Methods for Translating ReEDS Solutions to Production Cost Modeling Tools

Brady Cowiestoll and Will Frazier

National Renewable Energy Laboratory

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List of Acronyms and Abbreviations

CAES	compressed air energy storage
CEM	capacity expansion modeling/model
ERGIS	Eastern Renewable Generation Integration Study
gas-CT	gas-combustion turbine
hrs	hours
MT	medium-term PASA
MW	megawatts
NARIS	North American Renewable Integration Study
NREL	National Renewable Energy Laboratory
PASA	projected assessment of system adequacy
PCA	power control authority
PCM	production cost model
PIDG	PLEXOS Input Data Generator
ReEDS	Regional Energy Deployment System
ST	short-term PASA
TEPPC	Transmission Expansion Planning Policy Committee

Executive Summary

Capacity expansion models (CEMs) are increasingly being used to investigate a wide range of potential future scenarios, particularly those with high shares of variable generation and storage resources that may be operated differently than under current dispatch paradigms. CEMs are designed to identify optimal investment pathways—decisions that will be heavily impacted by the potential future operation of the power system. All CEMs, thus, represent power system operations, but capturing power system operations with adequate temporal or spatial detail is computationally intensive. Therefore, reduced form representations of operations are typically employed withing CEMs to limit computational requirements. Despite this reduced form approach, it is important when analyzing these potential futures systems to (1) determine whether such future systems could maintain reliability during a variety of grid conditions and (2) identify potential operational challenges for these systems at finer temporal resolution than is typically captured in CEMs. Therefore, having an automated tool that can translate many CEM investment pathways into inputs for a more detailed production cost model allows for more detailed analysis of reliability and operability for these future power systems. This report describes the methodology used to make that translation from the NREL-developed Regional Energy Deployment System, or ReEDS model, a CEM that uses two internally developed tools—the PLEXOS Input Data Generator (PIDG) and the python package beetle—along with a set of processing scripts to the PLEXOS model, a commercial production cost model. We describe the current assumptions, data sets, and important operational characteristics of these translations, and we provide an example of the extended analyses that may be done through this connection.

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1 Introduction

The electric power system is undergoing a period of rapid change (Markard 2018). The competitiveness of traditional power plants is evolving with changing fuel prices, natural gas prices, declining costs of renewable energy and storage resources (NREL 2021), and as states and local entities announce high clean or renewable energy targets (City of Gainesville 2018; City of Orlando 2017; Cochran and Denholm 2021; Barbose 2021). As system planners and policymakers look to this changing future, they desire to better understand the space under which they might find themselves in the future, and in particular, how new power systems might operate. This desire has led to a host of forward-looking studies analyzing both how the power system might evolve (Steinberg et al. 2021; Cole et al. 2020) and how it might operate (Greg Brinkman, Novacheck, and Ho 2021; Bloom et al. 2020; Steinberg et al. 2021). Tools exist to address these questions; however, they typically take one of two forms—capacity expansion models (CEM) or production cost models (PCM)—focusing on the expansion trajectory or the detailed operations of future power systems respectively. Harnessing the complementarity of these tools could lead to powerful analyses of potential future electric grid systems and a better understanding of the pathways and challenges to getting there. Therefore in this report, we describe a method of translating results from a CEM to a PCM, an approach that enables iterative analysis of these model types and allows for improved identification of optimal future power systems as well as any associated operational challenges for which to plan.

The capacity expansion model we use for the translation process described here is the Regional Energy Deployment System (ReEDS) (Ho et al. 2021), although many other CEMs exist and could undergo a similar translation process. ReEDS is a best-in-class CEM of the U.S. power sector that uses projections for future technology costs and performance and state-of-the-art methodology for representing the complex interactions to identify the least-cost mix of generation, transmission, and storage resources to meet demand of electricity from the present day to mid-century.

ReEDS is composed of a central linear program and a suite of submodules that run nonlinear simulations, calculations, or optimizations using seven years of coincident hourly load, wind, and solar data and return information to the linear program to constrain the linear program solution. Because of the computational limitations of simulating a continental system many decades into the future, the central linear program within ReEDS is solved across 134 spatial regions (Figure 1) and 17 temporal periods (or time-slices), with investment decisions informed by the information provided by the hourly submodules. This spatial resolution captures much of the spatial variability in demand and resource availability across the continent, but the limited temporal resolution does not captures all aspects of temporal variability in demand and supply, particularly with respect to storage and variable resource renewable generation sources. For this reason, a submodule of ReEDS (Augur) performs detailed hourly operational modeling of the power system between solve years; accounting for the effects of high shares of variable renewable energy and storage information from this hourly operational modeling is passed back to the investment optimization to inform the decision-making there according to the more detailed modeling at higher temporal resolution. Details on Augur and the ReEDS model can be found in Ho et al. (2021)

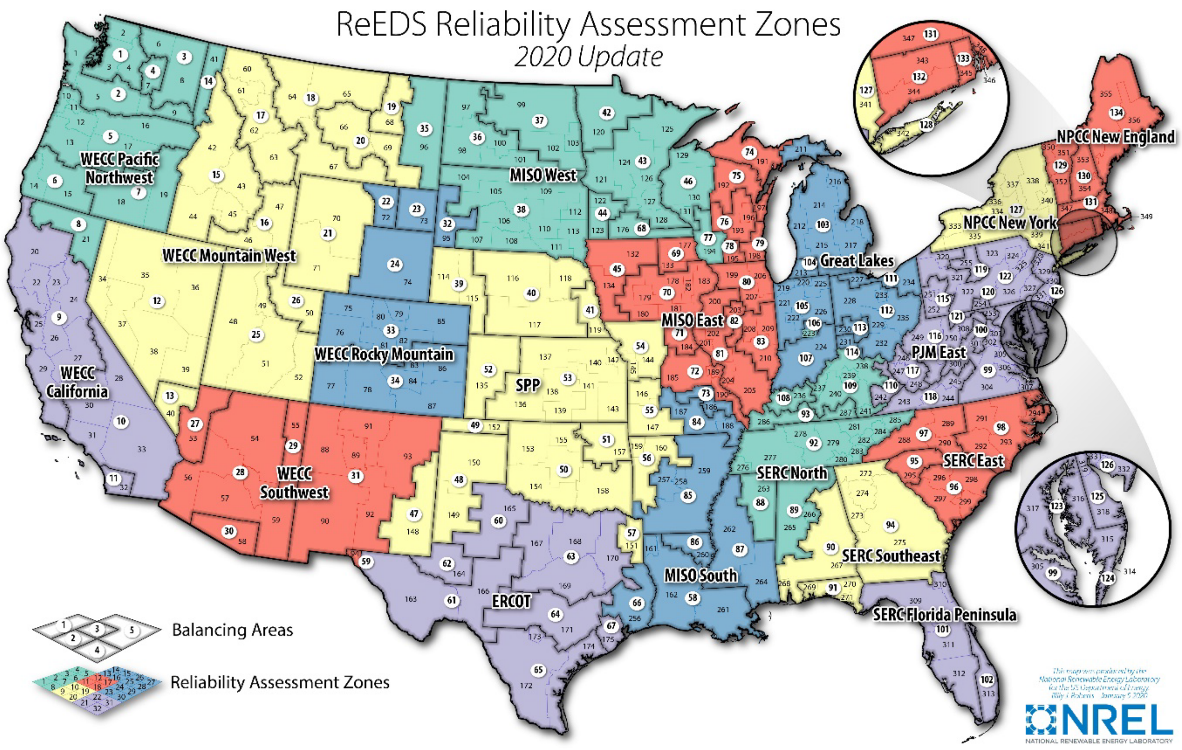

Figure 1. ReEDS region map showing the 134 spatial regions covered by the model

Source: Ho et al. 2021

The production cost model we use for the translation process is PLEXOS (PLEXOS Integrated Energy Model (version 7.400 R02 x64 Edition) 2018); though again, several other options could be the end point of a CEM-PCM translation. PLEXOS captures commitment and dispatch decisions for individual generators using a mixed-integer optimization function while respecting all constraints related to the operations of generators, the operation of the transmission system, and serving of load and ancillary services. The model typically represents hourly or subhourly operation of one or more years of a specified power system. It can be used to analyze detailed operational questions, including questions about ramping, commitment of generators, and provision of reserve. Operated as a PCM, PLEXOS does not adjust the capacity of the specified system, so it either may be unable to serve all load or might have excess capacity that never gets used on the system.

