Model Assessment Report:
Incorporating Climate Impacts into NRDC-NEMS

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I. Introduction and Overview

The National Energy Modeling System (NEMS) is an energy-economic model of U.S. energy markets that is accepted as a standard for evaluating the effects of energy policy. NEMS is developed and maintained by the Energy Information Administration (EIA) and is used to produce the EIA's Annual Energy Outlook (AEO). NEMS projects future flows of energy from production to consumption across several connected modules that represent different segments of the U.S. energy market. NEMS and variants of NEMS developed by researchers outside of EIA have been used to analyze the implications of various proposed and existing policies that address climate change, such as the Inflation Reduction Act (IRA) of 2022, as well as more challenging scenarios such as reaching net-zero emissions by 2050.[1]

The current version of the National Energy Model System (NEMS) contains a limited incorporation of future climate impacts on the U.S. energy sectors and associated economy, mainly in the representation of building heating and cooling demands. NEMS was developed by the Energy Information Administration (EIA) and is the official energy model of the U.S. Government. As continuing increasing temperatures and recent extreme weather events (e.g., extreme precipitation on West Coast, the Texas Polar Vortex, Western droughts, Eastern flooding) have demonstrated, the lack of internalized climate impacts can lead to misleading energy system and climate mitigation modeling and subsequent policy analyses.

The objective of this NEMS needs assessment is to explore existing literature on incorporating climate impacts into energy systems modeling and identify priority areas in NEMS where climate impacts should be incorporated. This report also describes the NEMS model enhancements and updates needed to incorporate climate impacts.

This NEMS assessment could be used as the basis for developing funding proposals for foundations, government agencies, or both. Proposals and subsequent projects would explore the full planning and implementation of the needed modeling enhancements to NEMS and perform analyses of climate impact implications to the U.S. energy system under alternative energy policy and climate scenarios.

[1] Two IRA analyses include J. Larsen, et al., "A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act," Rhodium Group, 2022, https://rhg.com/research/climate-clean-energy-inflation-reduction-act/ and DOE Office of Policy, Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Energy Economy and Emissions Reductions, August 2023, https://www.energy.gov/sites/default/files/2023-08/DOE%20OP%20Economy%20Wide%20Report_0.pdf . A version of NEMS was used in the recent Stanford Energy Modeling Forum analyzing net-zero emission scenarios: M. Browning, et al., "Net-zero CO2 by 2050 scenarios for the United States in the Energy Modeling Forum 37 study," Energy and Climate Change, December 2023, https://www.sciencedirect.com/science/article/abs/pii/S2666278723000119

II. NRDC Priority Setting: Climate Variables for Energy System Relevance

The climate change impact assessments from the U.S. Fourth National Climate Assessment[2] and the United Nations Intergovernmental Panel on Climate Change (UN IPCC)[3] identify several priority climate impacts. Our assessment for enhancing NEMS to reflect climate impacts begins with identifying which of these impacts are most likely to have a significant effect on the U.S. energy system and can be modeled at an appropriate level of energy sub-sector detail in NEMS. There are additional climate impacts that may have significant effect on other systems including agriculture, health, water quality and availability, and natural ecosystems, but these are not considered here because they are not within the scope of the NEMS model. Integrated Assessment Models (IAMs), e.g., PNNL's Global Change Analysis Model (GCAM)[4] or MIT's EPPA Model,[5] can be used to assess broader impacts from climate change. Table 1 identifies the impacts impacting the energy system with their specific energy sector relevance.

Several steps will be required to represent the effects of climate impacts on the energy sector. For each of the impacted areas, the steps include *Assessment, Translation, Relationship*, and *Enhancement*:

- *Assessing* output metrics from climate model scenarios that are available and likely to be most applicable to the impact (such as number of days with temperature exceeding some value, heating and cooling degree days, average precipitation per time period, etc.);
- *Translating* climate model output into NRDC-NEMS input assumptions at appropriate regional and temporal scale; this may involve hydrological or land use modeling;
- Developing the *relationship* between climate metric parameters and energy impact; and
- *Enhancing* NRDC-NEMS to accommodate representation of impact.

[2] USGCRP, "Fourth National Climate Assessment" (U.S. Global Change Research Program, Washington, DC, 2018), https://nca2018.globalchange.gov.
[3] "IPCC — Intergovernmental Panel on Climate Change," accessed September 15, 2023, https://www.ipcc.ch/.
[4] "GCAM: Global Change Analysis Model | Global Change Intersectoral Modeling System," accessed January 10, 2024, https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model.
[5] "EPPA Model Structure | MIT Global Change," accessed January 10, 2024, https://globalchange.mit.edu/research/research-tools/eppa.

Table 1. Priority Climate Variables for Energy System Relevance

Climate Impact	Description	Energy Sector Relevance
Annual Averages	Annual minimum and maximum temperatures Total annual precipitation	Peak capacity; Derating Planning for extremes Agriculture and Forestry yields
Heating and Cooling Degree Days	Degree-day estimates derived from difference between daily minimum and maximum temperature and user-defined heating/ cooling setpoint temperatures	Energy demand forecasting Capacity expansion
Extended Drought	Weather/hydrologic projections for extreme drought scenarios	Hydroelectric capacity Water availability for power plant cooling Planning for extremes Agriculture and forestry yields; crop and tree shifting
Extreme Precipitation	Frequency and intensity of precipitation events for various "extreme" event thresholds	Hydroelectric capacity; Distribution reliability; Storm hardening Agriculture and forestry damage
Sea Level Rise	Projects sea level inundating during 100-year storm events along coasts	Grid Hardening; Siting Planning for extremes Agriculture and forestry planning
Snowpack	Monthly snow water equivalent	Hydroelectric capacity Agriculture and forestry irrigation
Streamflow	Monthly and annual streamflow projections	Hydroelectric / Siting Agriculture and forestry irrigation
Wildfires	5- and 10-year averages of acres burned under different scenarios	Siting; Grid Hardening; Capacity Expansion; Planning for extremes Agriculture and forestry damage

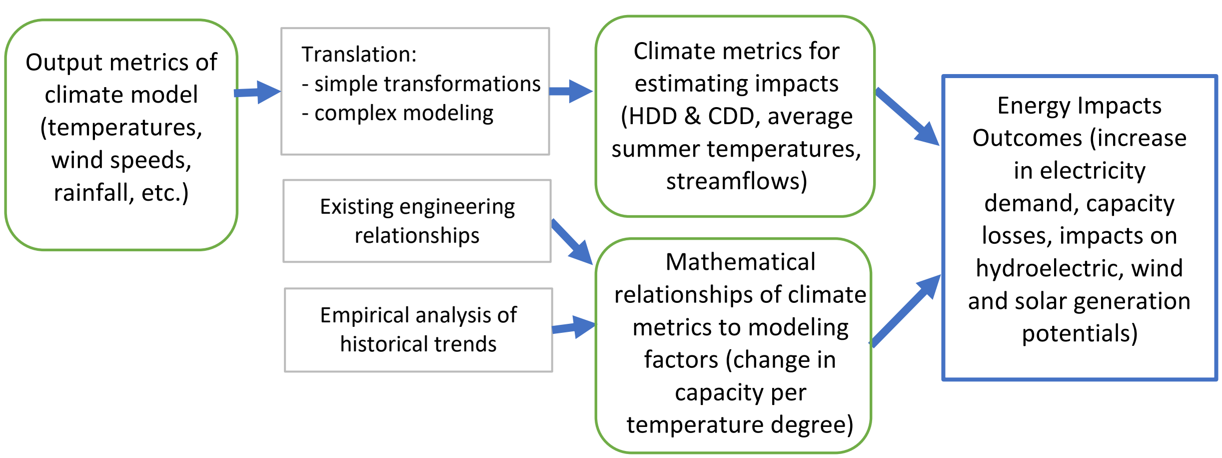

Figure 1. Data flow for modeling climate impacts

Depending on the components of the energy system, the first three steps may need to be iterative as analysis of the relationship of energy impacts and climate may determine which climate variables are most important.

The most straightforward example of this process is that of the impact on heating and cooling demands in buildings, which will be discussed in greater detail in Section V.

III. Treatment of Climate Impacts – Overview of the literature

Current approaches to incorporating climate impacts into energy modeling are typically narrowly focused but may prove useful for new data sources. A report by Craig et al. provides a review of recent studies that address potential climate impacts on individual components of the power sector and then assess potential system-wide impacts.[6] As described below, numerous studies conducted modeling focused on energy demand impacts, mainly on electricity use for heating and cooling buildings. Others look more comprehensively at supply and demand impacts on the power sector from a variety of climate factors. For example, Solaun et al. provide a useful compilation of studies assessing climate change impacts on renewable energy generation, and Tobin et al. examine impacts on thermal and renewable generation technologies in Europe.[7] Oak Ridge National Laboratory (ORNL) assessed quantitative methods for assessing extreme weather and climate vulnerabilities of the power system including electricity generation, transmission and distribution, and electricity demands; however, no connectivity was established to climate models or modeling projections. Perera et al. took a stochastic approach to assessing the effect of high impact, low probability events on the power grid.[8] We found no studies that comprehensively examine potential climate impacts across multiple areas of the energy system. The IEA modeling appears to be the broadest. While their 2022 global modeling system only incorporated climate impacts on annual space heating and cooling demands (all fuels), the most recent Global Energy and Climate (GEC) Model Documentation for 2023 describes updates that have made to incorporate impacts on load shapes as well. Production profiles for wind, solar PV and hydro are now hourly and weather dependent but appear to be based on historical conditions rather than future climate scenarios.[9]

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[6] Michael T. Craig et al., "A Review of the Potential Impacts of Climate Change on Bulk Power System Planning and Operations in the United States," *Renewable and Sustainable Energy Reviews* 98 (December 1, 2018): 255–67, https://doi.org/10.1016/j.rser.2018.09.022; Kepa Solaun and Emilio Cerdá, "Climate Change Impacts on Renewable Energy Generation. A Review of Quantitative Projections," *Renewable and Sustainable Energy Reviews* 116 (December 1, 2019): 109415, https://doi.org/10.1016/j.rser.2019.109415.

[7] I. Tobin et al., "Vulnerabilities and Resilience of European Power Generation to 1.5 °C, 2 °C and 3 °C Warming," *Environmental Research Letters* 13, no. 4 (April 2018): 044024, https://doi.org/10.1088/1748-9326/aab211.

[8] A. T. D. Perera et al., "Quantifying the Impacts of Climate Change and Extreme Climate Events on Energy Systems," *Nature Energy* 5, no. 2 (February 2020): 150–59, https://doi.org/10.1038/s41560-020-0558-0.

