Phase 1: Duke Energy Zero Emission Resource Integration Study (ZERIS)

Phase 2: Carbon-Free Resource Integration Study for Duke Energy

Cooperative Research and Development Final Report

CRADA Number: CRD-19-00801

NREL Technical Contacts: Bri-Mathias Hodge and Brian Sergi

NREL is a national laboratory of the U.S. Department of Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-87329
August 2023

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Cooperative Research and Development Final Report

Report Date: August 24, 2023

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement:

Duke Energy Business Services LLC, as agent for:

- Duke Energy Carolinas, LLC, Duke Energy Florida, Inc.
- Duke Energy Indiana, Inc., Duke Energy Kentucky, Inc.
- Duke Energy Ohio, Inc., and Duke Energy Progress, Inc.

CRADA Number: CRD-19-00801

CRADA Title:

Phase 1: Duke Energy Zero Emission Resource Integration Study (ZERIS)
Phase 2: Carbon-Free Resource Integration Study for Duke Energy

Responsible Technical Contacts at Alliance/National Renewable Energy Laboratory (NREL):

Bri-Mathias Hodge | bri.mathias.hodge@nrel.gov

Brian Sergi | brian.sergi@nrel.gov

Name and Email Address of POC at Company:

Nate Finucane | Nate.Finucane@duke-energy.com, for Wesley Davis | Wesley.davis@duke-energy.com)

Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

No NREL Shared Resources

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$0.00
TOTALS	$0.00

Executive Summary of CRADA Work

Phase 1: This statement of work makes up Phase 1 of a larger effort. During this Phase 1 effort, NREL will work with Duke Energy to analyze the impacts of integrating significant amounts of new solar power into the Duke Energy power system under a variety of different penetrations scenarios, with a maximum of ten (10) full scenarios examined. The existing fleet, particularly the nuclear generation, will be considered in the quantitative assessments and discussions.

Duke Energy is looking to quantify how much solar generation its system can handle. NREL will work with Duke Energy to quantify solar potential, identify likely integration challenges and possible opportunities for wind, storage, demand side resources and other technologies.

Phase 2: This Statement of Work consists of a follow-up effort (Phase 2) to a recently completed Phase 1 modeling effort. During Phase 2, NREL will work closely with Duke Energy to analyze the impacts of integrating significant amounts of variable generation resources (wind and solar) and storage into Duke Energy's system in the Carolinas. The existing fleet, particularly nuclear generation, will be considered in the quantitative assessment and discussions.

This Statement of Work also includes an extension to Phase II of the Carbon-Free Resource Integration Study for Duke Energy. In this extension, NREL will work closely with Duke Energy to extend the production cost analysis developed in Phase II to 2018 weather and load data for Duke Energy's territory. This extension leverages the modeling tools and datasets developed as part of Phase II. The analysis will compare results from Phase II (using 2012 weather and load) with 2018 results to assess system operations with increased penetration of renewables and storage. Simplifying assumptions will be made for modeling Duke Energy's neighbors in the production cost model.

CRADA benefit to DOE, Participant, and US Taxpayer

- Assists laboratory in achieving programmatic scope
- Enhances the laboratory's core competencies
- Uses the laboratory's core competencies
- Enhances U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities.

Summary of Research Results

Background

The National Renewable Energy Laboratory (NREL) is a national laboratory owned by the U.S. Department of Energy (DOE) and managed and operated by the Alliance for Sustainable Energy LLC under DOE Contract No. DE-AC36-08GO28308. NREL is DOE's premier laboratory for renewable energy, energy efficiency, and energy systems integration. As a Federally Funded Research and Development Center (FFRDC), NREL is a government-owned, contractor-operated facility with a mission to provide credible, science-based, unbiased support to organizations with energy-related challenges. Over the past 40 years, DOE has invested nearly $50 million in developing NREL's unique power sector modeling expertise, data, tools, facilities, and capabilities.

Duke Energy is one of the largest electric power holding companies in the United States, providing electricity to 7.6 million retail customers in six states. Duke Energy's regulated utilities have approximately 49,500 megawatts of electric generating capacity in the Carolinas, the Midwest and Florida. In addition, there are over 30,000 DER (distributed energy resource) facilities with a combined capacity of over 3,700 MW operating across all Duke Energy jurisdictions. Over 90% of this capacity is in the Carolinas, where more than 16,000 sites produce over 3,200 MW on the Transmission and Distribution system, making the Carolinas a national leader for integrating utility-scale solar generation on the distribution system. Over the next several years the capacity of solar generation across Duke Energy is expected to at least double.

Duke Energy endeavors to increase the portion of load met by carbon-free generation and seeks to analyze the impact of integrating significant amounts of new solar, storage, and wind into its power system. Under the Phase 1 Study, NREL conducted a net-load analysis indicating times and quantities of potential curtailment for various scenarios. The main conclusions from the analysis are the need to better understand the potential value of adding wind power and storage at high penetrations of solar power, and that when considering a goal of meeting load with carbon-free generation, nuclear retirement and transmission limitations are both challenges.

In Phase II, NREL completed analysis that involves combined resource, capacity expansion, and production cost modeling, with the production cost modeling analysis focusing on a 2030 system buildout and a 2050 zonal model run using 2012 weather and load data. This analysis demonstrated pathways for Duke Energy to decarbonize its system. As an extension to the Phase II study, the work also included a Phase III in which NREL explored the implications of an extended cold weather event.

