty Compliance, Waterloo, November 6-7, 2008

- "More than Desirable: Some Necessary, but not Sufficient, Conditions for Nuclear Expansion," Presentation at the Conference on The Future of Nuclear Energy, Organized by the Bulletin of the Atomic Scientists, Argonne National Laboratory, and the University of Chicago, Chicago, September 25-26, 2008

- "Nuclear Power and Energy Security in India," Presentation at Meeting on "The Proposal for Nuclear Trade with India," Organized by Heinrich Böll Foundation and Arms Control Association, Berlin, May 13, 2008

- "Some Implications of the US-India Nuclear Deal," Presentation at the NGO Panel on "The US-India Nuclear Deal and the NPT," Nuclear Non Proliferation Treaty Preparatory Committee Meeting, United Nations, Geneva, May 2, 2008

- "Fissile Material Implications of the US-India Nuclear Deal," Presentation at the Annual Meeting of the German Physical Society, Berlin, February 29, 2008

- "Nuclear Safety," Presentation at the Centre for Interdisciplinary Studies on Environment and Development Advisory Committee Meeting, Bangalore, January 11, 2008

- "Climate Change and Nuclear Power in Developing Countries," Presentation at "Nuclear Energy: Myth and Reality," Side event at 13th Conference of Parties to the United Nations Framework Convention on Climate Change, Organized by Heinrich Böll Foundation, Nusa Dua, Bali, December 13, 2007

- "Infeasible and Undesirable: A Nuclear Comeback and Climate Security," Presentation at 2nd TERI-KAF Conference on "Energy, Climate, and Security: The Inter-Linkages," Organized by The Energy and Resources Institute and Konrad Adaneur Foundation, Goa, October 13 - 14, 2007

- "Nuclear Reactors: Unsafe at any Price," Presentation at the International Conference on "Indo-US Nuclear Deal," Organized by the Heinrich Böll Foundation, CNDP, and PEACE, New Delhi, August 31-September 1, 2007

- "The U.S. India Nuclear Deal: Debates and Implications," Presentation at the Meeting on "Forging a New Consensus for the NPT," Article VI Forum, Vienna International Center, Vienna, March 29, 2007

- "Nuclear Energy: Projections and Economics," Presentation at Workshop on Power Sector Reforms and Regulation in India, Prayas, Pune, March 22-23, 2007

- "Economic and Environmental Costs of Nuclear Power," Presentation at the Ninth Biennial Conference of the International Society of Ecological Economics, New Delhi, December 16-18, 2006

- "Nuclear Economics in a Developing Country: The Case of India," Presentation at the Conference on The Future of Nuclear Energy, Organized by the Bulletin of the Atomic Scientists, Argonne National Laboratory, and the University of Chicago, Chicago, November 1-2, 2006

- "Nuclear Energy and Climate Change," Presentation at the Workshop for Journalists on Energy and Climate Change, Organized by PANOS South Asia, New Delhi, July 5, 2006

- "Feeding the Nuclear Fire," Presentation at the Conference on International Nuclear Cooperation with India, Simons Centre for Disarmament, University of British Columbia, Vancouver, November 22, 2005

- "India's Nuclear Enclave and the Practice of Secrecy," Presentation at the Second Workshop on "Culture, Society and Nuclear weapons in South Asia," Social Science Research Council, Washington, D.C., August 28-29, 2005

- "An Estimate of India's Uranium Enrichment Capacity," Presentation at the 17th International Summer Symposium on Science and World Affairs, Princeton, July 23-31, 2005
- Discussant, First Workshop on "Culture, Society and Nuclear weapons in South Asia," Social Science Research Council, Amsterdam, May 9-11, 2005
- "Nuclear Power: the Department of Atomic Energy's Plans and Constraints," Presentation at the Consultation Meeting on Strategies to Realize a Non-nuclear India organized by Citizens for Alternatives to Nuclear Energy and Centre for Interdisciplinary Studies in Environment and Development, Bangalore, January 29, 2005
- Coordinator, Environmental Sustainability Group, Workshop on "Neglected Dimensions of Electricity Sector Policies: Equity, Sustainability, and Institutions and Governance," Prayas, Pune, January 11-12, 2005
- "India and Nuclear Secrecy," Presentation at the Conference on "Transparency as a Pre-requisite of Arms Control," Peace Research Institute, Bensheim, November 19-20, 2004
- "Nuclear Energy and Security," Presentation at the Workshop on "The Challenge of Hiroshima: Alternatives to Nuclear Weapons, Missiles, Missile Defenses, and Space Weaponization in a Northeast Asian Context," International Network of Engineers and Scientists Against Nuclear Weapons, Hiroshima, October 8-11, 2004
- "Energy and Environmental Sustainability," Presentation at the National Seminar on Integrating Environmental Sustainability with Economic Development, Maharani's Arts College for Women, Bangalore, August 26, 2004
- "The Cost of Electricity from Indian Pressurised Heavy Water Reactors," Presentation at the Centre for Interdisciplinary Studies on Environment and Development Advisory Committee Meeting, Bangalore, January 12, 2004
- "Effects of Nuclear Explosions," Lecture at the Workshop on "Defence, Technology and Cooperative Security in South Asia", Regional Centre for Strategic Studies, Shanghai, December 3-13, 2003
- "Problems with Nuclear Early Warning Systems in South Asia," Lecture at the Workshop on "Defence, Technology and Cooperative Security in South Asia", Regional Centre for Strategic Studies, Shanghai, December 3-13, 2003
- "Nuclear Weapons Effects," Presentation at the Institute for Energy and Environmental Research Technical Training Workshop, Takoma Park, Maryland, June 19, 2003
- "Nuclear South Asia," Talk at Panel on "War and Public Health," Presentation at the American Public Health Association 130th Annual Meeting & Exposition, Philadelphia, November 11, 2002
- "Under the Nuclear Shadow," Discussion at Middlesex County College, October 31, 2002
- "Dangers of Nuclear War and Paths to Nuclear Weapons Abolition," Presentation at the American Friends Service Committee Conference on "Paths to a Just and Secure Future," Boston, October 11, 2002
- "Nuclear South Asia," Overview Lecture at the 1st International Professional Meeting of Independent Technical Security Analysts, Chicago, July 23-24, 2002
- Invited "Shadow Expert" at the SANITY (Students Against Nuclear Insanity and for Tomorrow's Youth) Youth Caucus at the Nuclear Non Proliferation Treaty Preparatory Committee Meeting, United Nations, New York, April 17, 2002