Combining the strengths of both these types of models (1) allows detailed multifaceted analyses of large-scale future power systems to be conducted and (2) allows for the ability to provide feedback to CEMs if adjustments are needed to adequately represent key aspects of future power system reliability and operations. Combinations of such tools have been used to explore future potential grid evolution in several studies of the entire continental United States, including the North American Renewable Integration Study (NARIS) (Brinkman et al. 2021), the Solar Futures Study (DOE 2021), and the Electrification Futures Study (Murphy et al. 2021; Zhou and Mai 2021). In Section 2, we present the methodology used to couple ReEDS and PLEXOS to further enable in-depth analyses of future grid evolution. And in Section 3, we present examples of results to demonstrate the capabilities described in the report.

2 Methodology

Though different types of models—and model inputs—can be connected manually, automation makes the connection more straightforward and faster, and it reduces the potential for error in translation. Therefore, we developed a tool to seamlessly create a production cost model representation of any arbitrary ReEDS solution. The tool currently interfaces with the PLEXOS production cost model (Energy Exemplar, n.d.), and we plan to extend it to other models, such as the Scalable Integrated Infrastructure Planning Model (Lara et al. 2021).[1] But in this report, we focus on PLEXOS. And the methodology we report here could be extended to translate other CEM outputs; for example, a similar formulation is currently used for another NREL-developed capacity expansion model, the Resource Planning Model (Mai et al. 2013). In this section, we describe the additional data needed to supplement the ReEDS solutions for PLEXOS operation, the assumptions made in interpreting the ReEDS solutions, and important adjustments of the PCM representation for certain technologies.

The translation process (Figure 2) consists of several tools linked by driver scripts to handle all formatting requirements and data processing between the tools. The PLEXOS Input Data Generator (PIDG) (Ehlen 2017)[2] and the python package beetle (Cowiestoll and Hale 2019) are the driving software packages in the translation process, and they programmatically create PLEXOS input files based on different sets of input data. We use them here in combination. First, PIDG is used to create a baseline system for the starting ReEDS' solve year. This system includes all transmission infrastructure, existing generators, and reserve products. Next, beetle is used to update the baseline system with all additional investments from ReEDS for the desired model year; in particular, it generates all time-series data required (e.g., load and variable generation profiles). Subsequent processes are used to create a PLEXOS input database from the beetle output Excel files and to then run and process the PLEXOS solutions.

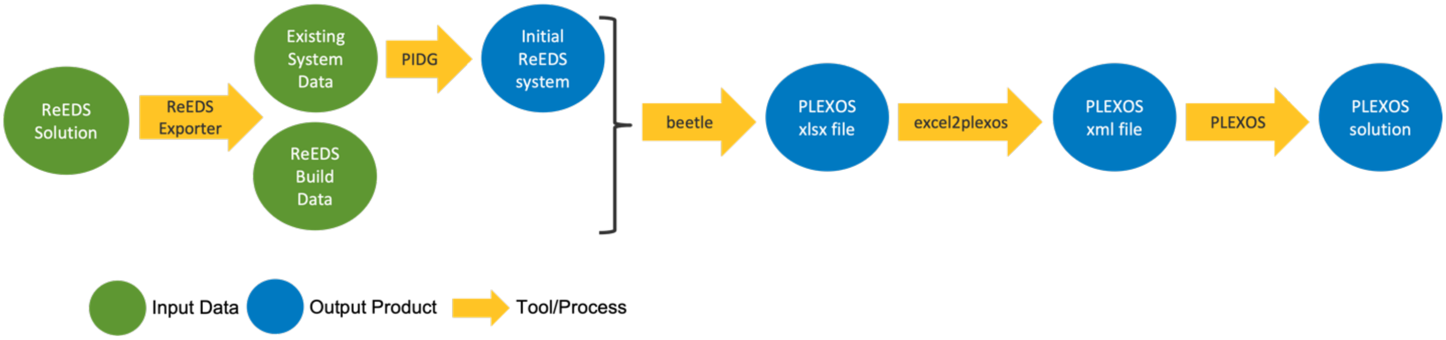

Figure 2. Steps in the ReEDS-to-PLEXOS translation process

Several NREL-developed tools are used in the translation process, including PIDG, beetle, and excel2plexos. The process is executed with a set of driver scripts to call each individual process and pass the data between processes.

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[1] "Scalable Integrated Infrastructure Planning Model," NREL, https://www.nrel.gov/analysis/siip.html.

[2] "PLEXOS Input Data Generator (PIDG)," GitHub, https://github.com/NREL/PIDG/

The overarching goal of the translation process is to produce a PLEXOS database as similar to the ReEDS outputs as possible while accounting for reasonable unit sizes for each type of generator (described in 2.2). Though other methods could be used to exactly match ReEDS capacities, the current methodology has less than 0.2% error. This enables analysis of ReEDS' solutions at finer temporal resolution while allowing for adjustments from the ReEDS solution in the representation of certain generator types or properties where needed for more realistic operational modeling at the increased temporal resolution in PLEXOS—in particular, incorporating more specific heat rates and adjustments to hydropower operations. Future work on the translation tool will enable more-detailed spatial resolution representations of ReEDS solutions in addition to the translation process discussed here.

2.1 Data Assumptions

Data are pulled for the PLEXOS model from one of three main categories within the ReEDS to PLEXOS process: (1) using ReEDS data directly, (2) improving ReEDS data for use in the more detailed PLEXOS model, and (3) adding additional data for properties that are not included in ReEDS but are important in PLEXOS. Which category is used for each piece of data depends on the property, how (and whether) it is used in ReEDS, and whether additional detail is available or required within PLEXOS. Each key properties on PLEXOS is listed in Table 1. For most cases, where data exist within ReEDS, those properties are used directly with minimal adjustments as discussed below. For data listed as being from ReEDS in Table 1, these values are taken from ReEDS outputs directly and so may change based on user inputs into ReEDS or from future changing data sources for the ReEDS model itself. However, some data are used differently within the CEM context than the PCM context, particularly those related to the ReEDS time-slices representing aggregate behaviors of connecting regions. For example, the hydropower minimum generation levels require adjustments to disaggregate the time-slice representation into hourly inputs, as is detailed in Section 2.1.1. Additionally, ReEDS does not capture certain grid needs (e.g., unit commitment) and so does not include properties relevant to those operations (e.g., minimum off time of units). These properties must be added from other data sources for use within PLEXOS, which are detailed in Table 2 (page 6) by technology type.

Table 1. Property Sources for Data Used in PLEXOS

If the data source is listed as ReEDS, values are taken directly from the parameters used in a ReEDS run and the comments describe the typical source used in ReEDS (Cole et al. 2021). If modified, the modification or source is described in the comments column. NARIS (Gregory Brinkman et al. 2021) and the Eastern Renewable Generation Integration Study (ERGIS) (Bloom et al. 2016) are large-scale grid energy studies that were performed by NREL.

Property	Data Source	Data Used in ReEDS	Comments
Emission rate	ReEDS	Yes	Values come from EGRID2007 Version 1.1 (EPA 2008)
Fuel cost	ReEDS	Yes	ReEDS fuel cost inputs are derived from the U.S. Energy Information Administration's Annual Energy Outlook.
Heat rate	ReEDS	Yes	ReEDS-to-PLEXOS users can use a technology-specific heat rate curve instead of ReEDS values; values are randomly adjusted by +/- 2% to reduce degeneracy.

