An Extended IEEE 118-Bus Test System With High Renewable Penetration

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***Abstract*—This article describes a new publicly available version of the IEEE 118–bus test system, named NREL-118. The database is based on the transmission representation (buses and lines) of the IEEE 118-bus test system, with a reconfigured generation representation using three regions of the US Western Interconnection from the latest Western Electricity Coordination Council (WECC) 2024 Common Case [Transmission expansion planning home and Grid-View WECC database]. Time-synchronous hourly load, wind, and solar time series are provided for one year. The public database presented and described in this manuscript will allow researchers to model a test power system using detailed transmission, generation, load, wind, and solar data. This database includes key additional features that add to the current IEEE 118-bus test model, such as the inclusion of ten generation technologies with different heat rate functions, minimum stable levels and ramping rates, GHG emissions rates, regulation and contingency reserves, and hourly time series data for one full year for load, wind, and solar generation.**

***Index Terms*—Electric grid database, load forecasts, renewable energy data, renewable forecasts, test power system.**

I. Introduction

DETAILED and reliable public databases of test power systems are highly valuable for researchers to conduct studies on new technologies and to test new algorithms. Many researchers use these databases for a number of important areas of power systems operations and planning, including: unit commitment, economic dispatch, congestion management, optimized allocation of distributed generation, fault detection, among many others. However, there are a number of fundamental limitations associated with many current test systems, such as: including only very brief periods of time, having generally smaller systems than those seen in practice, and other aspects that make many practitioners view them as "unrealistic." While test systems have limitations due to assumptions and simplifications, the models can inform electricity planning and market operation stakeholders, as well as policy makers, on the sensitivity of the system to critical variables. For example, some of the limitations of the models can include simplifications of the transmission lines or power generators –e.g. uniform transmission lines' capacities, or generators following linear heat input functions with very low voltage stable levels. Also, assumptions of dispatch modeling design can neglect power purchase agreements or ancillary services incentives. Despite the fact that these shortcomings can lead to errors, the use of reasonable assumptions can reduce the computational resource requirement and provide valid answers.

Test systems have been widely used in the research community because they provide standard public data, valuable for testing new algorithms, technologies, and control schemes. For example, Venkatesh *et al.* [2] test economic load dispatch models in the IEEE 14- [3] 30- [4] and 118-bus [5] systems. Zhao *et al.* [6] apply a stochastic economic dispatch model that includes wind generation and electric vehicles, and Yalcinoz and Short [7] apply a neural network approach to solve an economic dispatch model with transmission capacity constraints, in the IEEE 118-bus test system. Wang *et al.* [8] solve a security-constrained unit commitment problem that takes into account wind power intermittency in a 6-bus test system and in the IEEE 118-bus test system. Happ [9] presents an algorithm to solve a general optimal power dispatch problem using the Jacobian matrix, and applies it in a 9-bus test system and the IEEE 118-bus test system, noting that the results of the latter system are more representative of larger systems. Reid and Hasdorff [10] formulate the economic dispatch model as a quadratic programming problem, solve it using Wolfe's algorithm, and apply it in the IEEE 5-, 14-, 30-, 57- and 118-bus test systems. Fu *et al.* [11] apply an AC corrective/preventive contingency model based on a security-constrained unit commitment model in six case studies, formulated in, among others, the IEEE 118-bus test system and the 1168-bus system.

In addition, Hazra *et al.* [12] apply a multi-objective optimization technique for the congestion management problem to the IEEE 30- and 118-bus test systems, and the Northern Region Electricity Board, India (NERB) 390-bus test system. Wang and Nehrir [13] use the IEEE 6-bus test system [14], an IEEE 30-bus test system [4] and a subset of it to verify theoretical optimization methods for placing distributed generation. Zhao and Abur [15] use the IEEE 118-bus test system [5] and the 4520-bus ERCOT system to implement a state estimator for large power systems containing several control areas. Stott and Alsaç [16] test a load-flow solution method in various test systems, in-

Manuscript received July 12, 2016; revised November 11, 2016 and January 16, 2017; accepted February 12, 2017. This work was supported by the U.S. Department of Energy, through the Model & Tool Investment Fund under Contract no. DE_AC36-08-GO28308 from the National Renewable Energy Laboratory. Paper no. TPWRS-01056-2016. *(Corresponding author: Carlo Brancucci Martinez-Anido.)*

