Nodal Capacity Expansion Modeling with ReEDS: A Case Study of the RTS-GMLC Test System

Akash Karmakar and Wesley Cole

National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
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List of Acronyms

AC	Alternating Current
BA	Balancing Area
CCS	Carbon Capture and Sequestration
CEM	Capacity Expansion Model
CT	Combustion Turbine
GW	Gigawatt
HVDC	High-voltage Direct Current
IPM	Integrated Planning Model
LP	Linear Programming
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Council
PV	Photovoltaic
ReEDS	Regional Energy Deployment System
reV	Renewable Energy Potential tool
RTS-GMLC	Reliability Test System Grid Modernization Lab Consortium
UPV	Utility-scale Photovoltaic

Abstract

Test systems play an important role in power systems analysis and are used extensively for a range of purposes such as performing reliability analysis, modeling production costs, and studying the impacts of load shifting. These test systems have continued to evolve over the years to keep pace with changing system compositions because of technology and policy changes. In this work, we apply the Regional Energy Deployment System (ReEDS) model, a large-scale capacity expansion model (CEM), on the nodal Reliability Test System–Grid Modernization Laboratory Consortium (RTS-GMLC) system to perform capacity expansion of the bus-level test system. This work demonstrates that a national-scale CEM like ReEDS can successfully be applied to nodal systems and that the CEM can allow a test system to be evolved to meet desired criteria. The process allowed the coupling of CEM data not available in the test system (such as capital costs) with test system data to provide plausible system evolutions consistent with scenario specifications.

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1 Introduction

Standardized test systems were developed as a reference for power systems modeling to experiment and compare the results of different power systems evaluation techniques (Grigg et al. 1999). Bulk power system studies have frequently relied on smaller test systems that reflect the characteristics of a real-world power system and are enhanced enough to capture details relevant to aspects of the power system under study. Over the decades, these test systems have had to be upgraded and adapted as focus areas of research in power systems changed. One such system is the Reliability Test System (RTS) (Grigg et al. 1999), (Barrows et al. 2020) . Over the years, this RTS-96 was used for several studies on topics such as the management of intrazonal transmission congestion using reserves (Lyon, Hedman, and Zhang 2014), reliability study of integrated power-gas systems (Zeng et al. 2020), and optimization of the steady-state stability of a grid using communication networks (Pavlovski et al. 2017).

In 2019, a further update led to the system being referred to as the RTS–Grid Modernization Laboratory Consortium (GMLC) (Barrows et al. 2020). This 73-bus test system was enhanced with an updated generation mix and a few additional transmission constraints. It has subsequently been used for studies such as transmission grid resiliency using an investment decision optimization model (Garifi et al. 2022), transmission expansion decisions using stochastic optimization (Sigler et al. 2020), and using demand-responsive loads to resolve unit commitment issues (Sigler et al. 2022).

Capacity expansion models (CEMs) are tools for long-term power systems planning. They can help identify cost-optimal generation mixtures while considering various policies and other regulations, fluctuations in fuel prices, changes in electricity demand, and technological advancements. Here we focus on large-scale CEMs, which are national or continental in their geographic scope. These include the National Energy Modeling System (NEMS) (Nalley 2018)—developed by the U.S. Energy Information Administration to forecast energy production and consumption along with prices in the United States—and the Integrated Planning Model (IPM) (U.S Environmental Protection Agency 2021), developed by the U.S. Environmental Protection Agency to analyze air pollution strategies and their costs. For this work, we use the Regional Energy Deployment System (ReEDS) model (Ho et al. 2021), developed by the National Renewable Energy Laboratory, to simulate the evolution of the bulk power system—generation and transmission—from the present day to 2050 or beyond.

The ReEDS model has been used extensively to project the evolution of the U.S. electricity system under a variety of conditions. However, in many cases, there is a need to study systems at greater spatial and operational detail (Xu et al. 2020). As a result, modelers have had to either modify test systems according to their requirements or build their own capacity expansion models. Because of the customizations involved, maintaining the test system becomes difficult, so different modelers must go through this process of adaptation each time a different application needs to be tested or a study performed. To avoid this, we have developed the capability to adapt the ReEDS model, which typically is used to represent the full U.S. power system using 134 model zones or balancing areas, to a nodal test system. Because ReEDS is actively maintained and includes all the data needed for capacity expansion—such as current policy, technology costs, and financing data—applying it to a test system can enable the evolution of the test system to one with different generation mixtures consistent with projected costs and policy information.