Task Descriptions

Phase I

Task 1: Scenario Analysis

This task involves developing potential scenarios of renewable and thermal generation (with a focus on wind, solar, and nuclear generation capacities), in consultation with Duke. We will propose and analyze up to 10 agreed-upon scenarios, of possibly varying future timeframes, which best represent potential challenges and opportunities for renewable integration. This will be done by making estimated hourly solar, wind, net load, and system minimum generation time series for the different scenarios. An example of this would include an analysis of balancing solar, wind, and load for typical days during different seasons and extreme days. Initial estimates of curtailment can be made, based on the assumptions regarding the balance of the system (e.g., system-wide minimum generation levels, and maximum ramp rates). These estimates can help bookend the potential for curtailment. Storage and other demand-side technologies could potentially help mitigate some of the curtailment. The net load analysis will also identify key periods of ramping on the system and other potential balancing challenges. Duke Energy will review scenario assumptions around the generation fleet, reserve levels, and other key assumptions before analysis begins.

Table 1 summarizes the scenarios analyzed in Phase I, along with the key metrics of interest from the net load analysis.

Table 1. Annual Metrics Evaluation for All Scenarios in the Net Load Analysis

Scenario	DEP and DEC Modeled as a Single Region or Separately	Definition	Annual Load Met by Carbon-Free Generation (%)	Annual Curtailed Renewable Energy (%)	Annual Hours of Curtailment	Annual Maximum Instantaneous Curtailment (MW)
1. Solar energy penetration 5%	Single region	4,109 MW, 5.5% of total solar is rooftop	63%	0%	6	530
2. Solar energy penetration 10%	Single region	8,219 MW, 5.5% of total solar is rooftop	68%	1%	179	3,323
3. Solar energy penetration 15%	Single region	12,328 MW, 5.5% of total solar is rooftop	72%	8%	882	6,618
4. Solar energy penetration 20%	Single region	16,438 MW, 5.5% of total solar is rooftop	74%	17%	1,506	10,003
5. Solar energy penetration 25%	Single region	20,547 MW, 5.5% of total solar is rooftop	76%	27%	2,016	13,504
6. Solar energy penetration 30%	Single region	24,656 MW, 5.5% of total solar is rooftop	77%	35%	2,355	17,207
7. Solar energy penetration 35%	Single region	28,766 MW, 5.5% of total solar is rooftop	77%	42%	2,587	20,909
8. Higher ratio of distributed to utility solar added to the system	Single region	Based on the 25% solar energy penetration scenario, 18.91% of PV is uncurtailable rooftop	76%	27%	2,017	13,548

Scenario	DEP and DEC Modeled as a Single Region or Separately	Definition	Annual Load Met by Carbon-Free Generation (%)	Annual Curtailed Renewable Energy (%)	Annual Hours of Curtailment	Annual Maximum Instantaneous Curtailment (MW)
9. Additional storage	Single region	Based on the 25% solar energy penetration scenario, addition of 1,000 MW of 4-hour storage, 1,000 MW of 6-hour storage, and 2,000 MW of 8-hour storage	78%	12%	1,239	11,073
10. Nuclear retirement	Single region	Based on the 25% solar energy penetration scenario, assume a 10% nuclear reduction	71%	22%	1,804	12,551
11. Additional wind energy at 5% penetration	Single region	Based on the 30% solar energy penetration scenario, an additional 5% wind energy penetration is added	81%	32%	2,486	17,486
12—DEC 5%	Separate regions	Based on scenarios 1–3 inclusive, DEP and DEC are analyzed separately with an interconnection limit between	73%	0%	5	246
12—DEC 10%	Separate regions		78%	1%	213	1,886
12—DEC 15%	Separate regions		94%	7%	912	3,418
12—DEP 5%	Separate regions		52%	0%	5	246
12—DEP 10%	Separate regions		56%	1%	205	1,600
12—DEP 15%	Separate regions		60%	10%	905	3,418

Task 2: Geospatial Analysis

This task will create detailed maps of resource quality for the Duke service territory and analyze potential site locations for new solar and wind resources. This analysis will include sites selected for previous and ongoing studies. The locations and associated profiles will be the starting point for analysis in Task 1. Exclusion areas will be based on previous analysis and standard assumptions for exclusions.

Several maps and an online application were created by the geospatial analysis team at NREL to visualize the solar and wind resources in the Duke Carolinas territory. The solar energy resource is characterized by global horizontal irradiance, and the wind energy resource is characterized by wind speed. Capacity factors were produced to visualize solar and wind generation, and exclusions[1] were made based on land categories and use type (see appendix for details). One such map is shown in Figure 1, which shows the capacity factors that are not in excluded areas of the region.

