Capacity Expansion Planning Under the Risk of Hurricanes: An Analysis of The US East Coast

Victor. A. D. Faria1\*, Neda Jamaleddin2, Anderson Rodrigo de Queiroz 2,3, Luana Medeiros Marangon Lima 4, Mohammed Gabr 2

1 – Department of Operations Research, North Carolina State University, Raleigh, NC, 27695, USA

2 – CCEE Department, North Carolina State University, Raleigh, NC, 27607, USA

3 – Decision Sciences, Economics, and Finance Department, School of Business at North Carolina Central University, Durham, NC, 27707, USA

4 – Nicholas School of Environment, Duke University, Durham, NC, USA

\*Corresponding Author Contact: [vaduraes@ncsu.edu](mailto:vaduraes@ncsu.edu),

(+1) (919) 345 8185

1. **Summary of Database For the North Carolina Energy Systems**

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**Figure 2.4:** Summary of Total Capacity for Existing Technologies Considering The Capacity Expansion Model. Capacity Decreases as Existing Technologies Retire.

1. **Detailed Database Construction For The North Carolina Energy System**

This document details the data used to construct the database for the North Carolina Energy System considered in the main manuscript. In this section, costs are reported using 2020 US dollars. However, for optimization purposes, inside the optimization tool, values are adjusted to the first year of optimization (year 2023) using the Consumer Price Index (1.16 conversion rate) [1].

* 1. **Wind Speeds Data and Regionalization**

In this work, the Hazus FEMA model [2] is used to obtain statistical information regarding the recurrency of extreme winds in NC. Illustrated in Figures 2.1 and 2.2 are the wind characteristics linked to events with recurrence intervals of 100 years and 1000 years, respectively. It is important to mention that the full Hazus dataset also contains information for other recurrency periods (10, 20, 50, 100, 200, 500, 1000) which were also used in this work.

|  |  |
| --- | --- |
|  |  |
| **Figure 2.1:** One Every100 Years Extreme Wind Speeds From Hazus (peak gust at 10m height) | **Figure 2.2:** One Every1000 Years Extreme Wind Speeds From Hazus (peak gust at 10m height) |

With the objective of modeling the influence of extreme winds on the electric power system infrastructure, it is important to understand that although the location of existing generators is known with certainty, which allows the assignment of specific wind speed statistics to those generators, the same cannot be said about future deployments. In capacity expansion models, the location of new deployments is usually defined from a pool of prespecified regions, where the number of regions significantly affects the computational complexity.

In this work, the NC state was divided into three equivalent regions (R1, R2, and R3), allowing the definition of an equivalent wind speed risk metric that is specific to each new technology and region of deployment (R1, R2, or R3). This procedure enables the simulation of the stochastic optimization model and the assignment of risk to new generations with reasonable computational cost. It is important to mention that this is a simplification and leads to not representing the full wind speed variability that may exist inside each of the three regions created.

Figure 2.3 shows the three regions mentioned above. Based on 1000-year wind data (Figure 2.2), region R1 is defined as any place in NC with wind speeds above 130mph (category four hurricane), region R2 is defined as any place with wind speeds between 111-130mph (category three hurricane), and region R3 is defined by wind speed below 111mph (category one and two hurricane).

A map of the state of north carolina

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**Figure 2.3:** Regions for New Technology Deployment in NC With Different Risk Levels and Location of Existing Generators.

* 1. **Fragility Curves**
  2. **Technologies**

Tables 2.1 and 2.2 describe the existing and new energy generation technologies considered in our simulations, and Table 2.3 describes the non-energy generation technologies.

**Table 2.1:** Existing Generation Technologies Represented in The Model

|  |  |
| --- | --- |
| **Technology Code** | **Description** (Following EIA 860 Nomenclature) [2] |
| AB\_ST\_EXISTING | Steam Turbine Using Agricultural By-Products |
| BIT\_ST\_EXISTING | Steam Turbine Using Bituminous Coal |
| BLQ\_ST\_EXISTING | Steam Turbine Using Black Liquor |
| DFO\_CC\_EXISTING | Combined Cycle Combustion Turbine Using Petroleum |
| DFO\_GT\_EXISTING | Combustion Turbine Using Petroleum |
| DFO\_IC\_EXISTING | Internal Combustion Engine Using Petroleum |
| LFG\_GT\_EXISTING | Combustion Turbine Using Landfill Gas |
| LFG\_IC\_EXISTING | Internal Combustion Engine Using Landfill Gas |
| MWH\_BA1H\_EXISTING | Battery Storage- 1h |
| MWH\_BA2H\_EXISTING | Battery Storage- 2h |
| NG\_CC\_EXISTING | Combined Cycle Combustion Turbine Using Natural Gas |
| NG\_GT\_EXISTING | Combustion Turbine Using Natural Gas |
| NG\_ST\_EXISTING | Steam Turbine Using Natural Gas |
| NUC\_ST\_EXISTING | Nuclear Turbine |
| OBG\_IC\_EXISTING | Internal Combustion Engine Using Other Biomass Gas |
| SUN\_PV\_EXISTING | Solar Photovoltaic - Utility |
| WAT\_HY\_EXISTING | Conventional Hydroelectric |
| WAT\_PS\_EXISTING | Hydroelectric Pumped Storage |
| WDS\_ST\_EXISTING | Steam Turbine Using Wood Waste |
| WH\_ST\_EXISTING | Steam Turbine Using Waste Heat |
| WND\_WT\_EXISTING | Onshore Wind Turbine |