- "The Arms Race in South Asia," Presentation at the NGO Panel on "The Shape of Things to Come," Nuclear Non Proliferation Treaty Preparatory Committee Meeting, United Nations, New York, April 12, 2002

- "Alternatives to Missile Defense," Briefing for Delegates, NGOs and Press at the Nuclear Non Proliferation Treaty Preparatory Committee Meeting, United Nations, New York, April 11, 2002

- "Effects of Nuclear Explosions and Nuclear War in South Asia," Lecture at the Workshop on "Defence, Technology and Cooperative Security in South Asia", Regional Centre for Strategic Studies, Kalutara, Sri Lanka, January 5-14, 2002

- "Plutonium Dispersal and Health Hazards from Nuclear Weapon Accidents," Lecture at the Workshop on "Defence, Technology and Cooperative Security in South Asia", Regional Centre for Strategic Studies, Kalutara, Sri Lanka, January 5-14, 2002

- "Beyond Missile Defense: Arguments," Presentation at the 13th International Summer Symposium on Science and World Affairs, Berlin, July 21-30, 2001

- "The Missile Race in Critical Regions: Is there a way out?," Presentation at the Workshop on "Moving Beyond Missile Defense", International Network of Engineers and Scientists Against Nuclear Weapons, Santa Barbara, March 19-21, 2001

- "Is there a Missile Threat? The Dynamics of Missile Proliferation and the State of Missile Control," Presentation at the Workshop on "Moving Beyond Missile Defense", International Network of Engineers and Scientists Against Nuclear Weapons, Santa Barbara, March 19-21, 2001

- "Ballistic Missile Disarmament," Presentation at the Panel on "Outer Space: Disarmament Issues," Organized by the NGO Committee on Disarmament, Disarmament Week, United Nations, October 19, 2000

- "Why Nuclear Disarmament," Presentation at the Alliance for Nuclear Accountability Meeting, Amarillo, September 23, 2000

- "Plutonium Dispersion and Health Hazards from Nuclear Weapons Accidents," Presentation at the 12th International Summer Symposium on Science and World Affairs, Moscow, Russia, August 23-31, 2000

- "Scientists and Radiation Protection: A History," Presentation at the NGO Panel on "Health, Environment, Science and Society: Professional Responsibility in the Nuclear Age," Nuclear Non-Proliferation Treaty Review Conference, United Nations, New York, May 15, 2000

- "Environmental Aspects of the Nuclear Fuel Cycle," Presentation at the NGO Panel on "The Toxic Legacy of the Nuclear Age," Nuclear Non-Proliferation Treaty Review Conference, United Nations, New York, May 4, 2000

- "Scientists and Ideology," Presentation at the NGO Panel on "Personal Responsibility in the Nuclear Age," Nuclear Non-Proliferation Treaty Review Conference, United Nations, New York, May 1, 2000

- "NPT Forecast: Cloudy or Sunny," Presentation at the NGO Presentation in preparation for the Nuclear Non-Proliferation Treaty Review Conference, United Nations, New York, April 18, 2000

- "The Future of Post-Nuclear South Asia," Presentation at the Conference on "Rethinking the Past, Shaping the Future: Partition, History and Identity," South Asian Students Association of Smith College, Northampton, MA, March 25, 2000

- Overview presentation at the workshop (jointly organized with Srirupa Roy, New York University) on "Nuclear Understandings: Science, Society, and the Bomb in South Asia," Dhaka, February 17, 2000

- Overview presentation at plenary discussion on “Nuclear Policy and Understandings in India” at the 13th Annual SSRC-MacArthur Foundation Fellows' The Conference, New Delhi, August 19-23, 1999

- “Health Effects of Reactor Accidents,” Presentation at the 11th International Summer Symposium on Science and World Affairs, Shanghai, China, July 28 - August 5, 1999

- “Regional Proliferation,” NGO Presentation at the Nuclear Non Proliferation Treaty Preparatory Committee Meeting, United Nations, New York, May 10-21, 1999

- “Nuclear Capabilities of India,” Presentation at the session on “Physics and Disarmament” at the 63rd Annual Meeting of the German Physical Society, Heidelberg, March 18, 1999