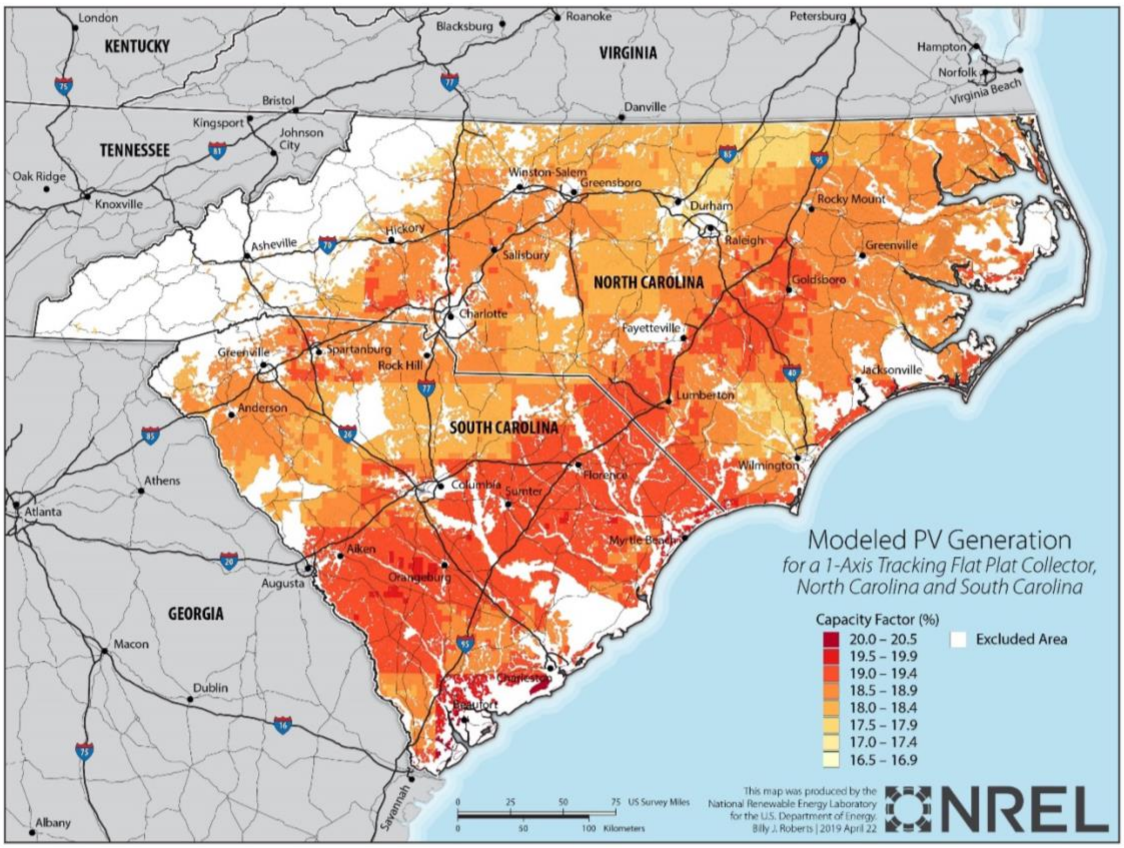

Figure 1. Multiyear mean capacity factors

The web application allows the user to examine these three layers of generation, energy resource, and exclusions for both wind and solar. The link for the website is: https://maps.nrel.gov/duke.

[1] Exclusions include a slope >5%, urban areas, water and wetlands, parks and landmarks, national parks, and other environmentally or culturally sensitive areas.

Task 3: Review of Relevant Studies

NREL will review previous work and summarize some of the key conclusions on renewable integration in the Duke service territory based on historical work, primarily done at NREL. Summarized reports will include major interconnection-level integration studies (e.g., Western Wind and Solar Integration Study) to technology-specific studies. Conclusions will be selected based on the likely application to the Duke service territory, and could range from discussions of operating practices, technologies, weather patterns, and Essential Reliability Services.

The review will also include suggestions for what type of modeling should be done in future work (e.g., phase 2) to more precisely understand the challenges and potential solutions for the Duke service territory.

This review provided for the work focuses on investigating the addition of solar power along with understanding how the integration of variable generation sources, especially at high penetration levels, comes with potential challenges to reliable power system operations. The variability and uncertainty of renewable energy sources are two major constraints to integrating them into the power system. In power network operations, generation planners will always need to ensure that there is enough capacity to serve load at any given time. Characterizing variable generation resources in planning operations becomes a challenge because of their tendency to disrupt the balance of the generation portfolio. Consequently, thermal and hydro generators are operated differently to accommodate the variability and uncertainty of renewable electricity generators (Lew, 2013).

Additionally, the integration of variable and uncertain power generation from wind and solar units at high penetration levels introduces another pivotal variable: net load (normal load less wind power and solar power). This creates a new set of requirements for integrated and reliable power system planning operations. The net load variability has created a further need to evaluate system flexibility because of its impacts on system operating costs. The ability of the power system to integrate additional renewable resources is largely a function of its flexibility, which is chiefly driven by the ability of individual plants to change their output to serve these variations in net electricity consumption (Ela, 2014). The key to managing the variability and uncertainty of variable generation sources is to increase the system-wide flexibility in the power system (Mai, et al., 2012).

Task 4: Develop Plan for Phase 2

This task will analyze results from Tasks 1, 2, and 3, highlight the resulting challenges, and suggest a scope and process for studying the identified challenges in more detail. Follow-on actions will be included in the draft memo and slide deck for Task 5.

This task will include extensive consultation with collaborators at Duke Energy, and possibly with stakeholders external to Duke Energy, as advised by Duke.

As part of this task, NREL worked closely with Duke to develop the scope for Phase II. The scope and process agreed upon by the two parties is summarized in Figure 2.