**Table 2.2:** New Generation Technologies Represented in The Model

|  |  |
| --- | --- |
| **Technology Code** | **Description** |
| BATT\_2H\_NEW | Battery Storage 2h – Utility Scale (NREL ATB 2022 Technology) [3] |
| BATT\_4H\_NEW | Battery Storage 4h – Utility Scale (NREL ATB 2022 Technology) [3] |
| BATT\_6H\_NEW | Battery Storage 6h – Utility Scale (NREL ATB 2022 Technology) [3] |
| BATT\_8H\_NEW | Battery Storage 8h – Utility Scale (NREL ATB 2022 Technology) [3] |
| BIOMASS\_CC90\_NEW | Generation From Biomass With 90% Carbon Capture (Technology from NREL ReEDS model Using BECC-mod) [4] |
| BIOMASS\_NEW | Generation From Biomass (NREL ATB 2022 Technology) [3] |
| COAL\_95CC\_NEW | Generation From Coal With 95% Carbon Capture (NREL ATB 2022 Technology) [3] |
| COAL\_99CC\_NEW | Generation From Coal With 99% Carbon Capture (NREL ATB 2022 Technology) [3] |
| COAL\_NEW | Generation From Coal (NREL ATB 2022 Technology) [3] |
| NG\_F-FRAME\_CC\_95CC\_NEW | Combined Cycle Natural Gas Turbine F-Frame With 95 % of Carbon Capture (NREL ATB 2022 Technology) [3] |
| NG\_F-FRAME\_CC\_97CC\_NEW | Combined Cycle Natural Gas Turbine F-Frame With 97 % of Carbon Capture (NREL ATB 2022 Technology) [3] |
| NG\_F-FRAME\_CC\_NEW | Combined Cycle Natural Gas Turbine F-Frame (NREL ATB 2022 Technology) [3] |
| NG\_F-FRAME\_CT\_NEW | Natural Gas Combustion Turbine F-Frame - Simple Cycle (NREL ATB 2022 Technology) [3] |
| NG\_H-FRAME\_CC\_95CC\_NEW | Combined Cycle Natural Gas Turbine H-Frame With 95 % of Carbon Capture (NREL ATB 2022 Technology) [3] |
| NG\_H-FRAME\_CC\_97CC\_NEW | Combined Cycle Natural Gas Turbine H-Frame With 97 % of Carbon Capture (NREL ATB 2022 Technology) [3] |
| NG\_H-FRAME\_CC\_NEW | Combined Cycle Natural Gas Turbine H-Frame (NREL ATB 2022 Technology) [3] |
| NUCLEAR-AP1000\_NEW | Nuclear Generation Using AP1000 PWR (NREL ATB 2022 Technology) [3] |
| NUCLEAR-SMR\_NEW | Small Modular Nuclear Reactor (NREL ATB 2022 Technology) [3] |
| PV-COMMERCIAL\_NEW | Commercial Solar PV (NREL ATB 2022 Technology) [3] |
| PV-RESIDENTIAL\_NEW | Residential Solar PV (NREL ATB 2022 Technology) [3] |
| PV-UTILITY\_NEW | Utility Solar PV (NREL ATB 2022 Technology) [3] |
| WAT\_HY\_NEW | Conventional Hydroelectric (NREL ATB 2022 Technology) [3] |
| WAT\_PS\_NEW | Hydroelectric Pumped Storage (NREL ATB 2022 Technology) [3] |
| WIND-LAND-C8\_NEW | Onshore Wind Turbine Class 8 From NREL ATB 2022 (NREL ATB 2022 Technology) [3] |
| WIND-OFFSHORE-C6\_NEW | Offshore Wind Turbine Class 6 From NREL ATB 2022 (NREL ATB 2022 Technology) [3] |

**Table 2.3:** Non-Generation Technologies Represented in The Model

|  |  |
| --- | --- |
| **Technology Code** | **Description** |
| CO2\_STORAGE | CO2 Storage |
| DISTRIBUTION | Energy Distribution |
| FT\_BIOMASS | Fuel for Generation Technologies That Use Biomass |
| FT\_COAL | Fuel for Generation Technologies That Use Coal |
| FT\_NG | Fuel for Generation Technologies That Use Natural Gas |
| FT\_NUCLEAR | Fuel for Nuclear Generation Technologies |
| FT\_PETROLEUM | Fuel for Generation Technologies That Use Petroleum |
| TRANSMISSION\_INTERREGIONAL | Transmission Between Different Regions |
| TRANSMISSION\_REGIONAL | Transmission In the Same Region |

* 1. **Existing Capacity**

Data from existing generation capacity comes from the EIA-860M reports [2]. Figure 2.1 shows the vintage (operational year) of each existing technology on the NC system and its corresponding capacity. On the left legend, the total existing capacity is shown in parathesis.

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**Figure 2.1:** Total Existing Capacity on the NC Power System by Different Operational Years (Vintages). The System Has 39GW of Total Capacity (end 2022) According to The EIA-860M reports [2].

* 1. **Lifetime Tech and Loan**

The default lifetimes and loan periods of the technologies considered in our models are detailed in Tables 2.4, 2.5, and 2.6 with their corresponding references.