- Keynote Speaker, Symposium on De-alerting of Nuclear Weapons, Organized by The United Nations Department of Disarmament Affairs, New York, October 26, 1998

- “Radioactivity Releases from Underground Nuclear Tests,” Presentation at the 10th International Summer Symposium on Science and World Affairs, Cambridge, Massachusetts, USA, July 13-21, 1998

- “India's Nuclear Tests: Some Technical Aspects,” Presentation at the 10th International Summer Symposium on Science and World Affairs, Cambridge, Massachusetts, USA, July 13-21, 1998

- “Effects of a Nuclear Explosion,” Presentation at the Institute for Energy and Environmental Research Technical Training Workshop, Takoma Park, Maryland, July 7-12, 1998

- Discussant, Panel Discussion on “India, Pakistan and Global Nuclear Disarmament,” Sponsored by Congresswoman Barbara Lee and Congressman John Conyers and the Institute for Policy Studies, Rayburn House Office Building, Washington, D.C., June 25, 1998

- “India's Nuclear Tests,” Presentation at the 12th Annual SSRC-MacArthur Foundation Fellows' Conference, San Salvador, May 17-23, 1998

- Invited Specialist to discuss “Agreements on controlling the components: a fissile material cut-off” at the International Consultation on “Global Security and Nuclear Disarmament” organized by the United Services Institution, Delhi and the Oxford Research Group, U.K., Neemrana, March 3-6, 1998.

- “Serving a Nuclear Summons: How to make the Nuclear Weapon States Negotiate Disarmament,” Presentation at the Pugwash Workshop on “Eliminating Nuclear Weapons,” New Delhi, March 1-3, 1998

- Participant, Meeting on “The Future of Russian-US Strategic Arms Reductions: START III and Beyond,” Jointly sponsored by The Center for Arms Control, Energy, and Environmental Studies, The Moscow Institute of Physics and Technology, and The MIT Security Studies Program, Cambridge, USA, February 2-6, 1998

- “Modelling Prithvi and Agni,” Presentation at the 9th International Summer Symposium on Science and World Affairs, Cornell University, Ithaca, USA, July 24 -August 3, 1997

- Participant, Conference on “The Future of Nuclear Weapons : A US-India Dialogue,” Center for Advanced Study of India, University of Pennsylvania, May 5-8, 1997

- “Nuclear Energy in India: Problems and Prospects,” Presentation at the NGO sessions of the NPT Preparatory Conference, United Nations, New York, USA, April 15, 1997

- “The Effects of Nuclear Explosions - a Case Study of Mumbai,” Presentation at the Regional Meeting of the International Physicians for the Prevention of Nuclear War, New Delhi, India, February 21-23, 1997

- "History of the Comprehensive Test Ban Treaty," Overview Presentation at Panel Discussion on South Asia and the CTBT, Massachusetts Institute of Technology, USA, September 24, 1997

- "India's Participation in a Fissile Material Production Cutoff Convention," Presentation at the 8th International Summer Symposium on Science and World Affairs, Beijing, China, July 23-31, 1996

- "India's Participation in a Fissile Material Production Cutoff Convention" Presentation at the 10th Annual SSRC-MacArthur Foundation Fellows' Conference, Oxford University, United Kingdom, May 18-23, 1996

- "New Flavor Physics in b Decays," Presentation at the 2nd Workshop on High Energy Physics Phenomenology, SN Bose Institute, Calcutta, January 1996

- "A New Physics Source of Hard Gluons in Top Quark Production," Presentation at the 17th Annual MRST Meeting on High Energy Physics, Rochester, NY, USA, May 8-9, 1995

- Participant, Theoretical Advanced Study Institute in Elementary Particle Physics, Boulder, Colorado, USA, June 2-28, 1991

INVITED SEMINARS AND LECTURES

- "Can Nuclear Power and Small Modular Reactors Help Mitigate Climate Change", webinar organized by Institute for Essential Services Reform, Jakarta, March 10, 2022
- "The Nuclear Arms Race in South Asia: The Case of India," Online (Zoom) Lecture in Course on Weapons of Mass Destruction and International Security, Princeton University, Princeton, March 4, 2022
- "Can Small Modular Reactors rescue nuclear power", webinar organized by Citizens' Nuclear Information Center, Tokyo, March 2, 2022
- "Radioactive Waste: The Next Generation," webinar organized by Northwatch, Thunder Bay, February 16, 2022
- "Myths and Realities: Small Modular Nuclear Reactors," webinar for panel on "Nuclear Power – Myth, Lure, Danger and Reality. A Climate Solution or a Dangerous Detour?," organized by Mass Peace Action, February 7, 2022
- "Nuclear power can't help," webinar at the City Club of Eugene, Oregon, February 4, 2022
- "Small Modular Reactors - the Estonian dream or distraction? Technical and Economic Problems," webinar hosted by Estonian Green Movement (Friends of the Earth Estonia), November 30, 2021
- "Nuclear Power and Climate Change: Can Small Modular Reactors Deliver?," part of online panel discussion hosted by the School of Public Policy and Global Affairs, University of British Columbia, Vancouver, October 6, 2021
- "Small modular reactors and other nuclear fantasies," Seminar, Colarado School of Mines, September 29, 2021
- Panelist, online discussion on "The University in Climate Action", Teachers Against Climate Crisis, July 17, 2021
- Panelist on webcast organized by *The Globe and Mail* on "Nuclear energy and the climate change response" June 30, 2021
- "Why Small Modular Nuclear Reactors won't help with mitigating climate change," Webinar for Manitoba Energy Justice Coalition, June 16, 2021
- "The World Nuclear Industry Status Report 2020+ (WNISR2020+): Middle East Edition," co-presented with Mycle Schneider and Ali Ahmad, Issam Fares Institute, American University of Beirut and Heinrich Böll Foundation, Beirut, June 8, 2021
- "The sodium-cooled and molten salt experimental nuclear reactors planned for the Bay of Fundy site," Talk at Online Panel organized by The RAVEN project at the University of New Brunswick, Canadian Coalition for Nuclear Responsibility, Coalition for Responsible Energy Development in New Brunswick, International Physicians for the Prevention of Nuclear War Canada, NB Media Co-op, Prevent Cancer Now, Sierra Club Canada Foundation Atlantic Chapter, Sierra Club Maine Chapter, April 29, 2021
- "The Nuclear Arsenals of India and Pakistan: Programmes, Plans and Dangers," Lecture in Course on Nuclear Weapons and Disarmament, University of Melbourne, April 18, 2021
- "No Escape from Accidents," Talk at Online Panel on Ten Years after Fukushima: Commemoration and Lessons for the Future, organized by The University of Tokyo, Graduate School of Public Policy, Institute for Future Initiatives, and The University of British Columbia, School of Public Policy and Global Affairs, Centre for Japanese Research, March 17, 2021