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2017.2695963

TABLE I
LOCATION OF NREL-118 SYSTEM DATABASE

	Link
Solar, wind, hydro and load data	http://www.nrel.gov/esif/assets/docs/input-files.zip
System as .csv files and FAQ	http://www.nrel.gov/esif/assets/docs/additional-files-mti-118.zip
Plexos Model as plexos file	http://www.nrel.gov/esif/assets/docs/mti-118-mt-da-rt-reserves-all-generators.xml
Plexos model as .xls file	http://www.nrel.gov/esif/assets/docs/plexos-export.xls

TABLE II
EXAMPLES OF POWER FLOW AND ECONOMIC DISPATCH MODELS THAT COULD USE THE NEW IEEE 118-BUS TEST (NREL-118) SYSTEM

Example of existing research using a bus-test system	**Data added in the NREL-118 relevant to the study and advantage to use NREL-118**
Venkatesh [2] uses economic dispatch and economic emission dispatch to estimate optimal fuel cost and optimal emission of generating units	Data added: -Operation costs by technology -Emissions coefficient and costs. Advantage of using NREL 118-bus system: -Sensitivity of results based on time-series data. -Comparison of the associated results of emission costs by technology. -Inclusion of transmission capacity constraints.
Yokoyama [4], uses a multi-objective formulation to the optimal power flow problem, i.e. minimizing generation cost, total emissions and flow deviation.	Data added: -Generating characteristics -NOx emission characteristics Advantage of using NREL 118-bus system: Sensitivity of results based on time-series data. -Use of a larger system that includes generators with various cost and heat input functions. -Emission results for CO_2.
Yalcinoz, T. and Short, M. J. [7] present a Neural networks approach for solving economic dispatch with transmission capacity constraints	Data added: -Flow limits of transmission lines -Operation costs Advantage of using NREL 118-bus system: -Sensitivity of results based on time-series data. -A three-area system, which can lead to comparison of results with the two-area findings

cluding the IEEE 118-bus test system. Lo *et al.* [17] test a new method for detecting fault locations using the IEEE 118-bus test system. While certainly not an exhaustive listing of all uses of some of the standard test cases, the examples above provide a broad sampling of the various use cases.

While the existing IEEE test systems have thus been utilized to study a broad range of research topics, including economic dispatch models, congestion management and fault location, they often require extensive modifications to do so, and thus are no longer the standard system, and often lose most of their value for making direct comparisons between algorithms. The NREL-118 database presented allows for a broader range of use cases due to its higher data resolution, more detailed system characteristics (including differentiation of three separate regions and heat input functions for 10 power technologies), and time-series data for a full year that includes seasonal variations. It also incorporates many of the challenges of integrating variable and uncertain renewable energy resources, expanding its utility to a new generation of power system problems.

This article presents a modified database, named NREL-118 test system, using the transmission representation (buses and lines) of the IEEE 118-bus test system [18]. Table I provides the links where the database is located. A file with a unit commitment and electricity dispatch model run in Plexos was included, with the intention that users of this test-bed can run the model, compare results and verify that they have set their system appropriately. A user can choose to edit the system components for his/her purpose.

The complete NREL-118 test system database can be considered in the community as a standard medium-size IEEE bus-test system, and certain variables, such as generator heat input and ramping functions, emission rates, fuel costs, and transmission line capacities, can be incorporated in other test systems. The new NREL-118 test system database can be used across different research topics allowing for consistency between results from different studies. Such uniformity at this detail level is a tremendous gain and can support further collaboration between research topics. Table II summarizes some advantages of using the NREL-118 test system proposed database in three studies of power flow and economic dispatch algorithms.

In addition, there is a growing need for large-scale databases of realistic systems. For instance, one of the most common large-scale power system models used by the industry are the databases of The Eastern Interconnection Reliability Assessment Group (ERAG). ERAG creates and maintains a power flow base case series and the System Dynamics Database (SDDB) and dynamic simulation studies, used in the systems of the Eastern Interconnection [19], but these are for use by the regions of the Eastern Interconnection and their member systems [20]. The European Network of Transmission System Operators for Electricity (ENTSO-E) [21] model is accessible [22] but only for the power flow simulation of winter 2009. Some researchers have also proposed virtual power grids for the research community. For instance, Liu *et al.* [23] propose a large-scale system of more than 1,000 generators and 5,000 transmission lines, and with different renewable energy penetration scenarios. While these models intend to test controls for implementation at a regional or national level, they are not widely available and lack long-term, high-resolution time series data.

