PNNL-28596

Future Grid State Modeling for Transactive Systems

April 2019

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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Executive Summary

The simulation design and evaluation of a transactive energy system is contingent on the setting in which it would exist, which could vary significantly with the many drivers that impact the potential future states of the power system. This report summarizes the development of the Transactive Future Grid State (TFGS) model, which is a lightweight capacity expansion model that will support transactive energy research by allowing users to explore alternative future states.

The TFGS model determines the long-term generation capacity needs of a given power system that satisfy specified constraints and support a least cost hourly dispatch. This is accomplished by solving a single optimization problem that simultaneously finds the generation fleet with capacity sufficient to meet peak load and the flexibility to meet hourly operational dispatch, all at lowest cost.

The TFGS model was applied to a larger ongoing study taking place that will be simulating how distribution system operators (DSOs) could use a transactive energy system to manage distributed energy resources. The larger study, commonly referred to as the DSO+T study, involves two parallel analyses; one that represents the system today and one that represents a future system with a high degree of renewable energy penetration. The TFGS model provided the generation mix of the high renewable base case.

As the TFGS model was being used to provide inputs to the DSO+T study, two issues became apparent. First, additional functionality would have been useful, and second, a larger-than-anticipated amount of user inputs and data were required to successfully use the TFGS model. These discoveries have lead to the recommendation of specific functionality that can be added in future development of the tool.

Acronyms and Abbreviations

DSO	distribution system operators
ERCOT	Energy Reliability Council of Texas
RPS	renewable portfolio standards
TES	transactive energy system
TFGS	Transactive Future Grid State

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1.0 Introduction

As documented by Hardy and Corbin (2018), the simulation design and evaluation of a transactive energy system (TES) is contingent on the context, or system state, in which the system would be present. In some cases, it is meaningful to evaluate the transactive system a future state of the power system. Many future states of the electric power system are plausible and vary significantly because of the many possible combinations of political, economic, societal and technological drivers. Being able to explore alternative future scenarios will not only guide the development of a TES but will also help define scenarios that would be suitable to use in simulation studies. This report summarizes the effort to facilitate that exploration of future states through an optimization model that was developed and used to support ongoing transactive energy research. Specifically, the model was developed to define the generation mix at a future point in time for a particular power system given data related to load behavior, generation capital costs, fuel costs, and renewable portfolio standards. This model, the Transactive Future Grid State (TFGS) model, can provide a more concrete understanding of the context of a future grid state and will allow for a more robust simulation and TES design.

The TFGS model requires user inputs regarding system requirements, compositions, and costs. Given a particular requirement (such as load growth or a renewable energy requirement), the model then works to find a least-cost solution. This solution would be limited by generation profiles, load profiles, generator ramp rates, and other system limitations. While the model requires extensive user inputs, it allows the TFGS model to produce an output that is plausible and cost optimal. The model's simplicity, while necessarily producing less accurate and detailed results than other similar, higher fidelity models, is able to provide a plausible generation mix at a future point in time. This is a key component in understanding the future state of the power system. Though there are other tools that provide similar functionality (see Section 4.0 for further details), all are more complicated and require even more extensive input data. As such their use was out of out of scope in this work.

The TFGS model was designed with the immediate purpose of providing inputs to a larger ongoing study (specifically, a reasonable generation mix to use in their analysis and simulations) that will be simulating how distribution system operators (DSO) could use a TES to manage distributed energy resources. The study commonly referred to as the DSO+T study, involves parallel analyses of two scenarios—one with a moderate amount of renewable energy penetration, which is similar to the current state of the power system, and one with a high level of penetration of energy from renewable resources. The TFGS model will provide inputs to the second scenario of high renewable energy penetration, specifically a coherent generation mix representing key assumption about this high renewable future state. Discussions of how the TFGS model was used to achieve this and the results of the model are included in Section 1.0 to demonstrate potential applications of the model.

2.0 TFGS Model Description

The TFGS model is a capacity expansion model that determines the long-term generation capacity needs of a given power system (potentially over many years of operation) by determining the least-cost generation dispatch to meet load on an operational time-scale. The result of the model is an evolving generation mix driven by load growth and changes in costs of construction and operation of generation assets. The model accomplishes this by solving a single optimization problem that answers the following two key questions simultaneously:

1. For each generation investment period (e.g., annually), what is the least-cost generation fleet that is necessary to meet load for the year?
2. Given a particular generation fleet, what is the least-cost dispatch of that fleet to meet the load for a given operational period (i.e., for a given hour of the year in question).

These two questions are very similar and inter-related but address the challenge of meeting load on two different time scales (i.e., the investment time period vs. the operational time period) by determining which generators need to exist and how to best use them. For example, if we think of the 20 consecutive investment periods of one year each and each investment period is composed of 8760 consecutive one-hour operational periods, the TFGS model simultaneously determines 1) which generators to construct (and decomission for every year and 2) the most economical means of dispatching the generation during each year to meet load.

The TFGS model formulates this as an optimization problem that solves the problem on the two distinct time scales simultaneously. This optimization is implemented as relatively a simple linear programming problem that limits the potential constraints to be implemented but also takes very little time to solve. A full mathematical description of optimization formulation is provided in Appendix A but some of the key assumptions and constraints are summarized below.