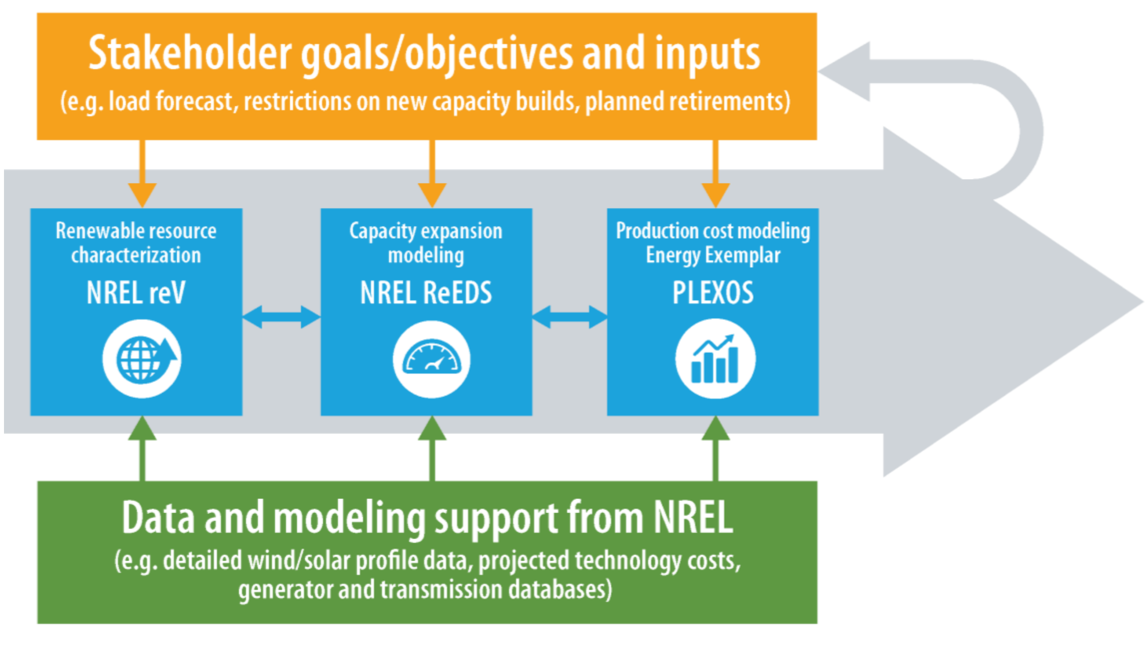

Figure 2. Depiction of the modeling workflow conducted in Phase 2 of the Duke Energy Carbon-Free Resource Integration Study

NREL presented the proposed Phase II plan, along with a summary of the results from Phase I, to Duke Energy stakeholders in the fall of 2019.

Task 5: Draft Memo and Slide Deck

NREL will draft an external report and slide deck based on the analysis performed. The external report will be approximately 20 pages, including a summary of the scenario analysis and a review of relevant studies. The external report will also be condensed into a presentation slide deck. A more extensive internal memo which contains additional detail of the analysis performed will be provided, but not made publicly available.

NREL published the results of the Phase I study as a standalone NREL technical report in January 2020. (NREL/TP-5D00-74337).

Phase II

Task 1: Stakeholder Engagement

Under this task, NREL shall provide communications support to Duke throughout the Phase 2 effort. As part of this effort, NREL shall attend and participate in up to four in-person meetings in the Carolinas (either public stakeholder meeting or internal Duke Energy leadership/technical staff); one Duke-NREL project meeting to be held at NREL, and up to two public webinars.

The meetings are described below.

- Public presentation of Phase 1 Results. This meeting will likely be held in Raleigh or Charlotte, North Carolina in December 2019 or Q1 2020, perhaps in conjunction with the North Carolina Department of Environmental Quality. The purpose of the meeting will be to present the results of the Phase 1 analysis, and to give stakeholders an opportunity to weigh in on the proposed Phase 2 scope.
- Presentation to Duke Energy's Senior Management Committee and CEO, and Board of Directors. These meetings likely occur in Q4 2019 or Q1 2020.
- Up to two presentations on Phase 2. Working in close coordination with Duke Energy, NREL shall attend and present the interim and/or final results of the Phase 2 effort at a time and location to be determined, though likely to be in Charlotte or Raleigh.
- One internal Duke-NREL meeting, to be held at NREL, approximately mid-way through the project to discuss project results, messaging, and stakeholder engagement strategies
- One to two webinars to present the interim and final results of Phase 2

In addition, NREL's communication team shall provide input to Duke Energy on the development of strategic messaging, Frequently Asked Questions (FAQs) and other documents to assist with stakeholder engagement during the Phase 2 effort.

Although the pandemic ultimately prevented many of the planned, in-person presentations originally proposed, NREL did provide communication and presentation support as requested by Duke Energy. This included a virtual presentation of the Phase I results in the fall of 2019 (coupled with a presentation of the proposed Phase II scope), a presentation on modeling methods and details in the summer of 2020, and presentation of interim results in the winter of 2020, and a final presentation to stakeholders in the spring of 2022.

Task 2: Creation of Solar Power and Wind Power Profiles

Solar and wind profiles will be created using the reV model, which combines into a unified platform NREL's National Solar Resource Data Base (NSRDB), the WIND Toolkit, and the System Advisor Model (SAM). The NSRDB and WIND Toolkits contain resource data and SAM is a techno-economic model which can model wind farms as well as photovoltaic systems for small residential rooftop to large utility-scale systems. In addition, reV will associate wind and solar power profiles with available land area and capacity (in megawatts) while considering various technical, sociopolitical, and ecological spatial constraints and estimating the levelized cost of transmission (LCOT) for connecting to the grid. Optional spatial constraints will be presented to Duke, and Duke will have the opportunity to provide its own spatial constraint layers. reV will combine all of the data and create supply curves, that will serve as the data foundation feeds into the ReEDS and PLEXOS models.

Figure 3 provides a summary of the solar and wind profiles compiled from reV for use in this study.