In particular, the NREL-118 system includes the following information, which is currently not included in other public IEEE bus test systems:

1) Detailed generation constraints (such as upward/downward ramping, minimum generation level, minimum up/down times, heat rate and fuel use at different load levels, start and shutdown costs).
2) Time-synchronous yearlong actual and day-ahead forecast time series for wind and solar power as well as regional electricity load.

3) Results from a unit commitment and economic dispatch model that simulates the operation of the test power system for one year with hourly resolution, including day-ahead unit commitments and real time commitment and dispatch decisions.

Incorporating more details in the generators' models allows performing more realistic unit commitment and economic dispatch studies because operational constraints are defined. One advantage of having these details is that users can adjust the generators' parameters over time or location, as efficiencies improve. Time-synchronous data are critical for renewable integration studies, and one year allows including seasonal variability. Lastly, the results of the unit commitment and dispatch model allow users to benchmark their models.

The presented NREL-118 test database uses the transmission representation (buses and lines) of the IEEE 118-bus test system [18] –scaled up based on the higher installed generation capacity and peak load from three regions of the US Western Interconnection from the latest WECC 2024 Common Case database [1]. One year of time-synchronous hourly actuals (i.e. real time, RT) of wind power, solar power, and load are included. Also, one year of time-synchronous hourly day-ahead (DA) forecasts of wind power, solar power, and load are also provided[1] [24]. The three regions in the test power system are defined to allow for more research applications, such as the assessment of regional power interchanges. The NREL-118 test database does not correspond to an existing real system, but rather each region is a representation of the generation capacity mix of a real power system, using the transmission characteristics of the former IEEE 118-bus test model [18]. The database is made freely and publically available online in comma separated files (.csv) and plexos format (.xml). This manuscript presents how the database can be used to run a unit commitment and an economic dispatch model that includes DA and RT markets. Although not addressed here, this database can be utilized to study the impacts on a system's planning and operations that occur under higher renewable energy scenarios, including increasing cycling of coal and gas power, the role of forecast uncertainty of renewable resources, the expected emissions reductions, the changing of locational marginal prices (LMP), the role of specific generator characteristics in the integration of higher renewable energy shares (such as minimum stable level and heat input functions), and line congestion dynamics. New elements, such as demand response mechanisms, electric vehicles, storage capacity and combined heat and power capacity and services, can be included directly, opening opportunities for further research.

The article is structured as follows: Section II describes the existing versions of the IEEE 118-bus test system and the transmission grid characteristics that are included in the NREL-118 database. Section III describes the WECC generators of the three regions that are included in the NREL-118 test system database and Section IV includes a summary of the time series and emission rates. Section IV describes solar, wind and load data used in the database. Sections V and VI present the assumptions and results, respectively, of a unit commitment and economic dispatch model using the NREL-118 test system database. Finally, Section VII includes concluding remarks for further use of the NREL-118 test system database.

[1]The 2024 load, wind and solar power generation data were generated using weather year 2011.

TABLE III
EXISTING VERSIONS OF THE IEEE 118-BUS TEST SYSTEM

	University of Washington	University of Edinburgh	Illinois Institute of Technology. IIT (various researchers), version of 2004
Regions	1	N/A	3
Number of Buses	118 (32 with installed generation capacity)	118 (19 with installed generation capacity)	118 (54 with installed generation capacity)
Load Data	No Load Participation factors or time series load data available	No Load Participation factors or time series load data available	Load participation: 0.05%-7.4% across 91 buses. Hourly load data for one day available
Number of Generators (MW)	19 (plus 13 compensators) (4,377) (plus - 574 MW of compensators)	19 (4,377)	54 (7,220) SRMC based on heat input function coefficients
Number of Lines	186 lines, with resistance of 0 to 0.099 p.u.; reactance of 0.004 to 0.412 p.u.; and max. flow limit between 140 MW-500 MW (only established by the IIT)		