- *Single electrical node.* The TFGS model does not implement a transmission system model and assumes all load and generation are co-located. There are other more complex models and tools (some of which are discussed in Section 1.0) that do not make this assumption. The results they produce can be more readily tied to a real power system; however, the computation and data requirements of those models are much greater and exceeded the scope of this work.
- *Vertically integrated power system operator.* The TFGS model assumes the same entity that is paying for power plants to be built also will be paying to operate them and collecting revenue from customers. That is, the model is more similar to the situation a vertically integrated utility would face when making integrated resource planning decisions than what may be faced in deregulated energy markets. The TFGS model does not model market operations in any way.
- *Renewable portfolio standards (RPS) targets are defined.* The TFGS model allows users to define an RPS target for each investment period that the tool must meet through commissioning (and if necessary, decommissioning) the appropriate power plants for that investment period. The RPS target is defined on an annual energy basis.
- *Generation is grouped by user-defined classes and classified as dispatchable or non-dispatchable.* Users define generators by type and with identical ratings across the entire class. Dispatchable generation is dispatched based on cost and performance, while non-dispatchable generation (renewables) uses a user-pre-defined load profile to determine its output. Thus, users can create a wide variety of classes of generation based on fuel type, generation technology, marginal cost, etc.

This allows for greater flexibility when defining existing or candidate generators and dramatically reduces the data entry requirements.

- *Generation classes dispatched with continuous output.* To avoid the computationally complex difficulty of handling the unit commitment problem, each generator class is dispatched as a single unit with a capacity equal to the total installed capacity of that class. It is assumed that a well-managed fleet of each generator type could manage unit commitment in an efficient manner.
- *Load can be unserved.* The user provides a fixed cost of not meeting load, and the TFGS model may find it is cost optimal to not meet load during some operational periods rather than build a whole new generator that runs very few hours of the year or over its lifetime. Practically speaking, is an option of last-resort but including a specified cost of unserved load places an upper limit on what should be reasonably spent before looking for other methods of managing the balance-of-load and generation.
- *Load growth is fixed with a pre-defined profile.* Load growth is defined as a fixed value over each investment period. The load profile is defined for each operational period and used for each investment period, scaling as defined by the load growth factor.
- *Reserve requirements are defined as a fixed percentage of total generation and there is a cost of not meeting this reserve.* Similar to how loads may go unserved if a new power plant is required with only a few hours of operation to meet load, the reserve requirement of the system also can be violated if the costs of meeting it are sufficiently high. As in unserved load, this value is determined by the user and presumably is lower than the cost of unserved load.
- *Fossil-fueled generation has both constraints on power as well as ramp rates.* Least-cost, steady-state operation is a key concern for economic operation of the power system, but ramping capability of generation is an essential consideration when attempting to balance generation and load. The TFGS model provides the user with the ability to define both the marginal operating costs and the power and ramping capabilities of each class of generation.
- *Generation has both commissioning and decommissioning costs.* Not only does the TFGS model consider how much it costs to build a power plant, it also considers the costs of removing it from operation. These costs are non-trivial and may lead to marginally profitable generators remaining in the dispatchable generation fleet even if they hardly operate at all, It may be cheaper to infrequently run those generators rather than decommissioning them. Commissioning costs are annualized based on the expected lifetime of generators. If this were not the case, the entire cost of commissioning would have to be realized in one investment period for the TFGS model solution.
- *Generators have age and operational lifetime.* Although the performance of the generator does not change over time (i.e., investment periods), the age of each generator is defined, and each generator has a fixed lifetime. Once a generator reaches end-of-life, it is decommissioned.
- *Renewable generation is modeled with a pre-defined output profile.* The output profile has a unique value for each operational period. The pre-defined profile is used for all generation of that type for every investment period.

As mentioned previously, the TFGS model solves for a least-cost generation profile that meets the load for a given operational period. In addition, a user can add additional constraints that must be met, such as load growth or an RPS requirement over a given investment period. In solving for an optimal outcome, the model considers constraints and assumptions that were discussed previously. Because the optimization is run on a least-cost basis, all of the relevant system costs are necessary inputs that the user must provide. Additional user inputs include a detailed load profile, renewable-generation profiles, and reasonable initial generation composition and limitations. The required cost-related user inputs are the value of lost load, reserve value, commissioning and decommissioning costs per generator, fixed operating costs, and fuel costs, which are treated as the marginal costs. If the TFGS model is being used to estimate the additional capacity needs of a power system that is experiencing load growth or an RPS standard, it would be expected that commissioning of new units would be necessary. In a load growth scenario, the model will consider the load profile and generation profile when determining what type of generating unit would be adequate to meet additional load. The adequate generation source with the least costs associated with it would then be commissioned unless the cost-optimal solution was to undersupply, which was discussed previously. In a scenario requiring a certain percentage of the load to be met with renewable energy generation sources, the TFGS model will likely build additional renewable-generation units. In this case it is likely that the TFGS model will build units of the least-cost generation source until the requirements are met unless additional system requirements, such as the maximum number of units that can be within the system for a particular generator, limit the least-cost option. Each generation source has associated costs, so it may be applicable to have different generation classes for the same resource with different costs and a maximum number of units to represent early development opportunities within a system.

Within any given time interval, the TFGS model will choose to operate the system on a least-cost basis. Because the marginal costs are limited to fuel costs, load will not be served from generators with the highest fuel costs when that is an option. This will be subject to the previously discussed constraints; however, however, because no fuel costs associated with renewables and very little fuel cost is associated with nuclear power, the model will choose to fulfill the load with these options when possible. The result is a system minimizes costs by operating with the least amount of fuel, or marginal costs, as possible.

Decommissioning can be expected if a generator unit is consistently not being used by the system. The TFGS model compares the ongoing fixed operating costs to the decommissioning costs of the unit. At the point at which the fixed operating costs exceed the decommissioning costs, the output of the TFGS model will show decommissioned units. This may not happen in an analysis with a small amount of investment periods, because it may take multiple periods for the operating costs to exceed the decommissioning costs.