- “Ten Years Later: Nuclear Power after Fukushima,” Online (Zoom) Lecture to the Osher Lifelong Learning Institute, March 11, 2021

- “The Nuclear Arms Race in South Asia: The Case of India,” Online (Zoom) Lecture in Course on Weapons of Mass Destruction and International Security, Princeton University, Princeton, March 8, 2021

- “Globalization and the Environment: Climate Change,” Lecture in Course on Introduction to International Studies, Douglas College, February 4, 2021

- “Nuclear Energy: Prospects & Challenges,” Webinar, Rayagada Autonomous College, October 24, 2020

- “Debunking the myths around Small Modular Reactors,” Webinar for Beyond Nuclear, Canadian Environmental Law Association, and Coalition for Responsible Energy Development in New Brunswick, October 21, 2020

- “After Fukushima: Nuclear Power around the World,” Webinar, Jawaharlal Nehru University, October 21, 2020

- “Globalization and the Environment: Climate Change,” Lecture in Course on Introduction to International Studies, Douglas College, October 21, 2020

- “Small Modular Nuclear Reactors,” Launch of the 2020 World Nuclear Industry Status Report, September 24, 2020

- “Why Nuclear Power is not the Answer to Climate Change,” Online Presentation to Teachers Against Climate Change, Delhi, August 25, 2020

- “Small Modular Nuclear Reactors: Claims and Challenges,” Presentation to Murray City Council, Murray, Utah, August 4, 2020

- “The Future of Nuclear Energy,” Seminar, NMIMS University, Mumbai (delivered online), July 1, 2020

- “The Nuclear Arsenals of India and Pakistan: Programmes, Plans and Dangers,” Lecture in Course on Nuclear Weapons and Disarmament, University of Melbourne, May 17, 2020

- “Nuclear Energy and Climate Change: Narratives, Hazards, and Trends," Online (Zoom) Seminar “at” Yale University, April 8, 2020

- “The Nuclear Arms Race in South Asia: The Case of India,” Online (Zoom) Lecture in Course on Weapons of Mass Destruction and International Security, Princeton University, Princeton, April 6, 2020

- “Climate Change,” Lecture in Course on Introduction to International Studies, Douglas College, March 9, 2020

- “Nuclear Energy After Fukushima: Stories and a Puzzle,” Colloquium, Department of Physics and Engineering Physics, Tulane University, December 2, 2019

- “Globalization and Doom,” Lecture in Course on Introduction to International Studies, Douglas College, June 5, 2019

- “Nuclear Energy: Three Stories and a Puzzle,” Colloquium, Department of Physics, Boston University, April 16, 2019

- “The Nuclear Arms Race in South Asia: The Case of India,” Lecture in Course on Weapons of Mass Destruction and International Security, Princeton University, Princeton, April 15, 2019