II. IEEE 118-BUS TEST SYSTEM CHARACTERISTICS INCLUDED IN THE NREL-118 DATABASE

In 1962, a portion of the U.S. Midwest Interconnect System was made publicly available, which would become known as the IEEE 118-bus test system. In 1993, Richard Christie from the University of Washington [3] edited it into the PECO PSAP format [3], [5]. The original version [5] consists of 118 buses and 186 transmission lines, 19 generators with a total installed capacity of 4,377 MW and 13 compensators with a total installed capacity of 574 MW. Out of the 118 buses, 32 have installed elec-tricity generation capacity, and all buses belong to a single zone. Since the early 2000's, researchers from the Mathematics Department at the University of Edinburgh [25] and the Illinois Institute of Technology (IIT) [18] worked with the system and added line characteristics such as resistance, reactance and maximum flow limits [18]. It is important to note that there are at least two different diagrams of the system published by IIT, mainly differing in the backbone (i.e. high voltage lines). The major difference between these newer versions and the original version is that the newer versions have 54 generators with a larger total installed capacity of 7,220 MW, and the system is divided into three regions.

Table III compares the online publicly available IEEE 118-bus test system versions, while Table IV compile the resistance and reactance of the IIT version of the IEEE 118-bus test sys-

TABLE IV
LINE CHARACTERISTICS FROM THE IIT 2004 VERSION

Line Characteristics	Average	No. Lines	Min	Max
Reactance (p.u.)	0.107	186	0.004	0.412
Resistance (p.u.)	0.027	186	0	0.099

TABLE V
REGIONAL LINE CHARACTERISTICS IN THE NREL-118 SYSTEM

Average Line Characteristics	Region 1 (Zone 1 in Fig. 3)	Region 2 (Zone 2 in Fig. 3)	Region 3 (Zone 3 in Fig. 3)
Reactance (p.u.)	0.0945	0.1133	0.1119
Resistance (p.u.)	0.0226	0.0297	0.03

Reactance and resistance was not modified from the original version. The differences noted in average reactance and resistance is due to reporting regional vs. full system estimates.

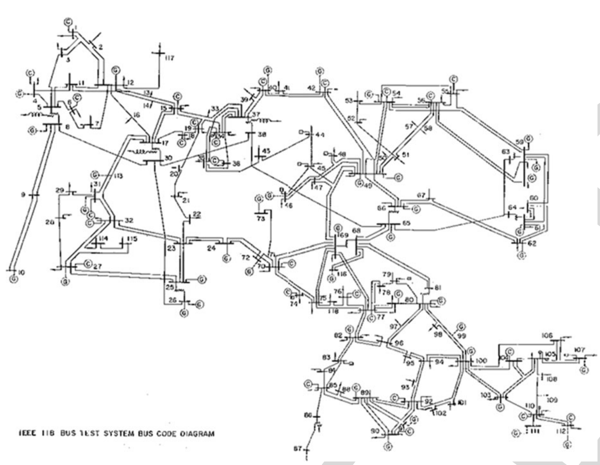

Fig. 1. One-line diagram of the IEEE 118-bus test system, by University of Washington, version of 1993 [5].

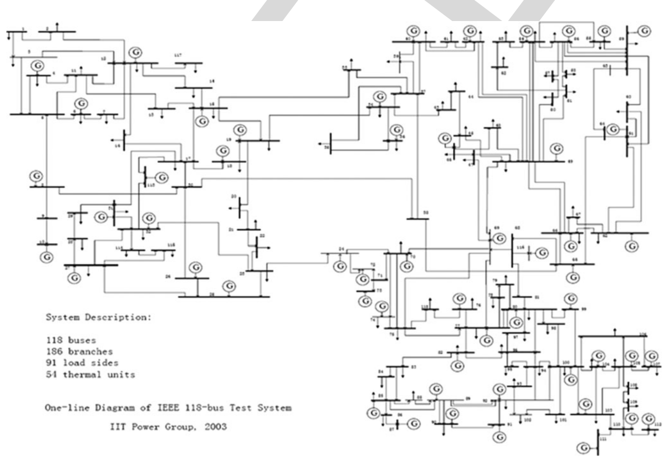

Fig. 2. One-line diagram of the IEEE 118-bus test system, by Illinois Institute of Technology, version of 2003 [18].