3.0 TFGS Model Demonstration

3.1 Demonstration Problem Description and Setup

As the the most immediate user of the functionality provided by the TFGS model, a use-case from the DSO+T project was used to demonstrate it's capability. To evaluate the effects of the transactive systems in a wide variety of grid states including one where RPSs (in this case, with a goal of 50% energy), a dramatically different generation mix than exists today needed to be defined via the TFGS model.

We used the TFGS model to provide a generation mix to be used in the DSO+T transmission system model and to help define the distribution-side solar penetration in the high renewable-generation analysis. This use of the model differs from what may be considered a typical use of the TFGS model because it is being used to generate a system that represents an alternative present day rather than a future state. That is, the system was allowed to change radically (widespread commissioning and decommissioning) to achieve the high renewable energy targets rather than evolve over the course of decades to more naturally reach a new state. To achieve this, only a single investment period of one year was modeled, thus forcing the TFGS model to determine a single set of generation facilities to commission and decommission to both meet this RPS requirement and the load over that single year. Decommissioning costs were also set to zero for all generation types except nuclear power plants (see later discussion on the special treatment of nuclear power plants). This one-year process reduces the input data requirements while allowing a reasonable approximation of what a high-renewables generation mix could look like.

The inputs to the model in this scenario consist of 2016 data for the State of Texas, which was provided by the Energy Reliability Council of Texas (ERCOT). These data include generation profiles for each source of generation, a load profile, and the costs associated with the system. The load growth factor that was entered into the model was 1 with a renewable requirement of 0.5, which means that system shown in the output will be serving the same load but with half of the generation coming from a renewable source, in this case wind or solar. Because of the one-year analysis for this application, decommissioning costs of the generators were not included, other than for nuclear power plants. This was done to ensure a resulting generation mix that not only added renewable generation to the system but removed non-renewable generation that may have not needed to be built in a scenario with such a high renewable generation standard. Decomissioning costs were included for nuclear power plants due to the cost, safety and political factors as it was assumed they would be retained for even if their marginal operating costs were higher than renewable generation sources.

An additional requirement—a defined amount of energy coming from solar to meet the set requirement of 50% renewable energy—was added to ensure the model outputs were reasonable. In solving for an optimal solution to the renewable requirement without this additional requirement, the TFGS model will build the most cost-optimal generation to meet the renewable requirement, which in this case was wind generation. The model is only aware of the cost-related limitations that would require a mix of renewables to be added to the system and the cost benefit to having a diverse generation profile. In this case, it was known that the desired outcome was that 20% of the renewable energy came from solar, so that requirement was added to the model. An additional way to achieve this would have been to change the input that limits the units of each generation type allowed within the system. If wind had been limited to a number of units that would only account for 30% of the energy, the TFGS model would have developed solar to meet the 50% RPS requirement.

Following is a listing of the key data sets constructed to serve as input for the TFGS model when run to determine the generation mix under a 50% RPS for ERCOT.

- Value of lost load: https://www.ferc.gov/CalendarFiles/20160629114652-3%20-%20FERC2016_Scarcity%20Pricing_ERCOT_Resmi%20Surendran.pdf. ERCOT defines a Value of Lost Load at $9,000/MWh which effectively sets a price cap for the energy market.
- Generation parameters:
  - Generator nominal capacity by fuel type: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf. Table 1 for 2016.
  - Generator fixed operations and maintenance costs by fuel type: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf. Table 1 for 2016 adjusted by regional factors defined in Table 4.
  - Generator commissioning costs fuel type: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf. Table 1 for 2016, overnight capital costs, adjusted by regional factors defined in Table 4.
  - Generator decommissioning costs fuel type: http://www.rff.org/files/document/file/RFF%20Rpt%20Decommissioning%20Power%20Plants.pdf. Table 1. No costs for nuclear power plants were provided, and this entry into the TFGS model was left blank as the existing nuclear power plants in ERCOT were assumed to remain during a 50% RPS mandate.
  - Generator lifetimes by fuel type: http://www.rff.org/files/document/file/RFF%20Rpt%20Decommissioning%20Power%20Plants.pdf. Table 2.
  - Generator heat rate by fuel type: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf. Table 1 for 2016 adjusted by regional factors defined in Table 4.
  - Generator fuel costs by fuel type: https://www.eia.gov/electricity/annual/html/epa_08_04.html
- Energy Storage: http://www.pacificorp.com/content/dam/pacificorp/doc/Energy_Sources/Integrated_Resource_Plan/2017_IRP/10018304_R-01-D_PacifiCorp_Battery_Energy_Storage_Study.pdf. All parameters used are for a lithium-based battery.
- Load profile: http://www.ercot.com/gridinfo/load/load_hist/. 2016 hourly load data.
- Solar generation profile – Solar generation profiles for the State of Texas were synthesized by aggregating solar installations at the county level. To begin, a list of residential, commercial, and industrial solar installations was retrieved from National Renewable Energy Laboratory's Open PV Project. Similar installations, in terms of panel tilt and azimuth, within each county were aggregated so that each county was represented by between 1 and 12 installations. The geographic location of the installations, which is used in the power production calculation, was set equal to the geographic center of the respective county. Next, solar irradiance and weather measurements were collected from the National Solar Radiation Data Base for each county at one-hour resolution for the year 1998. To generate a solar generation profile, a time period of interest was selected. The aggregated solar installation parameters and measurements then were used to calculate power production. Finally, the state-level profile was generated by summing the solar output from all aggregated solar installations.