[9] "IEA, Global Energy and Climate Model Documentation," December 2023, https://iea.blob.core.windows.net/assets/ ff3a195d-762d-4284-8bb5-bd062d260cc5/GlobalEnergyandClimateModelDocumentation2023.pdf.

A. General Circulation Models for climate impacts assessment

Climate models known as General Circulation Models (GCM) are generally used for understanding, simulating, and predicting earth's climate system. GCMs are mathematical models that simulate the Earth's climate system with different levels of complexities up to three-dimensional atmosphere-ocean-land models for predicting changes over time of many variables such as temperature, humidity, winds, sea ice cover, and soil moisture. GCMs employ a combination of mathematical expressions that represent governing physics of circulation processes for planetary atmosphere or ocean and data-based empirical calculations to replicate processes. A well-known application of GCMs is to assess climate change over lengthy time periods for future plausible scenarios which are either due to natural changes in various components of the earth system, increases in greenhouse gas emissions that are chiefly responsible for global warming, or a combination of both.

Updated climate models by different modeling groups around the world are coordinated around the schedule of the Intergovernmental Panel on Climate Change (IPCC) assessment reports (AR), including the Coupled Model Intercomparison Projects (CMIP).[10,11] The goal of CMIP is to generate a set of standard simulations which allows results to be directly comparable across different models. One of the main sets of simulations run by models are future climate scenarios chosen to provide a range of distinct climate change outcomes in 2100. For example, the IPCC AR5 features four Representative Concentration Pathways (RCPs) for the climate modeling community which examine different possible future concentrations of greenhouse gases (GHG) as a basis for long-term and near-term modeling experiments (reflecting different emission trajectories over time as determined by the underlying socioeconomic assumptions).[12]

The four RCPs span the range of year 2100 radiative forcing values (cumulative measure of human emissions of GHGs from all sources expressed in Watts per square meter), from 2.6 to 8.5 W/m^2.[13] The higher values mean higher GHG emissions and thus higher global temperatures and more pronounced effects of climate change, while lower RCP values require more stringent climate change mitigation efforts to achieve them.

- RCP8.5: high pathway for which radiative forcing reaches >8.5 W/m^2 (~1370 ppm CO^2-eq) by 2100 and continues to rise thereafter.
- RCP4.5, RCP6.0: two intermediate "stabilization pathways" in which radiative forcing is stabilized at approximately 6 W/m^2 and 4.5 W/m^2 (~850 and ~650 ppm CO^2-eq) after 2100.

[10] "IPCC — Intergovernmental Panel on Climate Change."
[11] David W. Pierce et al., "Future Increases in North American Extreme Precipitation in CMIP6 Downscaled with LOCA," *Journal of Hydrometeorology* 24, no. 5 (May 2023): 951–75, https://doi.org/10.1175/JHM-D-22-0194.1.
[12] "IPCC — Intergovernmental Panel on Climate Change."
[13] Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An Overview," *Climatic Change* 109, no. 1 (August 5, 2011): 5, https://doi.org/10.1007/s10584-011-0148-z.

- RCP2.6: the pathway where radiative forcing peaks at approximately 3 W/m^2 (~490 ppm CO^2-eq) before 2100 and then declines.

Based on IPCC's Fifth Assessment report, RCP 2.6 is considered the “very stringent” pathway, likely needed to keep global temperature rise below 2 °C by 2100. For intermediate scenarios, RCP4.5 is the most probable baseline scenario with global temperature rise between 2 °C and 3 °C by 2100, while in RCP6 the global temperature rises by about 3–4 °C by 2100. RCP8.5 generally is taken as the basis for worst-case (with overestimation of projected coal outputs) climate change scenario with global temperature rise by 5 °C by 2100.[14]

These scenarios have been complemented further (in CMIP6) by integrating with Shared Socioeconomic Pathways (SSP) which explore how socioeconomic factors (e.g., population, economic growth, and education) affect GHG emissions and how different levels of emission mitigation can be achieved when the RCP emission targets are combined with the SSPs.[15] This was accomplished with defining new RCPs such as RCP1.9 (a pathway that limits global warming to below 1.5 °C, compatible with the Paris Agreement goal), and RCP3.4 (an intermediate pathway between the "very stringent" RCP2.6 and less stringent mitigation efforts associated with RCP4.5).

GCMs and their pathways for future emission targets provide inputs (as trajectories of climate and weather variables; e.g., temperature and precipitation levels) for energy system modeling purposes to capture climate change impacts on various energy subsectors. In addition, hydrological models are employed to estimate water flows.

As GCMs do not resolve small spatial scales, for greater spatial resolution, some researchers use Regional Climate Models (RCMs) as a dynamical downscaling tool (for covering a limited area of the globe) driven by coarse resolution GCM outputs. This allows providing information at fine, sub-GCM grid scales more suitable for studies of regional phenomena (such as the representation of precipitation in mountainous regions).[16] The available GCM and RCM simulations have horizontal grid spacings of typically 100–300 km and 10–50 km, respectively.[17]

[14] thomas harrisson, “Explainer: How ‘Shared Socioeconomic Pathways’ Explore Future Climate Change,” Carbon Brief, April 19, 2018, https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/.

[15] Keywan Riahi et al., “The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview,” *Global Environmental Change* 42 (January 1, 2017): 153–68, https://doi.org/10.1016/j.gloenvcha.2016.05.009.

[16] Filippo Giorgi, “Thirty Years of Regional Climate Modeling: Where Are We and Where Are We Going Next?,” *Journal of Geophysical Research: Atmospheres* 124, no. 11 (2019): 5696–5723, https://doi.org/10.1029/2018JD030094.

[17] Silje Lund Sorland et al., “Bias Patterns and Climate Change Signals in GCM-RCM Model Chains” (Environmental Research Letters, 2018).

IV. Enhancing the NEMS Modeling Framework

For energy modeling, it is helpful to categorize climate impacts by the energy sector impacted. Table 2 is a rearrangement of Table 1 to better frame the discussion of NEMS modeling enhancements.

The modeling discussion focuses more on chronic climate effects rather than acute, short-term events due to the nature of NEMS and other energy system models that make projections over decades of time and do not capture short-term energy market disturbances. To the extent that acute events lead to changes in long-term investments, they can and should be represented in NEMS. For example, increased frequency of extreme weather events due to climate change could lead to changes in infrastructure and capacity planning as energy providers act to increase resiliency. However, the representation of acute events themselves, such as severe hurricanes and heat waves for which the location and timing is unknowable, is not appropriate.

Table 2. Sectoral Components Impacted by Climate Change

Sector	Energy Component	Climate Impact	Anticipated Impact Range
Residential, Commercial	Building heating and cooling demands	Higher air temperatures	High
Electricity	Deration of capacity/ reduced efficiency	Higher temperatures (ambient air and/or water)	Medium
	Transmission capacity	Higher air temperatures	High
	Hydroelectric capacity and generation	Extended Drought	High
		Streamflows	High
		Snowpack	High
	Reserve Margin targets	Planning for extreme temperatures	High
	Solar technical potential	Altered solar irradiance	Low
		Higher air temperatures	Low
	Wind technical potential	Altered wind speeds	Low
Oil & Gas	Production, storage, pipelines	Extreme weather, sea level rise, water availability, ground thawing	Medium to High
Agriculture and Forestry (biomass supply)	Yields and/or damage reducing supplies	Higher CO_2 concentrations	Medium
		Higher air temperatures	High
		Extended Drought	High
		Extreme Precipitation	Medium
		Streamflows	Medium to High
		Snowpack	Medium
		Wildfire	High

A. Energy Demands

Climate Impact

Climate change is likely to have the greatest impact on energy demands through warming temperatures that decrease heating demands and increase cooling demands. Temperature changes may include higher average daily temperatures, more frequent and extreme temperatures, and longer lasting heat waves.

Relevant Literature and Findings

Changes in electricity and fuel demands related to projected temperature increases are not currently modeled within most energy and electricity models. For example, increased electricity demand in summers due to higher air conditioning loads or less demand for natural gas and electricity in winters for heating. NEMS includes warming effects by using an extrapolation of historical trends, rather than explicitly modeling specific climate scenarios. Models relying on the AEO demand projections consequently include the same trends implicitly. Nevertheless, climate effects on electricity demand is the most widely studied climate impact. Various metrics are used to measure temperature impacts resulting from climate change depending on the methodology used to estimate electricity demands.

Examples of such studies include Sullivan et al.[18] which describes how temperature impacts on electricity demand was approached in the Regional Energy Deployment System (ReEDS) model.[19] Historical data for hourly electricity demands for utilities and balancing authorities were obtained through FERC Form 714, and temperature data was from the 1991-2010 National Solar Resource Database (NSRDB). "Temperature-neutral" and "Temperature-sensitive" loads were estimated for each of the 300 transmission zones. The temperature-sensitive loads were converted into averages for every *time-slice-day* and regressed against temperature to calculate heating and cooling load sensitivity parameters, where time-slices were defined to align with the ReEDS model. After applying geospatial smoothing, the parameters were redistributed to the 134 ReEDS balancing areas. Projected gridded daily average temperatures from MIT's Integrated Global System Model's (IGSM) RCP4.5 scenario were used to construct seasonal degree days and smoothed across years. Then the differences in projected degree days from historical values were applied to the temperature sensitivity parameters to estimate electricity demand changes by time-slice and balancing area. As described by the authors, one limitation to this method is the assumption that the proportions of temperature sensitive loads remain constant over time. The findings describe a 1% increase

[18] Patrick Sullivan, Jesse Colman, and Eric Kalendra, "Predicting the Response of Electricity Load to Climate Change," July 28, 2015, https://doi.org/10.2172/1215283.
[19] Stuart M. Cohen et al., "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2018" (National Renewable Energy Lab. (NREL), Golden, CO (United States), April 2, 2019), https://doi.org/10.2172/1505935.

in annual electricity demand by 2030. The more amplified changes are to the peak demand which rose by 5% in the model.

Auffhammer et al. also explored how the effects of weather events due to climate change will alter annual and peak electricity demand.[20] The study used observed average and maximum daily loads at balancing authorities together with daily minimum and maximum temperatures and precipitation data to derive a function of how temperature affects electricity demand in different regions. Average and peak load regression equations were estimated with precipitation included to isolate the effect of temperature. Two RCPs from multiple downscaled GCMs were used to assess the impact of climate change. In RCP4.5, the daily peak load is expected to increase 3.5% on average with a 7% increase for the 95th percentile increase in peak that is more indicative of an annual peak increase that would impact capacity planning. RCP8.5 leads to a greater increase in daily peak load of 18% for the 95th percentile increase.