**Table 2.4:** Default Technologies Lifetime For Existing Generation Technologies

|  |  |  |
| --- | --- | --- |
| **Technology Code** | **Lifetime Tech** | |
| **Years** | **Reference** |
| AB\_ST\_EXISTING | 27 | Weighted Average of Past Retirements on US [2] |
| BIT\_ST\_EXISTING | 56 | Weighted Average from DEC/DEP in IRPs [5, 6] |
| BLQ\_ST\_EXISTING | 55 | Weighted Average of Past Retirements on NC [2] |
| DFO\_CC\_EXISTING | 58 | Weighted Average of Past Retirements on NC [2] |
| DFO\_GT\_EXISTING | 69 | Weighted Average from DEC/DEP in IRPs [5, 6] |
| DFO\_IC\_EXISTING | 36 | Weighted Average of Past Retirements on the East Coast [2] |
| LFG\_GT\_EXISTING | 20 | Weighted Average Retirement on the East Coast [2] |
| LFG\_IC\_EXISTING | 16 | Weighted Average Retirement on the East Coast [2] |
| MWH\_BA1H\_EXISTING | 15 | From NREL ReEDS [4] |
| MWH\_BA2H\_EXISTING | 15 | From NREL ReEDS [4] |
| NG\_CC\_EXISTING | 37 | Weighted Average from DEC/DEP in IRPs [5, 6] For NG CA and CT |
| NG\_GT\_EXISTING | 42 | Weighted Average from DEC/DEP in IRPs [5, 6] |
| NG\_ST\_EXISTING | 53 | Weighted Average Retirement on the East Coast [2] |
| NUC\_ST\_EXISTING | 59 | Weighted Average from DEC/DEP in IRPs [5, 6] |
| OBG\_IC\_EXISTING | 15 | Weighted Average of Past Retirements on US [2] |
| SUN\_PV\_EXISTING | 30 | From NREL ReEDS [4] |
| WAT\_HY\_EXISTING | 109 | Weighted Average from DEC/DEP in IRPs [5, 6] for WAT\_HY |
| WAT\_PS\_EXISTING | 109 |
| WDS\_ST\_EXISTING | 50 | From NREL ReEDS [4] for Biopower |
| WH\_ST\_EXISTING | 33 | Weighted Average of Past Retirements on US [2] |
| WND\_WT\_EXISTING | 30 | From NREL ReEDS [4] |

In Table 2.4, “weighted average” refers to the weighted average of the technology lifetime using reported device capacities. In this table, when reference [2] is used if the total capacity of past technology retirements in NC is below 100MW, the average for the entire US-East Coast is used, and if the total capacity for existing data is still below 100MW, data of the whole US is used.

**Table 2.5:** Default Technologies Lifetime and Loan Periods Times For New Generation Technologies

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technology Code** | **Lifetime Tech** | | **Loan Period (Recovery Period)** | |
| **Years** | **Reference** | **Years** | **Reference** |
| BATT\_2H\_NEW | 15 | From NREL ReEDS [4] | 15 | From NREL ReEDS [4] |
| BATT\_4H\_NEW | 15 | From NREL ReEDS [4] | 15 | From NREL ReEDS [4] |
| BATT\_6H\_NEW | 15 | From NREL ReEDS [4] | 15 | From NREL ReEDS [4] |
| BATT\_8H\_NEW | 15 | From NREL ReEDS [4] | 15 | From NREL ReEDS [4] |
| BIOMASS\_CC90\_NEW | 50 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| BIOMASS\_NEW | 50 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| COAL\_95CC\_NEW | 65 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| COAL\_99CC\_NEW | 65 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| COAL\_NEW | 65 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NG\_F-FRAME\_CC\_95CC\_NEW | 60 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NG\_F-FRAME\_CC\_97CC\_NEW | 60 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NG\_F-FRAME\_CC\_NEW | 60 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NG\_F-FRAME\_CT\_NEW | 50 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NG\_H-FRAME\_CC\_95CC\_NEW | 60 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NG\_H-FRAME\_CC\_97CC\_NEW | 60 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NG\_H-FRAME\_CC\_NEW | 60 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NUCLEAR-AP1000\_NEW | 60 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| NUCLEAR-SMR\_NEW | 60 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| PV-COMMERCIAL\_NEW | 30 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| PV-RESIDENTIAL\_NEW | 30 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| PV-UTILITY\_NEW | 30 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| WAT\_HY\_NEW | 109 | Average from DEC/DEP in IRPs [5, 6] for WAT\_HY | 20 | From NREL ReEDS [4] |
| WAT\_PS\_NEW | 109 | 20 | From NREL ReEDS [4] |
| WIND-LAND-C8\_NEW | 30 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |
| WIND-OFFSHORE-C6\_NEW | 30 | From NREL ReEDS [4] | 20 | From NREL ReEDS [4] |

**Table 2.6:** Default Technologies Lifetime and Loan Periods For Non-Generation Technologies

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technology Code** | **Lifetime Tech** | | **Loan Period (Recovery Period)** | |
| **Years** | **Reference** | **Years** | **Reference** |
| DISTRIBUTION | 60 |  | 20 |  |
| TRANSMISSION\_INTERREGIONAL | 60 |  | 20 |  |
| TRANSMISSION\_REGIONAL | 60 |  | 20 |  |
| CO2\_STORAGE\* | NA\* | | | |
| FT\_BIOMASS\* | NA\* | | | |
| FT\_COAL\* | NA\* | | | |
| FT\_NG\* | NA\* | | | |
| FT\_NUCLEAR\* | NA\* | | | |
| FT\_PETROLEUM\* | NA\* | | | |

\*We do not consider investment costs for this technology (all costs for it are variable or fixed); as such, the lifetime of the tech and its loan period can be ignored.

Some existing generation units managed by Duke Energy in North Carolina have estimated retirement dates available at [5, 6] (123 units – 24.5 GW – 63% of the NC existing capacity). Because of those generation units, modifications to the available capacity were made at each vintage to ensure proper capacity retirement of each technology type. However, for generators without estimated retirement dates from Duke Energy [5, 6], the lifetimes reported in Tables 2.4 and 2.5 were assumed.