- "SMRs and Canada," Online Seminar (webinar), Northwatch, Thunderbay, Ontario, March 3, 2019
- "Will China rescue nuclear power?," Seminar, Centre for Chinese Research, University Of British Columbia, February 26, 2019
- "Intellectuals in the policy process: on nuclear weapons and energy in India," Lecture in Course on Intellectuals and Public Policy in Asia, University Of British Columbia, February 25, 2019
- "What's all the fuss about Nuclear Energy: Three Stories and a Puzzle," Lunch Seminar, Program on Science and Global Security, Princeton University, August 22, 2018
- "The Nuclear Arsenals of India and Pakistan: Programmes, Plans and Dangers," Lecture in Course on Nuclear Weapons and Disarmament, University of Melbourne, May 7, 2018
- "The Fukushima Accidents and the Future of Nuclear Energy," Seminar organized by Sigma Xi Chapter of the University of New Mexico, April 19, 2018
- "Life Under the Shadow: Twenty years of Nuclear Weapons in India and Pakistan," Seminar, Centre For India And South Asia Research, University Of British Columbia, March 29, 2018
- "Global Environmental Crises," Lecture in Course on Introduction to International and Intercultural Studies, Douglas College, March 26, 2018
- "The Fukushima Accident, Policy Choices and the Contested Future of Nuclear Energy," Lecture in Course on Urban Systems and Society, School of Community and Regional Planning, University Of British Columbia, March 12, 2018
- "Can Nuclear Energy be a Solution to Climate Change? Possible? Desirable? Feasible?," Colloquium, Indiana University of Pennsylvania, February 22, 2018
- "Nuclear energy, radioactive waste, and sustainability," Lecture in Course on Sustainability, Indiana University of Pennsylvania, February 22, 2018
- "The Nuclear Arms Race in South Asia: The Case of India," Lecture in Course on Weapons of Mass Destruction and International Security, Princeton University, Princeton, February 21, 2018
- "Nuclear Weapons in India: History and Risk," Seminar, Ethnic Studies Department & International Institute, University Of California, San Diego, November 30, 2017
- "Nuclear Power in the Middle East," Seminar, University of San Diego, November 30, 2017
- "Nuclear Energy and SMRs: Products and Problems," Lecture in Course on Nuclear Energy and Policy, Michigan State University, November 15, 2017
- "Nuclear Bombs and Nuclear Power: World Peace & Energy Security -- Unravelling the Promises," Asian College of Journalism, Chennai, India, November 6, 2017
- "Nuclear Energy and SMRs in Indonesia," Energy Studies Institute, National University of Singapore, October 25, 2017
- "The Global Future of Nuclear Energy," School of Public Policy and Global Affairs, University of British Columbia, Vancouver, October 18, 2017
- "The Nuclear Arsenals of India and Pakistan: Programmes, Plans and Dangers," Lecture in Course on Nuclear Weapons and Disarmament, University of Melbourne, May 8, 2017
- "The Nuclear Arms Race in South Asia: The Case of India," Lecture in Course on Weapons of Mass Destruction and International Security, Princeton University, Princeton, April 10, 2017

- "Why do States Build Nuclear Weapons? The Case of India," Carleton College, MN, November 4, 2016
- "Nuclear Power: Overview, Economics, and India," Carleton College, MN, November 4, 2016
- "Small Modular Reactors: An Inadequate Response to the Challenges Faced by Nuclear Power," Nanyang Technological University, Singapore, October 18, 2016
- "U.S. Launch of the World Nuclear Industry Status Report 2016," with Mycle Schneider, Natural Resources Defense Council, Washington, D.C., September 19, 2016
- "After Fukushima: Nuclear Power Programs Around the World," Google Hangout with Sigma Xi, October 11, 2016
- "Nuclear Weapons in South Asia: Programmes, Plans, and Dangers," Dr. Asghar Ali Engineer Memorial Advisory Committee and Coalition for Nuclear Disarmament and Peace, Mumbai, August 27, 2016
- "The Future of Nuclear Energy in India: Expectations and Constraints," School of Media and Cultural Studies, Tata Institute of Social Sciences, Mumbai, August 26, 2016
- "Understanding Nuclear Energy and Nuclear Diplomacy," Asian College of Journalism, Chennai, August 22, 2016
- "Whither Nuclear Power in the Middle East: The Cases of Saudi Arabia and Jordan," Nonproliferation Policy Education Center, Washington, D.C., May 5, 2016
- "Connections Between Nuclear Energy and Nuclear Weapons," Liu Institute for Global Issues, University of British Columbia, Vancouver, January 8, 2016
- "Exit, Voice, and Loyalty: Policy Choices and the Future of Nuclear Energy since Fukushima," Liu Institute for Global Issues, University of British Columbia, Vancouver, January 7, 2016
- "Nuclear Power and India's Energy Needs: Lessons from History," Energy Policy Institute at the University of Chicago- India Centre, New Delhi, December 23, 2015
- "Status of nuclear power in India and the potential impact of India- Japan nuclear cooperation," Citizens' Nuclear Information Center, Tokyo, November 6, 2015
- "Nuclear Energy in China and India: Can Ambitions Meet Reality?" Kyoto University, Kyoto, November 4, 2015
- "Assessing Risk Assessment: Nuclear Regulation and Reactor Safety," Princeton Institute for International and Regional Studies, Princeton University, Princeton, October 15, 2015
- "Nuclear Fission Energy: Status and Policies," ExxonMobil – Princeton University Workshop, Princeton, October 13, 2015
- "Nuclear India: Politics, Rhetoric and Reality," The Alliance for a Secular and Democratic South Asia & Science for the People, Massachusetts Institute of Technology, Cambridge, October 5, 2015
- "Challenges in Licensing Small Modular Reactors," Bapeten (Nuclear Energy Regulatory Agency of Indonesia), Jakarta, June 26, 2015
- "Reprocessing and Breeder Reactors in India," International Panel on Fissile Materials Panel on the Global Challenge of Reprocessing and Plutonium Disposal, NPT Review Conference, United Nations, New York, May 7, 2015