One of the outcomes of adapting a CEM such as ReEDS to work with a nodal test system is that it allows the creation of alternative systems using a narrative relevant for a system which in turn allows for a more comprehensive analysis of a desired region. For example, if a test system with high wind or full decarbonization is preferred in the generation mix, such a system can be created by running the CEM and letting it evolve the original test system as desired. The resultant new system can then be used for production cost or power flow studies.

This report demonstrates the capability of the ReEDS model to work with more granular systems such as the RTS-GMLC test system. In doing so, we make several simplifying assumptions because the test system selected is not intended to represent a real system.

Section 2 describes the RTS-GMLC test system and the ReEDS model and the adaptations that were required to run a nodal system in ReEDS. Section III discusses results in the form of sample generation mixtures produced by the CEM. Section IV draws some conclusions based on this effort and provides recommendations for future work.

2 System, Model, and Methods

2.1 RTS-GMLC system

Introduced first by IEEE in its original form, the Reliability Test System was one of many test systems to help the engineering community with bulk power system reliability studies—beginning with RTS-79, which was developed and published in 1979 to conduct generation and transmission outage-related analysis of a power system [1]. A significant update was made to the RTS in 1996 with the release of RTS-96, which linked three individual RTS-79 systems to achieve three regions to enhance the capability to analyze interregional or multi-area power systems. With the advent of greater computing power in the industry at the time, there was an interest in studying power transactions between different regions. To do this more accurately, the update added operational costs and constraints of the generating units—such as net plant incremental heat rates, unit startup, cycling restrictions, ramping rates, and unit emissions. The update also added some newer transmission technologies such as a phase shifter, a two-terminal DC transmission line, and five inter-area AC ties.

In 2019, the RTS-GMLC model was developed as a result of several updates to RTS-96 to enable the model to help study and understand challenges associated with modern power systems in terms of variable and uncertain generation fleet, flexibility of dispatch in terms of unit commitment and economic dispatch given the uncertain nature of the generation fleet, and reliability of the overall system. With the growth of renewable technologies and low-cost natural gas, coal and oil generators were being replaced, and so it became evident that test systems would also have to evolve to represent this shift so that bulk power system operations could be accurately examined. To emulate some transmission constraints (because RTS-96 does not have any), the GMLC update adopted changes suggested by Hedman et al. (Hedman et al. 2009), adding transmission congestion by removing some lines and reducing the capacities of others. Another update was to the heat rates of fossil generators to reflect the turbines in operation more accurately during that time. An additional upgrade of the GMLC is the arbitrary geographical projection of the RTS system/layout on an area of about 250 square miles covering parts of Arizona, Nevada, and California in the southwestern United States. This projection enabled users to obtain a reference for load, solar, wind, and hydrologic time-series data. Despite now having spatiotemporally coincident weather data, the system remains synthetic and does not represent a real-world power system.

To represent diverse electricity demand profiles, load data from all balancing authorities (BAs) in or near the represented area were taken and normalized to peak regional load in the RTS model. The RTS power flow case was used to obtain a static peak load distribution that was then used to derive a nodal load time series. Variable renewable generation profiles for technologies such as wind, utility photovoltaics (PV), rooftop PV, and hydro were selected from random generators from the Western Wind and Solar Integration Study 2 (WWSIS-2) data set (Lew et al. 2013) to fit the RTS system's size because the WWSIS-2 data set was too large. Some oil and coal generators were replaced with natural gas combined cycle and combustion turbine units (Gas-CC and Gas-CT, respectively) to represent the evolving generation mix. A small storage device was also added to the mix with unbounded ramp rates and no other operational constraints.