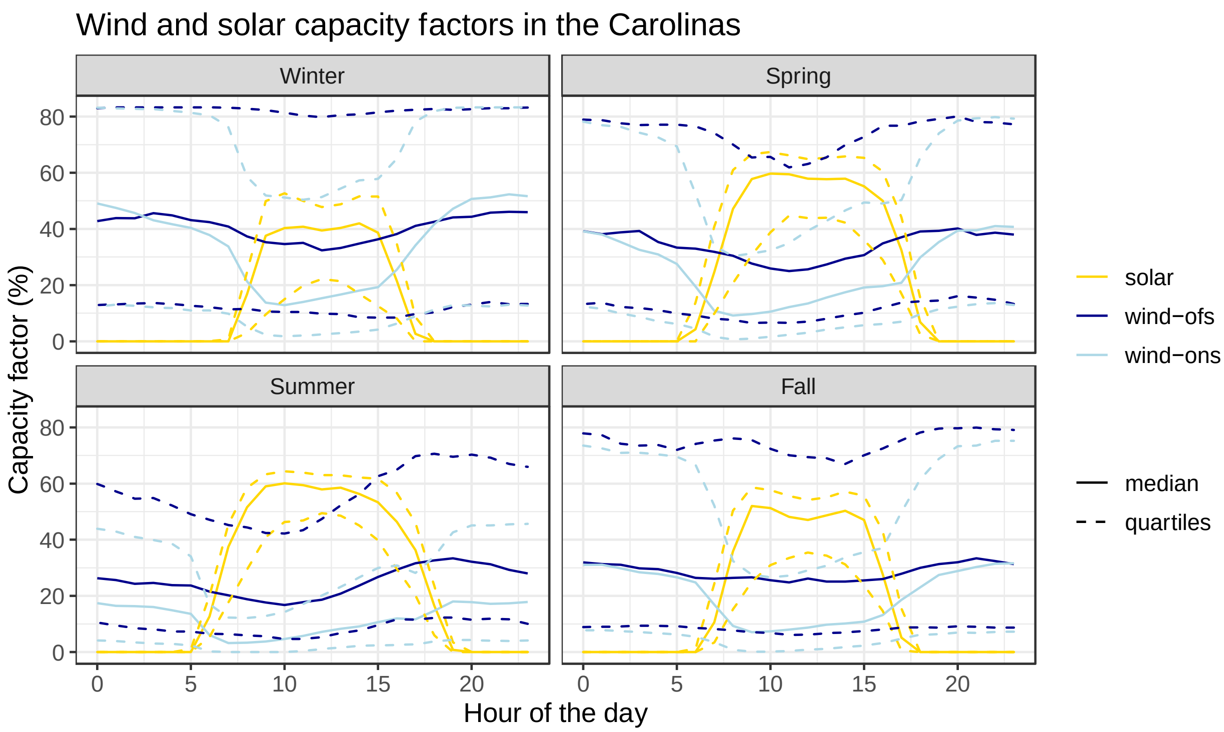

Figure 3. Wind and solar profiles for the Carolinas.

Task 3: Utilization and Customization of Existing Capacity Expansion Results

The capacity expansion will be based on existing NREL-made models built (e.g., using a modified form of ReEDS for NARIS) and customized to suit Duke's needs. Results from the capacity expansion will represent the cost optimal mix of all energy sources in Duke Energy's Carolinas region, given an emissions target or emissions price, as well as results from a BAU case. The location of generation and storage will be based on resource availability and transmission connection cost.

Deliverable 3.1: Conduct project webinar with Duke Energy staff to discuss NARIS ReEDS models and develop a Duke Energy customization plan.

Deliverable 3.2: Delivery of Slide deck containing plots, figures, and tables for results of the capacity expansion modeling, explanation of the methodology and discussion of the results, to be completed within 6 months of contract modification date.

NREL met with Duke Energy staff several times over the course of 2020 and 2021to customize the ReEDS and PLEXOS models for this project and delivered a slide deck summarizing the approach in advanced of the public stakeholder webinar in summer 2020.

Task 4: Public Webinar and Internal Slide Deck of Capacity Expansion Results

NREL will hold a public webinar and deliver an internal NREL-styled slide deck requiring NREL internal review. These will be based on the results and efforts undertaken from Task 1 to Task 4 inclusive.

NREL presented the interim results of the capacity expansion modeling results to Duke Energy stakeholders in a public webinar in the winter of 2020. Figure 4 summarizes one part of the capacity expansion results for the policy and policy + no fossil in 2050 scenarios, illustrating the type of capacity that could be deployment to meet Duke Energy's policy targets.