- "Nuclear Energy: Global Overview & the Case of India," Program on International Relations and Strategic Affairs, Princeton University & Center for Policy Research, Princeton, April 9, 2015
- "Atomic Development and Democratic Dissent: Opposition to the Koodankulam Nuclear Plant in India," Lecture, Program for South Asian Studies, Princeton University, Princeton, March 4, 2015
- "Nuclear Energy After Fukushima," Colloquium, Department of Physics, Ohio State University, February 23, 2015
- "Nuclear Energy in India: Current Status and Future Outlook," Korea Advanced Institute of Science and Technology, Daejeon, December 22, 2014
- "Nuclear Energy in India: Historical Record and Future Prospects," Institute of South Asian Studies, National University of Singapore, August 19, 2014
- "Nuclear Power in India: History and Prospects," Melbourne University, August 15, 2014
- "Motivations and Challenges for Small Modular Reactors," Nuclear Engineering Department, Universidade Federal do Rio de Janeiro, March 18, 2014
- "The Power of Promise: Examining the Feasibility of a Rapid Expansion of Nuclear Energy in India," South Asia Institute and the Kennedy School Project on Managing the Atom, Harvard University, Cambridge, December 6, 2013
- "Fukushima: Implications for the Understanding of Severe Accidents and the Future of Nuclear Energy," Colloquium, Department of Physics, Case Western University, Cleveland, November 21, 2013
- "Nuclear Energy: Issues in India and Around the World," Presentation at Prayas Energy Group, Pune, November 1, 2013
- "Challenges in Licensing Small Modular Reactors," Trilateral Meeting, University of Maryland, College Park, September 19-20, 2013
- "Nuclear Energy and Climate Change," Presentation at the Heinrich Böll Foundation, Beijing, August 6, 2013
- "Nuclear Power: Why, What, Why Not," Lecture, Vermont Law School, South Royalton, July 12, 2013
- "Nuclear Arms Race in South Asia: The Case of India," Lecture at the Heinrich Böll Foundation, Berlin, April 29, 2013
- "The Future of Nuclear Energy in India: History, Technology, and Economics," Program in South Asia Studies, Princeton University, Princeton, March 28, 2013
- "Nuclear Energy in India: History, Technology, and the Future," King's College London, March 20, 2013
- "The Potential for Severe Accidents Associated with Nuclear Power," Round Table on Liability Legislation in India, New Delhi, March 17, 2013 (over Skype)
- "Nuclear Energy in India: Learning from the Past, Thinking about the Future," Indian Institute of Technology, Madras, February 22, 2013
- "The Power of Promise," Jawaharlal Nehru University, New Delhi, February 20, 2013
- "Risk Perception in the Indian Nuclear Establishment," The Energy and Resources Institute (TERI), New Delhi, February 20, 2013

- "Nuclear Power: Motivations and Problems," National Institute of Immunology, New Delhi, February 19, 2013
- "Nuclear Energy in India: Perspectives on its Past, Present and Future," Madras Institute of Development Studies, Madras, February 18, 2013
- Is Nuclear Energy the Answer to India's energy needs? Loyola College, Madras, February 18, 2013
- "Nuclear Accidents and Learning: The Indian Experience," National Institute of Advanced Studies, Bangalore, February 15, 2013
- "Nuclear Energy in India: Past and Future," Indian Institute of Management, Bangalore, February 14, 2013
- "Nuclear Energy in India: Perspectives on its Past, Present and Future," Hyderabad Central University, Hyderabad, February 13, 2013
- "Nuclear Energy in India," Panel Discussion at Lamakaan: An Open Cultural Space, Hyderabad, February 12, 2013
- "Worried in Koodankulam: Nuclear Safety and Public Protests in India," Lecture at the San Jose Peace and Justice Center, San Jose, December 22, 2012
- "Organizing for Nuclear Disarmament and Peace in India," Hiroshima/Nagasaki Commemoration, Coalition for Peace Action, Princeton, August 6, 2012
- "Small Modular Reactors: Features, Motivations," Exploring the End of Nuclear Power and Examining its Proliferation and Health Problems, Institute for Energy and Environmental Research, Washington, D.C., July 25, 2012
- "Connections Between Nuclear Power and Nuclear Weapons: Production," Exploring the End of Nuclear Power and Examining its Proliferation and Health Problems, Institute for Energy and Environmental Research, Washington, D.C., July 25, 2012
- "Nuclear Power: Why, What, Why Not," Lecture, Vermont Law School, South Royalton, July 13, 2012
- "Small Modular Reactors: Overview," Seminar at the Brookhaven National Laboratory, Upton, New York, May 9, 2012
- "Nuclear Power After Fukushima," Colloquium, Department of Mathematical Sciences, Montclair State University, Montclair, New Jersey, November 30, 2011
- "The Future of Nuclear Power" Fall 2011 Maclean House Lecture Series, Sponsored by the Office of the Alumni Association, Princeton University, Princeton, October 6, 13, & 20, 2011
- "The Economics of Nuclear Power," Seminar at the Indian Institute of Science, Bangalore, August 29, 2011
- "Nuclear Power: Risk and Ethics," Lecture at Ashoka Trust in Ecology and Environment, Bangalore, August 29, 2011
- "United Kingdom," Presentation at panel discussion on "The Challenges of Spent Fuel Management: Experience and Lessons from Around the World" at the AAAS Center for Science, Technology and Security Policy, Washington D.C., June 3, 2011
- "Nuclear Power: Global Trends, Future Projections," Presentation at panel discussion on "The Jobs, Costs, and Security Landscape of a US Nuclear Expansion," Organized by Center for Earth, Energy, and Democracy, Institute for Agriculture and Trade Policy, Minneapolis, March 25, 2011