2.2 Regional Energy Deployment System model

ReEDS is an open-source linear programming (LP) model that minimizes the capital and operating costs of the power system from the present day through 2050, although the model can be run until after 2050 if the required data are supplied (Krishnan and Cole 2016). The U.S. model has 134 regions, called model balancing authority areas, to represent the U.S. power system. ReEDS represents conventional thermal generating technologies such as coal, oil, gas, and nuclear—with each technology having several subdivisions such as coal plants with or without carbon capture and sequestration (CCS) and natural gas plants being categorized into combustion turbine, combined cycle, or Gas-CC with CCS. The model also represents renewable energy resources and technologies such as land-based wind, offshore wind, solar PV, concentrating solar power, geothermal, hydropower, biopower, hydrogen, and battery technologies; several variances among each are also represented. From a transmission perspective, ReEDS represents AC and HVDC lines, with voltage classes for the AC lines being assigned using the Homeland Security Infrastructure Project (HSIP). The largest population centers in each BA are used to designate the modeled node for that BA.

On the temporal side, ReEDS includes 7 years of hourly chronological, time-synchronous wind, solar, and load profiles. These profiles can be used directly in the model or sampled to produce representative days that capture the variations among wind, solar, and load. To keep runtimes manageable, the model is typically run with 33 representative days, with each day having six 4-hour blocks. The full 7 years of hourly wind, solar, and load profiles are then used in between solve years to calculate the capacity credit of wind, solar, and storage resources. ReEDS also provides seasonal capacity credit estimates for wind and solar technologies across different regions and classes, which are then utilized to assess the capacity contribution of each resource towards meeting the planning reserve requirement.

The ReEDS model minimizes the investment and operating costs of all power sector resources. Capital investment costs include technology investment costs (differentiated by region), cost of upgrading or converting technologies (such as adding scrubbers to coal plants), transmission spur line costs, network reinforcement costs, and costs of new transmission lines. The operational component can comprise technology-specific variable operational and maintenance costs, fixed operational and maintenance costs, fuel costs, taxes on emissions, alternative compliance payments, CO_2 transportation and storage costs, and production tax credits. The model includes several constraints such as regional supply-demand energy balance, planning reserve margins, operating reserve margins, regional and temporal resource constraints, policy constraints, and operational constraints (e.g., flexibility and minimum generation).

In 2022–2023, the ReEDS model added spatial flexibility as a feature, allowing the representation of spatial extents more granular than the 134 model BAs. This new capability is leveraged to represent the RTS-GMLC system in the ReEDS model. The model equations and constraints do not need to be altered to study different regions or spatial resolutions. Thus, the extension of the ReEDS model to a nodal test system required an exercise only in data preparation and formatting.

2.3 Methods to adapt RTS data set for ReEDS

For the nodal system implementation, we chose to model each of the 73 buses/nodes as a region in ReEDS. To facilitate the inclusion of the RTS-GMLC system into ReEDS, we mapped each node in the RTS-GMLC data set to a U.S. county and state using the latitude and longitude data given for the buses, creating a mapping among these spatial extents (state, county, and bus). This mapping allowed various inputs from ReEDS that are defined at respective geographic regions to be applied to the RTS-GMLC system if the RTS-GMLC system did not already supply them. These inputs include state renewable portfolio standards or North American Electric Reliability Council (NERC) -recommended planning reserve margins. Individual generators were mapped in the same way. In addition, the ReEDS model works with 7 years of weather data (2007-2013). However, because the RTS-GMLC data set includes only 1 year of weather data (2020), we duplicated the data to create a 7-year data set (with each year having the same 2020 weather data) and can supply it to ReEDS without impacting functionality.

The RTS data set comes with its transmission branch information and structure, so we adapted the transmission data to match the ReEDS input structure. Because the RTS data set gives continuous megawatt (MW) flow limits for each line, for this case study, we used those flow limits for the transmission constraints in ReEDS. An input that the RTS data set does not contain is the cost to build new transmission, interconnection, or spur lines, so we have assumed the median $/MW-mile costs from ReEDS for the regions considered. The cost and performance of new generators were also applied in the same way, with ReEDS providing the cost, performance, and financing values for the southwest United States as inputs for the RTS-GMLC system.