It is important to mention that due to limitations on data availability and model approximations, an existing generator reported at the EIA-860M [2] and not available at [5, 6] may be retired prior to the first year of simulation (year 2023), as we consider an average retirement date for all generators not referenced on [5, 6]. In this case, this capacity is eliminated from the pool of existing capacity; these conditions account for less than 0.39GW (less than 1% of the NC existing capacity).

Figure 2.2 shows the retirement dates and capacity for existing technologies retired after 2023, and Figure 2.3 shows the retirement dates and capacity for existing technologies retired before or in 2023 (a modeling effect of the values in Tables 2.4 and 2.5).

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\*A technology retired at year X does not contribute to the generation at year X.

**Figure 2.2:** Retirement Year and Capacity for Existing Technologies Retired After 2023.

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\*A technology retired at year X does not contribute to the generation at year X.

**Figure 2.3:** Retirement Year and Capacity for “Existing Technologies Retired Before or at 2023”. This Happens Because of the Average Lifetime Approximations Considered and Limitations on Data Availability. This Corresponds To Less Than 1% of the Existing Capacity.

Finally, Figure 2.4 summarizes the total installed capacity for existing technologies considered by the capacity expansion model simulation from 2023 to 2055.

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**Figure 2.4:** Summary of Total Capacity for Existing Technologies Considering The Capacity Expansion Model. Capacity Decreases as Existing Technologies Retire.

* 1. **Costs**

In this work, we assume that new capacity can only be added using the technologies described in Table 2.7, which also contains the investment costs in millions of dollars per new GW installed at each future period in the capacity expansion model. Table 2.7 also contains the discount rate (weighted average cost of capital) for each technology investment.

**Table 2.7:** Investment Cost For New Technologies and Discount Rates

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Technology Code** | **Investment Cost at Different Tech Vintages [M$/GW]** | | | | | | | **Discount**  **Rate** | **Reference** |
| **2023** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| BATT\_2H\_NEW | 809 | 762 | 682 | 682 | 682 | 682 | 682 | 0.065 | [3] |
| BATT\_4H\_NEW | 1394 | 1312 | 1174 | 1174 | 1174 | 1174 | 1174 | 0.065 | [3] |
| BATT\_6H\_NEW | 1978 | 1862 | 1666 | 1666 | 1666 | 1666 | 1666 | 0.065 | [3] |
| BATT\_8H\_NEW | 2563 | 2413 | 2158 | 2158 | 2158 | 2158 | 2158 | 0.065 | [3] |
| BIOMASS\_CC90\_NEW\* | 5529 | 5495 | 5410 | 5333 | 5255 | 5178 | 5100 | 0.058 | [4, 3] |
| BIOMASS\_NEW | 4332 | 4276 | 4186 | 4046 | 3906 | 3766 | 3626 | 0.058 | [3] |
| CO2\_STORAGE | Assuming no Investment Costs and Only Variable Costs as in The NREL ReEDS Model [3] | | | | | | | | |
| COAL\_95CC\_NEW | 4750 | 4677 | 4495 | 4313 | 4131 | 3949 | 3766 | 0.065 | [3] |
| COAL\_99CC\_NEW | 4860 | 4786 | 4599 | 4414 | 4227 | 4040 | 3853 | 0.065 | [3] |
| COAL\_NEW | 3047 | 3027 | 2962 | 2861 | 2761 | 2664 | 2567 | 0.065 | [3] |
| DISTRIBUTION | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.050 |  |
| NG\_F-FRAME\_CC\_95CC\_NEW | 2117 | 2066 | 1974 | 1892 | 1812 | 1732 | 1658 | 0.065 | [3] |
| NG\_F-FRAME\_CC\_97CC\_NEW | 2150 | 2099 | 2004 | 1922 | 1841 | 1760 | 1683 | 0.065 | [3] |
| NG\_F-FRAME\_CC\_NEW | 1026 | 1010 | 989 | 967 | 946 | 925 | 905 | 0.065 | [3] |
| NG\_F-FRAME\_CT\_NEW | 900 | 872 | 838 | 815 | 793 | 772 | 750 | 0.065 | [3] |
| NG\_H-FRAME\_CC\_95CC\_NEW | 1997 | 1948 | 1862 | 1785 | 1709 | 1635 | 1564 | 0.065 | [3] |
| NG\_H-FRAME\_CC\_97CC\_NEW | 2027 | 1978 | 1889 | 1811 | 1736 | 1659 | 1587 | 0.065 | [3] |
| NG\_H-FRAME\_CC\_NEW | 981 | 958 | 929 | 909 | 889 | 869 | 854 | 0.065 | [3] |
| NUCLEAR-AP1000\_NEW | 7302 | 7040 | 6966 | 6731 | 6496 | 6261 | 6026 | 0.058 | [3] |
| NUCLEAR-SMR\_NEW | 7839 | 7739 | 7661 | 7405 | 7150 | 6894 | 6639 | 0.058 | [3] |
| PV-COMMERCIAL\_NEW | 1574 | 1549 | 1494 | 1352 | 1210 | 1069 | 927 | 0.056 | [3] |
| PV-RESIDENTIAL\_NEW | 2569 | 2488 | 2285 | 1968 | 1651 | 1334 | 1016 | 0.057 | [3] |
| PV-UTILITY\_NEW | 1161 | 1157 | 1150 | 1051 | 952 | 853 | 754 | 0.053 | [3] |
| TRANSMISSION\_INTERREGIONAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.050 |  |
| TRANSMISSION\_REGIONAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.050 |  |
| WAT\_HY\_NEW | 2574 | 2574 | 2590 | 2590 | 2590 | 2590 | 2590 | 0.054 | [3]-Class 1 |
| WAT\_PS\_NEW | 1999 | 1999 | 2011 | 2011 | 2011 | 2011 | 2011 | 0.054 | [3]-Class 1 |
| WIND-LAND-C8\_NEW | 1323 | 1231 | 1006 | 981 | 956 | 931 | 906 | 0.071 | [3]-Class 8 |
| WIND-OFFSHORE-C6\_NEW | 3855 | 3726 | 3570 | 3450 | 3362 | 3294 | 3238 | 0.066 | [3]-Class 6 |

\*Costs from [4], discount rate from [3]

Table 2.8 contains the fixed and variable costs for the existing generation technologies represented in the capacity expansion model.