Property	Data Source	Data Used in ReEDS	Comments
Hydropower energy	ReEDS, modified	Yes	Time-slice specific hydropower constraints from ReEDS are modified to achieve similar total seasonal energy limits, but they are simulated as monthly limits in PLEXOS. See Section 2.1.1 (page 6) for details.
Minimum stable level	ReEDS; Eastern Renewable Generation Integration Study	Only for hydropower and in Augur	Values for all non-hydropower generators are taken from the Transmission Expansion Planning Policy Committee (TEPPC) 2026 database and are aggregated by generator type. Hydropower modifications are described in Section 2.1.1.
Minimum up and down time	NARIS	No	Values in TEPPC are aggregated by technology type for use in PLEXOS.
Outage duration	NARIS	No	Values in TEPPC are aggregated by technology type for use in PLEXOS.
Outage rate	ReEDS	Yes	Both planned and forced outages are included by generator type based on the North American Electric Reliability Corporation's Generating Availability Data System.
Ramp rate	NARIS	No[a]	Values in TEPPC are aggregated by technology type for use in PLEXOS.
Start cost	NARIS	Only in Augur	Values in TEPPC are aggregated by technology type for use in PLEXOS.
Storage efficiency	ReEDS	Yes	Values come from NREL's Annual Technology Baseline.[c]
Transmission loss rates	ReEDS	Yes	Bulk transmission loss rates in ReEDS are 1% per 100 miles. Line distances are traced along the shortest path of existing transmission lines between the largest population center in each power control authority (PCA) (Ho et al. 2021).
Variable operation and maintenance cost	ReEDS	Yes	Values come from NREL's Annual Technology Baseline.
Variable renewable energy profiles	reV (Renewable Energy Potential model)[b]	Yes	Hourly variable renewable energy capacity factor profiles are created using reV (Maclaurin et al. 2021). Profiles are scaled to match generation in ReEDS, including adjustments for degradation, inverter loading ratios, and future improvements in technology performance.

[a] Ramp rates are used within ReEDS to determine eligibility to provide different operating reserves and are used within Augur but are used within the ReEDS dispatch optimization.

[b] "reV: The Renewable Energy Potential Model," NREL, https://www.nrel.gov/gis/renewable-energy-potential.html

[c] "Annual Technology Baseline," NREL, https://atb.nrel.gov.

Table 2. Properties that are Fixed within Translation for New Generators

Technology	Minimum Up Time (hrs)[a]	Minimum Down Time (hrs)[a]	Outage Duration (hrs)[b]	Minimum Stable Level (%)[c]	Ramp Rate (%/min)[a]	Start Cost ($/MW)[a]
Gas-combined cycle	6	8	48	50	5	79
Gas-combustion turbine	0	0	48	60	8	69
Coal	24	12	55	40[d]	2	129
Bio-gen	7	7	38	100	14	5
Nuclear	n/a[e]	n/a[e]	298	100	n/a[e]	0

[a] These values are taken from Table 5 in Gregory Brinkman et al. (2021).

[b] These values are taken as averages by technology type of those used by Gregory Brinkman et al. (2021).

[c] These values are taken from Table 26 in Bloom, Townsend, Palchak, Novacheck, King, Barrows, et al. (2016).

[d] Coal units have differing minimum stable levels based on size. For this work, we average these values.

[e] Nuclear units are represented as must-run units; as such, they do not have unit commitment decisions in the model and are not allowed to ramp. This is a difference from ReEDS, which may decommit units for an entire season.

2.1.1 Hydropower

In ReEDS, hydropower is split into two categories: dispatchable and non-dispatchable. Non-dispatchable hydropower in ReEDS represents systems such as run-of-river hydropower that do not have modulated water flow through their turbines. Non-dispatchable hydropower provides a constant energy output in each season in ReEDS, and it is currently represented the same way in PLEXOS and ReEDS: the same seasonal derating factors that change the output of non-dispatchable hydropower are used, and the generation from non-dispatchable hydropower maintains a constant output throughout each season as defined by the ReEDS time-slices.

Dispatchable hydropower represents systems that can control their water output; however, they are typically also subject to constraints involving seasonal water availability or water access for environmental, agricultural, or municipal needs. Dispatchable hydropower is allowed to perform some diurnal load following within the seasonal capacity and energy limits assumed. For dispatchable hydropower, the ReEDS-to-PLEXOS translation process uses the seasonal generation adjustments to create an average seasonal capacity factor. The minimum generation fraction from ReEDS is then multiplied by the maximum capacity and the average seasonal capacity factor to produce a "minimum stable level" for each season for use in PLEXOS:

$$minimum\ stable\ level = [maximum\ capacity] * [seasonal\ capacity\ factor\ adjustment] * [mingen\ fraction]$$

The maximum capacity and average seasonal capacity factor are also used to create a monthly energy budget for dispatchable hydropower in PLEXOS. The monthly energy budget is equal to the total amount of energy that would be generated were a hydropower plant to operate at its average capacity factor for the whole month but the plant was free to operate anywhere between its minimum stable level and its maximum capacity provided it does not exceed its monthly energy budget for the whole month:

$$monthly\ energy\ budget = [maximum\ capacity] * [seasonal\ capacity\ \text{factor}\ adjustment] * hours$$

$$minimum\ stable\ level\ \leq generation\ \leq maximum\ capacity$$

2.1.2 Must-Run Units

Several technology types from ReEDS are by default included as must-run units. In particular nuclear, biopower, and landfill gas are defined as must-run units because the cost-optimization parameters in PLEXOS typically do not fully capture reasons for these technologies' operations (e.g., operating nuclear power at a loss), and we do not discount biopower for the federal production tax credit or for renewable energy credit generation, both of which impact real operations of these technologies. Including these generator categories as must-run units therefore helps their generation better match historically observed values. The set of generators included as must-run units is a user input in the translation process, and it may be adjusted or changed based on desired operational strategies.

Important to note is that including nuclear generators as must-run units presents a potential discrepancy between ReEDS and PLEXOS, where ReEDS allows nuclear plants to decommit for an entire season—spring, summer, winter, or fall—if doing so is optimal. PLEXOS, however, does not easily allow for such long-term outages within the optimization, so nuclear can be modeled as either must-run or fully dispatchable.

Hydropower is also defined as must-run in the translation process because of limitations of our water representation. Constraints for hydropower are described above in Section 2.1.1.

2.1.3 Reserve Requirement

The reserve representation and risk included in the ReEDS-to-PLEXOS translation process does not try to replicate more-detailed local reserve requirements or their risk profiles any more accurately than does ReEDS; however, it does use hourly data to create such risk profiles and reserve requirements. Three reserve products are included: spinning, regulation, and flexibility. Within PLEXOS, these are defined according to a:

- Response time, which limits the reserve a generator can provide based on its availability and ramp rate within the time frame
- Duration, which is predominantly used by storage objects to determine whether they have sufficient stored energy to fully respond to the reserve time frame
- Value of reserve shortage, which indicates the cost to the optimization if the reserve product is not provided (This is mostly used to create a value order for the reserve.)
- Risk profile for the amount of reserve required within each reserve region.

Table 3 shows these values for each reserve product used in PLEXOS.

Table 3. Reserve Product Definitions[a]

Reserve Product	Response Time (min)	Duration (hr)	Value of Reserve Shortage ($/MWh)[b]	Risk
Spinning	10	1	400,000	3% of load
Regulation	5	1	410,000	1% of load + 0.3% of PV + 0.5% of wind
Flexibility	20	1	390,000	4% of PV + 10% of wind

[a] Load risk is calculated as fraction of total load. PV risk is calculated as fraction of capacity during daylight hours. Wind risk is calculated as fraction of generation.

[b] The value of reserve shortage is not an actual cost expected to be paid for violation of reserve but rather a penalty cost to the optimization used to limit reserve violations. Variations in this value indicate the ranking of reserves and which should be violated first if needed.

Generators are allowed to provide the same set of reserve products they are allowed to within a ReEDS run, for the reserve products that cover their reserve sharing region only (i.e., generators cannot provide reserve for neighboring regions unless they are in the same reserve sharing group). Storage resources can provide reserve so long as they have sufficient stored energy to provide the procured reserve product for the entirety of its duration.

2.1.4 Representation of Electricity Trade with Canada

ReEDS can endogenously include trade with Canada and Mexico, but the model is typically run for only the contiguous United States with Canadian trades represented exogenously. Exports from the United States to Canada are specified by Canadian province and in the National Energy Board's Canadian Electricity Futures Reference Scenario (Ho et al. 2021). Exports to Canada from ReEDS' power control authorities (PCAs) are added directly to the load profile for exporting ReEDS regions. Imports from Canada into represented PCAs are assumed to come from hydropower resources and are represented the same way as domestic hydropower (Section 2.1.1).