In general, studies have projected greater impacts on peak demand than average annual demands. A review conducted by Craig et al. found that annual electricity demands are generally predicted to rise by less than 5% while peak loads rise by 10-20% as a result of climate change.[21]

While these studies have used regression analyses to estimate total electricity demand sensitivity to temperature, others have used estimations of heating (HDD) and cooling degree days (CDD) to specifically project heating and cooling electricity usage. HDD and CDD are the differences between the mean daily outdoor temperatures and a base temperature, traditionally specified as 65°F, summed over a year. Projected HDD and CDD values are sometimes estimated from monthly mean temperature climate data, as in Jaglom et al.,[22] or from minimum and maximum daily temperatures as in Larsen et al.[23] IEA uses HDD and CDD that they derive from relevant projections published in the IPCC Working Group I Interactive Atlas.[24] In addition to directly impacting electricity demands for heating and cooling, higher CDDs are associated with an increase in the adoption rate of air conditioners as described by Jaglom.

[20] Maximilian Auffhammer, Patrick Baylis, and Catherine H. Hausman, “Climate Change Is Projected to Have Severe Impacts on the Frequency and Intensity of Peak Electricity Demand across the United States,” *Proceedings of the National Academy of Sciences* 114, no. 8 (February 21, 2017): 1886–91, https://doi.org/10.1073/pnas.1613193114.
[21] Craig et al., “A Review of the Potential Impacts of Climate Change on Bulk Power System Planning and Operations in the United States.”
[22] Wendy S. Jaglom et al., “Assessment of Projected Temperature Impacts from Climate Change on the U.S. Electric Power Sector Using the Integrated Planning Model®,” *Energy Policy* 73 (October 1, 2014): 524–39, https://doi.org/10.1016/j.enpol.2014.04.032.
[23] Kate Larsen et al., “Assessing the Effect of Rising Temperatures: The Cost of Climate Change to the U.S. Power Sector,” *Rhodium Group* (blog), January 19, 2017, https://rhg.com/research/assessing-the-effect-of-rising-temperatures-the-cost-of-climate-change-to-the-u-s-power-sector/.
[24] “IEA, Global Energy and Climate Model Documentation.”

Applicability to NEMS

NEMS has the capability to account for future changes in weather and climate in energy demand from the residential and commercial sectors. HDDs and CDDs are used as indicators of space heating and space cooling energy service demands in the Residential Demand Module (RDM) and Commercial Demand Module (CDM). As described in a case study below in Section V, we have modified these HDD and CDD assumptions to reflect a climate scenario rather than the historical rolling average values that are customarily used by EIA. The methodology, assumptions, and results are described. While energy demand associated with buildings in the industrial sector in NEMS is linked to projected average energy efficiencies from the commercial sector, the effects of changing HDD and CDD are not included. This energy use is relatively small, but for completeness these temperature effects should be included here as well.

In the longer run, the HDD and CDD relationships to demand could be re-examined to determine their accuracy using historical data. If necessary, these relationships could be modified or other climate data introduced as HDD and CDD are rather blunt metrics for determining heating and cooling requirements. Extreme temperatures and their frequency, higher minimum temperatures, as well as levels of humidity may also play an important role. The use of other variables would need to be coordinated with availability of projections from climate models.

B. Power Sector Model

1. Overview of the Electricity Market Module in NEMS

There are two primary modules within the NEMS Electricity Market Module (EMM): the electricity capacity planning module (ECP) and the dispatch module (EFD). Both are solved using optimization techniques and minimize the cost of providing electricity subject to fuel costs provided by NEMS supply models, electricity demand provided by the NEMS demand models, and a number of constraints in the EMM such as existing capacity, operating constraints, and environmental requirements for air emissions. The ECP looks out over a 30-year time horizon and makes decisions about plant retirements, retrofits, and capacity additions. The EFD then dispatches the plants that are available each year to meet load requirements in each of 25 EMM regions organized around North American Electric Reliability Corporation (NERC) regions, see Figure A- 1 the Appendix for map of EMM regions. Electricity demand in each year is represented by nine time slices that comprise three levels of demand within three seasons. In addition to meeting annual electricity demand, the ECP also must satisfy region-specific capacity reserve margins, and both models contain operating reserve requirements which are particularly important in regions and scenarios with a significant share of variable renewable generation (such as solar and wind).

Annual energy demands as projected by each of the residential, commercial, and industrial demand models are passed to the EMM. Using load shapes specific to end uses, the annual loads are used to create 864 representative hours of load (24 hours for 12 months for three day types). As end-use demands change over time at different rates, the system load shapes in each region will change and will generally become peakier with more cooling. In addition to being aggregated into the nine time periods for the ECP and EFD, this greater temporal resolution is used by the REStore Submodule to resolve the value of storage and variable renewable generation.

2. Thermal Power Plant Capacity Ratings, Availability, and Efficiencies

Climate Impacts

The primary climate impact on thermal (fossil-fired and nuclear) power plants are high ambient temperatures that decrease their efficiency and capacity. High temperatures are likely to occur at the same time as an increased electricity demand for cooling, thus creating stress on the electricity grid. Increases in frequency and extremity of weather events that can occur at any time of year, as well as increased fire risks, could also impact grid reliability although these types of events are more difficult to represent in long-term energy system models, such as NEMS.

Relevant Literature and Findings

The relationships of higher temperatures to capacity losses and decreased efficiencies were examined by Ke et al. on an hourly basis in a study of the potential impact of heat waves on power grid operation.[25] The study developed and applied a production cost and unit commitment model combined with hourly temperature data. Engineering formulas were used to relate changes in capacity and efficiency with temperatures for turbines and combined cycles. A case study to demonstrate the model and potential impacts made a simple assumption of temperature increases for a heat wave in July across the Eastern Interconnect.

The same approach is not feasible for NEMS in that it, like most energy models that extend to the year 2050, has a fairly aggregate annual temporal resolution, but the concepts could be applied. Jaglom et al. used temperature-performance relationships available from manufactures and those published in EPRI's 1993 TAG along with unit level regressions to modify net dependable capacity and average heat rates of combined cycle and simple cycle gas turbines in IPM based on plant locations and projected change in average summer temperatures in climate scenarios relative to an historical average (1990 to 2010).[26] The paper authors acknowledged that changes in water temperatures for cooling were not considered.

[25] Xinda Ke et al., "Quantifying Impacts of Heat Waves on Power Grid Operation," *Applied Energy* 183 (December 1, 2016): 504–12, https://doi.org/10.1016/j.apenergy.2016.08.188.

[26] Jaglom et al., "Assessment of Projected Temperature Impacts from Climate Change on the U.S. Electric Power Sector Using the Integrated Planning Model®."

Relying on the Jaglom et al. study and an early study from ICF (1995), the NREL 2018 ReEDS model assumed a temperature penalty that increases thermal power plant heat rates by 0.1% to 0.2% and reduces available capacity by 0.5% to 0.75% per 1°C increase during summertime time slices, with other time periods unaffected.[27] Cooling system performance, and hence water intake, is also assumed to be affected by warmer water temperatures presumed to be associated with higher ambient temperatures. However, there does not appear to be any assumption of increased outages caused by higher water temperatures in the model.

Other studies explicitly consider how water availability and temperature, along with ambient air temperature, could impact thermal plants. Petrakopoulou et al. utilized commercial software used for the design and simulation of thermodynamic processes to estimate the effect of higher ambient and water temperatures on capacities and efficiencies, as well as water use, for natural gas combined-cycle and coal power plants using recirculating and once-through cooling systems.[28] VanVliet et al. used a hydrological water temperature model together with global climate model (GCM) outputs to estimate changes in daily water temperature and water flows.[29] These were used to estimate the usable capacity of individual thermoelectric power plants using plant-specific data of cooling system, efficiency, and environmental restrictions.

Applicability to NEMS

NEMS currently reflects winter and summer capacities for power plants where summer capacity is lower to reflect higher summertime temperatures. Summer capacity is used for capacity planning purposes. To incorporate the effects of climate change, the summer capacities and heat rates of existing individual power plants could be modified based on their locations. Effects on new power plants could be reflected at the regional level using capital cost multipliers that effectively raise the cost to account for loss of capacity due to weather effects. Current region-specific cost multipliers applied to new gas combustion turbine and combined cycle plants to reflect ambient air temperature, relative humidity, and elevation effects that reduce effective capacity could be modified to change over time and by scenario.

In general, adjustment factors for thermal generator capacities and efficiencies could be estimated from the climate scenarios of interest using engineering relationships to temperature found in the literature, although different researchers have used slightly different methods to apply them to all or individual power plants and applied them at different temporal scales. One consideration is whether capacity effects should reflect changes in average summer

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[27] Jaglom et al.; Cohen et al., "Regional Energy Deployment System (ReEDS) Model Documentation."
[28] Fontina Petrakopoulou, Alexander Robinson, and Marina Olmeda-Delgado, "Impact of Climate Change on Fossil Fuel Power-Plant Efficiency and Water Use," *Journal of Cleaner Production* 273 (November 10, 2020): 122816, https://doi.org/10.1016/j.jclepro.2020.122816.
[29] M. T. H. Van Vliet et al., "Coupled Daily Streamflow and Water Temperature Modelling in Large River Basins," *Hydrology and Earth System Sciences* 16, no. 11 (November 21, 2012): 4303–21, https://doi.org/10.5194/hess-16-4303-2012.

temperatures or changes in extreme temperatures when peak load is likely to occur. The former may underestimate the effect of lower thermal capacity while the latter might overestimate its effect, especially because the future generation mix is likely to have a substantial share of solar power that shifts the timing of net peak. In those circumstances, the reliability of thermal generators at time of net peak becomes more critical than at times of peak load.

Most engineering relationships are based solely on air temperature changes. Including the effect of warmer water temperatures in more complex and requires hydrology modeling.

3. Hydroelectric Generation Potential

Climate Impacts

Climate change can impact the hydropower generation potential through changes in the quantity and timing of precipitation and snowpack levels. The extent of such impacts on generation potential varies between facilities with and without reservoirs and their storage capacity. The impact is expected to vary significantly between and within regions. To account for climate changes while forecasting hydropower capacity, hydrological models and data including historical and projected water fluxes are usually incorporated into the underlying model for power generation, such that water flows are translated into generation given the hydropower facility characteristics (e.g., storage volume/reservoir operation).