**Table 2.8:** Fixed and Variable Costs for Existing Generation

|  |  |  |  |
| --- | --- | --- | --- |
| **Technology Code** | **Fixed Cost [M$/GWyr]**  **Same For all Vintages and Periods** | **Variable Cost [$/MWh]**  **Same For all Vintages and Periods** | **Reference\*** |
| AB\_ST\_EXISTING | 151 | 5.8 | [3]-Biopower (Conservative-2020) |
| BIT\_ST\_EXISTING | 141 | 13.86 | [3]-Coal IGCC (Conservative-2020) |
| BLQ\_ST\_EXISTING | 151 | 5.8 | [3]-Biopower (Conservative-2020) |
| DFO\_CC\_EXISTING | 28 | 1.78 | [3]-Same as NG F-Frame CC \*\* (Conservative-2020) |
| DFO\_GT\_EXISTING | 21 | 5.1 | [3]-Same as NG F-Frame CT \*\* (Conservative-2020) |
| DFO\_IC\_EXISTING | 21 | 5.1 | [3]-Same as NG F-Frame CT \*\* (Conservative-2020) |
| LFG\_GT\_EXISTING | 151 | 5.8 | [3]-Biopower (Conservative-2020) |
| LFG\_IC\_EXISTING | 151 | 5.8 | [3]-Biopower (Conservative-2020) |
| MWH\_BA1H\_EXISTING | 31 | 0 | [3]-Commercial Storage (Conservative-2020) |
| MWH\_BA2H\_EXISTING | 25 | 0 | [3]-Utility Storage (Conservative-2020) |
| NG\_CC\_EXISTING | 28 | 1.78 | [3]-NG F-Frame CC (Conservative-2020) |
| NG\_GT\_EXISTING | 21 | 5.1 | [3]-NG F-Frame CT (Conservative-2020) |
| NG\_ST\_EXISTING | 21 | 5.1 | [3]-NG F-Frame CT (Conservative-2020) |
| NUC\_ST\_EXISTING | 146 | 2.84 | [3]-Nuclear AP1000 (Conservative-2020) |
| OBG\_IC\_EXISTING | 151 | 5.8 | [3]-Biopower (Conservative-2020) |
| SUN\_PV\_EXISTING | 23 | 0 | [3]-Solar Utility (Conservative-2020) |
| WAT\_HY\_EXISTING | 64 | 0 | [3]-Hydropower Class 1 (Conservative-2020) |
| WAT\_PS\_EXISTING | 18 | 0.513 | [3]-Pumped Hydropower Class 1 (Conservative-2020) |
| WDS\_ST\_EXISTING | 151 | 5.8 | [3]-Biopower (Conservative-2020) |
| WH\_ST\_EXISTING | 21 | 5.1 | [3]-Same as NG F-Frame CT (Conservative-2020) |
| WND\_WT\_EXISTING | 43 | 0 | [3]-Wind Class C8 (Conservative-2020) |

\*Reference and comment on the technology (in the reference) considered equivalent to the technology code

\*\*Gas turbines can typically run either on natural gas or refined liquid fuels

Tables 2.9 and 2.10 contain the fixed costs for the new-generation and non-generation technologies represented in the capacity expansion model. Technologies with zero fixed costs are not represented.

**Table 2.9:** Fixed Costs for New Generation

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Technology Code** | **Fixed Cost at Different Tech Vintages [M$/GWyear]**  **(Only Varies With the Vintage)** | | | | | | | **Reference** |
| **2023** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| BATT\_2H\_NEW | 20 | 19 | 17 | 17 | 17 | 17 | 17 | [3] |
| BATT\_4H\_NEW | 35 | 33 | 29 | 29 | 29 | 29 | 29 | [3] |
| BATT\_6H\_NEW | 49 | 47 | 42 | 42 | 42 | 42 | 42 | [3] |
| BATT\_8H\_NEW | 64 | 60 | 54 | 54 | 54 | 54 | 54 | [3] |
| BIOMASS\_CC90\_NEW | 162 | 162 | 162 | 162 | 162 | 162 | 162 | [4] |
| BIOMASS\_NEW | 151 | 151 | 151 | 151 | 151 | 151 | 151 | [3] |
| COAL\_95CC\_NEW | 115 | 115 | 115 | 115 | 115 | 115 | 115 | [3] |
| COAL\_99CC\_NEW | 117 | 117 | 117 | 117 | 117 | 117 | 117 | [3] |
| COAL\_NEW | 74 | 74 | 74 | 74 | 74 | 74 | 74 | [3] |
| NG\_F-FRAME\_CC\_95CC\_NEW | 58 | 58 | 58 | 58 | 58 | 58 | 58 | [3] |
| NG\_F-FRAME\_CC\_97CC\_NEW | 59 | 59 | 59 | 59 | 59 | 59 | 59 | [3] |
| NG\_F-FRAME\_CC\_NEW | 28 | 28 | 28 | 28 | 28 | 28 | 28 | [3] |
| NG\_F-FRAME\_CT\_NEW | 21 | 21 | 21 | 21 | 21 | 21 | 21 | [3] |
| NG\_H-FRAME\_CC\_95CC\_NEW | 53 | 53 | 53 | 53 | 53 | 53 | 53 | [3] |
| NG\_H-FRAME\_CC\_97CC\_NEW | 54 | 54 | 54 | 54 | 54 | 54 | 54 | [3] |
| NG\_H-FRAME\_CC\_NEW | 27 | 27 | 27 | 27 | 27 | 27 | 27 | [3] |
| NUCLEAR-AP1000\_NEW | 146 | 146 | 146 | 146 | 146 | 146 | 146 | [3] |
| NUCLEAR-SMR\_NEW | 114 | 114 | 114 | 114 | 114 | 114 | 114 | [3] |
| PV-COMMERCIAL\_NEW | 18 | 17 | 17 | 16 | 14 | 13 | 12 | [3] |
| PV-RESIDENTIAL\_NEW | 28 | 27 | 25 | 22 | 19 | 16 | 13 | [3] |
| PV-UTILITY\_NEW | 20 | 20 | 20 | 19 | 18 | 16 | 15 | [3] |
| WAT\_HY\_NEW | 64 | 64 | 64 | 64 | 64 | 64 | 64 | [3]-Class 1 |
| WAT\_PS\_NEW | 18 | 18 | 18 | 18 | 18 | 18 | 18 | [3]-Class 1 |
| WIND-LAND-C8\_NEW | 43 | 43 | 43 | 43 | 42 | 42 | 41 | [3]-Class 8 |
| WIND-OFFSHORE-C6\_NEW | 115 | 112 | 106 | 102 | 99 | 97 | 95 | [3]-Class 6 |