2.2 Processing ReEDS Solutions

The first step in the ReEDS-to-PLEXOS translation is to create a baseline PLEXOS database that represents the state of the power system at the beginning of a ReEDS simulation. This database represents initial system conditions in PLEXOS for any ReEDS solution, and a PLEXOS model can be created by manipulating this starting database according to the investments, retirements, and other changes that occur over the course of that ReEDS solution for whichever future year—through 2050 typically—is desired for analysis. This initial condition database is created using the PIDG tool, as shown in Figure 2 (page 3).

ReEDS represents aggregated regions—or PCAs—*not* individual nodes and transmission lines. For the standard ReEDS-to-PLEXOS translation process, we keep this regionality from ReEDS for the sake of simplicity of computation and analysis. Doing so allows for reasonable run times in PLEXOS and analyses that focus on aggregate behaviors, similar to ReEDS. More-resolved nodal translations will require additional downscaling, which is outside the scope/capability of the current approach. For the zonal analysis, in PLEXOS, we represent each ReEDS PCA as an individual node, similar to the representation within ReEDS. The transmission network follows as well, with lines in PLEXOS representing the aggregated connections between PCAs included in ReEDS. Reserve regions and reserve provision requirements are also held constant from

ReEDS into PLEXOS with the same PCAs being grouped together for provision of operating reserve.

Once the baseline PLEXOS database is created, all additional generator and transmission builds are identified and formatted to be added to the baseline PLEXOS model for the specified years of interest. In this step, all incremental builds and retirements are identified and the appropriate properties described in Table 1 (page 4) and Table 2 (page 6) are assigned to each technology type.

One key aspect of creating plants in PLEXOS is identifying appropriate sizes for these units. Currently, no limit or minimum build size to different types of plants is implemented within the ReEDS linear program or within Augur—the subhourly dispatch model. This is less consequential within ReEDS, as it does not enforce commitment decisions. However, in PLEXOS, plant size will interact with commitment decisions and other operational parameters, and therefore accurate characterization of plant size is needed to ensure a robust solution. The translation converts capacity estimates to discrete units based on typical sizes by generator type based on the distribution of unit sizes from Brinkman et al. (2015). The disaggregation or aggregation required to create discrete units occurs in several steps within the translation process. The first step is to identify for each generator category what is a reasonably sized unit. For these data, we analyze all generators within the Western Interconnection (Brinkman et al. 2015) to identify the minimum and maximum generator size for each category as well as the average generator size. Builds smaller than the minimum generator size are flagged for aggregation and builds larger than the maximum are flagged for disaggregation into units of typical sized generators. Figure 3 (page 10) shows the process used to aggregate or disaggregate generators. This is done for each generator category, vintage, and PCA within ReEDS.

The aggregation logic was created to minimize changes from the ReEDS solution while maintaining reasonable unit sizes in PLEXOS.[3] Aggregation over vintage is done first because generators of the same technology and vintage have all the same properties (e.g., heat rate and variable operation and maintenance cost). If any generators remain that are still too small, aggregation of the same technology type over state occurs next, as in many cases the building of capacity is driven by regional concerns whereby moving a small amount of capacity from one PCA to a near-by PCA would have minimal impact on the overall operational parameters. Beyond these aggregations, if there is still capacity smaller than the minimum generator size for that technology, the remaining capacity is dropped. Dropped capacity is reported in the output from the translation process to ensure this is only a small amount. Typically, dropped capacity totals only a few megawatts over the entire ReEDS solution.

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[3] Users can specify a condensed set of years over which to maintain consistency in generator units. This specification can help resolve changes in the power system over time that might occur from the aggregation and disaggregation process if the process is performed separately for each individual year, leading to potential difficulties in tracking unit evolution over time.

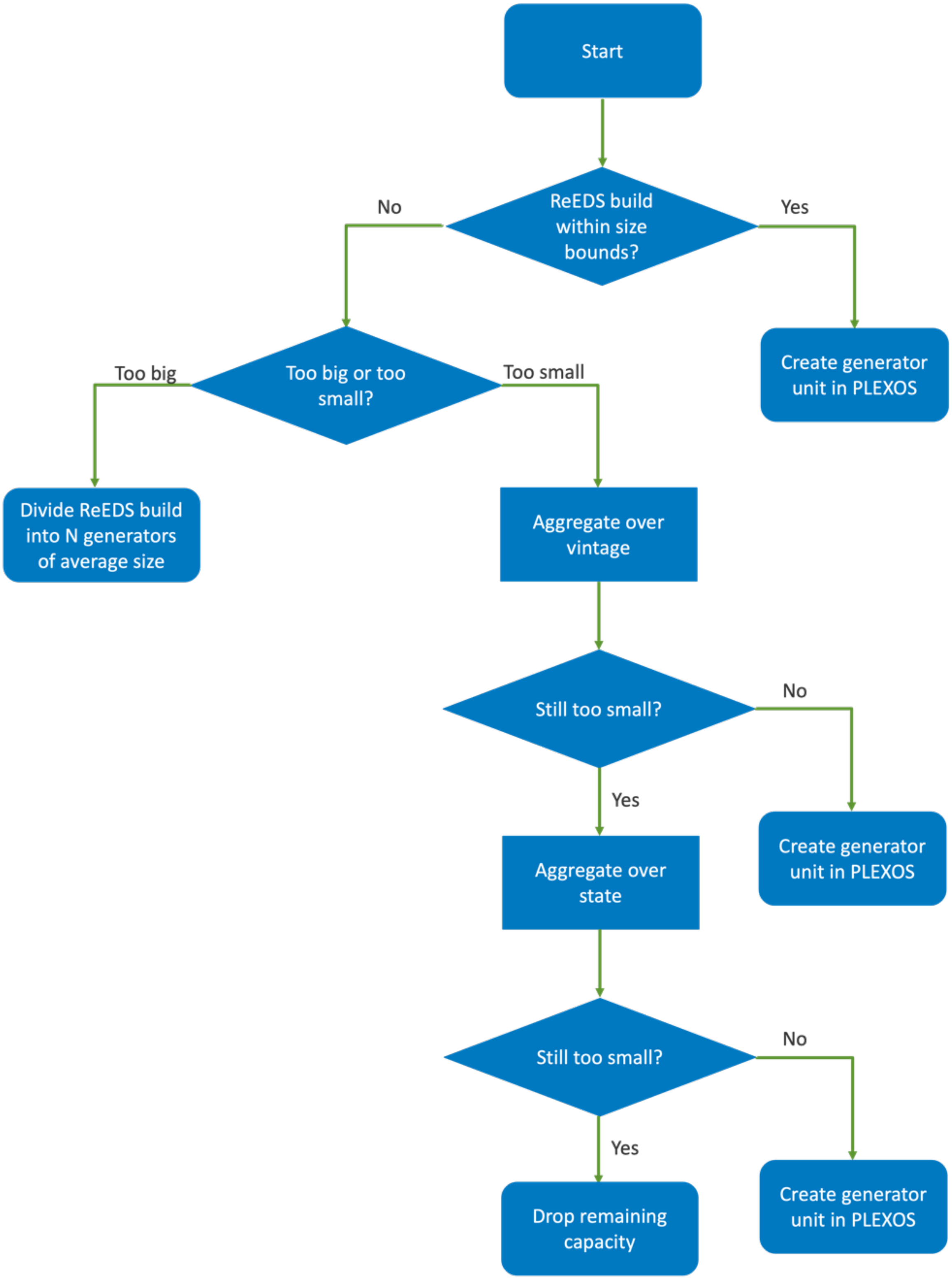

Figure 3. Aggregation and disaggregation logic for ReEDS builds, applied to each technology type, vintage, and region

Disaggregation follows the aggregation step, with a similar goal of creating generator units of typical size. ReEDS builds that are larger than the maximum allowed capacity are divided into N generators of size:

$$N = \left\lfloor \frac{C_{ReEDS}}{C_{Avg}} \right\rfloor$$

where C_{ReEDS} is the total ReEDS build and C_{Avg} is the average capacity of that generator type.