- Wind generation profile: https://www.nrel.gov/docs/fy18osti/70414.pdf. The specific profile used was the "Northwestern TX" profile distributed with the System Advisor Model.

3.2 Results

Running the TFGS model for the scenario described above resulted in a generation mix shown in Figure 1. As can be seen, the installed capacity of coal is extremely small in this alternative power grid state, 63 out of 65 coal power plants would have not been built as the capacity was not needed once the RPS was met by installing additional solar and wind generation. Solar installations went from 720 MW to 37,600 MW and wind installations from 20,000 to 223,500 MW this ratio roughly met the target of 20% solar and 30% wind for the RPS.

Given the much higher capacity factor of the wind generation profile (approximately 0.51 for wind and 0.21 for solar), **Figure 2** even with the much smaller number of wind installations , the resulting energy generation was much higher. Wind generation was 20% of the installed capacity but produced 30% of the energy while solar generation was 32% of the installed capacity but produced 20% of the energy.

Looking at the traditional thermal generator classes, nuclear generators operated in baseload mode producing their rated power for the entire simulation; that is, 4% of the installed capacity but 11% of the generated energy. On the other end of the spectrum, fast-ramping natural gas combustion turbines were 5% of the installed capacity but provided less than 1% of the energy. This result is expected as these types of units are installed to provide ramping capability as the load (and renewables) output vary. Interestingly, no additional natural gas combustion turbines were required to meet the additional ramping requirements caused by adding a significant amount of renewables to the power system. This implies that the ramping capability of the current generation mix is sufficient to meet the presumably much higher ramping rates caused by significant wind and solar installations.

Figure 1. Comparison of Installed Capacity between the Base Case and High Renewable Case

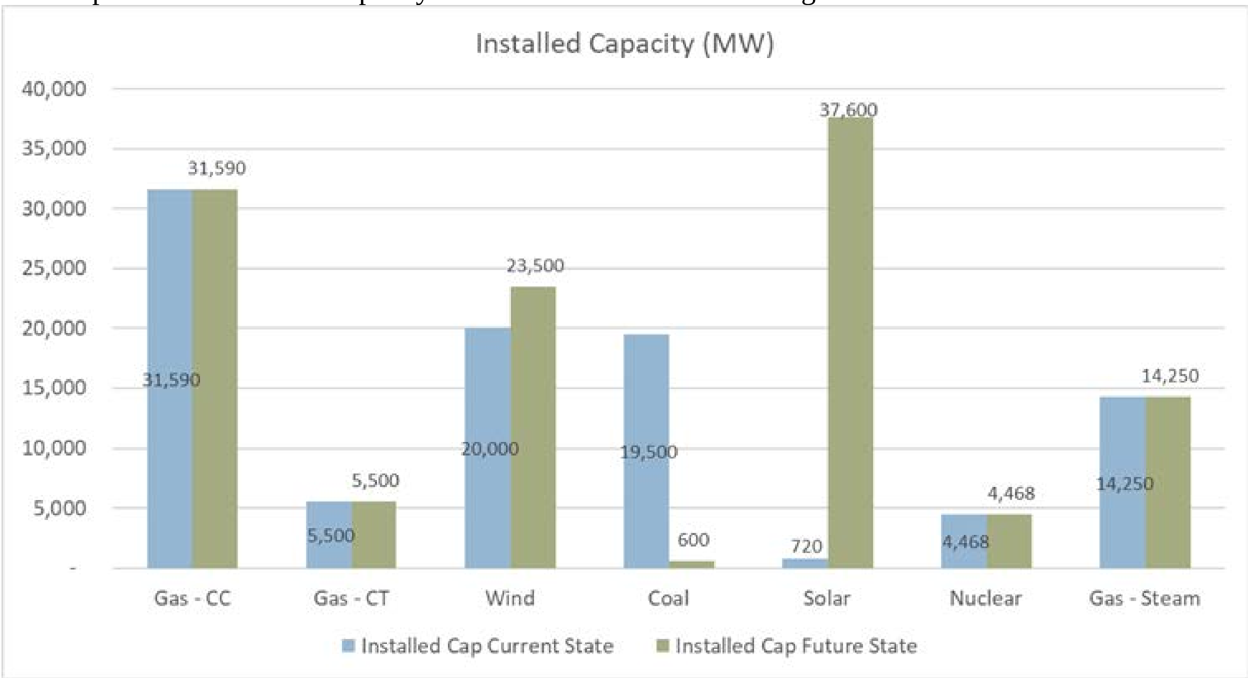
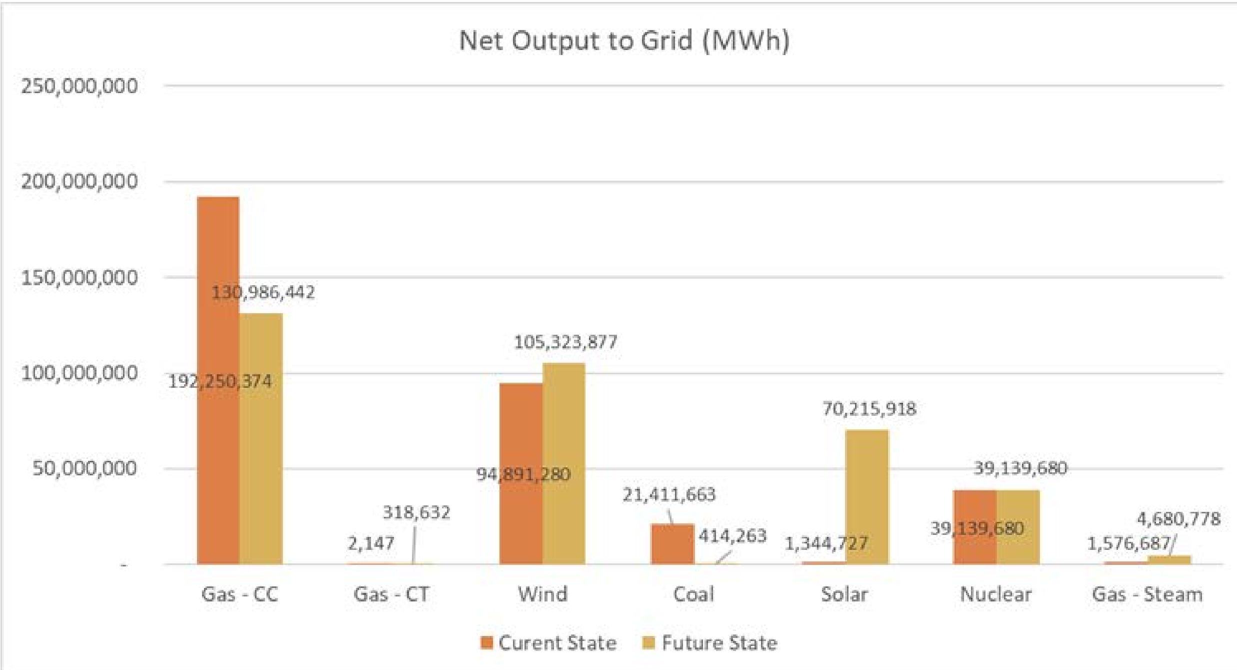