Relevant Literature and Findings

Drought and higher temperatures affect the outputs of hydro-electric plants. Both lower inflows and lower reservoir levels mean less water available for power generation and thus degraded water-to-energy conversion factors. In a study by Argonne National Laboratory, drought scenarios were developed for the U.S. Southwest to assess the impacts of drought on the power system including thermal and hydropower capacity loss and reserve margin reductions.[30] A five-year drought period (with defined extent and severity) was assumed with stream flow level variations. The corresponding hydro-thermal capacity loss factors were calculated using Harto and Yan 1st Order Formulas which are used to calculate the reduction in capacity:

Loss of Hydro Gen (MWH) = Ave Annual Hydro Gen (MWH)x (1-HGF)

HGF (Fraction) = Hydro Gen Factor = Drought Flow/Average Flow

Hydrologic data, power plant capacity data, and drought severity data were obtained from multiple sources including USGS and NOAA.

[30] Argonne National Laboratory, “Impacts of Long-Term Drought on Power Systems in the U.S. Southwest.”

A study by the Pacific Northwest National Laboratory (PNNL) evaluated the effects of drought on hydropower generation in the western U.S. (divided into distinct climate regions) by correlating generation capacity to water-year precipitation. They derived statistical models based on historical precipitation and annual hydropower generation data to analyze regional hydropower generation in the 21st century using both current and prior water-year precipitation inputs.[31] They found that while individual dams can be severely affected by drought, the overall effect on hydroelectricity output usually is not pronounced because drought does not affect the whole region at the same time. In five of the eight subregions studied, historical annual hydroelectric generation was primarily related to precipitation during the water-year. In other regions, water storage, both in soils upstream and reservoirs, impact generation. Therefore, analyses should include both current and prior year precipitation. Although many models project decreases of U.S. hydroelectric generation with climate change, a U.S. study by Boehlert, et al, projects that hydroelectric generation may increase overall due to increasing river runoff in the Pacific Northwest.[32] This study used a set of linked models including a water resources systems model of over 2,000 river basins, along with an energy water model and a water runoff model that used projected temperature and precipitation from General Circulation Models.

Another example is VanVliet et al. which implemented global gridded projections of streamflow and water temperature with three different global hydrological models (GHMs).[33] GHMs were forced with outputs of GCMs for both lowest and highest representative concentration pathways (RCP2.6 and RCP8.5). The ensembles of streamflow and water temperature projections from the GHMs under climate change for the period of 1950-2099 were then used to quantify the impacts on hydropower potential and cooling water discharge capacity of rivers worldwide and to identify locations with largest declines in both hydropower potential and cooling water discharge capacity due to projected declines in mean annual streamflow combined with strong increases in water temperature. The authors claimed that their projections of long-term future changes in hydropower potential and cooling water discharge capacity could serve as physical boundary conditions for large-scale planning of future power plant sites and technologies, when combined with energy models (e.g., multi-model assessment of global hydropower and cooling water discharge potential under climate change).

The IEA 2023 GEC Model includes a detailed representation of reservoir and pumped storage hydro in addition to run-of-river hydro generation.[34] Assumptions regarding run-of-river hydro

[31] Sean Turner et al., "Drought Impacts on Hydroelectric Power Generation in the Western United States: A Multiregional Analysis of 21st Century Hydropower Generation" (U.S. Department of Energy, September 2022).
[32] Brent Boehlert et al., "Climate Change Impacts and Greenhouse Gas Mitigation Effects on U.S. Hydropower Generation," *Applied Energy* 183 (December 1, 2016): 1511–19, https://doi.org/10.1016/j.apenergy.2016.09.054.
[33] Michelle T. H. van Vliet et al., "Power-Generation System Vulnerability and Adaptation to Changes in Climate and Water Resources," *Nature Climate Change* 6, no. 4 (April 2016): 375–80, https://doi.org/10.1038/nclimate2903.
[34] "IEA, Global Energy and Climate Model Documentation."

electricity production potential and inflow profiles for reservoir hydro were generated using the Atlite open-source Python library based on Hoffman.[35]

Applicability to NEMS

There is currently no distinction between run-of-river or reservoir sources for hydroelectric plants in NEMS. The model characterizes each hydroelectric plant by a capacity rating and monthly average capacity factors which implicitly assume there is enough water available in reservoirs and stream flows to maintain generation at recent historical levels. There is a set of annual adjustment factors by EMM region that can be used to modify outputs for future years as well as historical. These factors are primarily used to match recent hydroelectric generation and could be modified to vary by season and by EMM region. Because the impact of drought on water flows will affect run-of-river plants differently than plants that rely on a reservoir, the distinction of hydro plant type could be introduced, but coordinating dispatch among hydro facilities in the same river system is more complex than is appropriate for an energy module such as NEMS.

4. Solar and Wind Technical Potential

Climate Impacts

Solar and wind power generation are intrinsically dependent on weather-related phenomenon. Changes in solar irradiance, wind speeds and patterns, temperatures, and other factor caused by climate change could have a meaningful impact as power grids become more reliant on these technologies in order to reduce emissions and climate change.

Relevant Literature and Findings

Gernaat et al. examined how climate change will affect the technical potential for renewable energy sources including wind and solar.[36] Climate change was characterized by using climate projections from four GCMs. The data taken from the GCMs pertained to solar irradiance, temperature, wind speed, and runoff. Sugarcane and maize yields were also used for estimating bioenergy potential. The projections for each model are produced using RCPs 2.6 and RCPs 6.0 from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). The pathways represent different levels of climate change over the 21st century. With the data gathered, economic information was added to produce cost-supply curves that are applied in the Integrated Model to Assess the Global Environment (IMAGE) to assess impacts on renewable generation.

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[35] Fabian Hofmann et al., "Atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series," *Journal of Open Source Software* 6, no. 62 (June 24, 2021): 3294, https://doi.org/10.21105/joss.03294.

[36] David E. H. J. Gernaat et al., "Climate Change Impacts on Renewable Energy Supply," *Nature Climate Change* 11, no. 2 (February 2021): 119–25, https://doi.org/10.1038/s41558-020-00949-9.

Tobin et al. investigated the effects of climate change on solar, wind, hydro, and thermal existing generating facilities in Europe.[37] Five regional climate model simulations were used from three GCMS and three RCMs with four RCP8.5 and one RCP4.5 scenarios. The variables deemed relevant for the study were wind speed, solar radiation, temperature, precipitation, temperature, summer temperatures, and heat waves. These projections had already been compared to observed historical data in previous studies.

For wind power, climate impacts were assessed by estimating the change in wind production over time at existing wind farms. Projected 10m wind speeds from the scenarios were extrapolated to turbine hub heights, and a standard power curve was applied to project power generation. The results of this determined a reduction in wind power to be less than 5% even at the 3°C level except for countries on the Baltic Sea which were between 5% and 10%.

Solar performance is projected to have a drop similar to that of wind with a reduction of 5-10% except in some southern European countries (Greece, Portugal, Spain, and Cyprus) where there was a smaller than 5% reduction. An explanation for these effects were provided as "the decreases in solar power are due to a decrease in downwelling shortwave radiation, likely linked to the increase of water vapor due to warming." [38] The methodology behind these findings uses a similar method to that of their wind predictions. Three-hour downwelling solar radiation along with near surface air temperature, wind speed, and are used to determine PV power generation potential. The calculations are done in geographically gridded areas and then combined with the installed PV in each cell to produce the final PV power production.

The IEA GEC model assumptions for production profiles for wind and solar PV were generated using the Atlite open-source Python library that contains functions that convert weather data such as wind speeds, solar irradiance, and temperature into renewable specific profiles. Weather data for 30 historical weather years (1987-2016) was obtained from the ERA5 reanalysis dataset of European Centre for Medium-Range Weather Forecasts (ECMWF), which covers the entire globe at 30-km resolution. The GEC model documentation is unclear whether these renewable profiles are altered by scenario to reflect projected climate conditions.

Applicability to NEMS

Solar and wind energy potentials are derived within NEMS using regionally available land for development characterized by level of resource, six levels of solar insolation in the case of solar and four wind quality classes for onshore and offshore wind. These resources are converted into potential generating capacity. In addition, the hourly pattern of potential electricity generation is characterized by average capacity factors by month for 24 hours. The energy resources and capacity factors are estimated using historical data and are assumed to be unchanged over time. However, to include the impacts of climate changes, the relationship of

[37] Tobin et al., "Vulnerabilities and Resilience of European Power Generation to 1.5 °C, 2 °C and 3 °C Warming."
[38] Tobin et al.

solar and wind capacity and generation potential to land area and the pattern of output throughout the year may need to be modified. The hourly generation potentials input tables are flexibly defined so the mechanics of adjusting them over time would be relatively simple. The bigger challenge is determining whether and how the daily pattern of generation would be affected by climate change as projected by climate models.

The recommended approach is to use Tobin's methodology to estimate wind and solar potential focusing on *changes* in wind speeds and solar radiation that occur in climate scenarios and hence *changes* in MW potentials that can be applied to NEMS and also be used to shift the timing of regional wind and solar generation potential. The impacts may be very location specific, so careful mapping will need to be conducted between the climate models and the EMM regions. Further investigation into the alite tool used by IEA may also be warranted.

5. Transmission Capacity and Line Losses

Climate Impacts

High temperatures are the climate impact most likely to adversely impact transmission and distribution, although wildfires, high winds, floods, ice storms and other extreme weather could also inflict damage.

Relevant Literature and Findings

Not many modelers have incorporated these effects. ORNL provides a summary of potential impacts along with quantification methods for many elements with a propensity of danger to each system based on each effect.[39] The main impact for our project is the effect of raised ambient air temperature with its direct relation to climate change. The study reports that "power output decreases 0.7% to 1% per 1°C increase in air temperature, above a reference temperature (usually taken to be 20°C)." Besides the decrease in power output due to increased temperatures, the longevity of transformers can be reduced by higher ambient temperatures. Also, very high temperatures in combination with associated increases in load can lead to catastrophic transformer failures.

The capacity of transmission lines is impacted by their temperature which in turn is a function of ambient temperature and wind speed. The risk of higher temperatures leading to sagging lines that could pose a safety risk can lead to the system operator reducing line capacity in those conditions. A CEC study estimated that at temperatures over 100°F, capacity is roughly 7-8% below design capacity. Transmission and distribution line losses rates are also impacted by high temperatures as line resistance increases. However, this effect is relatively small.

[39] Melissa Dumas, Binita Kc, and Colin I. Cunliff, "Extreme Weather and Climate Vulnerabilities of the Electric Grid: A Summary of Environmental Sensitivity Quantification Methods" (Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), August 1, 2019), https://doi.org/10.2172/1558514.

Other climate effects such as high winds, flooding, and increased wildfires can lead to greater transmission failures. Fragility curves are used to relate these weather events and outages.