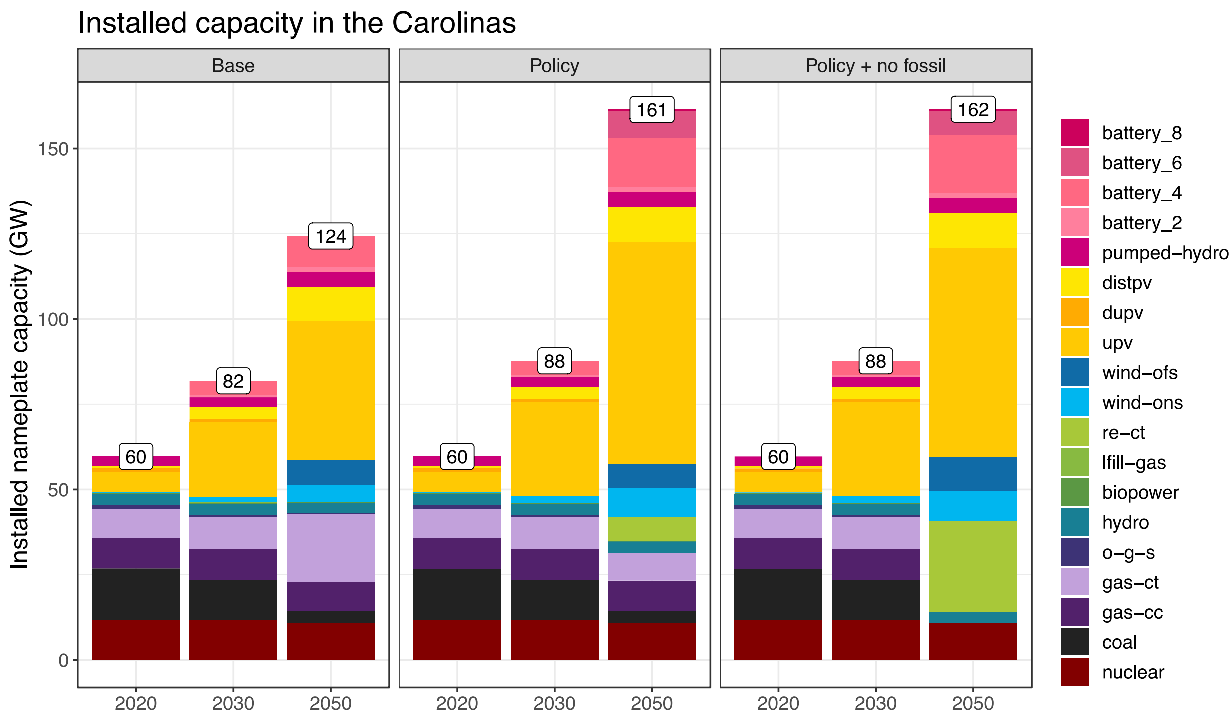

Figure 4. Installed capacity results by year (2020, 2030, and 2050) for the Carolinas for the main cases run in ReEDS

Task 5: Production Cost Modeling

NREL shall build off data already supplied from Duke Energy to create a full nodal production cost model. The model will use generation and transmission capacity data from results of NREL's capacity expansion models, as well as load data, supplied by Duke Energy Corporation, representing an extreme weather year. Further data could include:

- Costs and properties of existing generation, storage, and transmission.
- Reserve requirements and operational strategies.

This production cost model will be first built with data from Duke Energy, with reference to ERGIS, to represent the existing power system. Then, capacity expansion results will be utilized to modify the modeled system to a cost-optimal generation mix and transmission system, given a price on emissions or emissions target, as well as for a BAU case. NREL will model operation of these future cost-optimal capacity expansion cases, with load, transmission and generation resource disaggregated to a full nodal model, containing approximately 2,000 nodes. Each node enables representation of load, generation, storage, or connection to transmission. Transmission will be represented at the full nodal level, to enable a detailed assessment of transmission constraints.

This task will include extensive consultation with collaborators at Duke Energy, in order to validate the model outputs.

NREL worked closely with Duke Energy to develop the capacity expansion results from the previous tasks into a production cost model to study the proposed system at an hourly resolution. This include determining the placement of new wind and solar capacity on the Duke Energy system, as summarized in Figure 5.

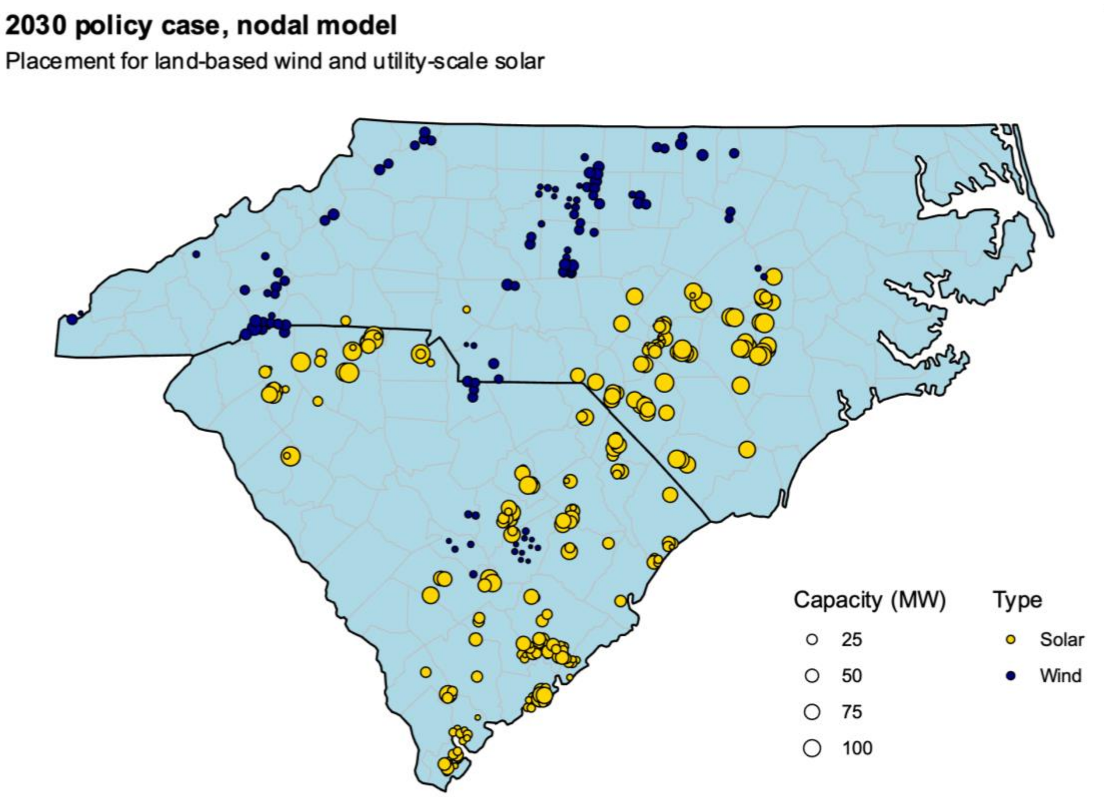

Figure 5. Map showing the placement of new utility-scale solar PV and wind resources to build the 2030 nodal PLEXOS model

Figure 6 provides an illustration of dispatch in 2050 during select winter and summer periods from the production cost modeling. Overall, the production cost modeling illustrated that the system was able to serve load in all hours and was helpful in providing insights into factors that Duke Energy should consider as part of its transition.