- “Implications of Fukushima for Nuclear Safety: A Preliminary Assessment,” Presentation at panel discussion on “After the Earthquake: Japan’s Nuclear Plant Crisis” at the Woodrow Wilson School for Public and International Affairs, Princeton University, March 24, 2011
- “Nuclear Energy and Climate Change,” Plenary Lecture at the Conference on “Towards a Nuclear Weapon Free World” and the 10th Anniversary National Convention of the Coalition for Nuclear Disarmament and Peace, New Delhi, December 11, 2010
- “Nuclear Power: Current Trends, Future Projections, Developing Countries,” Bulletin of the Atomic Scientists, Doomsday Clock Symposium, Washington, D. C., November 4, 2010
- “Looking up at the Apocalypse: Disarmament, Climate Change, and Justice,” Panel Presentation at “For a Nuclear Free, Peaceful, Just, Sustainable World Conference”, Riverside Church, New York City, May 1, 2010
- “India: Climate Debates, Energy Trends,” Princeton Environmental Institute, Princeton University, February 5, 2010
- “Dealing with Climate Change: Equity, Justice, and Social Change,” Climate Change Panel, Bulletin of the Atomic Scientists, Doomsday Clock Symposium, New York City, January 13, 2010

- “A Nuclear Powered Solution to Climate Change: Feasible? Desirable?,” Environment Affairs Forum, Princeton University, November 24, 2009
- “India’s Energy Future: How Much Can Nuclear Power Contribute?,” Science, Technology, and Environmental Policy Seminar, Princeton University, September 28, 2009
- “Nuclear Energy in India: History and Future,” Rotary Club, Bangalore, March 14, 2009
- “Kya Dam Hai? The Economics of Nuclear Power,” Gujarat Vidyapeeth, December 8, 2008
- “Between Three Hard Places: India's Energy and Climate Change Policies,” Seminar, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, October 14, 2008
- “Nuclear Power as a Solution to Climate Change?,” Seminar, John F.Welch Technology Centre, General Electric Company, Bangalore, September 15, 2008
- “Economic Costs of Nuclear Power in India,” Seminar, Indian Institute of Management, Bangalore, March 21, 2008
- “Can Nuclear Power Help with Climate Change? Lessons from the Experience in India and Elsewhere,” Lecture for Postgraduate Certificate Course on Technology and Sustainable Development, Indian Institute of Technology, Madras, January 14, 2008
- “The Nuclear Deal and the Evolving Indo-US Relationship,” Lecture for course on “Globalization”, Swaraj Vidyapeeth, Bangalore, December 29, 2007
- “Indo-US Nuclear Deal,” Talk to CONCERNS, Student Group, Indian Institute of Science, Bangalore, November 17, 2007
- “The US-India Nuclear ‘Deal’: Underlying Issues and Debates,” Seminar, Institute for Social and Economic Change, Bangalore, November 15, 2007
- “Some Aspects of the US India Nuclear Deal,” Seminar, Indian Statistical Institute, Bangalore, November 7, 2007

- “Nuclear Energy: Economic and Environmental Aspects,” Lecture for course on “Approaching the Environment in India – New Theories and Methods in the Study of the Nature-Society Interface,” Institute for Social and Economic Change, Bangalore, August 9, 2007

- “Implications of the US India Nuclear Deal,” Presentation to the Citizens for Alternatives to Nuclear Energy, Bangalore, April 19, 2007

- “Breeder Reactors: Overview and Economics,” Seminar, National Institute for Advanced Studies, Bangalore, November 29, 2006

- “An Overview of Nuclear Power in India,” Presentation to the Greenpeace International Advisory Committee, Greenpeace, Bangalore, June 4, 2006

- “India: Prisoner of the Nuclear Dream,” Special Energy and Environmental Policy Lecture, Center for Energy and Environmental Policy, University of Delaware, May 18, 2006

- “The US-India Nuclear Deal,” Seminar, Science, Technology and Global Security Working Group, Program in Science, Technology and Society, Massachusetts Institute of Technology, May 12, 2006

- “Nuclear Power in India: Failed Past, Dubious Future,” Seminar, Nonproliferation Policy Education Center, Washington, D.C., May 10, 2006

- “The US-India Nuclear Deal,” Seminar, Center for International Security and Cooperation, Stanford University, May 1, 2006

- “The US-India Nuclear Deal,” Joint Seminar with Zia Mian, South Asia Studies Committee, Princeton University, April 25, 2006

- “Nuclear Weapons in India: Glimpses from History” and “Atomic Energy in India”, Two lectures at the National Law School of India University, Bangalore, April 1, 2006

- “South Asia: Under the Nuclear Shadow,” Seminar, Liu Institute for Global Studies, University of British Columbia, Vancouver, Canada, November 23, 2005

- “Promises and Failures: The Story of Atomic Energy in India,” Colloquium, Raman Research Institute, Bangalore, October 6, 2005

- “Nuclear Power: Plans, Prospects, and Constraints,” Presentation to Greenpeace, Bangalore, August 24, 2005

- “Nuclear Power in India: Current Status, Future Prospects,” Seminar, Centre for International Security and Cooperation, Stanford University, July 20, 2005