In the 2018 version of the ReEDS model, NREL assumed higher temperatures reduce transmission capacity in the summer afternoon time slices by 0.55% reduction in transmission capacity per 1°C increase. No derivation is provided in the documentation for this assumption. The 2020 version does not have climate impacts included but NREL indicated they intend to include them again in later versions.

Bartos et al. also investigated the effects of climate change and temperature increases on the transmission of electricity. They developed thermal models of conductors to estimate reductions in rated ampacity of transmission lines due to higher temperatures. In general, higher voltage lines are more impacted than lower voltage lines because they are usually thicker and thus dissipate less heat. The Homeland Security Infrastructure Program (HSIP) database was the source of transmission line "locations, geometrics, and voltage classes" and manufacturer data was used for cable specifications.[40] Future maximum daily temperatures were downscaled from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble of GCMs, and three RCP scenarios (RCP2.6, 4.5 and 8.5) were analyzed. Across the study, the ambient temperature increases lead to reduced ampacity between 1.9%-5.8% based on the RCP. At the same time, peak summertime loads are projected to increase with a range of 4.2%-15% by 2050.

Applicability to NEMS

The current regional configuration of the EMM is 25 regions that are roughly aligned with Regional Transmission Organization (RTOs) or Independent System Operators (ISOs) as illustrated by Figure A-1 in the Appendix. Transmission is explicitly represented for power flows between EMM regions but is only implicitly represented within regions. Maximum capacity flows between regions are specified for winter and summer seasons for current transmission capacity based on historical data. That capacity can also be augmented by transmission built within the projection period. Only 75% of new transmission capacity additions can be counted in fulfilling a neighboring region's generation capacity requirements, rather than just energy, and as a result more transmission capacity will be built in those circumstances. This extra transmission capacity is to reflect the potential for outages.

Climate impacts could be represented for existing power lines by decreasing the summer transmission capacity between select regions over time. For new transmission capacity, the cost could be increased to reflect the anticipation of greater outages, or the 75% dependable

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[40] Matthew Bartos et al., "Impacts of Rising Air Temperatures on Electric Transmission Ampacity and Peak Electricity Load in the United States," *Environmental Research Letters* 11, no. 11 (November 2016): 114008, https://doi.org/10.1088/1748-9326/11/11/114008.

capacity ratio could be reduced. The reductions can be computed from climate scenarios by adopting the relationship of capacity vs. temperature from ReEDS or other studies. It does not appear to be necessary or worth starting from engineering first principles to develop a new methodology.

6. Planning and Operating Reserve Requirements

Increased weather uncertainty and rapid swings in temperatures create greater uncertainty in peak loads and generating capacity performance, so higher planning and operating reserve margins may be necessary to ensure reliable capacity. In NEMS, target planning reserve margins are specified by EMM region based on margins established by NERC and ISOs or inferred from historical experience. These in turn are often computed using probabilistic estimates of load loss with targets of no more than 1 outage in 10 years. New reserve targets could be estimated external to NEMS using a probabilistic model with assumptions of wider distributions of loads and power plant outage rates. This analysis would be conducted after examining how power plant outputs are affected by climate change by scenario.
Operating reserve requirements in the EMM are determined based on the variability of loads and the share of variable renewable generation. The variability is determined based on projected loads by time slice on a seasonal basis and will adjust endogenously, so no further adjustments are likely necessary.

C. Agriculture and Forestry Biomass Supplies

Climate Impacts

Several forms of biomass are represented as sources of energy within NEMS. Cellulosic biomass in the forms of agricultural energy crops and residues, forestry materials, and urban wood waste can be used for power generation and biofuel production. Food crops, such as corn and soy oil, are also used to produce biofuels. Most of these sources could be impacted by climate change causing higher temperatures, more frequent flooding and droughts in some areas, as well as by higher concentrations of CO_2.

Relevant Literature and Findings

European researchers have used the dynamic global vegetation model LPJmL to assess potential climate impacts on crop yields and potential bioenergy. Haberl et al. used three emissions scenarios from five GCMs to create 15 scenarios in which changes in monthly mean temperature and precipitation were used to estimate changes in agricultural yields.[41] The

[41] Helmut Haberl et al., "Global Bioenergy Potentials from Agricultural Land in 2050: Sensitivity to Climate Change, Diets and Yields," *Biomass and Bioenergy*, Land use impacts of bioenergy. Selected papers from the IEA Bioenergy Task 38 Meetings in Helsinki, 2009 and Brussels, 2010, 35, no. 12 (December 1, 2011): 4753–69, https://doi.org/10.1016/j.biombioe.2011.04.035.

scenarios in LPJmL were run both with and without higher CO_2 concentrations to examine the uncertainty associated with CO_2 fertilization. With full CO_2 fertilization assumed, crop yields increased in all of the 11 global regions while yields declined considerably in most regions without the fertilization effect turned on. Using the same LPJmL, Zapata et al. also found a positive increase for biomass potential due to the CO_2 fertilization effect.[42]

Applicability to NEMS

NEMS represents agricultural and food crop supplies using the Policy Analysis Systems Model (POLYSYS), which was developed at the University of Tennessee and Oak Ridge National Laboratory (ORNL) for projecting land-use changes. POLYSYS is a partial equilibrium model of the U.S. agricultural sector, capable of estimating the competitive allocation of agricultural land between food crops for humans and livestock, pasture for grazing, energy crops, and the crop prices associated with changes in yield and management practices. A reduced version of POLYSYS runs within NEMS to produce endogenous biomass supply curves for agriculture residues and energy crops. A new version of POLYSYS is anticipated to be released along with a new ORNL report on biomass resources in the Fall of 2023, and climate change impacts may be addressed.[43]

From simplest to most complex, options for representing climate impacts in NEMS include adjusting the biomass supply curves created by POLYSYS before use within NEMS, setting up alternative assumptions in POLYSYS to reflect climate scenarios, or adopting an alternative land-use model that more explicitly represents climate effects. The first step will be to assess the new version of POLYSYS as well as other land use models that could be used to estimate biomass supplies under different climate conditions.

V. Case Study: Heating and Cooling Degree Days Adjustment for Climate Scenarios

As a case study for incorporating climate impacts into energy sector modeling, we analyzed the energy system impact of modifying heating and cooling degree days (HDD and CDD) inputs from key climate scenarios. The general procedure for estimating the HDD and CDD data for U.S. census regions is presented below, followed by analysis of the modeling results. The reference case used in this case study is was developed for NRDC using a customized version of NEMS, called NRDC-NEMS, that is a modification of the AEO 2022 version of NEMS. The primary modifications include inclusion of the Inflation Reduction Act (IRA) energy-related provisions, alternative technology costs in the power, transportation, and industrial sectors. For this analysis, the most relevant projection differences from the AEO 2022 reference case are higher

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[42] Victhalia Zapata et al., "Climate Change Impacts on the Energy System: A Model Comparison," *Environmental Research Letters* 17, no. 3 (March 1, 2022): 034036, https://doi.org/10.1088/1748-9326/ac5141.
[43] "2023 Billion-Ton Report, in Preparation."

deployment of renewable generation in response to IRA tax credits, lower technology costs and higher electricity demand due to greater adoption of electric vehicles.

First, HDD and CDD data for all U.S. counties are obtained from the National Oceanic and Atmospheric Administration (NOAA) from their online Climate Explorer website.[44] NOAA's climate data are generated by global climate models for the Coupled Model Intercomparison Project Phase 5 (CMIP5) which were then statistically downscaled using the Localized Constructed Analogs (LOCA) method for the U.S.[45] For each county, data is available for two possible futures: RCP4.5, labeled as lower emission, and RCP8.5 labeled as higher emissions (note that although RCP4.5 is labeled as lower emission case in NOAA, generally it is considered as an intermediate scenario for emission reduction based on the IPCC reports). Second, average HDD and CCD for each state are computed using the county level data weighted by their proportional population within that state (the ratio of the county population to the total population of the state) in 2022. Third, the state-level data are aggregated further to obtain HDD and CDD averaged for census divisions. Following the method used in the AEO, the regional weighted averages are computed using state level population projections,[46] rather than a static historical year, so that the regional HDD and CDD reflect anticipated shifts in population in addition to changing climate.

In contrast, rather than using climate projections, future HDD and CDD in the AEO, and hence NRDC-NEMS, are estimated based on 30-year linear trends of historical HDDs and CDDs using state-level degree day data from the NOAA with the same trend continued into the future. The degree days are population-weighted from the state to the census-division level.[47] One should note that the use of rolling average HDD and CDD data implicitly assumes that any past warming will continue into the future and therefore the AEO22 reference data should not be considered as a "no climate change" case, although it is not directly derived from any particular climate scenario.

We found a disconnect between the historical years for the HDD and CDD data estimated based on the NOAA county-level data in this work and NRDC-NEMS reference data which exists most likely due to different historical data sources, as NOAA database uses simulated history for 2005-2023. To resolve this issue, we compare a 10-year average of the modeled history for the RCP scenarios to the same 10-year period of NEMS data for each region and then use the difference as a factor to adjust the RCP-based regional data in accordance with the NRDC-NEMS reference data. Figure 2 shows the modified HDD and CDD trajectories estimated for RCP8.5

[44] "Climate Explorer," accessed October 2, 2023, https://crt-climate-explorer.nemac.org/.
[45] "LOCA Statistical Downscaling - LOCA Statistical Downscaling (Localized Constructed Analogs)," accessed October 23, 2023, https://loca.ucsd.edu/.
[46] "National Population Projections | Weldon Cooper Center for Public Service," accessed October 2, 2023, https://demographics.coopercenter.org/national-population-projections/.
[47] U.S. Energy Information Administration (EIA), "Annual Energy Outlook 2022: Alternative Weather Assumptions," June 2022, https://www.eia.gov/outlooks/aeo/IIF_weather/index.php.

and RCP4.5 in this study along with the reference NRDC-NEMS case for an example region (census division four: West North Central).

Figure 2.Estimated HDD and CDD data for census division 4 (West North Central) based on RCP8.5, RCP4.5 scenarios along with the NRDC-NEMS reference (REF) data

Heating and cooling degree days data are used to adjust the heating and cooling energy demands for energy sectors. As an example, effects of degree days data on cooling demands in residential sector is captured by the following equation:

$$CDDFACT_{y,r} = \left(\frac{CDDADJ_{y,r}}{CDDADJ_{baseyr,r}}\right)^{1.5}$$

Where the $CDDFACT_{y,r}$ is the cooling degree day adjustment factor for weather differences between the base year (RECS survey year) and the year under consideration.[48] The $CDDFACT_{y,r}$ is used to adjust Unit Energy Consumption for all equipment classes and building types in each region. Similarly, adjustment factors are defined for heating (with the exponent of 2) in the residential sector as well as for heating and cooling (with exponents of 1.1 and 1.0, respectively) within the commercial sector.