This method does potentially produce many identically sized generators, with a slight bias of generator sizes above the average. Future work could instead sample from a distribution of generator sizes. To break degeneracies between these disaggregated generators, we apply a random variation of ± 2% to the variable operation and maintenance and the heat rate properties.

Additionally, the default behavior of the translation process is to aggregate all variable renewable generators in the same PCA to reduce computational complexity of the optimization. Doing so reduces the total number of generators represented without losing detail, as these generators do not have commitment and dispatch decisions—only total generation and curtailment for the region based on the variable generation profile of the resource.

Transmission builds in ReEDS are represented as increases to transfer capacity limits between regions. These expansions are represented in PLEXOS as increased line capacities with the same line properties, specifically reactance, along the same corridor. As the ReEDS transmission expansions are representative of aggregate transfer capacity limits and not specific transmission plans, we determined that increasing the overall size of the line and not changing the reactance or adding lines was most representative in PLEXOS.

Retirement of generators can also take any of a range of values within ReEDS, up to the total capacity installed. When existing capacity is retired in ReEDS, generators in PLEXOS are identified for retirement based on a rank ordering of their heat rate followed by size, such that more-inefficient and smaller units are retired first. In selecting generators to retire, a partial generator retirement might arise. In this situation, a unit is retired if at least half of its capacity is retired within ReEDS. If less than half a generator's capacity is retired in ReEDS, it is not retired in PLEXOS. Any retirements that cannot be processed because of this requirement are noted in the translation outputs. Retirements are included in PLEXOS by setting their "units" property to 0 for the model simulation, but the generators do remain within the model if the user would like to make adjustments.

2.3 Representation within PLEXOS

To the extent possible, we represent generators and storage exactly the same as is done in ReEDS. However, PLEXOS has some unique and important aspects and there are more-accurate ways to capture generator operation within a PCM than a CEM. So, we adjust those operations more accurately. In this section, we detail how the ReEDS-to-PLEXOS translation parameterizes the models within PLEXOS.

2.3.1 Simulation Setup

Within PLEXOS, individual models are set up to run commitment and dispatch decisions for specified scenarios and time periods. The ReEDS-to-PLEXOS process defines all simulation objects required for PLEXOS to run the desired ReEDS solve year. Default production details include a 1% mixed-integer program gap, an Xpress-MP solver, a maximum solve time of 1.8 hrs/step, and unserved energy allowed with a simulation value of 1,000,000 $/MWh of unserved energy.

The simulation itself is consists of three parts: projected assessment of system adequacy (PASA), medium-term (MT), and short-term (ST) steps. The PASA schedules all planned outages throughout the year for each generator according to an expectation of when would be most advantageous for the grid based on the expected timing of reliability concerns. These outage schedules are then passed to later stages. The MT stage is used to simulate longer-term operational aspects of the power grid. This includes (1) hydropower, enabling the simulation to schedule output from hydropower facilities that may be governed by monthly minimum or maximum energy draws and (2) battery storage, allowing the simulation to identify the value of stored energy in the mid-term. The ST stage simulates the commitment and dispatch of generators over a specified period of time, generally simulating a day-ahead unit commitment phase.[4]

The ST modeling for ReEDS-to-PLEXOS is done at an hourly time-step with either 1 or 2 days of look-ahead at reduced resolution. The choice of look-ahead is a user input based on the desired number of overlapping periods. Default behavior of the translation process is to use monthly optimization runs (typically run in parallel on NREL's Eagle high performance computer[5]) with 2 days of look-ahead at a 4-hour resolution. The look-ahead period enables the model to anticipate future grid needs while maintaining realistic foresight of coming load and variable renewable output. To allow for starting conditions to resolve, we use 3 days of overlap between each month (Barrows et al. 2014), with, for example, the June month beginning May 29. The overlapping start-up days are then removed from the solution during post-processing. Monthly simulations allow for parallelization and faster overall run times. However, the translation process also includes optional annual and biannual simulation steps.

A final simulation parameter is the solution type used. PLEXOS enables both mixed-integer program and linear program solutions. A user chooses one solution or the other when running the translator; the default behavior is to use the mixed-integer program solution. Linear program solutions have a faster solve time, but the solver will linearize all constraints, including commitment decisions allowing partial commitment of generators.

2.3.2 Temporal Adjustments

Current iterations of ReEDS-to-PLEXOS include hourly temporal resolution in all data (load, variable renewable energy, and reserve profiles). No subhourly or forecast data or forecast errors

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[4] The ReEDS to PLEXOS translation process does not model two-stage commitment and dispatch simulating day-ahead and real-time operations, and it does not include forecast errors.

[5] " Eagle Computing System," NREL, https://www.nrel.gov/hpc/eagle-system.html.

are included in the translation process at this time. Seven weather years (2007–2013) are available in the translation process; users indicate which to use as an input.

Within the ReEDS-to-PLEXOS translation process, all time-series data are converted to Eastern Standard Time, ignoring daylight saving time. Additionally, the simulation period is typically assumed to be 365 days; in the monthly simulation, 28 days are modeled for February even if the simulated year is a leap year, though users may change this behavior. The PLEXOS simulation, however, follows the calendar year for the year simulated (i.e., it models February 29 for leap years). To maintain our desired behavior, March 1 is repeated, when needed, on February 29 for look-ahead purposes as used in PLEXOS. This day is then dropped from the outputs in the post-processing steps.

2.3.3 Transmission

Transmission in ReEDS is aggregated to modeled transmission corridors between the largest population centers in each PCA. Transmission corridors trace the "least-cost path" distance along existing transmission lines. Transmission uses a pipe-flow representation where transmission lines are enforced but angles and optimal power flow are ignored. Bulk transmission system losses are enforced as linear loss rates of 1% per 100 miles for AC transmission and 0.5% per 100 miles for DC transmission power flow between PCAs. In addition, distribution losses of 5% are assumed and are added to end-use demand uniformly.

The default representation of transmission in the ReEDS-to-PLEXOS translation closely represents the transmission formulation in ReEDS. In that respect, all PLEXOS results generated from ReEDS solutions represent the bulk power system with demand at the busbar level rather than the consumer or end-use level. Though early versions of the ReEDS-to-PLEXOS translation directly included the losses identified by ReEDS, the current version includes loss representation within PLEXOS according to the power flows within the PLEXOS simulation. Given the lack of true transmission infrastructure represented, we believe this to be most accurate for the zonal ReEDS-to-PLEXOS translation.

2.3.4 Generators

In general, all properties and generator parameters are taken exactly from ReEDS with representation of technologies such as storage, concentrating solar power, and fossil generation being modeled in the same way in PLEXOS as in ReEDS. Note that heat rates are included with the option of (1) representing an average heat rate formulation as is done in ReEDS or (2) including more-detailed representation of partial load heat rates based on an average heat rate curve (Figure 4, page 14). Currently, we have only part-load heat rates for gas plants, but future work could include creating these curves for coal and other generator types.

Additionally, several generator types are set to must-run status within PLEXOS, as described in Section 2.1.2 (page 7). This setting is governed by an input csv file listing the generator categories that should be included. The default types include biopower, non-dispatchable hydropower, landfill gas, and nuclear power.

Compressed air energy storage (CAES) generators are represented uniquely. CAES plants are complex in that they are storage technologies that also use gas to decompress air when generating. PLEXOS does not include a default technology type to represent such operation, so we instead include CAES as two coupled generators: one representing the storage facility and one representing the gas facility. These generators are linked through constraints in PLEXOS, ensuring they operate together and produce an equivalent output to a true CAES facility. This representation is used both for the existing CAES facility in Alabama and for any new CAES facilities built by ReEDS.