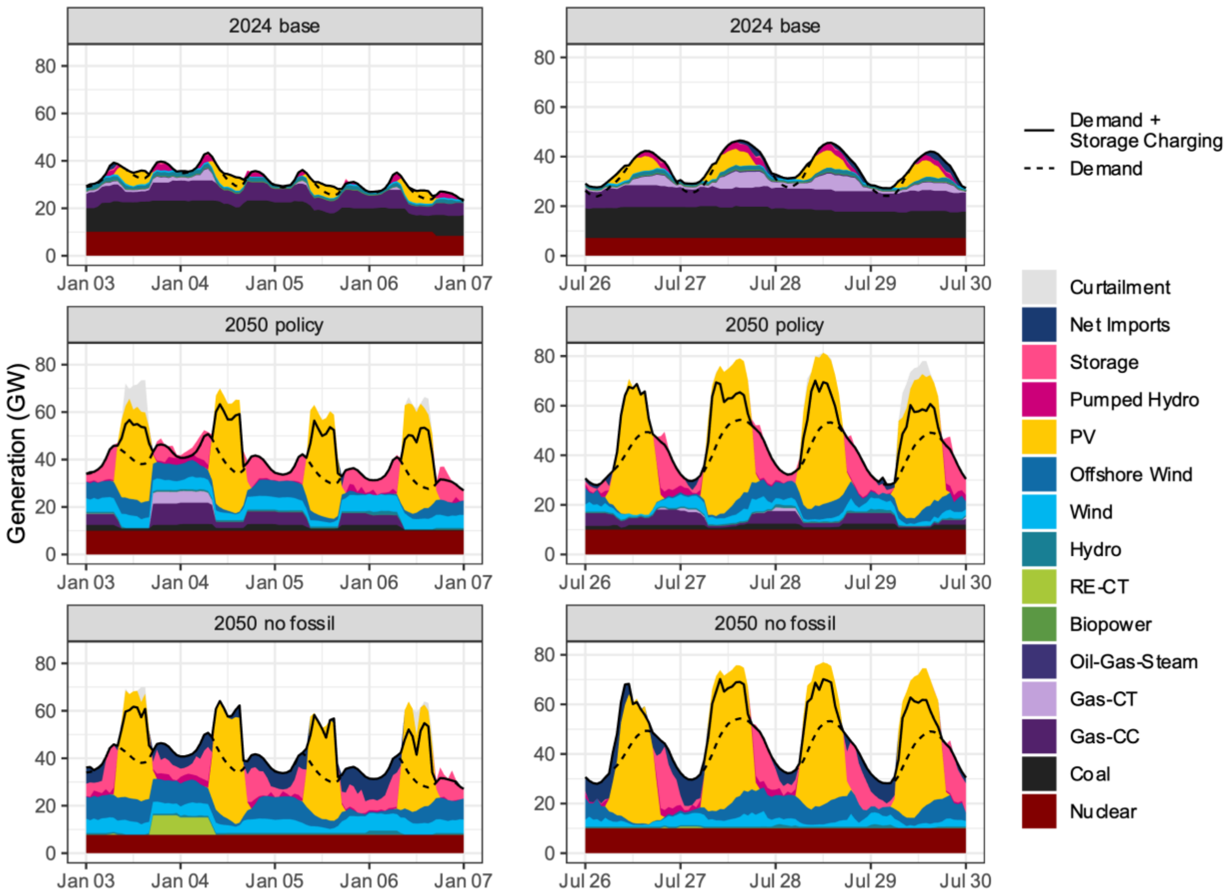

Figure 6. Generation dispatch for the 4 days surrounding the hour of the net load peak in the winter and summer for the 2024 base case and the 2050 policy cases

Task 6: Reporting

NREL will develop a Draft external report and slide deck based on the analysis completed above. The draft external report will be approximately 10-20 pages, including a summary of the scenario analyses and of overall modeling results. The draft external report will also be condensed into one or more presentation(s).

Duke Energy will provide NREL with comments on the Draft report and presentation and a meeting between Duke Energy and NREL will be held to elicit feedback on the report. Following this meeting, NREL shall complete modifications to the report to develop a Final Report. The Final Report to be published, and an associated final slide deck, will be presented to the public, at a location suggested by NREL.

NREL shall also prepare a memo documenting the assumptions and data used in the project.

Results from Phase II were presented to stakeholders in March 2022, and the final Phase II report was publicly released the following August (NREL/TP-6A40-82431).

Phase III

Task 1: Production Cost Modeling for 2018

For this extension, NREL shall utilize the production cost models built in the Phase II study. To extend the analysis to 2018, NREL will work closely with Duke to develop the following data sets:

- Hourly wind and solar data for the entire Eastern Interconnect corresponding to 2018
- Hourly load data for Duke Energy's territory corresponding to 2018
- Hourly, day-ahead wind, solar, and load forecasts for Duke Energy's territory corresponding to 2018
- Reserve timeseries for Duke Energy as a function of the wind, solar, and load data and forecast input data described above

NREL worked closely with Duke Energy to generate the wind, solar, and load timeseries data needed for the 2018 load modeling case, highlighted in Table 2.

Table 2. ReEDS Cases Tested with Either Nodal or Zonal Production Cost Modeling

Model Type	Model Name	ReEDS Buildout Year	Policy Constraint?	Weather Year
Nodal model	Duke 2024	2024	N	2012
	Duke 2030	2030	Y	2012
	Duke 2030 coal retirements	2030 + accelerated coal retirements	Y	2012
	Duke 2036 extended cold snap	2036	Y	2018
Zonal model	Carolinas 2024	2024	N	2012
	Carolinas 2050	2050	Y	2012

Figure 7 summarizes the generator dispatch in all the production cost modeling runs, with the "Duke 2036 extended cold snap" scenario representing the 2018 weather assumptions produced for Phase III. The results illustrate that the cold weather conditions in this year required more generation from natural gas to meet sustained high load levels. This finding reflects the importance of planning for winter events.