Figure 2. Comparison of Energy Generation between the Base Case and High Renewable Case



4.0 Conclusion and Additional Needs

As shown in section 3.0, the TFGS model was able to produce a plausible generation mix for the alternative grid state defined by the requirements of the DSO+T study. Additionally, the model was able to produce these results very quickly (less than ten seconds for a single, hourly one-year run) with publicly available data.

Through the process of developing the TFGS model and applying it to the DSO+T study, it became apparent that certain aspects of the model may limit its utility. It is important to discuss these issues so potential users can make appropriate model selections and to identify additional efforts that could be made to address the issues.

The data requirements for the TFGS model are non-trivial and may hinder application of the model to studies that do not have access to the necessary data. Even with available data, its collection and input into the model is a time-consuming effort that should be considered when planning for use of the TFGS model. The TFGS model's data needs include, but not limited to, load profiles, generation profiles, current generation mix, capital costs, operating costs, fuel costs, commissioning and decommissioning costs, and ramp rates. For an analysis similar in nature to the one provided for the DSO+T project (see discussion in Section 3.0), to produce results that most closely match the region in question, the data must come from said geographic area under analysis, which poses an additional hurdle in the availability of data specific to that location and system.

The TFGS model does not include a transmission system model and doing so would be essential for studies that evaluate the evolution of an integrated transmission and generation system. The transmission system has significant associated costs and creates limitations in the ability for any generator to effectively serve any load. For this reason, the TFGS model may generate a solution to the constraints that involves building new generation units that would not be able to be supported by the existing transmission system. This additional cost would not be factored into the solution, and those costs would likely impact whether or not the added generation was actually part of a viable solution. If some transmission limitations are known, it might be able represent them by adjusting the maximum unit of a generation source limitation, but additional data would be needed to define the limit.

The least-cost optimization also inherently results in some results that conflict with what one would reasonably expect to see in the generation mix for a power system in the real world. The differences primarily result from the inability to fully and efficiently express both the economic and non-economic factors that drive generation decisions as parameters in the optimization. It is important, though, to understand the extent to which results provided by a model differ from reality before applying a modeling approach to an analysis. One example of this encountered during application of the TFGS model to the DSO+T study was the treatment of renewables and nuclear generation. Because the marginal costs in the TFGS model are represented by fuel costs, nuclear generators had a very minimal associated fuel cost, whereas wind and solar had none; therefore, the model would choose to curtail nuclear generation prior to wind and solar, which is not how the power system is typically operated today. Nuclear generation is treated as a baseload resource, and renewable generators would be expected to curtail even in a situation in which penetration by renewable generation is high. Most problems like this can be solved, like the previously mentioned drawbacks, by adjusting inputs to ensure a reasonable output from the TFGS model, but in some cases it might be necessary to add features to the model. In the example of nuclear power, input adjustments would include lowering ramp rates on nuclear generators to better mimic normal operating practice.

The TFGS model is an electricity generation capacity expansion model. Other models of this type also have difficulty reflecting normal hourly operating practice in a model of capacity decisions on a time scale of decades. The TFGS model determines the costs associated with unit commitment decisions and can be configured to model some portion of the discrete nature of unit commitment decisions if it is solved as a mixed integer program rather than a linear program. To include this level of unit commitment detail, individual plants must be aggregated to the technology level. When a given technology contains a large number of plants or the model is solved as a linear program to keep the solution time manageable, the hourly operating results can be unrealistic when compared to actual operating results.

Other capacity expansion models have addressed these difficulties in different ways. The National Energy Modeling System (Gabriel et al. 2001) and the Regional Energy Deployment System (Short et al. 2011) are two examples in which individual plant fidelity, unit commitment decisions, and even the discrete nature of capacity decisions are not prioritized. The Renewable Energy Solutions Model (Energy and Environmental Economics, Inc. 2016) and some clustered unit commitment models (Palmintier, Bryan, and Webster 2014; Levin and Botterud 2015) are closer to the approach used for the TFGS model. All of these models are more complex and require greater input data sets and generating corresponding results to compare to the TFGS model results was out of scope for this project.