**Table 2.10:** Fixed Costs For Non-Generation Technologies

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Technology Code** | **Fixed Cost Tech at Different Tech Vintages [M$/GWyear]** | | | | | | | **Reference** |
| **2023** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| DISTRIBUTION | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| TRANSMISSION\_INTERREGIONAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| TRANSMISSION\_REGIONAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |

Tables 2.11 and 2.12 contain the variable costs of the new-generation and non-generation technologies represented in the capacity expansion model. Technologies with zero variable cost are not shown for simplicity.

**Table 2.11:** Variable Costs for New Generation

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Technology Code** | **Variable Cost at Different Tech Vintages [$/MWh]**  **(Only Varies With the Vintage)** | | | | | | | **Reference** |
| **2023** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| BIOMASS\_CC90\_NEW | 16.60 | 16.60 | 16.60 | 16.60 | 16.60 | 16.60 | 16.60 | [4] |
| BIOMASS\_NEW | 5.80 | 5.80 | 5.80 | 5.80 | 5.80 | 5.80 | 5.80 | [3] |
| COAL\_95CC\_NEW | 14.03 | 14.03 | 14.03 | 14.03 | 14.03 | 14.03 | 14.03 | [3] |
| COAL\_99CC\_NEW | 14.37 | 14.37 | 14.37 | 14.37 | 14.37 | 14.37 | 14.37 | [3] |
| COAL\_NEW | 7.96 | 7.96 | 7.96 | 7.96 | 7.96 | 7.96 | 7.96 | [3] |
| NG\_F-FRAME\_CC\_95CC\_NEW | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | [3] |
| NG\_F-FRAME\_CC\_97CC\_NEW | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | [3] |
| NG\_F-FRAME\_CC\_NEW | 1.78 | 1.78 | 1.78 | 1.78 | 1.78 | 1.78 | 1.78 | [3] |
| NG\_F-FRAME\_CT\_NEW | 5.10 | 5.10 | 5.10 | 5.10 | 5.10 | 5.10 | 5.10 | [3] |
| NG\_H-FRAME\_CC\_95CC\_NEW | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | [3] |
| NG\_H-FRAME\_CC\_97CC\_NEW | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | [3] |
| NG\_H-FRAME\_CC\_NEW | 1.76 | 1.76 | 1.76 | 1.76 | 1.76 | 1.76 | 1.76 | [3] |
| NUCLEAR-AP1000\_NEW | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | [3] |
| NUCLEAR-SMR\_NEW | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | [3] |
| WAT\_PS\_NEW | 0.513 | 0.513 | 0.513 | 0.513 | 0.513 | 0.513 | 0.513 | [3]-Class 1 |

**Table 2.12:** Variable Costs For Non-Generating Technologies

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Technology Code** | **Variable Cost at Different Periods**  **(Does not Vary With the Tech Vintage**  **But Vary With The Period)** | | | | | | | **Reference** |
| **2023** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| CO2\_STORAGE [$/Metric Ton CO2] | 12.87 | 12.87 | 12.87 | 12.87 | 12.87 | 12.87 | 12.87 | [7]\* |
| DISTRIBUTION | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| FT\_BIOMASS [$/MMBTU] | 5 | 5 | 5 | 5 | 5 | 5 | 5 | [3] |
| FT\_COAL [$/MMBTU] | 5.84 | 4.10 | 3.21 | 3.71 | 4.01 | 3.86 | 3.75 | [8]- AEO23 Reference Case |
| FT\_NG [$/MMBTU] | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | [8]- AEO23 Reference Case |
| FT\_NUCLEAR [$/MMBTU] | 14.66 | 13.43 | 13.23 | 13.72 | 14.13 | 14.42 | 14.83 | [8]- AEO23 Reference Case |
| FT\_PETROLEUM [$/MMBTU] | 2.25 | 2.20 | 2.04 | 2.06 | 2.02 | 2.02 | 2.01 | [8]- AEO23 Reference Case |
| TRANSMISSION\_INTERREGIONAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| TRANSMISSION\_REGIONAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |

\*$11/tonne (2011$)- Converted to 2020 using 1.17 rate

For all tables shown in this section, when reference [3] is used, cost values refer to the conservative cost assumption from ATB 22 if otherwise not specified.

* 1. **Efficiency**

Table 2.13 shows the fuel-to-electricity conversion rates for existing generation technologies, represented in the capacity expansion model.

**Table 2.13:** Fuel to Electricity Conversion Rates For Existing Generation Technologies

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technology Code** | **Units** | **Fuel** | **Efficiency-Same for All Periods and Tech Vintages** | **Reference** |
| AB\_ST\_EXISTING | [MMBtu/MWh] | Biomass | 20.46 | [9] |
| BIT\_ST\_EXISTING | [MMBtu/MWh] | Coal | 10.38 | [9] |
| BLQ\_ST\_EXISTING | [MMBtu/MWh] | Biomass | 5.31 | [9] |
| DFO\_CC\_EXISTING | [MMBtu/MWh] | Petroleum | 10.17 | [9] |
| DFO\_GT\_EXISTING | [MMBtu/MWh] | Petroleum | 11.61 | [9] |
| DFO\_IC\_EXISTING | [MMBtu/MWh] | Petroleum | 11.82 | [9] |
| LFG\_GT\_EXISTING | [MMBtu/MWh] | Landfill Gas | 16.22 | [9] |
| LFG\_IC\_EXISTING | [MMBtu/MWh] | Landfill Gas | 10.59 | [9] |
| MWH\_BA1H\_EXISTING | [MWh/MWh] | Electricity | 0.85 | [4] |
| MWH\_BA2H\_EXISTING | [MWh/MWh] | Electricity | 0.85 | [4] |
| NG\_CC\_EXISTING | [MMBtu/MWh] | Natural Gas | 7.97 | [9] |
| NG\_GT\_EXISTING | [MMBtu/MWh] | Natural Gas | 11.62 | [9] |
| NG\_ST\_EXISTING | [MMBtu/MWh] | Natural Gas | 9.92 | [9] |
| NUC\_ST\_EXISTING | [MMBtu/MWh] | Uranium | 10.43 | [9] |
| OBG\_IC\_EXISTING | [MMBtu/MWh] | Biomass | 10.24 | [9] |
| WAT\_PS\_EXISTING | [MWh/MWh] | Electricity | 0.80 | [4] |
| WDS\_ST\_EXISTING | [MMBtu/MWh] | Biomass | 11.04 | [9] |

Table 2.14 shows the fuel-to-electricity conversion rates for new generation technologies, represented in the capacity expansion model.

**Table 2.14:** Fuel to Electricity Conversion Rates For New Generation Technologies

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Technology Code** | **Units** | **Fuel** | **Efficiency at Different Tech Vintages**  **(Only Varies With the Vintage)** | | | | | | | **Reference** |
| **2023** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| BATT\_2H\_NEW | [MWh/MWh] | Electricity | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | [4] |
| BATT\_4H\_NEW | [MWh/MWh] | Electricity | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | [4] |
| BATT\_6H\_NEW | [MWh/MWh] | Electricity | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | [4] |
| BATT\_8H\_NEW | [MWh/MWh] | Electricity | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | [4] |
| BIOMASS\_CC90\_NEW | [MMBtu/MWh] | Biomass | 8.10 | 8.04 | 7.91 | 7.78 | 7.66 | 7.54 | 7.41 | [9, 4]\* |
| BIOMASS\_NEW | [MMBtu/MWh] | Biomass | 7.21 | 7.21 | 7.21 | 7.21 | 7.21 | 7.21 | 7.21 | [9]\*\* |
| COAL\_95CC\_NEW | [MMBtu/MWh] | Coal | 10.94 | 10.94 | 10.94 | 10.94 | 10.94 | 10.94 | 10.94 | [3] |
| COAL\_99CC\_NEW | [MMBtu/MWh] | Coal | 11.12 | 11.12 | 11.12 | 11.12 | 11.12 | 11.12 | 11.12 | [3] |
| COAL\_NEW | [MMBtu/MWh] | Coal | 8.49 | 8.49 | 8.49 | 8.49 | 8.49 | 8.49 | 8.49 | [3] |
| NG\_F-FRAME\_CC\_95CC\_NEW | [MMBtu/MWh] | Natural Gas | 7.22 | 7.22 | 7.22 | 7.22 | 7.22 | 7.22 | 7.22 | [3] |
| NG\_F-FRAME\_CC\_97CC\_NEW | [MMBtu/MWh] | Natural Gas | 7.26 | 7.26 | 7.26 | 7.26 | 7.26 | 7.26 | 7.26 | [3] |
| NG\_F-FRAME\_CC\_NEW | [MMBtu/MWh] | Natural Gas | 6.36 | 6.36 | 6.36 | 6.36 | 6.36 | 6.36 | 6.36 | [3] |
| NG\_F-FRAME\_CT\_NEW | [MMBtu/MWh] | Natural Gas | 9.72 | 9.72 | 9.72 | 9.72 | 9.72 | 9.72 | 9.72 | [3] |
| NG\_H-FRAME\_CC\_95CC\_NEW | [MMBtu/MWh] | Natural Gas | 7.01 | 7.01 | 7.01 | 7.01 | 7.01 | 7.01 | 7.01 | [3] |
| NG\_H-FRAME\_CC\_97CC\_NEW | [MMBtu/MWh] | Natural Gas | 7.05 | 7.05 | 7.05 | 7.05 | 7.05 | 7.05 | 7.05 | [3] |
| NG\_H-FRAME\_CC\_NEW | [MMBtu/MWh] | Natural Gas | 6.20 | 6.20 | 6.20 | 6.20 | 6.20 | 6.20 | 6.20 | [3] |
| NUCLEAR-AP1000\_NEW | [MMBtu/MWh] | Uranium | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | [3] |
| NUCLEAR-SMR\_NEW | [MMBtu/MWh] | Uranium | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | [3] |
| WAT\_PS\_NEW | [MWh/MWh] | Electricity | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | [4] |

\*Average values from all biomass technologies reported on EIA-923 [9] times increase in heat rate for BECC tech in ReEDS [4]

\*\*Average values from all biomass technologies reported on EIA-923 [9]. Used as a way to account for the use of different biofuels in NC

Table 2.15 shows the efficiencies for non-generating technologies.

**Table 2.15:** Efficiency For Non-Generating Technologies

|  |  |  |
| --- | --- | --- |
| **Technology Code** | **Efficiency** | **Reference/Rational** |
| DISTRIBUTION | 96.96 | From [10], NC had 4.96% T&D losses from 2021-2019. Using [11] as an approximate reference, assume 40% of these losses are due to transmission and 60% due to distribution. |
| TRANSMISSION\_REGIONAL | 98.02 |

* 1. **Emission Activity and Limits**

Tables 2.16 and 2.17 show the emissions per MMBtu of fuel used by different technologies considered in our simulation.

**Table 2.16:** Technology Emission per MMBtu of Fuel Used (Existing Tech)

|  |  |  |  |
| --- | --- | --- | --- |
| **Technology Code** | **Fuel** | **Lbs CO2 / MMBtu** | **Reference** |
| AB\_ST\_EXISTING | Biomass | 0 | [3] |
| BIT\_ST\_EXISTING | Coal | 214.13 | Emissions from [10], fuel consumption from [9] |
| BLQ\_ST\_EXISTING | Biomass | 0 | [3] |
| DFO\_CC\_EXISTING | Petroleum | 229.79 | Emissions from [10], fuel consumption from [9] |
| DFO\_GT\_EXISTING | Petroleum | 229.79 | Emissions from [10], fuel consumption from [9] |
| DFO\_IC\_EXISTING | Petroleum | 229.79 | Emissions from [10], fuel consumption from [9] |
| LFG\_GT\_EXISTING | Landfill Gas | 0 | [3] |
| LFG\_IC\_EXISTING | Landfill Gas | 0 | [3] |
| NG\_CC\_EXISTING | Natural Gas | 119.42 | Emissions from [10], fuel consumption from [9] |
| NG\_GT\_EXISTING | Natural Gas | 119.42 | Emissions from [10], fuel consumption from [9] |
| NG\_ST\_EXISTING | Natural Gas | 119.42 | Emissions from [10], fuel consumption from [9] |
| OBG\_IC\_EXISTING | Biomass | 0 | [3] |
| WDS\_ST\_EXISTING | Biomass | 0 | [3] |

**Table 2.16:** Technology Emission per MMBtu of Fuel Used (New Tech)

|  |  |  |  |
| --- | --- | --- | --- |
| **Technology Code** | **Fuel** | **Lbs CO2 / MMBtu** | **Reference** |
| BIOMASS\_CC90\_NEW | Biomass | -190.37 | [12, 2]\* |
| BIOMASS\_NEW | Biomass | 0 | [3] |
| COAL\_95CC\_NEW | Coal | 10.12 | [3] |
| COAL\_99CC\_NEW | Coal | 2.02 | [3] |
| COAL\_NEW | Coal | 202.32 | [3] |
| NG\_F-FRAME\_CC\_95CC\_NEW | Natural Gas | 5.93 | [3] |
| NG\_F-FRAME\_CC\_97CC\_NEW | Natural Gas | 3.558 | [3] |
| NG\_F-FRAME\_CC\_NEW | Natural Gas | 118.6 | [3] |
| NG\_F-FRAME\_CT\_NEW | Natural Gas | 118.6 | [3] |
| NG\_H-FRAME\_CC\_95CC\_NEW | Natural Gas | 5.93 | [3] |
| NG\_H-FRAME\_CC\_97CC\_NEW | Natural Gas | 3.558 | [3] |
| NG\_H-FRAME\_CC\_NEW | Natural Gas | 118.62 | [3] |

\*CO2 data in lb/MMBtu for various biomass resources was collected from reference [12]. A weighted average was then calculated using the total MMBtu consumed of fuel by each technology in North Carolina [9] (2021) to determine a comparable emission value, which was then adjusted for 90% carbon capture. (EIA Fuel Code [lbs CO2/MMBtu] [12]: LFG=130, OBG=127, BLQ=222, ABWDS=207).

Regarding the limits on CO2 emissions, according to the NC - House Bill 951 [13], the electric power sector should plan to achieve 70% CO2 reduction from 2005 levels by 2030 and reach carbon neutrality by 2050. In 2005, the NC electric power sector was estimated to emit 80.15 million metric tons of CO2 [14]. Therefore, by 2030, this work considers a maximum CO2 emission of 24.05 million metric tons, with zero net emissions by 2050.

* 1. **Capacity Factors**
  2. **Capacity Credit and Planning Reserve Margin**
  3. **Maximum Capacity**

**>Hydro and pumped**

* 1. **Maximum Activity**

**>Biomass**

**>Wind (Discuss)**

**>Solar (Discuss)**

* 1. **Minimum Activity**

**>Solar Residential**

**>Solar Commercial**

* 1. **Regionalization**

**>**Differentiate existing and future tech

**>**Plot with their Location

* 1. **Fragility Curves and Damage Statistics**

>Define fragilities considered

>Table with damages at each hurricane speed and per scenario

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|  |  |
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