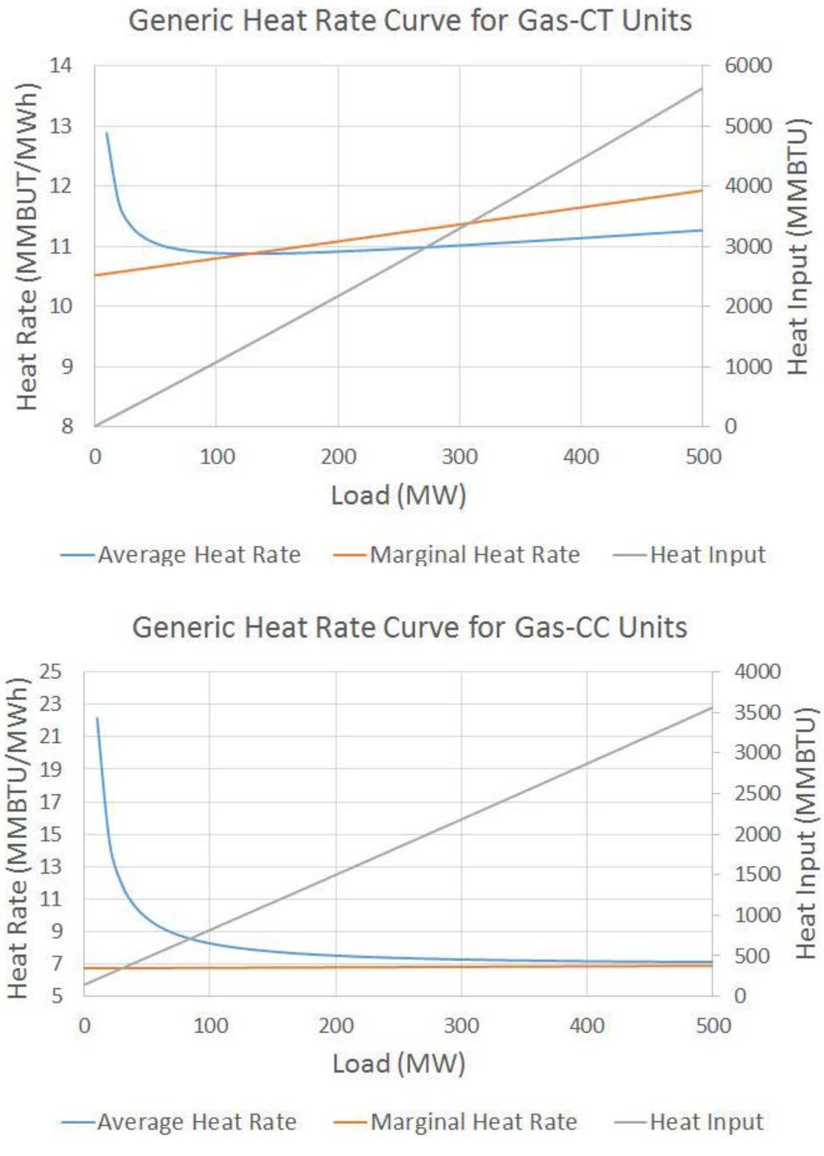

Figure 4. Generic heat rate curves for gas generators

The variable renewable profiles used are the same profiles by region and supply curve bin as are used in the ReEDS solutions for the particular weather year indicated in the input file, with individual profiles being scaled based on degradation (for solar photovoltaics) and technology improvement (for wind) as is done in ReEDS. The inverter loading ratio is used directly in the profiles, but the clipping of energy based on inverter rating is not modeled within PLEXOS. This feature may be included in future work for more accurate representation of hybrid technologies. Additionally, all variable renewable energy and load profiles are shifted to be in Eastern Standard Time.

3 Example of ReEDS-to-PLEXOS Analysis

In this section, we present an example of a scenario from ReEDS that was processed in PLEXOS, both to demonstrate the capability of the methodology to reproduce ReEDS outputs with fidelity and to showcase a few analyses that can be done with this capability. Though we anticipate many analyses will use this capability in the future, the results we present here are not intended to provide any analysis on the scenarios presented or CEMs in general—they are intended only to demonstrate the ability of this translation process to accurately represent outputs from ReEDS as well as the potential benefits of enabling a tool to analyze hourly unit commitment and dispatch of future grid scenarios created by CEMs.

The results shown here represent mid-line and low renewable energy cost scenarios from the 2020 version of ReEDS.

3.1 Comparison to ReEDS

3.1.1 Capacity

After generator aggregation and disaggregation, the resulting installed capacities in the production-cost modeling database and the ReEDS solution are effectively equal (Figure 5). Thermal generators have been broken up into realistically sized units as described in Section 2.2 (page 8), and only minor amounts were dropped as shown in Table 4. These figures simply demonstrate that the translation process is accurately representing the ReEDS solution in PLEXOS, enabling analysis of multiple diverse ReEDS solutions.

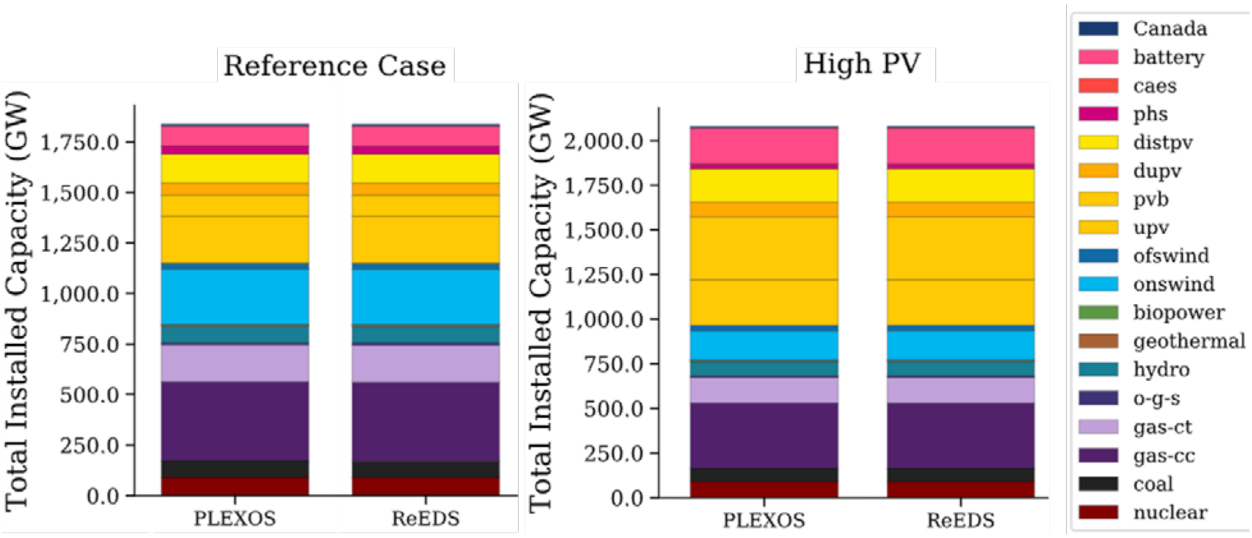

Figure 5. Comparison of the total installed capacity in PLEXOS and ReEDS for the 2050 ReEDS solution for the Reference Case (left) and with High PV capacity (right), demonstrating the translation effectively reproduces ReEDS total capacity

Table 4. Capacity Totals by Type: ReEDS and PLEXOS

The translation process drops small amounts of capacity to maintain reasonable unit sizes, and it may not fully retire units if partial unit retirements would be required to meet ReEDS specified retirement value

	Reference Case			High PV Capacity		
Technology	**ReEDS Capacity (GW)**	**PLEXOS Capacity (GW)**	**Difference (GW)**	**ReEDS Capacity (GW)**	**PLEXOS Capacity (GW)**	**Difference (GW)**
Canada imports	8.8	8.8	0.0	8.8	8.8	0.0
Battery	98.0	97.9	0.1	200.8	200.7	0.1
CAES[a]	0.00	0.22	-0.22	0.00	0.22	-0.22
Pumped storage hydropower	41.1	41.0	0.1	26.8	26.8	0.0
Distributed PV	141.1	141.1	0.0	186.5	186.5	0.0
Distributed utility PV	61.4	61.4	0.0	83.4	83.4	0.0
PV-battery	104.9	104.7	0.2	351.4	351.3	0.1
Utility PV	231.7	231.7	0	255.7	255.7	0.0
Offshore wind	31.3	31.3	0.0	31.3	31.3	0.0
Onshore wind	272.8	272.8	0.0	162.1	162.1	0.0
Biopower	2.7	2.4	0.3	2.7	2.4	0.3
Geothermal	7.5	7.5	0.0	6.4	6.8	-0.4
Hydropower	79.7	79.7	0.0	79.5	79.4	0.1
Oil-gas-steam	10.5	10.1	0.4	9.5	9.0	0.5
Gas-combustion turbine	184.4	183.9	0.5	144.7	144.3	0.4
Gas-combined cycle	390.2	390.6	-0.4	363.0	363.4	-0.4
Coal	82.4	83.6	-0.8	77.3	77.2	0.1
Nuclear	88.8	88.9	-0.1	88.8	88.9	-0.1

[a] The Alabama CAES plant is represented as a gas-combustion turbine in ReEDS. It is converted to a CAES plant during the translation process.

3.1.2 Generation

A small but noticeable difference in the generation results for the two models is due to the lower temporal resolution in ReEDS and subsequent heuristics made within ReEDS to better represent grid operations. The largest differences in generation between ReEDS and PLEXOS tend to be in the thermal fleet, including gas-combustion turbine, gas-combined cycle, and coal technologies (Figure 6, page 17). Specifically, resources that might be used for peaking purposes such as natural gas-combustion turbine (gas-CT) units have large relative differences in generation.

The 2021 Standard Scenarios (Cole et al. 2021) included a minimum capacity factor requirement in ReEDS such that all capacity has to operate with at least a 6% annual capacity factor or the units would be retired, added in ReEDS to prevent excessive mothballing. This leads to increased generation from gas-CT units in ReEDS relative to the operation as determined by PLEXOS, which has no such annual requirement. Comparison of these annual generation numbers are useful for understanding any potential differences that might arise between the models. Though exact matching is not necessarily expected, being able to explain the noted differences (as in the gas-CT requirement above) is important for both models and having confidence in the results.

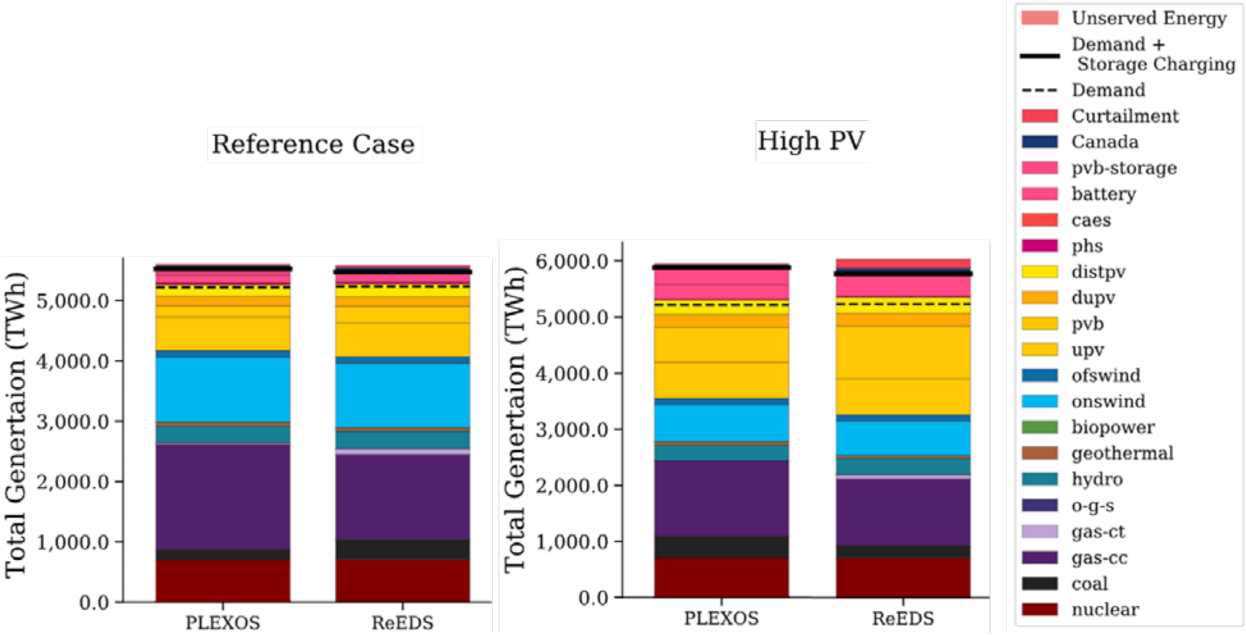

Figure 6. Comparison of the total generation in PLEXOS and ReEDS for the 2050 ReEDS solution for the Reference Case (left) and with High PV capacity (right)

3.2 Hourly Operations

A major benefit of running ReEDS scenarios through PLEXOS is that you can better capture operational challenges that might be seen in these scenarios under the variable conditions that occur from day-to-day changes in load and variable generation output, including potential resource adequacy concerns if load cannot be met in certain regions. As noted above, PLEXOS typically runs full-year hourly simulations with unit commitment of individual generators for a specified weather year, which allows for detailed analysis of how the future grid might operate throughout that entire year. Figure 7 shows the hourly operations for a specific week of dispatch for the entire continental United States, in this case the week containing the peak demand period. Though ReEDS dispatch time-slices capture major factors such as total demand, periods of availability of wind and solar, and dispatch of storage, time-slices represent average conditions during the specified time frame and cannot explicitly capture phenomenon such as multiday periods of low-quality resource, extreme weather events, or forecast uncertainty. While the Augur module in ReEDS is designed to address these issues, providing important feedback to the ReEDS investment formulation, using a PCM in tandem with ReEDS helps to more completely understand potential operational challenges that a changing grid might encounter.

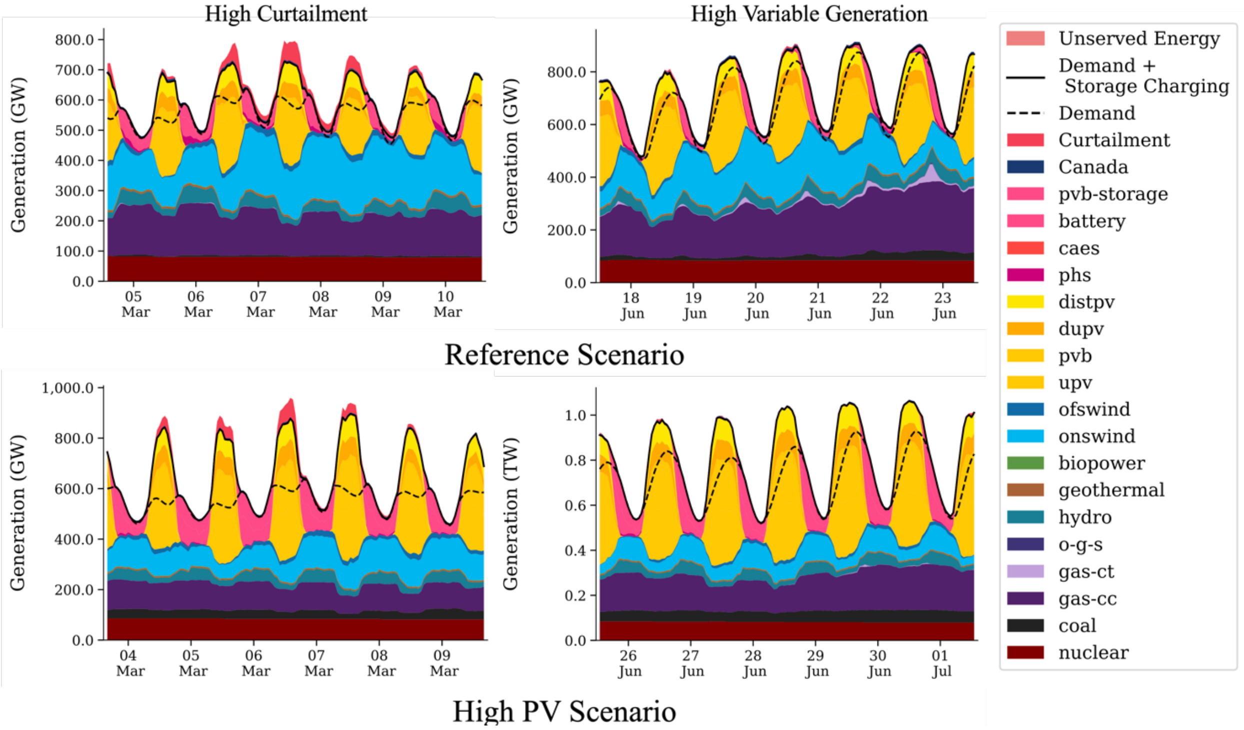

Figure 7. Hourly operation of two weeks showing high curtailment (left) and high variable generation (right) for the Reference Case (top) and the High PV Scenario (bottom)

Hourly dispatch allows for identification of low probability but important operational challenges that may occur in future power systems.

Curtailment is another important aspect of grid operations that is typically challenging to accurately capture in capacity expansion models because of the wide range of factors that influence curtailment in real systems. ReEDS includes a linear hourly dispatch module—Augur (Gates et al. 2021)—to estimate curtailment for existing and potential new units to better inform the modeling investment decisions.[6] Comparing curtailment seen in PLEXOS modeling with ReEDS estimations provides an important feedback for ReEDS modelers to understand how they might improve ReEDS' representation of curtailment to better capture this important driver of build decisions in the model. This feedback cycle has occurred several times and is likely to (1) be a continual process as both models are further refined and (2) incorporate new drivers in higher-penetration systems. Figure 8 shows the curtailment duration curve from PLEXOS and ReEDS simulations.

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[6] Within ReEDS, estimations of curtailment and capacity credit must be made for each potential new technology type to better represent their impact on the grid for investment decision making.

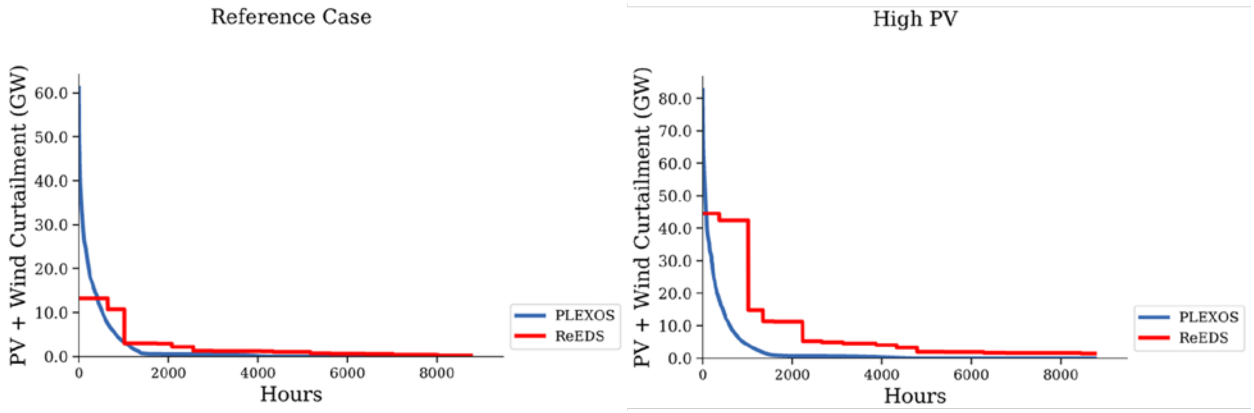

Figure 8. Curtailment of variable resources in ReEDS and PLEXOS for the Reference Case (left) and High PV Capacity Scenario (right)

The Augur module computes hourly expected curtailment and then passes the aggregated curtailment by time-slice back to the main ReEDS optimization model. The time-slice aggregated curtailment, as seen in the investment optimization within ReEDS, tends to miss the hours of highest curtailment, as would be expected for a limited resolution model. This underscores the ability of full hourly dispatch to capture low-frequency but important events. These low-frequency events might not strongly impact investment decisions, but they are important for grid operators to understand how future and changing grid systems might be operated differently than today.

3.3 Unserved Energy

Unserved energy, or dropped load, is unacceptable when planning for typical operations in any power system. While some unserved load may be acceptable and expected to occur during times of system stress, typical requirements are for dropped load on no more than 1 day in 10 years. When modeling ReEDS solutions in PLEXOS, checking for dropped load is used as a proxy for assessing system adequacy. ReEDS uses a planning reserve margin for capacity as a resource adequacy requirement, such that in theory no load should be dropped under normal operating conditions. However, dropped load can appear in PLEXOS because of model approximations, planning reserve margin definitions, or differences in assumptions between ReEDS and PLEXOS. Developers iterate between PLEXOS and ReEDS to improve assumptions where needed.

Planning a least-cost set of resources for the power system necessitates serving demand with the minimum investment required. With this in mind, we use dropped load in PLEXOS to assess resource adequacy assumptions, methods, and data in ReEDS. Depending on the analysis being done, we might tolerate very small amounts of dropped load or even find validation in the fact that these small occurrences indicate our solutions are likely close to the true optimal least-cost solution. However, PLEXOS is a deterministic tool that models only a subset of potential operating conditions. However, tools such as the Probabilistic Resource Adequacy Suite (Stephen 2021) can be used to assess resource adequacy more robustly and under a wide range of operating conditions. Such analysis can be done either in tandem with a ReEDS-to-PLEXOS translation or separately to specifically analyze resource adequacy.

Figure 9 shows the time-series profile of unserved energy in the Reference Case and High PV Capacity Case. In both scenarios, a few hours have dropped load throughout the year, but they never exceed 50 MW in a system that peaks around 950 GW, or 0.005% of demand. This small amount of unserved load could be further analyzed if researchers determined it were of concern or could be caused by imperfect representation within PLEXOS—and not an expectation of failure to serve load in these hours.

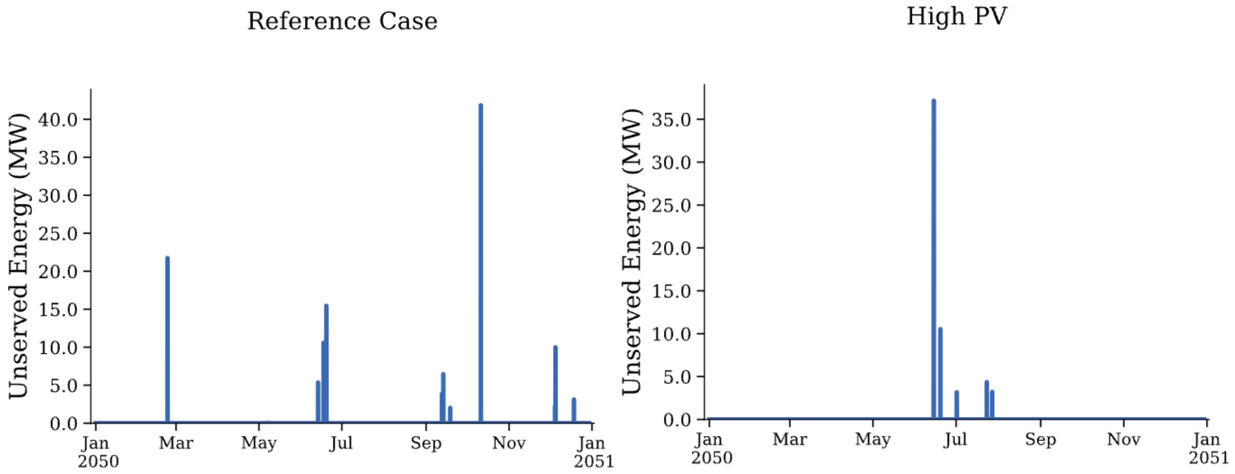

Figure 9. Unserved energy in PLEXOS for the Reference and High PV scenarios

Unserved energy represents less than 0.005% of demand.

4 Conclusions

Capacity expansion models and production cost models are important tools used to analyze important aspects of future grid systems, particularly under the changing drivers and market conditions we expect to see in the future. We have here presented the assumptions and data used for a tool to translate between these types of models and thus enable a richer set of analyses for the evolution of the power system. This translation process ensures the production cost model databases created mirror the ReEDS capacity investments as closely as possible while adding in detail needed to accurately capture commitment and dispatch decisions at an hourly resolution. The assumptions made are configurable by the end user, but they represent generally applicable values. We also present results from two examples of scenarios to demonstrate the improvement in temporal resolution that is possible with this two-staged analysis approach.

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