All of these tools are more complex and have greater data requirements than the TFGS model, and they incorporate higher fidelity models that would be expected to produce more realistic results. For example, the National Energy Modeling System has a multiple modules that consider specific energy activities such as the electricity market, oil and gas market, and the liquid fuels market, and it also has modules that can model more general features such as residential demand and general macroeconomic activity.[1] The model is used to produce the *Annual Energy Outlook* report and, as such, is intended to be a high-fidelity, robust model. Because of its complexity, it is used mostly within the Energy Information Administration[2] although it is largely an open-source model that is available for use by others. While these drawbacks to the TFGS model may hinder the further its applicability to additional studies, it was able to fulfill its original intent of providing a base case generation profile for the high renewable analysis in the DSO+T study.

[1] https://www.eia.gov/outlooks/aeo/nems/documentation/.
[2] https://www.eia.gov/outlooks/aeo/info_nems_archive.php.

5.0 Recommendations

The TFGS tool provides a reasonable method of estimating a plausible generation mix given the definition of a relatively limited number of parameters (generator costs and operating parameters, fuel costs, expected load profile, etc…). Many of these parameters can be estimated from publicly available data sources and though general in nature, capture the distinct operating characteristics of the generation sources. Additionally, TFGS is specifically built to ensure the resulting generation mix meets a user-defined RPS.

The simplicity of the model, though, produces limitations that have been discussed:

- Even though dramatically reduced, the data requirements are non-trivial
- The transmission system is not modeled and its effects on generation construction are thus not considered.
- Non-economic factors (business relationships, political factors, technical system constraints) that drive real-world generation decisions are not easily, fully represented which can lead to results that are less realistic.

Adding to the above, the method in which these system constraints are currently expressed is an input spreadsheet with parameterization that is convenient for the optimization developers but somewhat obtuse for the users of the tool. The expediency of this method was deemed acceptable given the research nature of the tool development. However, it can be awkward for other researchers to use more generally.

This tool occupies a niche for lightweight capacity planning that produces plausible results. All future development of the tool would need to maintain this lightweight nature while improving the usability or expanding the scope of considerations for the capacity planning study. Given this, consideration should be given to the following points regarding the development of the technical capability and usability of the tool.

1. Develop a more user-friendly method of capturing the necessary inputs from the user.
2. Develop a set of standard or default inputs (where appropriate) that users can leverage. Examples include generator costs and technical capabilities.
3. Explore methods by which transmission system constraints can be added to the optimization formulation without overly complicating the input requirements the user must provide. A similar, but more modeling intensive tool used by Energy and Environment Economics called RESOLVE splits the load and generation into a small number of nodes with defined transfer limits between them. Adding similar functionality in the TFGS model would allow a general understanding of the transmission system impacts to the capacity expansion without getting into the detail of running powerflows.

From a more general standpoint, the functionality of TFGS is such that it has potential for use in many other projects. Projects that need some understanding of capacity expansion in their work but face high uncertainties in future assumptions and may not have the budget to invest in more detailed tools (discussed in Section 4.0) could benefit from the lightweight nature of the tool and the reduced amount of input data requirements. To enhance the value of the tool and increase its application, it is recommended that consideration be given to finding other partners to include the in future developments of TFGS. This should include other potential use-cases to increase the usability to a broader set of users. These partners could be other projects within the national laboratory system and the research community in general. The immediate or anticipated future projects that have a need of TFGS could be used to determine the specific development path of the tool.

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Appendix A

Mathematical Description of Optimization Formulation

Appendix A

Mathematical Description of Optimization Formulation

A.1 Symbol Reference

Table A.1. Sets

$i \in I$	technologies (any unique identifier, e.g. string)
$s \in S$	investment time periods ($\{0, 1, \ldots, \lvert S\rvert - 1\}$)
$t \in T$	operational time periods ($\{0, 1, \ldots, \lvert T\rvert - 1\}$)
$n \in N$	operational age indices ($\{0, 1, \ldots, \lvert N\rvert - 1\}$)

Table A.2. Subsets

$Therm \subset I$	thermal generation technologies
$Var \subset I$	variable generation technologies
$Renew \subset I$	renewable generation technologies
$Stor \subset I$	storage technologies

Table A.3. Variables

x_{is}	number of units operating (dimensionless; $i \in I, s \in S$)
x_{isn}	number of units operating with age equal to n investment periods (dimensionless; $i \in I, s \in S, n \in N$)
a_{is}	number of units commissioned (dimensionless; $i \in I, s \in S$)
b_{is}	number of units decommissioned (dimensionless; $i \in I, s \in S$)
b_{isn}	number of units decommissioned with age equal to n investment periods (dimensionless; $i \in I, s \in S, n \in N$)
p_{ist}	power supply (net output to grid) (MW; $i \in I, s \in S, t \in T$)
f_{ist}	power charging (MW; $i \in Stor, s \in S, t \in T$)
g_{ist}	power discharging 0 (MW; $i \in Stor, s \in S, t \in T$)
q_{st}	load undersupply (MW; $s \in S, t \in T$)
r_{ist}	reserve supply (MW; $i \in Therm, s \in S, t \in T$)
w_{st}	reserve undersupply (MW; $s \in S, t \in T$)
h_{ist}	energy storage level (at start of operational time period) (MWh; $i \in Stor, s \in S, t \in T$)