We created an NRDC-NEMS scenario using the RCP8.5 HDD and CDD assumptions and contrast it with our NRDC22-NEMS reference case (REF). Figure 3 and Figure 4 show the electricity and natural gas demands for space heating and cooling by sector. In the residential sector, electricity demand is 11.0% lower for space heating and 10.6% higher for space cooling in RCP8.5 than in the NRDC22-NEMS scenario (REF) in 2050, while natural gas demand is 8.3% lower for space heating. In contrast, electricity demand in the commercial sector is 6.0% lower

[48] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis," accessed October 23, 2023, https://www.eia.gov/consumption/residential/data/2020/.

for space heating and 7.6% higher for space cooling in RCP8.5 in 2050, while natural gas demand is 6.0% lower for space heating.

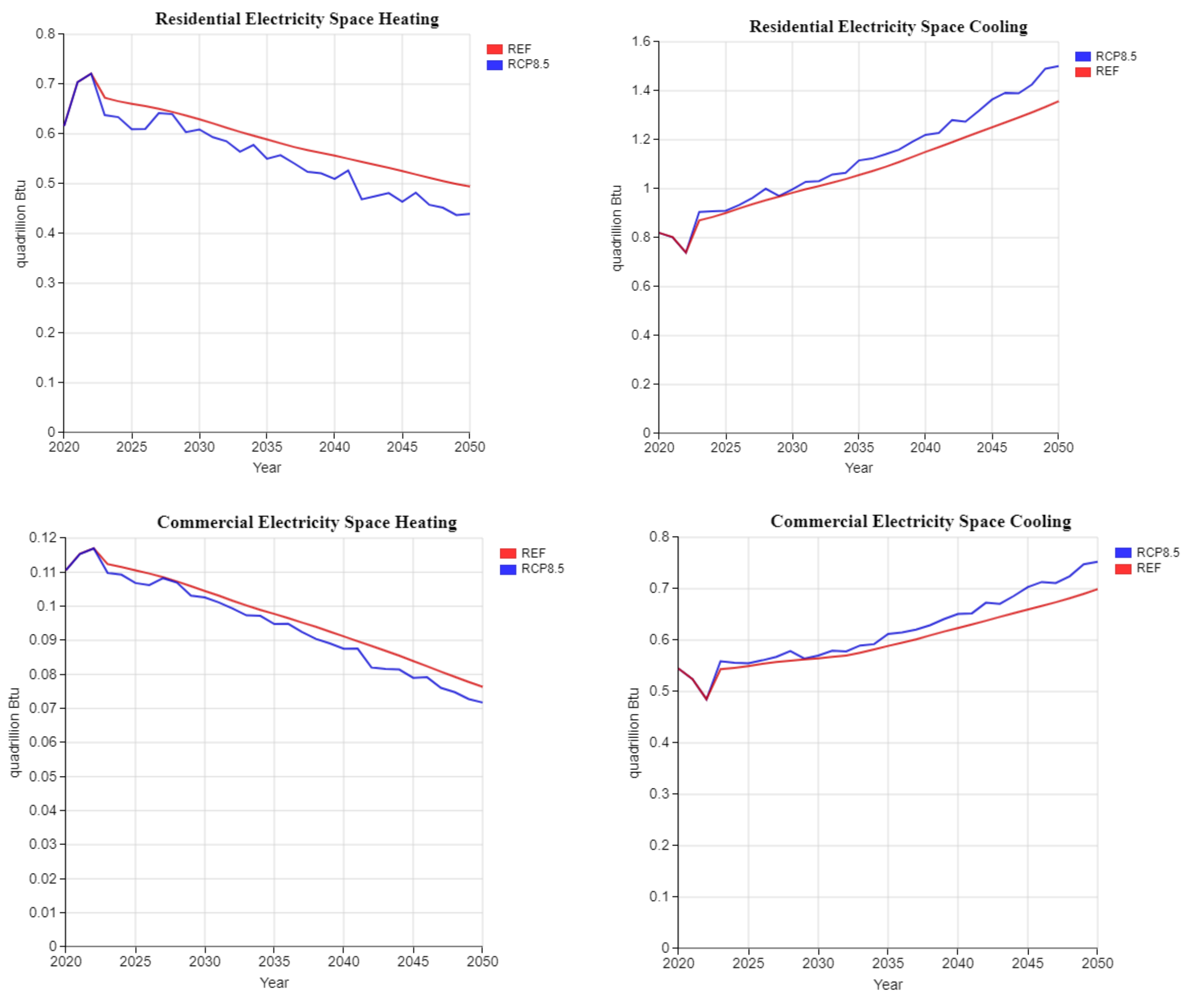


Figure 3. Electricity demand for space heating and cooling for RCP8.5 and NRDC22-NEMS (REF) scenarios in residential and commercial sectors

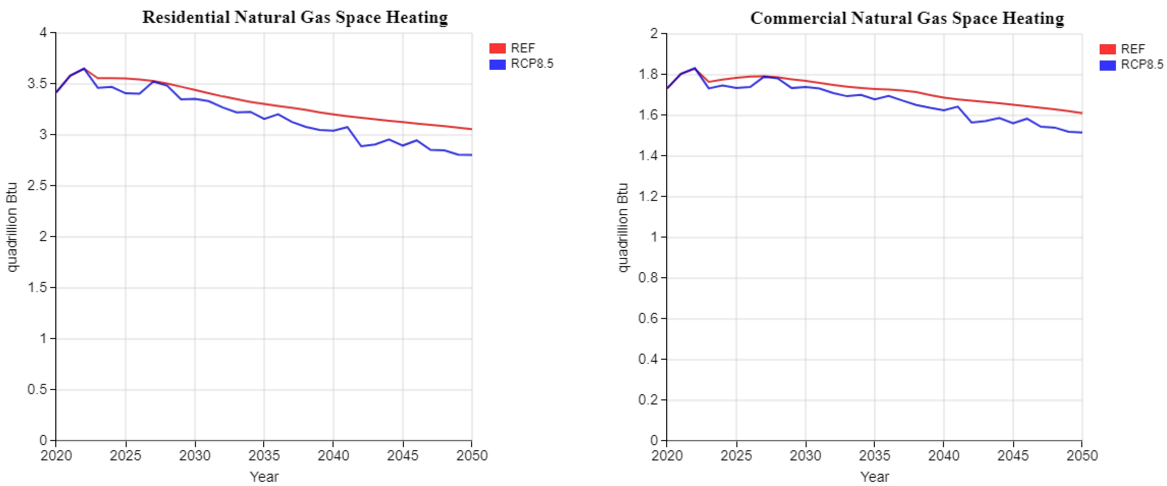


Figure 4. Natural gas demand for space heating for RCP8.5 and NRDC22-NEMS (REF) scenarios in residential and commercial sectors

Figure 5 and Figure 6 show the energy demand by the end-use. For the residential sector, space cooling is 10.5% higher in RCP8.5 than in the NRDC22-NEMS scenario in 2050, while space heating is 8.3% lower. For commercial buildings, space cooling is 7.7% higher in RCP8.5 scenario in 2050, while space heating is 5.7% lower. Although the percentage increase in space cooling is greater than the space heating reduction, the total delivered energy consumption is lower in the RCP8.5 scenario, because cooling energy consumption is a smaller share of total on-site energy use than the heating energy.

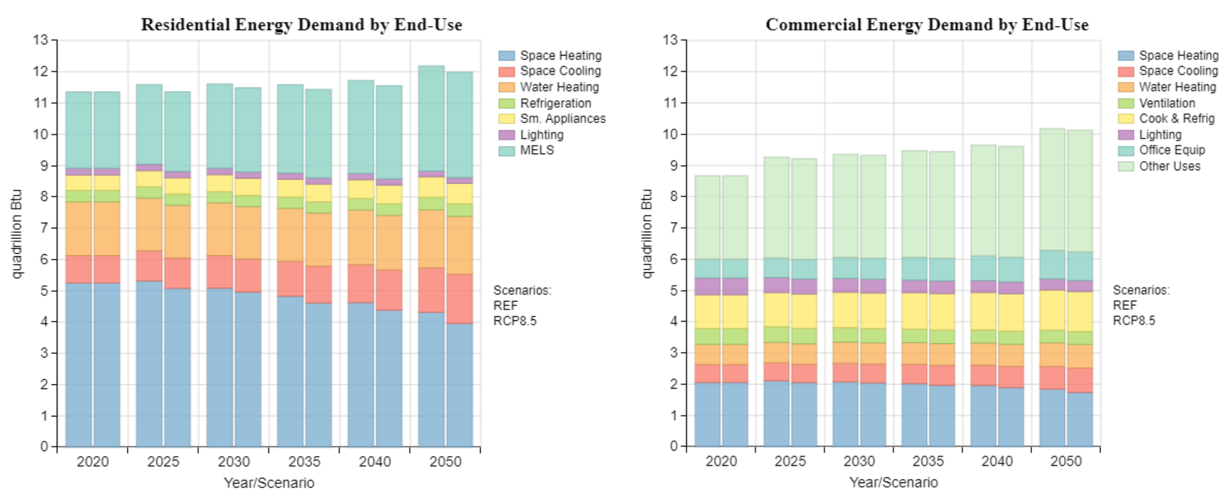


Figure 5. Energy demand by end use in residential and commercial sectors for RCP8.5 and NRDC22-NEMS (REF) scenarios

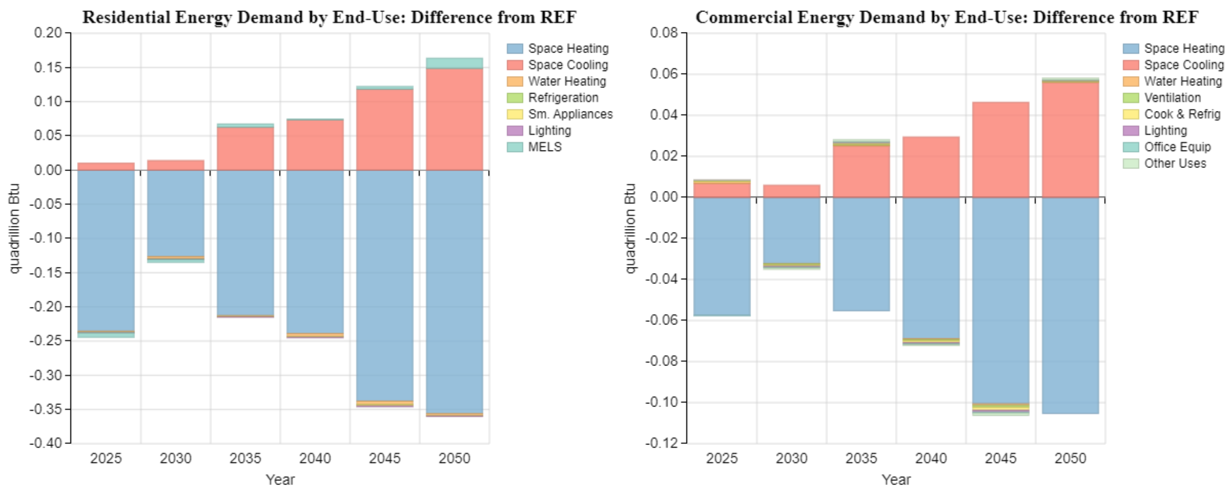


Figure 6. Energy demand by end use in residential and commercial sectors for RCP8.5 scenario as a difference from the NRDC22-NEMS REF scenario; note difference in scale

Figure 7 and Figure 8 show energy demand by the fuel type. For the residential sector, electricity demand is 1.7% higher in RCP8.5 than in the NRDC22-NEMS in 2050, while the natural gas demand is 5.3% lower. In contrast, for the commercial sector, electricity demand is 1.0% higher in RCP8.5 in 2050, while the natural gas demand is 2.5% lower.

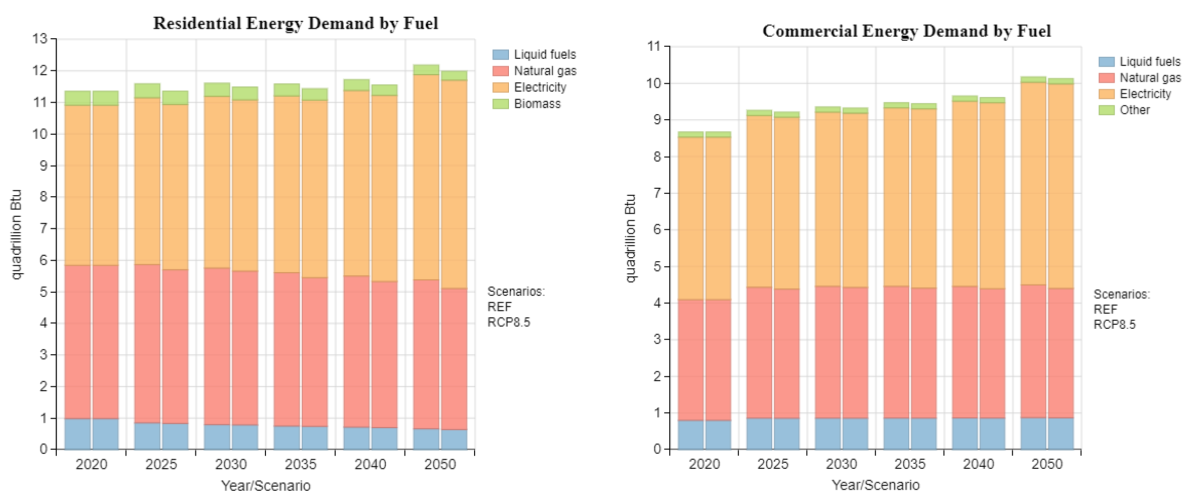
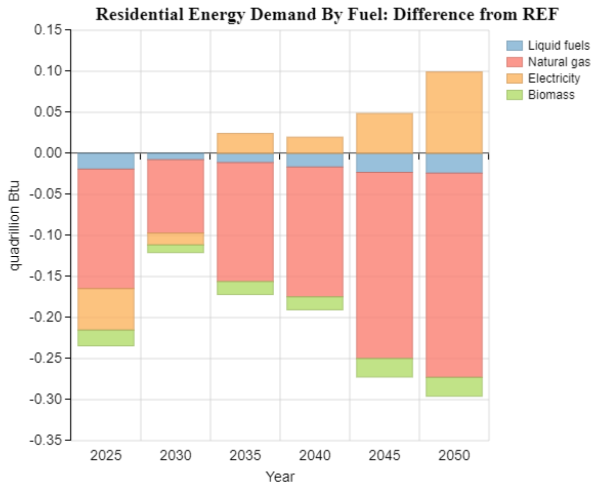


Figure 7. Energy demand by fuel type in residential and commercial sectors for RCP8.5 and NRDC22-NEMS (REF) scenarios



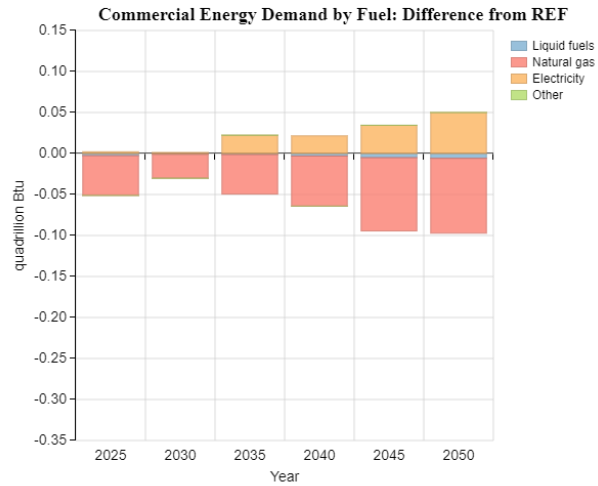


Figure 8. Energy demand by fuel type in residential and commercial sectors for RCP8.5 scenario as a difference from the NRDC22-NEMS REF scenario; note difference in scales

As illustrated, the overall impact of RCP8.5 scenario is relatively modest compared to the NRDC22-NEMS case. In part this is because the reference case already has some climate change implicitly embedded due to the use of rolling average HDD and CDD assumptions. In addition, the results indicate that the residential energy demands are more affected by the RCP8.5 scenario than commercial demands as greater sensitivity to HDD and CDD is assumed through the underlying degree day adjustment factors defined for each sector.

To provide insights on regional variations in total electricity demand, Figure 9 shows the electricity demand for census divisions in 2050, where census division seven (West South Central) shows the highest demand increase (1.4%) in RCP8.5 compared to the NRDC22-NEMS. Total national electricity sales increase of 0.8% in RCP8.5 than in the NRDC22-NEMS in 2050 as the result of higher residential and commercial electricity demands.

Electricity peak demands by electricity region (see map in the Appendix) are shown in Figure 10. The greatest difference in peak demand (in 2050) happens for the Midcontinent/East (MISE), EMM region five where the RCP8.5 has 10.2% higher peak demand compared to the NRDC22-NEMS (REF) scenario. SRCA and NWPP experience decreases in peak demand because these regions have winter peaks by 2050, and heating demands are lower in RCP8.5. NWPP has historically been a winter peaking region. Over time, the peak shifts in SRCA to the winter months due to increasing numbers of electric vehicles (EV) that are charging at night which is coincident with the highest heating demands. If EV charging occurs more during the daytime, then SCRA and NWPP would likely also have summer peaks that increase with climate change. At the same time, the summer peak percent increases due to climate effects might decrease due to the larger share of weather insensitive loads occurring at peak.[49] The national non-coincident peak electricity demand in 2050 is 2.1% higher in RCP8.5 than in REF scenario.

The result found in our case study of relatively small changes in annual electricity demand and higher peak demand impacts is consistent with findings in other studies as described previously.

The increased demands are met primarily by increased generation of gas- and solar-based electricity Figure 11. Because of the relatively small total difference in generation and regional variations, there are not very clear technology trends in the change in generation mix. In 2050, total capacity is 33 GW (0.9%) higher in RCP8.5, with most of the increase in combustion turbines, gas combined cycles, and PV systems.

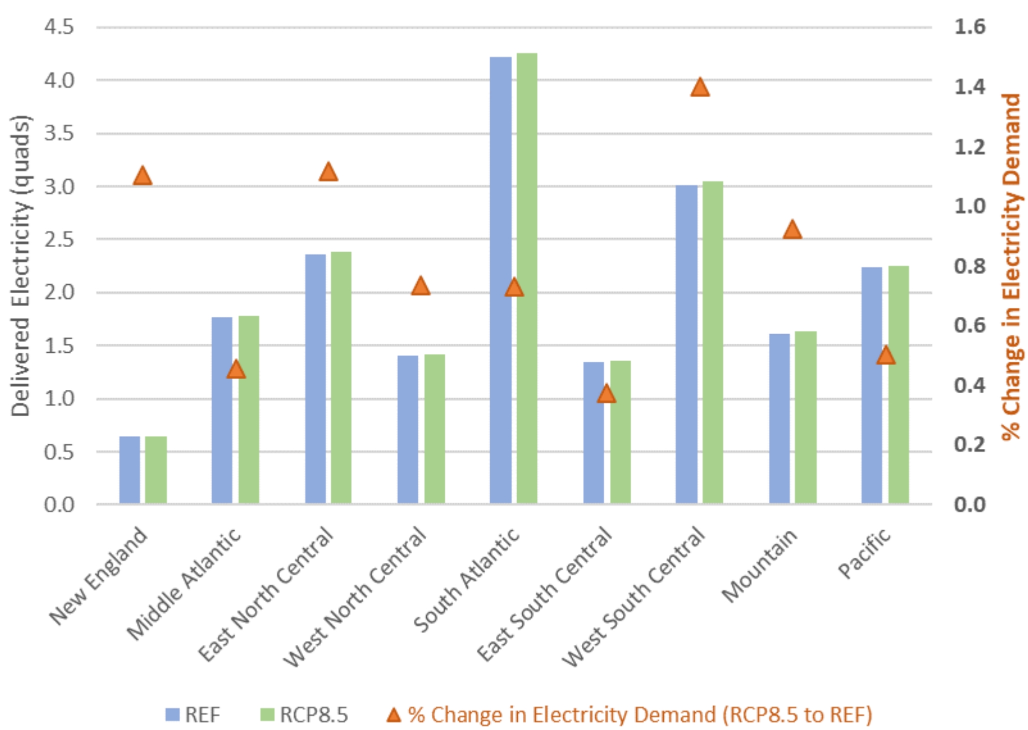


Figure 9. Delivered electricity by census divisions in 2050, for RCP8.5 and NRDC22-NEMS (REF) scenarios

[49] Some studies such as NREL's report, Highly Resolved Projections of Passenger Electric Vehicle Charging Loads for the Contiguous United States, NREL/TP-5400-83916, June 2023, estimate that EV charging patterns will be somewhat temperature sensitive due to heating and air conditioning requirements.

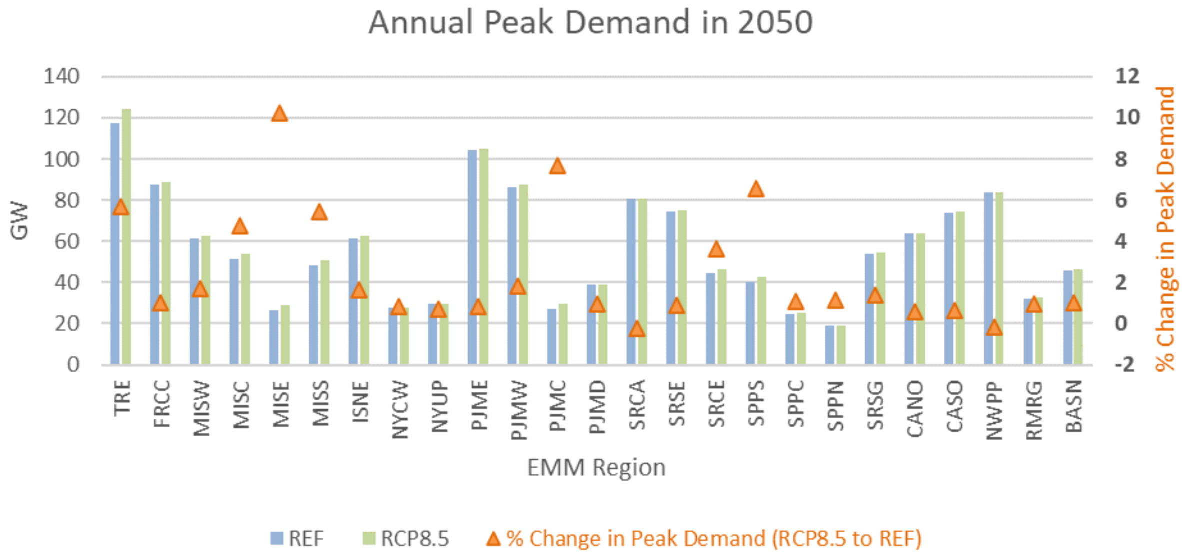
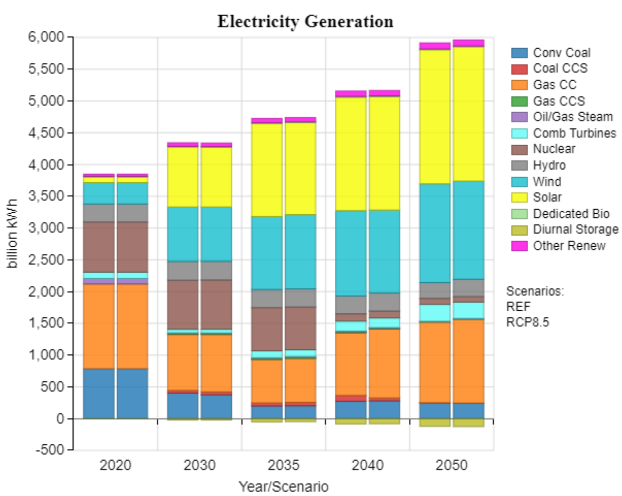


Figure 10. Electricity peak demand for RCP8.5 and NRDC22-NEMS (REF) scenarios across Electricity Market Module (EMM) regions



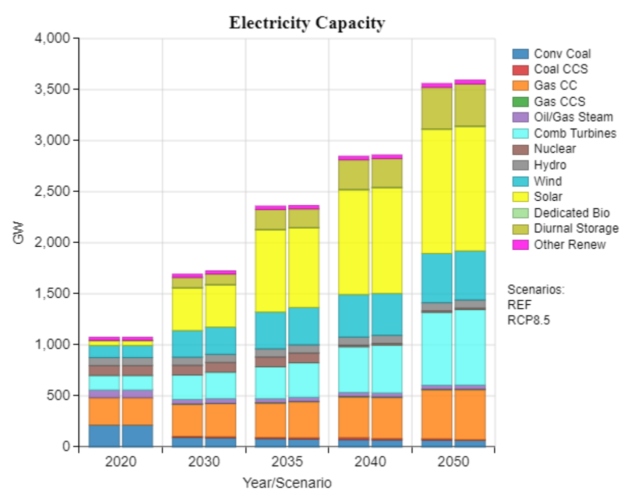


Figure 11. Electricity generation and electricity capacity by sources for RCP8.5 and NRDC22-NEMS (REF) scenarios

Overall, NRDC-NEMS as an integrated model can assess impacts on electricity and other markets though the impact was small in this comparison. For example, primary energy consumption is 0.8% and 0.4% lower for RCP8.5 in 2040 and 2050, respectively, compared to the NRDC22-NEMS case. Electricity and natural gas prices are approximately the same between these scenarios. However, under different climate scenarios and with consideration of other climate impacts, effects on the energy system are anticipated to be greater.

VI. Implementation Plan and Timeline

Based on the identified priority energy sectors and critical climate impacts, an implementation and model research plan will be developed including level of effort for each sector. To undertake further development of NRDC-NEMS that more fully incorporates climate impacts and analyze effects on the U.S. energy system, key implementation actions include the following:

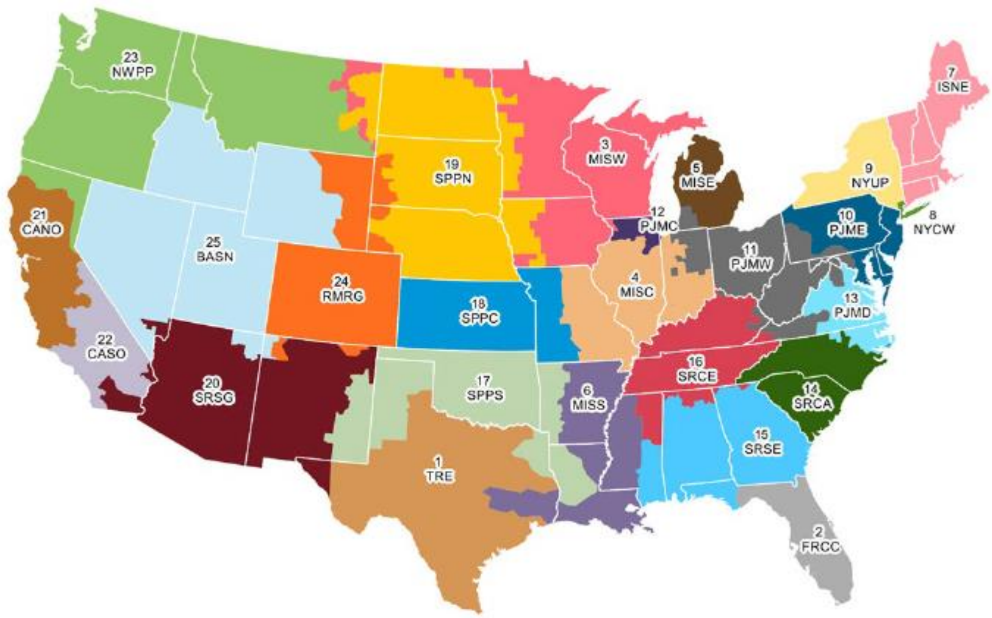
1. Assess output metrics from climate model scenarios that are most applicable to the climate impact (such as number of days with temperature exceeding some value, heating and cooling degree days, average precipitation per time period, etc.);
2. Translate climate model output into NRDC-NEMS input assumptions at appropriate regional and temporal scale; this may involve hydrological or land use modeling;
3. Develop the relationship between climate metric parameters and energy impact;
4. Enhance NRDC-NEMS to accommodate representation of impacts;
5. Implement a variety of model runs with NRDC-NEMS including a new Reference Case and two to three mitigation cases, e.g., Net-Zero GHG by 2050;
6. Compare the model runs between the enhanced NRDC-NEMS and previous version;
7. Make any needed model changes based on comparisons of results;
8. Finalize enhancements to NRDC-NEMS and new model documentation; and
9. Write and publish a paper suitable for publication in a peer-reviewed journal demonstrating the new model and analysis (could also consider writing a joint NRDC and OnLocation white paper for distribution).

In terms of timeline for implementation, the entire effort is estimated to take about one year with the following breakdown:

Actions 1-4:	4 to 7 months
Actions 5-8:	3 to 4 months
Action 9:	1 to 2 months

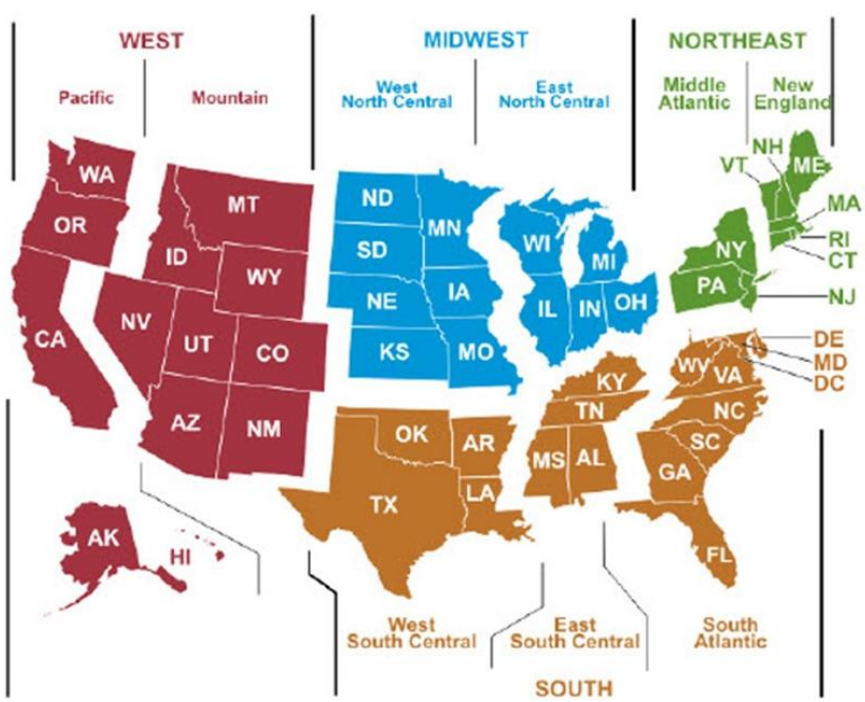
Some of the implementation actions could be done concurrently to reduce the overall timeline. Funding and staff resources will influence the schedule.

VIII. Appendix



Source: U.S. Energy Information Administration

Figure A- 1. Electricity Market Module (EMM) Regions



Source: U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau

Figure A- 2. U.S. Census Divisions Used by NEMS Demand Modules