As noted, the load data provided in the RTS data set are only for 1 year; however, we need hourly load data up to 2050 for the capacity expansion. For this work, we assumed an arbitrary 1% load growth factor to create the nodal load data for the entire system from 2010 to 2050. We left the load shape in its current form, so the 2050 hourly load is simply a scaled version of the 2020 hourly load, which is supplied with the RTS-GMLC test system.

The model also needed resource supply curves for several of the renewable energy technologies; these curves include the amount, quality, and cost of new resources, such as wind or solar PV. By default, ReEDS uses supply curve costs provided by the Renewable Energy Potential (reV) model (Maclaurin et al. 2019). For this case study, we created representative supply curves of cost and availability based on the data in ReEDS and assumed that any new resources would have the same hourly profiles as those already in the RTS-GMLC data set.

All regional inputs such as fuel price multipliers and hydrogen storage sites are adjusted to the nodal resolution using the mapping described previously. We also added the generator online and retirement dates which were chosen arbitrarily to inform the model as it evolves the fleet. For our default case, we set all retirements to be after 2050—which in effect ignores retirements—but we can alter this assumption to generate a different scenario as discussed in the Results section.

3 Scenarios

The ReEDS model was run on the RTS-GMLC system for the following scenarios:

- Reference
- Retire existing fossil resources in 2035
- 100% carbon reduction by 2035
- High wind buildout
- High solar buildout.

The scenarios all use default assumptions from ReEDS in cases where data in the RTS-GMLC are not available, except in the variation specified. The high wind and solar buildouts were created by changing technology costs to be favorable for the technology to have the high buildout. In all scenarios, the model is solved with 3-year time steps starting in 2020 and new builds are allowed in the model after 2024. This 3-year timestep is a user-specified option and can be set to other intervals as desired.

4 Results

Figure 1 shows the annual generation by technology through 2050 for the Reference scenario. Figure 2 shows the capacity mix for the same scenario and time frame. For 2020 and 2023, the model operates the system using only the existing capacity, which is sufficient to satisfy the load demands for those years. No new builds are allowed until after 2024. During this time, the system relies heavily on fossil-fuel-based generation technologies such as coal and Gas-CC, with the relative share shifting from year to year based on the differences in natural gas and coal fuel prices in those years. In 2026, once new builds are allowed by the model, we observe that renewables such as land-based wind and utility-scale solar PV systems (UPV) see the most growth over time.

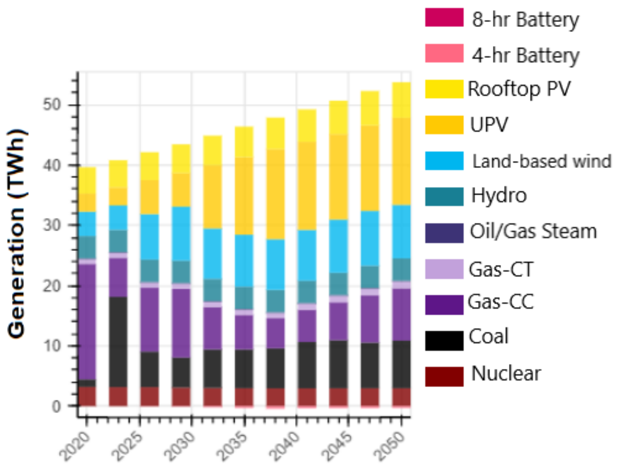

Fig. 1. Generation mix over time in the Reference scenario

The year 2026 sees a significant increase in UPV and land-based wind capacity and generation. There is also some 4-hour battery technology capacity added to the system. Renewables' contribution to the system mix goes from about 33% in 2020 to about 50% in 2035 and ends with approximately 55% in 2050.