Table A.4. Input Data Parameters

$InvTimeDur > 0$	duration of each investment time period (h)
$OperTimeDur > 0$	duration of each operational time period (h)
$DiscRate \in [0,1]$	discount rate (1/h)
$LoadResReqFact \in [0,1]$	load reserve requirement factor (dimensionless)
$LoadCost \geq 0$	load loss cost ($/MWh)
$ResCost \geq 0$	reserve shortfall cost ($/MWh)
$LoadGrowthFact_s \geq 0$	load growth factor (dimensionless; $s \in S$)
$LoadProfile_t \geq 0$	operational load profile (MW; $t \in T$)
$VarGenProfile_{it} \geq 0$	variable generation resource profile (MW; $i \in Var, t \in T$)
$UnitsMin_{is} \geq 0$ (int)	min num of units on the system (dimensionless; $i \in I, s \in S$)
$UnitsMax_{is} \geq 0$ (int)	max num of units on the system (dimensionless; $i \in I, s \in S$)
$PowMax_i \geq 0$	maximum power output per (MW; $i \in I$)
$PowMin_i \geq 0$	minimum power output per (MW; $i \in I$)
$RampUpMax_i \geq 0$	maximum ramp up rate (MW/h; $i \in Therm$)
$RampDownMax_i \geq 0$	maximum ramp down rate (MW/h; $i \in Therm$)
$ChMax_i \geq 0$	maximum charging power (MW; $i \in Stor$)
$DchMax_i \geq 0$	maximum discharging power (MW; $i \in Stor$)
$EnerMax_i \geq 0$	maximum stored energy (MWh; $i \in Stor$)
$EnerMin_i \geq 0$	minimum stored energy (MWh; $i \in Stor$)
$StoEff_i \in [0,1]$	storage round trip efficiency (dimensionless; $i \in Stor$)
$StoLoss_i \in [0,1]$	storage loss factor (1/h; $i \in Stor$)
$HeatRate_i \geq 0$	heat rate (BTU/MWh; $i \in Therm$)
$FuelCost_{is} \geq 0$	fuel cost ($/BTU; $i \in Therm, s \in S$)
$FixOperCost_i \geq 0$	fixed operating cost ($/h; $i \in I$)
$ComCost_i \geq 0$	commissioning cost ($; $i \in I$)
$DcomCost_i \geq 0$	decommissioning cost ($; $i \in I$)
$ResQualFact_i \in [0,1]$	reserve qualification factor (dimensionless; $i \in Therm$)
$ResReqFact_i \in [0,1]$	reserve requirement factor (dimensionless; $i \in Var$)
$LifetimeInvPeriods_i > 0$	lifetime number of investment periods (dimensionless; $i \in I$)
$ChCost_i \geq 0$	charging cost ($/MWh; $i \in Stor$)
$DchCost_i \geq 0$	discharging cost ($/MWh; $i \in Stor$)
$InitVint_{in} \geq 0$ (int)	initial number of units operating with age equal to n investment periods (dimensionless; $i \in I, n \in N$)
$IndividualRenewFrac_{is} \in [0,1]$	individual fraction of investment period generation to be renewables of type i (dimensionless; $i \in Renew, s \in S$)
$RenewFrac_s \in [0,1]$	total fraction of investment period generation to be renewable (dimensionless; $s \in S$

A.2 Objective Function

The objective of our optimization model is to minimize overall cost (subject to the constraints of the next section), which is defined as the sum of the terms that follow.

A.2.1 Commissioning Cost

$$\underset{s \in S, i \in I}{e^{s * DiscRate * InvTimeDur}} * \frac{ComCost_i}{LifetimeInvPeriods_i} * {}_{s' \in S: s - LifetimeInvPeriods_i + 1 \le s' \le s} \; a_{is'} \tag{1}$$

A.2.2 Decommissioning Cost

$$\underset{s \in S, i \in I}{e^{s * DiscRate * InvTimeDur}} * DcomCost_i * b_{is} \tag{2}$$

A.2.3 Fixed Operating Cost

$$e^{s * DiscRate * InvTimeDur} * InvTimeDur * FixOperCost_i * x_{is} \tag{3}$$

A.2.4 Fuel Cost

$$\underset{s \in S, t \in T, i \in Therm}{e^{s * DiscRate * InvTimeDur}} * (1/|T|) * InvTimeDur * FuelCost_{is} * HeatRate_i * p_{ist} \tag{4}$$

A.2.5 Charging Cost

$$\underset{s \in S, t \in T, i \in Stor}{e^{s * DiscRate * InvTimeDur}} * (1/|T|) * InvTimeDur * ChCost_i * f_{ist} \tag{5}$$

A.2.6 Discharging Cost

$$\underset{s \in S, t \in T, i \in Stor}{e^{s * DiscRate * InvTimeDur}} * (1/|T|) * InvTimeDur * DchCost_i * g_{ist} \tag{6}$$

A.2.7 Load Loss

$$\underset{s \in S, t \in T}{e^{s * DiscRate * InvTimeDur}} * (1/|T|) * InvTimeDur * LoadCost * q_{st} \tag{7}$$

A.2.8 Reserve Shortfall

$$\sum_{s\in S,t\in T} e^{s*DiscRate*InvTimeDur} * (1/|T|) * InvTimeDur * ResCost * u_{st} \tag{8}$$

A.3 Constraints

A solution in which variable values satisfy the following constraints is a considered feasible solution in the optimization model.