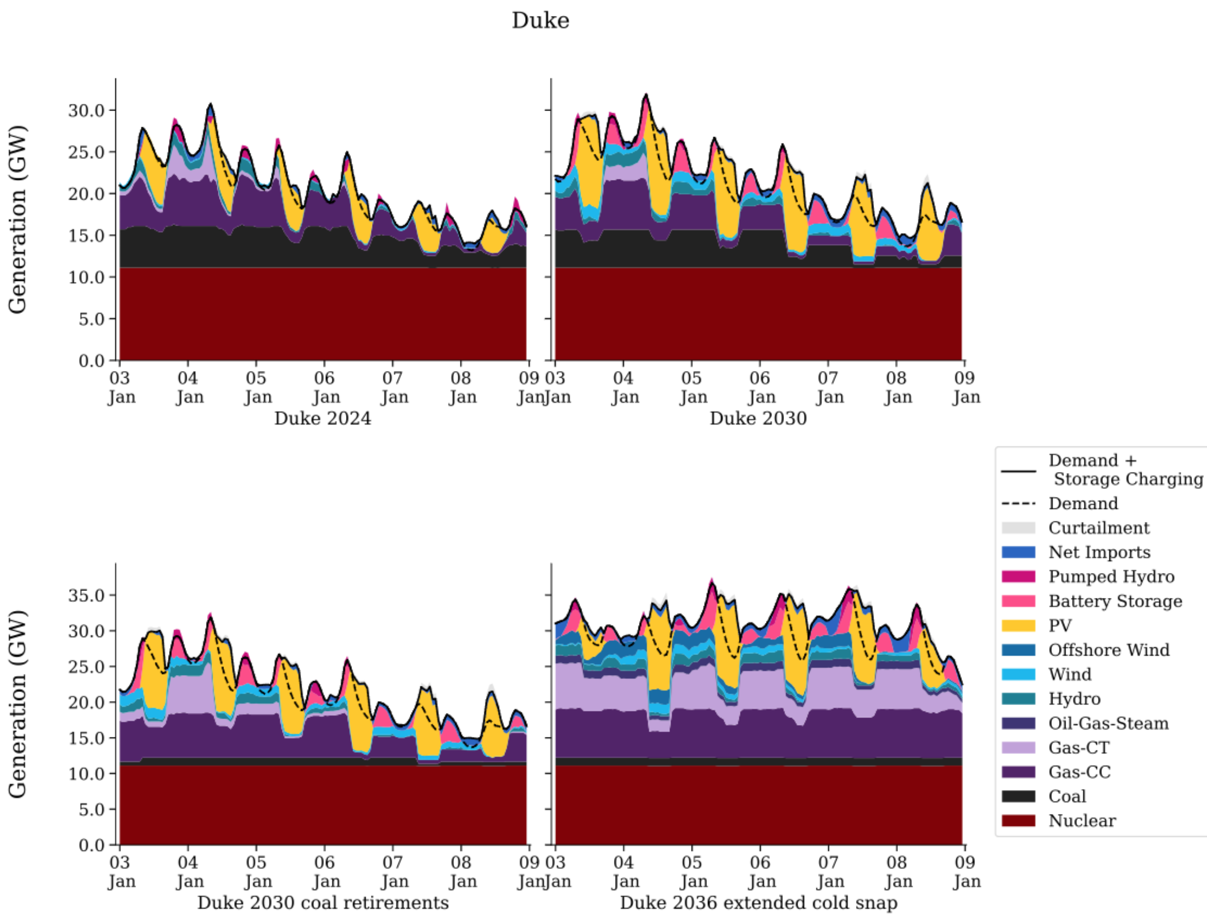

Figure 7. System dispatch during a winter peak for each nodal case

Task 2: Reporting

NREL will develop a Draft report and slide deck based on the analysis completed above.

Duke Energy will provide NREL with comments on the Draft report and presentation and a meeting between Duke Energy and NREL will be held to elicit feedback on the report. Following this meeting, NREL shall complete modifications to the report to develop a Final Report.

The Final report for the 2018 weather extension work will serve as an appendix to the main report published in Phase II of the Carbon-Free Resource Integration Study for Duke Energy. In addition, NREL will give a public presentation comparing the results from analyses using the 2012 and 2018 weather- year data.

NREL shall also prepare a memo documenting the assumptions and data used in the project.

Deliverable 2.1: Draft external report for Duke with associated data and assumptions, to be completed 2 months from project start date

Deliverable 2.2: Presentation slide deck summarizing findings from 2018 extension, to be completed 4 months from project start

Deliverable 2.3: Internal memo for Duke with associated data and assumptions, to be completed 5 months from project start date

Deliverable 2.4: Final External report, to be completed 6 months from project start

Deliverable 2.5: Final External Presentation, to be delivered in North or South Carolina at a public stakeholder meeting, to be completed 6 months from project start

Results from the Phase III extension analyzing the 2018 weather conditions were ultimately integrated directly into the Phase II report. The findings were presented to stakeholders in March 2022 along with the Phase II materials and were included in the final report publicly released in August (NREL/TP-6A40-82431).

<u>Subject Inventions Listing</u>:

None

<u>ROI #</u>:

None

<u>References</u>:

Ela, E., M. Milligan, A. Bloom, A. Botterud, A. Townsend, and T. Levin. 2014. *Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation.* Golden, CO. : National Renewable Energy Laboratory, NREL/TP-5D00-61765, 2014.

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Mai, T., et al. 2012. *Exploration of High-Penetration Renewable Electricity Futures. Vol. 1 of Renewable Electricity Futures Study.* Golden, CO : National Renewable Energy Laboratory, NREL/TP-6A20-52409-1, 2012.