- “Ionizing Radiation and Health,” Lecture, Bangalore Planetarium, May 27, 2005

- “Technology Choices and their Implications: the Case of Nuclear Energy in India,” Lecture, Course on Technology and Policy in India, Indian Institute of Management, Bangalore, March 16, 2005

- “Economics of Nuclear Power in India,” Seminar, Institute for Social and Economic Change, Bangalore, February 17, 2005

- “Nuclear Energy and Nuclear Weapons: Issues for an Informed Public Debate,” Public Lecture, Organized by Society for Promoting Participative Ecosystem, Prayas, Centre for Environment Education, and others, Pune, January 12, 2005

- “Technology and Development: Nuclear Energy in India,” Two lectures, Course on Technology and Sustainable Development, Indian Institute of Technology, Chennai, January 4, 2005

- “Future of Nuclear Power in India,” Lunch Seminar, Program on Science and Global Security, Princeton University, October 1, 2004
- “Nuclear Power in India: An Overview,” Seminar, Department of Chemical Engineering, Indian Institute of Science, Bangalore, August 19, 2004
- “Secrecy and India’s Nuclear Establishment,” Lecture, Alternate Law Forum, Bangalore, May 21, 2004
- “A Progressive Bomb?,” Seminar, China Study Group, New York, January 31, 2004
- “An Estimate of India’s Uranium Enrichment Capacity,” Lunch Seminar, Program on Science and Global Security, Princeton University, August 6, 2003
- “Nuclear Power in India,” Seminar, Center for Energy and Environmental Policy, University of Delaware, May 15, 2003
- “Steps Towards Operationalizing the Indian Nuclear Arsenal,” Lunch Seminar, Program on Science and Global Security, Princeton University, January 22, 2003
- “Normal Accidents and Nuclear War,” Lecture, Course on “Engineers in Society,” New Jersey Institute of Technology, October 24, 2002
- “Deployment of Nuclear Weapons and Early Warning in South Asia,” Technical Seminar, Security Studies Program, Massachusetts Institute of Technology, October 10, 2002
- “Beyond Missile Defense,” Division of Natural Sciences and Mathematics Colloquium, Colgate University, April 19, 2002
- “Health Impacts from Uranium Mining in India,” Presentation to ASHA, Princeton University, February 16, 2002
- “The Environmental and Health Impacts of the Nuclear Fuel Cycle,” Seminar, Institute for Social and Economic Change, Bangalore, January 3, 2002
- “Uranium Mining and Health in India,” Presentation to ASHA, Columbia University, November 4, 2001
- “Economics of Nuclear Power from Fast Breeder Reactors in India,” Seminar, Indira Gandhi Institute for Development Research, August 20, 2001
- “Nuclear Power Economics in India: Fast Breeders vs. Heavy Water Reactors,” Seminar, Center for Energy and Environmental Studies, Princeton University, July 10, 2001
- “Scientists and India’s Nuclear Bomb,” Seminar, Center for International Security and Cooperation, Stanford University, March 13, 2001
- “Scientists and India’s Nuclear Bomb,” Lecture, Yale Center for International and Area Studies, Yale University, October 26, 2000
- “Nuclear Weapons in South Asia: A Scientist’s Perspective,” Presentation to the Stanford India Association, Stanford University, June 29, 2000
- “Prisoners of the Nuclear Dream: India, Pakistan, and the Making of Nuclear Nations,” Seminar, Program on Science, Technology and Society, Massachusetts Institute of Technology, February 19, 1999
- “Nuclear Energy and Weapons in South Asia,” Seminar, Gettysburg College, January 29, 1998

- "The Effects of Nuclear Explosions - a Case Study of Mumbai," Seminar, School of International Studies, Jawaharlal Nehru University, New Delhi, February 24, 1997
- "Walking Technicolor Signatures at Hadron Colliders," Seminar, Center for Theoretical Studies, Indian Institute of Science, Bangalore, July 1992
- "Electroweak Symmetry Breaking, Walking Technicolor, and the SSC," Seminar, Department of Physics, University of Wuppertal, Germany, February 1992

VERIFICATION

I, Arjun Makhijani, pursuant to the Commission's *Order Establishing Additional Procedures and Requiring Issues Report* entered on April 1, 2022 in the above-referenced docket, hereby verify that the contents of the foregoing Report are true to the best of my knowledge and belief, except as to those matters stated on information and belief, and as to those matters, I believe them to be true.

This the 15 day of July, 2022.

Arjun Makhijani

Sworn to and subscribed before me this the 15 day of July, 2022.

Notary Public

10/20/2025
My commission expires:

SARAH L MARGGRAF
Notary Public - Maryland
Montgomery County
My Commission Expires on
October 20, 2025

VERIFICATION

I, M.V. Ramana, pursuant to the Commission's *Order Establishing Additional Procedures and Requiring Issues Report* entered on April 1, 2022 in the above-referenced docket, hereby verify that the contents of the foregoing Report are true to the best of my knowledge and belief, except as to those matters stated on information and belief, and as to those matters, I believe them to be true.

This the 15 day of July, 2022.

M.V. Ramana

M.V. Ramana

Sworn to and subscribed before me this the 15 day of July, 2022.

Notary Public

Jerome T.L. Tsang
Notary Public
205 - 5704 Balsam Street
Vancouver, BC V6M 4B9 Canada
Tel: (604) 266-6644 Fax: (604) 266-6614

Permanent

My commission expires: