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

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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**

Fragility curves associate the probability of damage to equipment given certain extreme conditions. In the literature, when the extreme condition is defined in terms of wind speeds, it can be referenced to different measurement heights and averaging periods. Although NOAA provides some guidance [3, 4] on the conversion of estimates to various references, uncertainty is also warned on these conversions [4].

As previously mentioned, the wind speed data statistics used in this work come from the FEMA – Hazus model [2] and is defined for 10m height and 3s gust speeds. To avoid inconsistencies when comparing the fragility curves of different works, only references that provide fragility estimates at the same speed reference from FEMA are used.

For wind turbines, references [5] and [6] investigated the fragility curve estimation of a 3.3MW land-based wind turbine with 100m of hub height. Figure 2.1 shows in green the fragilities estimated by these references. For simplicity in this work, the fragilities of offshore and land-based wind are considered the average of the probability of damage of references [5] and [6], represented in Figure 2.1 as a solid green line.

For solar generation, references [7] and [8] consider the determination of fragility curves for rooftop solar. Reference [8] investigates many different solar panel configurations and roof angles; however, for simplicity, we consider only three cases from this reference: the average behavior from 15-degree rooftops and the most and least vulnerable configurations. Figure 2.1 shows in orange the fragility curves for these references. As it is possible to see, there is good agreement between the different fragility curves; as such, we arbitrarily decided to use the data from (Kabre et al., 2022) [7], which has an intermediate behavior compared to the other curves. Regarding possible differences between the fragilities of rooftop and utility solar, we follow the approach of references [9, 7, 10], which argue that these fragilities can be approximated as similar as safety factors for operation in residential areas would be larger than those used in solar utility sites.

For other generation technologies such as utility batteries, natural gas, coal, petroleum, biomass, hydro, and nuclear, the literature is not as detailed regarding the fragility of these technologies to hurricanes. However, other works have considered [10, 11] the use of standard fragility curves created by FEMA to represent general building categories as a way to represent the vulnerability of these generation technologies to hurricanes.

In this work, we follow a similar approach of [10, 11]; however, instead of using the damage functions from the Hazus FEMA model, the loss functions were used. In Hazus, damage functions assign probabilities to different levels of physical damage to a building envelop components subject to hurricanes [12], whereas loss functions associate the percentage economic loss of the building infrastructure at different wind speeds. Damage functions are defined at different qualitative levels that associate the type of damage and its location, whereas loss functions are defined for different types of terrains (open, suburban, etc.).

In references [10, 11] moderate damage functions were considered, but no rationale was given to the use of such qualitative level. According to [12], moderate damage levels are characterized by major roof cover damage, moderate window breakage, minor roof sheathing failure, and some interior damage from water. As such, a moderate curve assigns at a given wind speed the probability that this type of damage happens.

When applied to capacity expansion studies, fragility curves are used to estimate the percentage of existing capacity that must be reduced from damages due to hurricanes; therefore, we understand that the use of Hazus loss functions is more appropriate.

For utility battery technologies, the Hazus loss function for steel-engineered commercial buildings with 1-2 stories (SECBL) was used. For natural gas, oil, coal, and biomass power plants, the loss function for steel-frame, engineered commercial buildings of 3–5 stories (SECBM) was used, and for hydro and nuclear powerplants, the loss function for concrete, engineered commercial buildings of 3–5 stories (CECBM) was used. All curves mentioned above were taken from Hazus considering an open terrain configuration and are shown in Figure 2.1 for comparison.

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**Figure 2.1:** Fragility Curves For Energy Generation Technologies.

Regarding the fragility of distribution systems to extreme winds, the literature is very extensive, with many works on the topic. Reference [13] investigated the fragility of wood and steel distribution poles during hurricane winds considering a class C4 pole (ANSI-O5.1 [14]); the fragility of new poles for this reference is shown in Figure 2.2 in green. Reference [15] estimated the fragility of wood poles to hurricanes considering a variety of pole classes, stating that class C5 was the most common in the Southeast US. Figure 2.2 shows in blue the fragility of 50-year-old C5 poles estimated by this reference (design parameter case).

References [16] and [13] also provide estimates of the fragilities of wood distribution poles due to hurricanes focusing on pole class C5. The estimates of [16] for new and 50-year-old poles are shown in Figure 2.2 in gray, and the estimates of [13] for 50-year-old poles are shown in red. Finally, Reference [17] makes a distinction between extreme winds from hurricanes and tornados and computes the fragility curves for C4 wood poles, which are shown in black.

As it is possible to see, there can be significant differences between the fragilities estimated by the references mentioned above, which are likely a consequence of the variety of mechanical and wind speed statistics considered in each study. In this work, we decided to approximate the fragility of distribution systems using the estimates from [13] for new wood poles as it approximated well to other references on the lower wind speed spectrum, which is the region most likely to happen and consequently, most likely to affect the capacity expansion model results. It is important to mention that the probability represented in Figure 2.2 is for the failure of the distribution poles (buckling); however, the probability of failure of the distribution lines, which is larger than that of the poles alone, is not considered in this work.

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**Figure 2.2:** Fragility Curves For Distribution Poles

Lastly, for transmission systems …

* 1. **Energy Demand**

From the EIA 861 form [18], historical electricity sales data is available for the state of NC from before 2021, and from the Duke Energy Carbon Plan 2023 [19] (Appendix F), forecasts for energy sales by Duke Energy Carolinas (DEC) and Duke Energy Progress (DEP) are available until 2037. As more than 60% of the total existing electricity capacity in NC belongs to Duke Energy [20], the percentage load forecast increases from the combined DEC and DEP systems are used to project the future load sales on the NC until 2037, and the average annual growth rate from 2033-2037 is used to extend the forecast until 2050. Table 1 shows values for load sales from the references mentioned above and the estimates made for NC. It is important to mention that load sales estimates from Duke Energy account for load reductions due to energy efficiency and distributed solar generation.

**Table 1:** Load Sales Estimates For DEC, DEP, and NC

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Year** | **DEC Load**  **[GWh]** | **DEP Load**  **[GWh]** | **DEC+DEP Load [GWh]** | **DEC+DEP Ratio of Increase From 2021** | **NC Net Load [GWh]** |
| 2021 | 86,880 | 60,139 | 147,019 | 1 | 135,693 |
| 2022\* | - | - | - | - | - |
| 2023 | 91,983 | 64,259 | 156,242 | 1.063 | 144,205 |
| 2024 | 92,304 | 64,636 | 156,940 | 1.067 | 144,850 |
| 2025 | 92,349 | 64,525 | 156,874 | 1.067 | 144,789 |
| 2026 | 92,667 | 64,408 | 157,075 | 1.068 | 144,974 |
| 2027 | 93,100 | 64,486 | 157,586 | 1.072 | 145,446 |
| 2028 | 93,815 | 64,752 | 158,567 | 1.079 | 146,351 |
| 2029 | 94,629 | 65,051 | 159,680 | 1.086 | 147,379 |
| 2030 | 95,454 | 65,376 | 160,830 | 1.094 | 148,440 |
| 2031 | 96,466 | 65,795 | 162,261 | 1.104 | 149,761 |
| 2032 | 97,447 | 66,391 | 163,838 | 1.114 | 151,216 |
| 2033 | 98,372 | 66,937 | 165,309 | 1.124 | 152,574 |
| 2034 | 99,313 | 67,570 | 166,883 | 1.135 | 154,027 |
| 2035 | 100,289 | 68,254 | 168,543 | 1.146 | 155,559 |
| 2036 | 101,284 | 69,026 | 170,310 | 1.158 | 157,190 |
| 2037 | 102,343 | 69,817 | 172,160 | 1.171 | 158,897 |
| Avg. Annual Growth  (2033-3037) | 0.85% | 0.79% | 0.82% | - | 0.82% |

\*Not Available from EIA 861-2022

From the projections mentioned above, it is important to take into consideration the effect that distributed solar energy generation has on the net load, as this effect may change the load distribution in systems where distributed solar energy generation is significant. In such cases, it is preferable to simulate the capacity expansion model using the total load, which can be approximated by adding the distributed solar energy generation projections to the data of Table 1. This approximation assumes that the distributed solar energy-generating units indirectly consume at least the energy they generate or more (no solar energy excess over the year).

Table 2 shows the residential and commercial solar energy generation projections derived from appendixes D and F of the Duke Energy Carbon Plan 2023 [19]. Unfortunately, [19] does not detail its solar projections for all years between 2022-2037. However, as this work adopts a simplified time discretization in its capacity expansion simulations, considering only the periods {2023, 2025, 2030, 2035, 2040, 2045, and 2050}, a simple interpolation of Table 2 was used to estimate solar energy projections from 2023 to 2035, and for the years after 2037 solar growth rates for the continental US from the AEO 2023 [21] (reference case) were applied to the 2037 duke energy estimates. These results are shown in Table 3 for the Duke Energy systems, which were scaled for NC using a factor of 0.922 (Table 1 ratio of 2021 estimates of net load between NC and DEC+DEP).

**Table 2:** Projection of Distributed Solar Energy Generation on DEC and DEP

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Year** | **Residential Solar Energy Generation**  **[GWh]** | | | **Commercial Solar Energy Generation**  **[MWh]** | | | **DEC+DEP Total Distributed Solar [MWh]** |
| **DEC** | **DEP** | **Total** | **DEC** | **DEP** | **Total** |
| 2022 | 223.447 | 138.325 | 361.772 | 86.816 | 44.755 | 131.571 | 493.343 |
| 2023 | 266.371 | 173.101 | 439.472 | 96.407 | 51.796 | 148.203 | 587.675 |
| 2030 | 577.702 | 327.493 | 905.195 | 179.008 | 106.847 | 285.855 | 1,191.050 |
| 2037 | 1,392.526 | 956.027 | 2,348.553 | 330.399 | 147.422 | 477.821 | 2,826.374 |

**Table 3:** Distributed Solar Energy Generation at “DEC+DEP” and NC and Total Load Estimations

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Year** | **DEC+DEP** | | | | | | **NC\*\*** | | |
| **Solar Residential** | | **Solar Commercial** | | **Net Load**  **[GWh]** | **Total Load:**  **(Net Load + Dist. Solar)**  **[GWh]** | **Generation from Solar Residential**  **[GWh]** | **Generation from Solar Commercial**  **[GWh]** | **Total Load**  **(Net Load + Dist. Solar)**  **[GWh]** |
| **Generation [GWh]** | **AEO 23 Increase from 2037 Values\*** | **Generation [GWh]** | **AEO 23 Increase from 2037 Values\*** |
| 2023 | 439 | - | 148 | - | 156,242 | 156,830 | 406 | 137 | 144,748 |
| 2025 | 573 | - | 188 | - | 156,874 | 157,634 | 528 | 173 | 145,490 |
| 2030 | 905 | - | 286 | - | 160,830 | 162,021 | 835 | 264 | 149,539 |
| 2035 | 1,936 | - | 423 | - | 168,543 | 170,902 | 1,787 | 390 | 157,736 |
| 2040 | 2,750 | 1.17 | 529 | 1.11 | 173,623 | 176,902 | 2,539 | 488 | 163,274 |
| 2045 | 3,582 | 1.52 | 581 | 1.22 | 175,099 | 179,262 | 3,306 | 537 | 165,452 |
| 2050 | 4,593 | 1.96 | 618 | 1.29 | 176,587 | 181,798 | 4,239 | 570 | 167,793 |

\*See Table 2 for total solar projection during 2037. \*\*Conversion from Duke to total load using a factor of 0.922

In terms of the load distribution, hourly demand for DEC and DEP from 2016-2019 was obtained from the EIA 930 reports [22] and used to define an average load distribution for NC; this time interval was chosen to avoid biases due to the COVID-19 pandemic. Figure 1 shows in black the demand distribution considered in this work. In this case, data from EIA 930 was not ajusted to account for distributed solar energy generation as was done for the total load since the current distributed solar generation is around 0.3% of the total electricity demand, and back in 2016-2019 this ratio would likely be much smaller.

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**Figure 1:** Demand Distribution From DEP+DEC From 2016 to 2019 (Demand Distribution Used for NC)

Finally, since this work considered the segmentation of NC in multiple regions (R1, R2, and R3), as explained in the previous sections, the total load shown in Table 3 (last column) was distributed based on the percentage of the total population at each region, and in this case, no changes were assumed to the seasonal/hourly load distribution (Figure 1). Using the 2020 census [23], the ratios considered were 7.02%, 12.98%, and 80.00% for regions R1, R2, and R3, respectively.

* 1. **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) [20] |
| 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) [23] |
| BATT\_4H\_NEW | Battery Storage 4h – Utility Scale (NREL ATB 2022 Technology) [23] |
| BATT\_6H\_NEW | Battery Storage 6h – Utility Scale (NREL ATB 2022 Technology) [23] |
| BATT\_8H\_NEW | Battery Storage 8h – Utility Scale (NREL ATB 2022 Technology) [23] |
| BIOMASS\_CC90\_NEW | Generation From Biomass With 90% Carbon Capture (Technology from NREL ReEDS model Using BECC-mod) [24] |
| BIOMASS\_NEW | Generation From Biomass (NREL ATB 2022 Technology) [23] |
| COAL\_95CC\_NEW | Generation From Coal With 95% Carbon Capture (NREL ATB 2022 Technology) [23] |
| COAL\_99CC\_NEW | Generation From Coal With 99% Carbon Capture (NREL ATB 2022 Technology) [23] |
| COAL\_NEW | Generation From Coal (NREL ATB 2022 Technology) [23] |
| NG\_F-FRAME\_CC\_95CC\_NEW | Combined Cycle Natural Gas Turbine F-Frame With 95 % of Carbon Capture (NREL ATB 2022 Technology) [23] |
| NG\_F-FRAME\_CC\_97CC\_NEW | Combined Cycle Natural Gas Turbine F-Frame With 97 % of Carbon Capture (NREL ATB 2022 Technology) [23] |
| NG\_F-FRAME\_CC\_NEW | Combined Cycle Natural Gas Turbine F-Frame (NREL ATB 2022 Technology) [23] |
| NG\_F-FRAME\_CT\_NEW | Natural Gas Combustion Turbine F-Frame - Simple Cycle (NREL ATB 2022 Technology) [23] |
| NG\_H-FRAME\_CC\_95CC\_NEW | Combined Cycle Natural Gas Turbine H-Frame With 95 % of Carbon Capture (NREL ATB 2022 Technology) [23] |
| NG\_H-FRAME\_CC\_97CC\_NEW | Combined Cycle Natural Gas Turbine H-Frame With 97 % of Carbon Capture (NREL ATB 2022 Technology) [23] |
| NG\_H-FRAME\_CC\_NEW | Combined Cycle Natural Gas Turbine H-Frame (NREL ATB 2022 Technology) [23] |
| NUCLEAR-AP1000\_NEW | Nuclear Generation Using AP1000 PWR (NREL ATB 2022 Technology) [23] |
| NUCLEAR-SMR\_NEW | Small Modular Nuclear Reactor (NREL ATB 2022 Technology) [23] |
| PV-COMMERCIAL\_NEW | Commercial Solar PV (NREL ATB 2022 Technology) [23] |
| PV-RESIDENTIAL\_NEW | Residential Solar PV (NREL ATB 2022 Technology) [23] |
| PV-UTILITY\_NEW | Utility Solar PV (NREL ATB 2022 Technology) [23] |
| WAT\_HY\_NEW | Conventional Hydroelectric (NREL ATB 2022 Technology) [23] |
| WAT\_PS\_NEW | Hydroelectric Pumped Storage (NREL ATB 2022 Technology) [23] |
| WIND-LAND-C8\_NEW | Onshore Wind Turbine Class 8 From NREL ATB 2022 (NREL ATB 2022 Technology) [23] |
| WIND-OFFSHORE-C6\_NEW | Offshore Wind Turbine Class 6 From NREL ATB 2022 (NREL ATB 2022 Technology) [23] |

**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 [20]. 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 [20].

* 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 [20] |
| BIT\_ST\_EXISTING | 56 | Weighted Average from DEC/DEP in IRPs [25, 26] |
| BLQ\_ST\_EXISTING | 55 | Weighted Average of Past Retirements on NC [20] |
| DFO\_CC\_EXISTING | 58 | Weighted Average of Past Retirements on NC [20] |
| DFO\_GT\_EXISTING | 69 | Weighted Average from DEC/DEP in IRPs [25, 26] |
| DFO\_IC\_EXISTING | 36 | Weighted Average of Past Retirements on the East Coast [20] |
| LFG\_GT\_EXISTING | 20 | Weighted Average Retirement on the East Coast [20] |
| LFG\_IC\_EXISTING | 16 | Weighted Average Retirement on the East Coast [20] |
| MWH\_BA1H\_EXISTING | 15 | From NREL ReEDS [24] |
| MWH\_BA2H\_EXISTING | 15 | From NREL ReEDS [24] |
| NG\_CC\_EXISTING | 37 | Weighted Average from DEC/DEP in IRPs [25, 26] For NG CA and CT |
| NG\_GT\_EXISTING | 42 | Weighted Average from DEC/DEP in IRPs [25, 26] |
| NG\_ST\_EXISTING | 53 | Weighted Average Retirement on the East Coast [20] |
| NUC\_ST\_EXISTING | 59 | Weighted Average from DEC/DEP in IRPs [25, 26] |
| OBG\_IC\_EXISTING | 15 | Weighted Average of Past Retirements on US [20] |
| SUN\_PV\_EXISTING | 30 | From NREL ReEDS [24] |
| WAT\_HY\_EXISTING | 109 | Weighted Average from DEC/DEP in IRPs [25, 26] for WAT\_HY |
| WAT\_PS\_EXISTING | 109 |
| WDS\_ST\_EXISTING | 50 | From NREL ReEDS [24] for Biopower |
| WH\_ST\_EXISTING | 33 | Weighted Average of Past Retirements on US [20] |
| WND\_WT\_EXISTING | 30 | From NREL ReEDS [24] |

In Table 2.4, “weighted average” refers to the weighted average of the technology lifetime using reported device capacities. In this table, when reference [20] 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 [24] | 15 | From NREL ReEDS [24] |
| BATT\_4H\_NEW | 15 | From NREL ReEDS [24] | 15 | From NREL ReEDS [24] |
| BATT\_6H\_NEW | 15 | From NREL ReEDS [24] | 15 | From NREL ReEDS [24] |
| BATT\_8H\_NEW | 15 | From NREL ReEDS [24] | 15 | From NREL ReEDS [24] |
| BIOMASS\_CC90\_NEW | 50 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| BIOMASS\_NEW | 50 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| COAL\_95CC\_NEW | 65 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| COAL\_99CC\_NEW | 65 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| COAL\_NEW | 65 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NG\_F-FRAME\_CC\_95CC\_NEW | 60 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NG\_F-FRAME\_CC\_97CC\_NEW | 60 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NG\_F-FRAME\_CC\_NEW | 60 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NG\_F-FRAME\_CT\_NEW | 50 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NG\_H-FRAME\_CC\_95CC\_NEW | 60 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NG\_H-FRAME\_CC\_97CC\_NEW | 60 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NG\_H-FRAME\_CC\_NEW | 60 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NUCLEAR-AP1000\_NEW | 60 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| NUCLEAR-SMR\_NEW | 60 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| PV-COMMERCIAL\_NEW | 30 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| PV-RESIDENTIAL\_NEW | 30 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| PV-UTILITY\_NEW | 30 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| WAT\_HY\_NEW | 109 | Average from DEC/DEP in IRPs [25, 26] for WAT\_HY | 20 | From NREL ReEDS [24] |
| WAT\_PS\_NEW | 109 | 20 | From NREL ReEDS [24] |
| WIND-LAND-C8\_NEW | 30 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |
| WIND-OFFSHORE-C6\_NEW | 30 | From NREL ReEDS [24] | 20 | From NREL ReEDS [24] |

**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 [25, 26] (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 [25, 26], 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 [20] and not available at [25, 26] 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 [25, 26]. 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).

A graph with numbers and letters

Description automatically generated with medium confidence

\*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.

A graph of different colored bars

Description automatically generated

\*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.

A graph of different colored lines

Description automatically generated

**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 | [23] |
| BATT\_4H\_NEW | 1394 | 1312 | 1174 | 1174 | 1174 | 1174 | 1174 | 0.065 | [23] |
| BATT\_6H\_NEW | 1978 | 1862 | 1666 | 1666 | 1666 | 1666 | 1666 | 0.065 | [23] |
| BATT\_8H\_NEW | 2563 | 2413 | 2158 | 2158 | 2158 | 2158 | 2158 | 0.065 | [23] |
| BIOMASS\_CC90\_NEW\* | 5529 | 5495 | 5410 | 5333 | 5255 | 5178 | 5100 | 0.058 | [24, 23] |
| BIOMASS\_NEW | 4332 | 4276 | 4186 | 4046 | 3906 | 3766 | 3626 | 0.058 | [23] |
| CO2\_STORAGE | Assuming no Investment Costs and Only Variable Costs as in The NREL ReEDS Model [23] | | | | | | | | |
| COAL\_95CC\_NEW | 4750 | 4677 | 4495 | 4313 | 4131 | 3949 | 3766 | 0.065 | [23] |
| COAL\_99CC\_NEW | 4860 | 4786 | 4599 | 4414 | 4227 | 4040 | 3853 | 0.065 | [23] |
| COAL\_NEW | 3047 | 3027 | 2962 | 2861 | 2761 | 2664 | 2567 | 0.065 | [23] |
| 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 | [23] |
| NG\_F-FRAME\_CC\_97CC\_NEW | 2150 | 2099 | 2004 | 1922 | 1841 | 1760 | 1683 | 0.065 | [23] |
| NG\_F-FRAME\_CC\_NEW | 1026 | 1010 | 989 | 967 | 946 | 925 | 905 | 0.065 | [23] |
| NG\_F-FRAME\_CT\_NEW | 900 | 872 | 838 | 815 | 793 | 772 | 750 | 0.065 | [23] |
| NG\_H-FRAME\_CC\_95CC\_NEW | 1997 | 1948 | 1862 | 1785 | 1709 | 1635 | 1564 | 0.065 | [23] |
| NG\_H-FRAME\_CC\_97CC\_NEW | 2027 | 1978 | 1889 | 1811 | 1736 | 1659 | 1587 | 0.065 | [23] |
| NG\_H-FRAME\_CC\_NEW | 981 | 958 | 929 | 909 | 889 | 869 | 854 | 0.065 | [23] |
| NUCLEAR-AP1000\_NEW | 7302 | 7040 | 6966 | 6731 | 6496 | 6261 | 6026 | 0.058 | [23] |
| NUCLEAR-SMR\_NEW | 7839 | 7739 | 7661 | 7405 | 7150 | 6894 | 6639 | 0.058 | [23] |
| PV-COMMERCIAL\_NEW | 1574 | 1549 | 1494 | 1352 | 1210 | 1069 | 927 | 0.056 | [23] |
| PV-RESIDENTIAL\_NEW | 2569 | 2488 | 2285 | 1968 | 1651 | 1334 | 1016 | 0.057 | [23] |
| PV-UTILITY\_NEW | 1161 | 1157 | 1150 | 1051 | 952 | 853 | 754 | 0.053 | [23] |
| 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 | [23]-Class 1 |
| WAT\_PS\_NEW | 1999 | 1999 | 2011 | 2011 | 2011 | 2011 | 2011 | 0.054 | [23]-Class 1 |
| WIND-LAND-C8\_NEW | 1323 | 1231 | 1006 | 981 | 956 | 931 | 906 | 0.071 | [23]-Class 8 |
| WIND-OFFSHORE-C6\_NEW | 3855 | 3726 | 3570 | 3450 | 3362 | 3294 | 3238 | 0.066 | [23]-Class 6 |

\*Costs from [24], discount rate from [23]

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 | [23]-Biopower (Conservative-2020) |
| BIT\_ST\_EXISTING | 141 | 13.86 | [23]-Coal IGCC (Conservative-2020) |
| BLQ\_ST\_EXISTING | 151 | 5.8 | [23]-Biopower (Conservative-2020) |
| DFO\_CC\_EXISTING | 28 | 1.78 | [23]-Same as NG F-Frame CC \*\* (Conservative-2020) |
| DFO\_GT\_EXISTING | 21 | 5.1 | [23]-Same as NG F-Frame CT \*\* (Conservative-2020) |
| DFO\_IC\_EXISTING | 21 | 5.1 | [23]-Same as NG F-Frame CT \*\* (Conservative-2020) |
| LFG\_GT\_EXISTING | 151 | 5.8 | [23]-Biopower (Conservative-2020) |
| LFG\_IC\_EXISTING | 151 | 5.8 | [23]-Biopower (Conservative-2020) |
| MWH\_BA1H\_EXISTING | 31 | 0 | [23]-Commercial Storage (Conservative-2020) |
| MWH\_BA2H\_EXISTING | 25 | 0 | [23]-Utility Storage (Conservative-2020) |
| NG\_CC\_EXISTING | 28 | 1.78 | [23]-NG F-Frame CC (Conservative-2020) |
| NG\_GT\_EXISTING | 21 | 5.1 | [23]-NG F-Frame CT (Conservative-2020) |
| NG\_ST\_EXISTING | 21 | 5.1 | [23]-NG F-Frame CT (Conservative-2020) |
| NUC\_ST\_EXISTING | 146 | 2.84 | [23]-Nuclear AP1000 (Conservative-2020) |
| OBG\_IC\_EXISTING | 151 | 5.8 | [23]-Biopower (Conservative-2020) |
| SUN\_PV\_EXISTING | 23 | 0 | [23]-Solar Utility (Conservative-2020) |
| WAT\_HY\_EXISTING | 64 | 0 | [23]-Hydropower Class 1 (Conservative-2020) |
| WAT\_PS\_EXISTING | 18 | 0.513 | [23]-Pumped Hydropower Class 1 (Conservative-2020) |
| WDS\_ST\_EXISTING | 151 | 5.8 | [23]-Biopower (Conservative-2020) |
| WH\_ST\_EXISTING | 21 | 5.1 | [23]-Same as NG F-Frame CT (Conservative-2020) |
| WND\_WT\_EXISTING | 43 | 0 | [23]-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 | [23] |
| BATT\_4H\_NEW | 35 | 33 | 29 | 29 | 29 | 29 | 29 | [23] |
| BATT\_6H\_NEW | 49 | 47 | 42 | 42 | 42 | 42 | 42 | [23] |
| BATT\_8H\_NEW | 64 | 60 | 54 | 54 | 54 | 54 | 54 | [23] |
| BIOMASS\_CC90\_NEW | 162 | 162 | 162 | 162 | 162 | 162 | 162 | [24] |
| BIOMASS\_NEW | 151 | 151 | 151 | 151 | 151 | 151 | 151 | [23] |
| COAL\_95CC\_NEW | 115 | 115 | 115 | 115 | 115 | 115 | 115 | [23] |
| COAL\_99CC\_NEW | 117 | 117 | 117 | 117 | 117 | 117 | 117 | [23] |
| COAL\_NEW | 74 | 74 | 74 | 74 | 74 | 74 | 74 | [23] |
| NG\_F-FRAME\_CC\_95CC\_NEW | 58 | 58 | 58 | 58 | 58 | 58 | 58 | [23] |
| NG\_F-FRAME\_CC\_97CC\_NEW | 59 | 59 | 59 | 59 | 59 | 59 | 59 | [23] |
| NG\_F-FRAME\_CC\_NEW | 28 | 28 | 28 | 28 | 28 | 28 | 28 | [23] |
| NG\_F-FRAME\_CT\_NEW | 21 | 21 | 21 | 21 | 21 | 21 | 21 | [23] |
| NG\_H-FRAME\_CC\_95CC\_NEW | 53 | 53 | 53 | 53 | 53 | 53 | 53 | [23] |
| NG\_H-FRAME\_CC\_97CC\_NEW | 54 | 54 | 54 | 54 | 54 | 54 | 54 | [23] |
| NG\_H-FRAME\_CC\_NEW | 27 | 27 | 27 | 27 | 27 | 27 | 27 | [23] |
| NUCLEAR-AP1000\_NEW | 146 | 146 | 146 | 146 | 146 | 146 | 146 | [23] |
| NUCLEAR-SMR\_NEW | 114 | 114 | 114 | 114 | 114 | 114 | 114 | [23] |
| PV-COMMERCIAL\_NEW | 18 | 17 | 17 | 16 | 14 | 13 | 12 | [23] |
| PV-RESIDENTIAL\_NEW | 28 | 27 | 25 | 22 | 19 | 16 | 13 | [23] |
| PV-UTILITY\_NEW | 20 | 20 | 20 | 19 | 18 | 16 | 15 | [23] |
| WAT\_HY\_NEW | 64 | 64 | 64 | 64 | 64 | 64 | 64 | [23]-Class 1 |
| WAT\_PS\_NEW | 18 | 18 | 18 | 18 | 18 | 18 | 18 | [23]-Class 1 |
| WIND-LAND-C8\_NEW | 43 | 43 | 43 | 43 | 42 | 42 | 41 | [23]-Class 8 |
| WIND-OFFSHORE-C6\_NEW | 115 | 112 | 106 | 102 | 99 | 97 | 95 | [23]-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 | [24] |
| BIOMASS\_NEW | 5.80 | 5.80 | 5.80 | 5.80 | 5.80 | 5.80 | 5.80 | [23] |
| COAL\_95CC\_NEW | 14.03 | 14.03 | 14.03 | 14.03 | 14.03 | 14.03 | 14.03 | [23] |
| COAL\_99CC\_NEW | 14.37 | 14.37 | 14.37 | 14.37 | 14.37 | 14.37 | 14.37 | [23] |
| COAL\_NEW | 7.96 | 7.96 | 7.96 | 7.96 | 7.96 | 7.96 | 7.96 | [23] |
| NG\_F-FRAME\_CC\_95CC\_NEW | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | [23] |
| NG\_F-FRAME\_CC\_97CC\_NEW | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | 4.30 | [23] |
| NG\_F-FRAME\_CC\_NEW | 1.78 | 1.78 | 1.78 | 1.78 | 1.78 | 1.78 | 1.78 | [23] |
| NG\_F-FRAME\_CT\_NEW | 5.10 | 5.10 | 5.10 | 5.10 | 5.10 | 5.10 | 5.10 | [23] |
| NG\_H-FRAME\_CC\_95CC\_NEW | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | [23] |
| NG\_H-FRAME\_CC\_97CC\_NEW | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | 4.09 | [23] |
| NG\_H-FRAME\_CC\_NEW | 1.76 | 1.76 | 1.76 | 1.76 | 1.76 | 1.76 | 1.76 | [23] |
| NUCLEAR-AP1000\_NEW | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | [23] |
| NUCLEAR-SMR\_NEW | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | [23] |
| WAT\_PS\_NEW | 0.513 | 0.513 | 0.513 | 0.513 | 0.513 | 0.513 | 0.513 | [23]-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 [$/Metric Ton CO2] | 12.87 | 12.87 | 12.87 | 12.87 | 12.87 | 12.87 | 12.87 | [27]\* |
| DISTRIBUTION | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |
| FT\_BIOMASS [$/MMBTU] | 5 | 5 | 5 | 5 | 5 | 5 | 5 | [23] |
| FT\_COAL [$/MMBTU] | 5.84 | 4.10 | 3.21 | 3.71 | 4.01 | 3.86 | 3.75 | [21]- AEO23 Reference Case |
| FT\_NG [$/MMBTU] | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | [21]- AEO23 Reference Case |
| FT\_NUCLEAR [$/MMBTU] | 14.66 | 13.43 | 13.23 | 13.72 | 14.13 | 14.42 | 14.83 | [21]- AEO23 Reference Case |
| FT\_PETROLEUM [$/MMBTU] | 2.25 | 2.20 | 2.04 | 2.06 | 2.02 | 2.02 | 2.01 | [21]- 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 [23] 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 | [28] |
| BIT\_ST\_EXISTING | [MMBtu/MWh] | Coal | 10.38 | [28] |
| BLQ\_ST\_EXISTING | [MMBtu/MWh] | Biomass | 5.31 | [28] |
| DFO\_CC\_EXISTING | [MMBtu/MWh] | Petroleum | 10.17 | [28] |
| DFO\_GT\_EXISTING | [MMBtu/MWh] | Petroleum | 11.61 | [28] |
| DFO\_IC\_EXISTING | [MMBtu/MWh] | Petroleum | 11.82 | [28] |
| LFG\_GT\_EXISTING | [MMBtu/MWh] | Landfill Gas | 16.22 | [28] |
| LFG\_IC\_EXISTING | [MMBtu/MWh] | Landfill Gas | 10.59 | [28] |
| MWH\_BA1H\_EXISTING | [MWh/MWh] | Electricity | 0.85 | [24] |
| MWH\_BA2H\_EXISTING | [MWh/MWh] | Electricity | 0.85 | [24] |
| NG\_CC\_EXISTING | [MMBtu/MWh] | Natural Gas | 7.97 | [28] |
| NG\_GT\_EXISTING | [MMBtu/MWh] | Natural Gas | 11.62 | [28] |
| NG\_ST\_EXISTING | [MMBtu/MWh] | Natural Gas | 9.92 | [28] |
| NUC\_ST\_EXISTING | [MMBtu/MWh] | Uranium | 10.43 | [28] |
| OBG\_IC\_EXISTING | [MMBtu/MWh] | Biomass | 10.24 | [28] |
| WAT\_PS\_EXISTING | [MWh/MWh] | Electricity | 0.80 | [24] |
| WDS\_ST\_EXISTING | [MMBtu/MWh] | Biomass | 11.04 | [28] |

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 | [24] |
| BATT\_4H\_NEW | [MWh/MWh] | Electricity | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | [24] |
| BATT\_6H\_NEW | [MWh/MWh] | Electricity | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | [24] |
| BATT\_8H\_NEW | [MWh/MWh] | Electricity | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | [24] |
| BIOMASS\_CC90\_NEW | [MMBtu/MWh] | Biomass | 8.10 | 8.04 | 7.91 | 7.78 | 7.66 | 7.54 | 7.41 | [28, 24]\* |
| BIOMASS\_NEW | [MMBtu/MWh] | Biomass | 7.21 | 7.21 | 7.21 | 7.21 | 7.21 | 7.21 | 7.21 | [28]\*\* |
| COAL\_95CC\_NEW | [MMBtu/MWh] | Coal | 10.94 | 10.94 | 10.94 | 10.94 | 10.94 | 10.94 | 10.94 | [23] |
| COAL\_99CC\_NEW | [MMBtu/MWh] | Coal | 11.12 | 11.12 | 11.12 | 11.12 | 11.12 | 11.12 | 11.12 | [23] |
| COAL\_NEW | [MMBtu/MWh] | Coal | 8.49 | 8.49 | 8.49 | 8.49 | 8.49 | 8.49 | 8.49 | [23] |
| NG\_F-FRAME\_CC\_95CC\_NEW | [MMBtu/MWh] | Natural Gas | 7.22 | 7.22 | 7.22 | 7.22 | 7.22 | 7.22 | 7.22 | [23] |
| NG\_F-FRAME\_CC\_97CC\_NEW | [MMBtu/MWh] | Natural Gas | 7.26 | 7.26 | 7.26 | 7.26 | 7.26 | 7.26 | 7.26 | [23] |
| NG\_F-FRAME\_CC\_NEW | [MMBtu/MWh] | Natural Gas | 6.36 | 6.36 | 6.36 | 6.36 | 6.36 | 6.36 | 6.36 | [23] |
| NG\_F-FRAME\_CT\_NEW | [MMBtu/MWh] | Natural Gas | 9.72 | 9.72 | 9.72 | 9.72 | 9.72 | 9.72 | 9.72 | [23] |
| NG\_H-FRAME\_CC\_95CC\_NEW | [MMBtu/MWh] | Natural Gas | 7.01 | 7.01 | 7.01 | 7.01 | 7.01 | 7.01 | 7.01 | [23] |
| NG\_H-FRAME\_CC\_97CC\_NEW | [MMBtu/MWh] | Natural Gas | 7.05 | 7.05 | 7.05 | 7.05 | 7.05 | 7.05 | 7.05 | [23] |
| NG\_H-FRAME\_CC\_NEW | [MMBtu/MWh] | Natural Gas | 6.20 | 6.20 | 6.20 | 6.20 | 6.20 | 6.20 | 6.20 | [23] |
| NUCLEAR-AP1000\_NEW | [MMBtu/MWh] | Uranium | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | [23] |
| NUCLEAR-SMR\_NEW | [MMBtu/MWh] | Uranium | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | 10.44 | [23] |
| WAT\_PS\_NEW | [MWh/MWh] | Electricity | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | [24] |

\*Average values from all biomass technologies reported on EIA-923 [28] times increase in heat rate for BECC tech in ReEDS [24]

\*\*Average values from all biomass technologies reported on EIA-923 [28]. 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 [29], NC had 4.96% T&D losses from 2021-2019. Using [30] 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 | [23] |
| BIT\_ST\_EXISTING | Coal | 214.13 | Emissions from [29], fuel consumption from [28] |
| BLQ\_ST\_EXISTING | Biomass | 0 | [23] |
| DFO\_CC\_EXISTING | Petroleum | 229.79 | Emissions from [29], fuel consumption from [28] |
| DFO\_GT\_EXISTING | Petroleum | 229.79 | Emissions from [29], fuel consumption from [28] |
| DFO\_IC\_EXISTING | Petroleum | 229.79 | Emissions from [29], fuel consumption from [28] |
| LFG\_GT\_EXISTING | Landfill Gas | 0 | [23] |
| LFG\_IC\_EXISTING | Landfill Gas | 0 | [23] |
| NG\_CC\_EXISTING | Natural Gas | 119.42 | Emissions from [29], fuel consumption from [28] |
| NG\_GT\_EXISTING | Natural Gas | 119.42 | Emissions from [29], fuel consumption from [28] |
| NG\_ST\_EXISTING | Natural Gas | 119.42 | Emissions from [29], fuel consumption from [28] |
| OBG\_IC\_EXISTING | Biomass | 0 | [23] |
| WDS\_ST\_EXISTING | Biomass | 0 | [23] |

**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 | [31, 20]\* |
| BIOMASS\_NEW | Biomass | 0 | [23] |
| COAL\_95CC\_NEW | Coal | 10.12 | [23] |
| COAL\_99CC\_NEW | Coal | 2.02 | [23] |
| COAL\_NEW | Coal | 202.32 | [23] |
| NG\_F-FRAME\_CC\_95CC\_NEW | Natural Gas | 5.93 | [23] |
| NG\_F-FRAME\_CC\_97CC\_NEW | Natural Gas | 3.558 | [23] |
| NG\_F-FRAME\_CC\_NEW | Natural Gas | 118.6 | [23] |
| NG\_F-FRAME\_CT\_NEW | Natural Gas | 118.6 | [23] |
| NG\_H-FRAME\_CC\_95CC\_NEW | Natural Gas | 5.93 | [23] |
| NG\_H-FRAME\_CC\_97CC\_NEW | Natural Gas | 3.558 | [23] |
| NG\_H-FRAME\_CC\_NEW | Natural Gas | 118.62 | [23] |

\*CO2 data in lb/MMBtu for various biomass resources was collected from reference [31]. A weighted average was then calculated using the total MMBtu consumed of fuel by each technology in North Carolina [28] (2021) to determine a comparable emission value, which was then adjusted for 90% carbon capture. (EIA Fuel Code [lbs CO2/MMBtu] [31]: LFG=130, OBG=127, BLQ=222, ABWDS=207).

Regarding the limits on CO2 emissions, according to the NC - House Bill 951 [32], 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 [33]. 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 and Max/Min Capacity/Activity**
     1. **Solar**

Data for global horizontal irradiance was downloaded from the NREL SAM model [34] from 1998 to 2020 for the load centroids of the three regions investigated in this work. Figure 1 shows the distribution of the total irradiance for each region by time of day and season. As it is possible to see, there are very small differences between each region's resources. As such, no distinction was made regarding the CF of solar in different regions.

For utility PV, from EIA 860 report [36] we can estimate that 90.6% of the total utility solar installed in NC form 2008-2021 is fixed til, 8.3% is 1-axis tracking and 1.1% is 2-axis tracking. From 2020 to 2021 79% of new solar installations were fixed tilt, 15% were 1-axis and 6% were 2-axis tracking. As a simplification, we assumed that all existing utility solar installations in NC follow a CF distribution composed of 90% fixed tilt and 10% 1-axis tracking, and that all future utility PV installations are composed of 80% fixed tilt and 20% 1-axis tracking. For residential and commercial solar, all PV generation is assumed to be fixed tilt. Figure 2 shows the CF profiles for fixed tilt and one-axis tracking solar PVs computed using the NREL PVWATT v.6 model [37] for the NC region.

|  |  |
| --- | --- |
|  |  |
| **Figure 1:** Percentage of total irradiance for solar technologies in different regions of NC | **Figure 2:** CF for 1-Axis Tracking and Fixed-Tilt Solar Energy Generation. Adjusted for an Annual CF of 0.215 |

Considering the 2021 EIA NC Summary Statistics report [29], the average annual CF of existing utility solar can be estimated at 0.215 in NC. Using the ATB 2022 conversions from utility to residential and commercial solar [24] (2020 conservative scenario), a 0.12 capacity factor was estimated for existing residential/commercial solar. The final capacity factors for existing solar technologies are shown in Figure 3.

As solar energy technology evolves, it is expected improvements in cost as well as in capacity factors. For future solar deployments, the annual CF estimates from the NREL ATB- 2022 [23] for technology class C6 (GHI 4.5-4.75 kWh/m2/day) were used to adjust the curves shown in Figure 3. Figure 4 shows the annual CFs considered in this work for different solar technologies.

|  |  |
| --- | --- |
|  | A graph of a number of solar panels  Description automatically generated with medium confidence |
| **Figure 3:** CF for Existing Utility and Residential Solar in NC | **Figure 4:** Average Annual CF for Solar Technologies By Deployment Year. CF For Existing Tech Shown For Comparison |

Regarding maximum capacity limits for solar, according to NREL [36], NC has the potential for 2953 TWh of utility PV generation, 17992 GWh of residential solar, and 23572 GWh of commercial solar. Due to the high availability of solar resources compared to the state electricity demand, this work found it unnecessary to enforce maximum limits of solar deployment. With respect to limits for minimum activity, the analysis made in Section 2.3 (Energy Demand, See tables 2 and 3) was used to estimate residential and commercial solar energy generation in NC throughout the optimization periods considered in this work. These values are shown in Table 1 and were enforced as minimum activity in the optimization model.

Also, due to the complexity of estimating the size of distributed solar energy at each year from before 2023, all existing distributed solar was approximate as being deployed in 2017, which corresponds to the average year of deployment for the current installed utility solar (weighted by capacity) in NC according to the 2022 EIA 860 report [36].

**Table 1:** Minimum Activity Enforced for Distributed Solar Energy Generation in North Carolina

|  |  |  |
| --- | --- | --- |
| **Year** | **Generation from Solar Residential**  **[GWh]** | **Generation from Solar Commercial**  **[GWh]** |
| 2022- Existing Solar\* | 334 | 121 |
| 2023 | 406 | 137 |
| 2025 | 528 | 173 |
| 2030 | 835 | 264 |
| 2035 | 1,787 | 390 |
| 2040 | 2,539 | 488 |
| 2045 | 3,306 | 537 |
| 2050 | 4,239 | 570 |

\* Estimated as done in Table 3 (Demand Section) Using 2022 data for DEC+DEP (Table 2 -Demand Section). This Value is Considered as Existing Distributed Solar.

Finally, since this work considered the segmentation of NC in multiple regions (R1, R2, and R3), as explained in the previous sections, the minimum activity limits shown in Table 1 were distributed based on the percentage of the total population at each region. Using the 2020 census [23], the ratios considered were 7.02%, 12.98%, and 80.00% for regions R1, R2, and R3, respectively.

* + 1. **Wind**

A resource characterization for wind energy technologies is provided by NREL in [35], with available capacity and annual CF for viable site locations based on 2030 ATB moderate designs [23]. This reference is used to compute the maximum available capacity and CFs for each of the NC regions modeled in this work. Site locations with CF below 0.25 were eliminated from the analysis of land-based wind as these are less likely to be explored and correspond to less than 17% of the total land-based wind power available in NC [35]. For offshore technologies, according to the ATB 22 [23], fixed bottom wind turbines (Class C1 to C7) are more likely to be explored in the near future. As such, the NC offshore wind site locations mapped by NREL [35] were filtered to account for sites with a maximum of 40m depth and distancing a maximum of 100km from shore.

Table 1 shows the resultant maximum available capacity and average annual CF for land-based and offshore technologies. The column “2030 - Annual CF” refers to the CF estimated directly from reference [35], which accounts for 2030 wind technologies, and the column “2020 - Annual CF” corresponds to the conversion of the 2030 CFs for 2020 equivalent technology using ATB 22 [23] estimates. Table 1 also shows the CF for existing wind energy technology, computed as the average values reported in [29] from 2021 to 2018.

**Table 1:** Maximum Available Capacity and CF For Wind Technology

|  |  |  |  |
| --- | --- | --- | --- |
| **Technology** | **Max Capacity**  **(GW)** | **Annual CF - 2030 Tech**  **(NREL 2030 Moderate Technology)** | **Annual CF – 2020 Tech**  **(ATB -2022 Conversion-**  **Conservative Case)** |
| New Offshore Wind\* | 15.26 | 0.427 | 0.378 |
| New Land-Based Wind (R1)\*\* | 0.85 | 0.410 | 0.382 |
| New Land-Based Wind (R2)\*\* | 4.07 | 0.402 | 0.374 |
| New Land-Based Wind (R3)\*\* | 11.00 | 0.330 | 0.307 |
|  |  |  |  |
| **Technology** | **Existing capacity (GW)** | **CF (NC Average Statistics 2021-2018)** [29] | |
| Existing Land-Based Wind\*\*\* | 0.21 | 0.290 | |

\* Based on [35], limited access case. \*\*Based on [35], reference access case.

To find the CF variation for wind generation during different hours of the day and seasons, the operation of hypothetical wind turbines was simulated across the region of study, and the average CF profile from these operations at each region was used for wind technologies. Two to three sample wind site locations were considered for each NC region, as in Figure 3, with wind speed data coming from the NREL SAM model [34] from 2007 to 2013, and the turbine design and parameters chosen based on NREL ATB- 2022 [23] conservative designs. For land-based wind, the turbine was rated at 4MW with 110m hub height, and for offshore wind, the turbine was rated at 12MW with 136m hub height; the power curves for these designs were obtained from the NREL SAM model [34].

|  |
| --- |
|  |
| **Figure 3:** Sample Locations Used for Determining the CF Profile of Wind on NC. Showing Sites With Capacity Above 20MW |

Finally, as done for solar energy generation, the CF profile at each region was adjusted to match the annual CF values reported in Table 1 for the year 2020, corrected by the technology vintage based on CF rates of improvement from NREL ATB- 2022 [23] (conservative case). Figure 4 shows the CFs profile for the wind technologies, and Figure 5 shows the average annual CF by deployment year.

|  |  |
| --- | --- |
|  |  |
| **Figure 4:** CF Profile For Wind Technology From Simulation of Individual Turbines (2007-2013) | **Figure 5:** Average Annual CF for Wind Technologies By Deployment Year. CF For Existing Tech is Also Shown For Comparison |

* + 1. **Hydropower**

For hydropower generation, the CF was assumed to vary only with the season and not with the time of the day, which is a common practice in many capacity expansion studies. The CF values used in this work for hydro technologies are shown in Table 1 and were computed by averaging the monthly CF values reported from 2017 to 2021 in the North Carolina electricity summary statistics [29, 36, 37, 38, 39].

In terms of maximum and minimum capacity for hydropower and pumped storage (shown in Table 1), this work assumes that the current installed capacity reported in the EIA-860 [20] is the maximum capacity available for each technology type. From the perspective of pumped storage, although Duke Energy has plans to add new capacity in South Carolina by 2035 [19] the same is not true for North Carolina, and from the perspective of new hydropower plants, existing environmental regulations and costs are likely to difficult increases in hydropower capacity above the current levels.

**Table 1:** Capacity Factor and Maximum Available Capacity For Hydropower

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Technology** | **Capacity Factor** | | | | **Maximum Capacity Available [MW]** |
| **S1-Winter** | **S2-Spring** | **S3-Summer** | **S4-Autumn** |
| WAT\_HY (EXISTING/NEW) | 0.389 | 0.385 | 0.302 | 0.316 | 2057.6 |
| WAT\_PS (EXISTING/NEW) | -\*\* | -\*\* | -\*\* | -\*\* | 95.0 |

\*Different from solar and wind, this technology does not have adjustments in CF due to tech vintage; \*\*No CF assumed for pumped hydro.

* + 1. **Biomass**

For biomass technologies, CF is used to limit the maximum average generation of technology throughout the years of simulation due to planned/non-planned outages. This value is determined using the Equivalent Availability Factor (EAF) reported by NERC [40] from 2017-2021 for coal turbines.

A maximum value for the amount of biomass available for use by the electric power sector in NC is also estimated using data from the 2016 Billion-Ton Report [41]. From reference [41], we assumed a maximum biomass price of 60$ per dry ton and that only biomass from forestry and waste would be available to the power sector (agricultural biomass is ignored, assuming it would be used to create biofuels). Dry ton units were converted to MMBtu using rates of 13 MMBtu/ton for forestry and 8MMBtu/ton for waste [41]. Landfill gas is also considered as part of the biomass technologies, and the total Btus available are assumed to not vary substantially from current consumption levels provided at the EIA 923 reports [42]

Table 1 summarizes the information mentioned above.

**Table 1:** Capacity Factor and Maximum Available Resource for Biomass Technology

|  |  |
| --- | --- |
| **Technology** | **CF (EAF)** |
| All Biomass Technologies | 0.786 |
|  |  |
| **Biomass Resource** | **Max Resource Available [Trillion Btu ]** |
| Forestry\* [41] | 64.28\* |
| Waste\* [41] | 48.16\* |
| Landfill Gas [42] | 5.16 |
| Total Biomass Available | 117.6 |

\*Average of the estimates provided in [41] from 2015-2040

* + 1. **Other Technologies**

In terms of coal, petrol, natural gas, and nuclear technologies, no max/min capacity limits were enforced; however, as done for biomass, the correspondent Equivalent Availability Factors (EAF) reported by NERC [40] from 2017-2021 were used as a way to limit the maximum average generation of each technology due to planned/non-planned outages.

**Table 1:** Capacity Factor and Maximum for Coal, Petrol, Natural Gas, and Nuclear Technologies

|  |  |
| --- | --- |
| **Technology Type** | **CF (EAF)** |
| Coal | 0.786 |
| Petrol | 0.781 |
| Natural Gas | 0.772 |
| Nuclear | 0.91 |

* 1. **Planning Reserve Margin and Capacity Credit**

Planning reserve requirements refer to the share of peak load that must be available to meet contingencies. In North Carolina, the peak load is estimated to happen during the early hours of the day during the winter [43]. In this work, we assume planning reserves at 17%, as done in [43] for DEC and DEP.

To estimate if reserve requirements are met, a variable called capacity credit is used to represent the fraction of the total installed capacity of a process that can be relied upon during the peak load condition, also called Effective Load Carrying Capability (ELCC). In the determination of this variable two main sources are used in this work: The ELCC report prepared for Duke Energy in 2022 [44], and the average Equivalent Forced Outage Rate demand (EFORd) reported by NERC [40] from 2017-2021. Table 1 details the capacity credits used in this work.

For battery, solar, and wind technologies, reference [44] provides ELCCs for different brackets of installed capacity and possible synergies between technologies; this work does not consider this level of detail in the capacity expansion model optimization and assumes average values from this reference. It is important to remember that future load and generation conditions may change the critical load periods and, consequently, the technology capacity credit; however, this uncertainty is not considered here.

**Table 1:** Capacity Credit for Different Technology Types

|  |  |  |
| --- | --- | --- |
| **Technology Type** | **Capacity Credit (ELCC)** | **Reference** |
| Coal | 0.91 | [40]: (1- EFORd) |
| Petrol | 0.87 | [40]: (1- EFORd) |
| Natural Gas | 0.88 | [40]: (1- EFORd) |
| Nuclear | 0.98 | [40]: (1- EFORd) |
| Biomass | 0.91 | [40]: (1- EFORd Coal) |
| Hydro | 0.92 | [40]: (1- EFORd) |
| Pumped Storage | 0.94 | [40]: (1- EFORd) |
| Battery | 0.70 | Based on [44] |
| Solar | 0.05 | Based on [44] |
| Wind Onshore | 0.40 | Based on [44] |
| Wind Offshore | 0.70 | Based on [44] |

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|  |  |
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