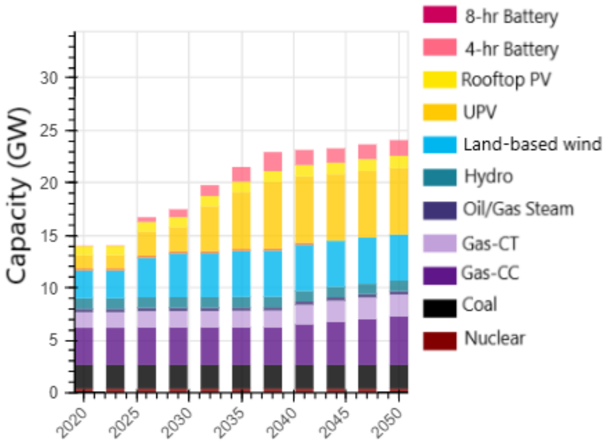

Fig. 2. Capacity by technology type over time in the Reference scenario

The system tends to prefer to build UPV over land-based wind, in large part, due to the selection of the U.S. desert southwest for the test system. This portion of the country has some of the best solar resources and has seen rapid growth in PV over the last decade. After 2040, Gas-CC, Gas-CT, and battery systems are added, indicating that load has grown sufficiently by that point to require additional firm capacity resources. Throughout the model planning horizon, the system continues to utilize existing fossil generation to meet load in part because there are no assumed retirements for the fossil generation fleet. The existing plants also do not have incentive to retire because they are not populated with fixed operations and maintenance costs, so the model does not see cost savings in making an endogenous retirement decision for those plants.

Figure 3 shows a scenario in which all existing fossil power plants were required to retire in 2035. This scenario results in a greenfield-like selection of fossil resources. We can see that the model chooses to replace the retired capacity with new UPV, Gas-CT, Gas-CC, and battery storage. The relative share of Gas-CT and Gas-CC reflects the value of the flexibility and lower utilization of the thermal units with the higher shares of wind and solar.

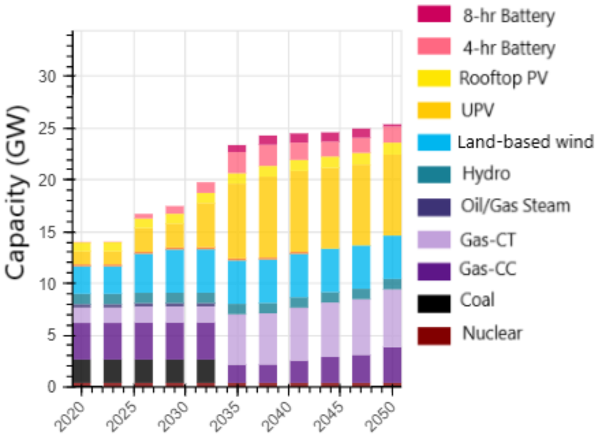

Fig 3. Capacity by technology type over time for the scenario in which all existing fossil power plants are retired in 2035

Figure 4 shows the capacity mix for the scenario that requires full decarbonization in 2035. This scenario results in a heavy investment in UPV, longer-duration battery storage, and hydrogen combustion turbines. Renewables' contribution to the system mix goes from about 33% in 2020 to 100% in 2035. The scenario specification results in an abrupt transition in 2035; if needed, a ramp-down in CO2 emissions could be used to create a more gradual transition in the generation mix.

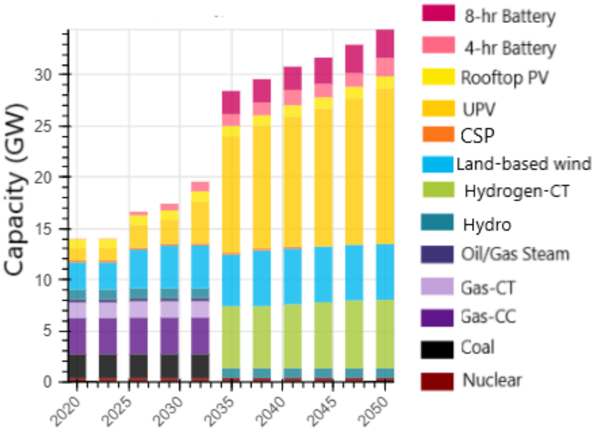

Fig. 4. Capacity by technology type over time for the 100% carbon reduction scenario by 2035

Figure 5 shows a scenario with a system with high land-based wind buildout. This is achieved by assuming “advanced’ technology costs and performance for land-based wind while assuming “conservative” costs and performance for UPV. The advanced and conservative costs are different projections provided by the 2023 Annual Technology Baseline (National Renewable Energy Laboratory 2023).