A.3.1 Load Balance

$$\sum_{i\in I} p_{ist} + q_{st} \geq LoadGrowthFact_s * LoadProfile_t \quad \forall s\in S, t\in T \tag{9}$$

A.3.2 Reserve Balance

$$\sum_{i\in Therm} r_{ist} + w_{st} \geq LoadResReqFact * LoadGrowthFact_s * LoadProfile_t + \sum_{i\in Var} ResReqFact_i * p_{ist} \; \forall s\in S, t\in T \tag{10}$$

A.3.3 Storage Power Definition

$$p_{ist} = g_{ist} - f_{ist} \qquad \forall i\in Stor, s\in S, t\in T \tag{11}$$

A.3.4 Thermal Power Bounds

$$PowMin_i * x_{is} \leq p_{ist} \; \forall i\in Therm, s\in S, t\in T \tag{12}$$

A.3.5 Thermal Reserve Bounds

$$0 \leq r_{ist} \; \forall i\in Therm, s\in S, t\in T \tag{13}$$

$$r_{ist} \leq ResQualFact_i * PowMax_i * x_{is} \quad \forall i\in Therm, s\in S, t\in T \tag{14}$$

A.3.6 Thermal Power and Reserve Bounds

$$p_{ist} + r_{ist} \leq PowMax_i * x_{is} \; \forall i\in Therm, s\in S, t\in T \tag{15}$$

A.3.7 Thermal Ramp-Up Bounds

$$p_{i,s,t+1} - p_{ist} \leq OperTimeDur * RampUpMax_i * x_{is} \quad \forall i \in Therm, s \in S, t \in T \setminus \max\{T\} \tag{16}$$

A.3.8 Thermal Ramp-Down Bounds

$$p_{ist} - p_{i,s,t+1} \leq OperTimeDur * RampDownMax_i * x_{is} \quad \forall i \in Therm, s \in S, t \in T \setminus \max\{T\} \tag{17}$$

A.3.9 Varying Resource Power Bounds

$$0 \leq p_{ist} \; \forall i \in Var, \; s \in S, \; t \in T \tag{18}$$

$$p_{ist} \leq VarGenProfile_{it} * x_{is} \quad \forall i \in Var, s \in S, t \in T \tag{19}$$

A.3.10 Storage Charging Bounds

$$0 \leq f_{ist} \; \forall i \in Stor, \; s \in S, \; t \in T \tag{20}$$

$$f_{ist} \leq ChMax_i * x_{is} \; \forall i \in Stor, \; s \in S, \; t \in T \tag{21}$$

A.3.11 Storage Discharging Bounds

$$0 \leq g_{ist} \; \forall i \in Stor, \; s \in S, \; t \in T \tag{22}$$

$$g_{ist} \leq DchMax_i * x_{is} \quad \forall i \in Stor, \; s \in S, \; t \in T \tag{23}$$

A.3.12 Stored Energy Bounds

$$EnerMin_i * x_{is} \leq h_{ist} \quad \forall i \in Stor, s \in S, t \in T \tag{24}$$

$$h_{ist} \leq EnerMax_i * x_{is} \quad \forall i \in Stor, s \in S, t \in T \tag{25}$$

A.3.13 Storage Operation

$$h_{i,s,t+1} = (1 - StoLoss_i) * OperTimeDur * h_{ist} + OperTimeDur * (StoEff_i * f_{ist} - g_{ist}) \quad \forall i \in Stor, \; s \in S, \; t \in T \tag{26}$$

A.3.14 Decommissioning Units with Vintages

$$b_{is} = \sum_{n \in N} b_{isn} \quad \forall i \in I, s \in S \tag{27}$$

A.3.15 Operating Units with Commissioning and Decommissioning

$$x_{isn} = InitVint_{in}|_{s=0} + a_{is}|_{n=0} + x_{i,s-1,n-1}|_{s>0,n>0} - b_{isn} \tag{28}$$

A.3.16 Operating Units with Vintages

$$x_{is} = \sum_{n \in N} x_{isn} \quad \forall i \in I, s \in S \tag{29}$$

A.3.17 Commissioning Units Bounds

$$0 \leq a_{is} \; \forall i \in I, \; s \in S \tag{30}$$

A.3.18 Decommissioning Units Bounds

$$0 \leq b_{is} \; \forall i \in I, \; s \in S \tag{31}$$

$$0 \leq b_{isn} \; \forall i \in I, \; s \in S, \; n \in N \tag{32}$$

A.3.19 Operating Units Bounds

$$0 \leq x_{isn} \; \forall i \in I, \; s \in S, \; n \in N \tag{33}$$

$$x_{isn} \leq 0 \quad \forall i \in I, s \in S, n \in N \text{ with } n > LifetimeInvPeriods_i \tag{34}$$

A.3.20 Investment Bounds

$$UnitsMin_{is} \leq x_{is} \qquad \forall i \in I, s \in S \tag{35}$$

$$x_{is} \leq UnitsMax_{is} \qquad \forall i \in I, s \in S \tag{36}$$

A.3.21 Total Renewable Energy

$$\sum_{i \in Renew} \sum_{t \in T} p_{ist} \geq RenewFrac_s \sum_{j \in I} \sum_{t \in T} p_{jst} \quad \forall s \in S \tag{37}$$

A.3.22 Individual Renewable Energy

$$\sum_{t\in T} p_{ist} \geq IndividualRenewFrac_{is} \sum_{j\in I}\sum_{t\in T} p_{jst} \quad \forall i\in Renew, s\in S \tag{38}$$

A.3.23 Integer Restrictions

$$x_{is} \in \mathbb{Z} \; \forall i \in I, \; s \in S \tag{39}$$

$$x_{isn} \in \mathbb{Z} \; \forall i \in I, s \in S, n \in N \tag{40}$$

$$a_{is} \in \mathbb{Z} \; \forall i \in I, s \in S \tag{41}$$

$$b_{is} \in \mathbb{Z} \; \forall i \in I, \; s \in S \tag{42}$$

$$b_{isn} \in \mathbb{Z} \;\; \forall i \in I, s \in S, n \in N \tag{43}$$

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