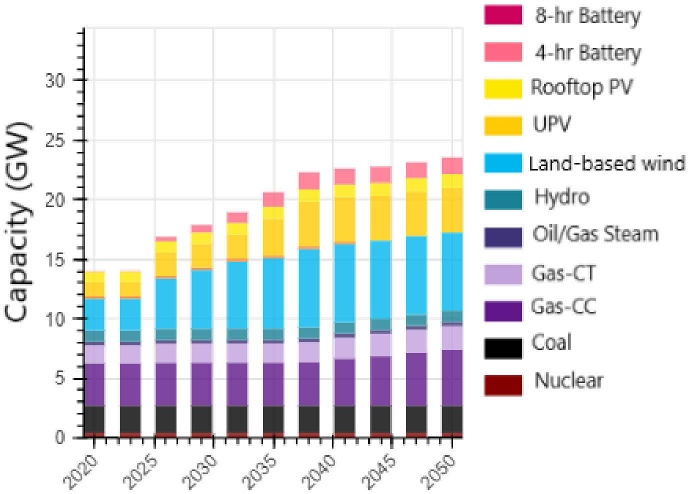

Fig. 5. Capacity by technology type over time for the scenario with a high wind buildout

Finally, Figure 6 shows a scenario with a system with high UPV buildout. This is achieved using assumptions of “advanced’ technology costs for UPV and “conservative” costs for land-based wind. This results in a smaller buildout of wind and a large buildout of UPV and battery storage.

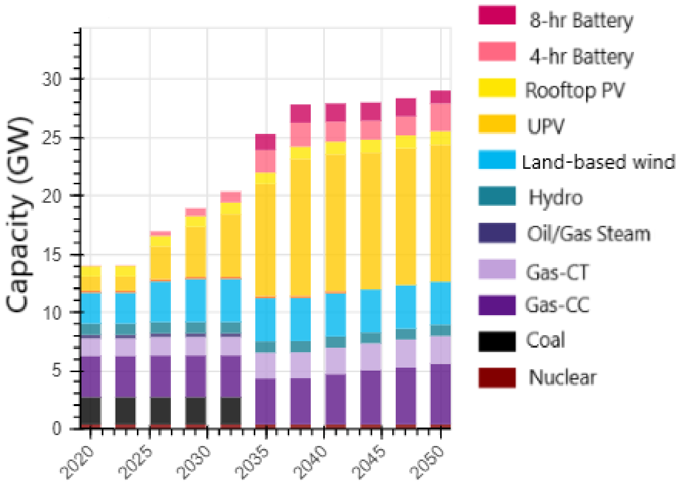

Fig. 6. Capacity by technology type over time for the scenario with a high UPV buildout

5 Conclusions

In this work, we demonstrate how an established, national-scale capacity expansion model can be applied to an IEEE test system (the RTS-GMLC system) to create a variety of futures that might be relevant for a power system researcher. This work also highlights that nodal-level resolution can be represented in systems and models that typically focus on far less granular representations of the power system. The bulk of the effort for adapting a nodal dataset within ReEDS was in the data preparation, and we expect other similar efforts to apply national-scale models to nodal systems to be data-centric rather than model-centric. The effort also required coupling inputs from the capacity expansion model with the test system because the test system did not have inputs needed for capacity expansion, such as capital and financing costs and policy constraints.

This work focused on creating five distinct futures of the RTS system, evolved using current cost, performance, financing, and policy inputs. Future work could extend the input linkages between the models, such as using forward-looking load data from ReEDS in the RTS, which would allow for evolving load shapes and multiple weather years. In addition, the RTS could be applied to other locations within the U.S. power system, with the mapping updated to provide resource data and profiles for the regions of interest. For example, linking a model like ReEDS to a nodal database would allow users at any given county or region of interest to create a test system using the regional data as input to run the CEM. This would allow the test system to be adapted to other environments, such as winter peaking systems or systems with higher-quality wind resources.

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