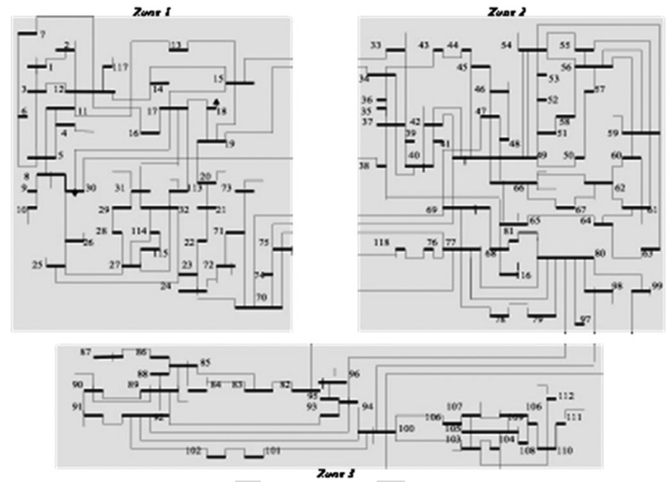

Fig. 3. One-line diagram of the IEEE 118-bus test system, by Illinois Institute of Technology, version of 2004 [18].

TABLE VI
CHANGES INTRODUCED IN LINE CHARACTERISTICS IN THE NREL-118 SYSTEM

	Line Flow Limits Levels (MW)
IEEE 118 IIT 2004	175, 200, 500, 1,000
NREL-118 2015	600, 700, 1,700, 3,500 Inter-regional lines: Region 1 to Region 2: Lines 44, 45, 54, 108, 116, 120, 185. Total flow limit: 6,400 MW Region 2 to Region 3: Lines 128, 148, 157, 158, 159. Total flow limit: 3,100 MW Region 1 to Region 3: No connections

The new Line Flow Limits were multiplied by the factor (3.5) by which total capacity installed increased

tem. Fig. 1 through Fig. 3 show the different existing diagrams. The University College of Dublin has also made available a visualization of the system showing the effective impedance of the branches [26].

A. NREL-118 Test System Characteristics

This database was based on the IIT 2004 transmission representation, the diagram and line characteristics are shown in Fig. 3 (see in reference [18], the "JEAS" files). The IIT IEEE 118-bus test system consists of a single region, where the load is defined for the entire system and for only one week. The NREL-118 system consists of three regions, each of which has a different load profile, and the resolution of the data is hourly for one full year.

B. NREL-118 Test System Line Characteristics

The line characteristics taken from the IIT 2004 version are the reactance and resistance (p.u.) (Table V). IIT lines' maximum flow levels were multiplied by the factor by which total system's installed capacity increased (x 3.5) and rounded for convenience, as shown in Table VI.

C. NREL-118 Test System Bus Characteristics

The total electricity generation capacity installed was increased 3.5 times compared to the original IEEE 118 system,

TABLE VII
BUS CHARACTERISTICS OF THE IIT IEEE 118-BUS TEST SYSTEM AND THE NREL-118 SYSTEM

Characteristics	Bus Load Participati on factor	Number of buses with load	Number of buses with installed capacity	Number of buses with no load and no generation capacity
IEEE 118 IIT 2004	**0.05-7.4%**	**91**	**54 buses**	**10**
NREL-118 2015	**0.2-15%**	**91**	**54 buses**	**10**
Region 1 (Zone 1 in Fig. 3)	*0.6-8.3%*	*30*	*136*	*0*
Region 2 (Zone 2 in Fig. 3)	*0.6-15%*	*37*	*72*	*6*
Region 3 (Zone 3 in Fig. 3)	*0.2-10%*	*24*	*119*	*4*

but the generation distribution throughout the buses was maintained, after normalizing the participation factors by region. The load participation factors were also taken from the IIT 2004 system and normalized by region (i.e. summing to one in each region, instead of summing to one in the entire system). Thus, the buses that have no capacity installed or zero load in the IIT system were left with no allocation. Table VII summarizes the load participation factors by region and the number of buses with capacity installed. The foundational elements of the electricity system representation needed for advanced dynamic studies are provided in the database though additional generator information may be required for some specific applications, such as advanced power control from wind turbines.

III. POWER CAPACITY INCLUDED IN THE NREL-118 TEST SYSTEM

The IEEE 118-bus test system only includes the generators' capacity and the bus number where they connect. It does not have details of generators' characteristics. In contrast, the new database includes characteristics of generators located in three existing regions. These regions and its generators were obtained from the WECC 2024 Common Case database [1], and their generation mixtures are shown in Fig. 4 through Fig. 6, respectively.

The total new installed capacity equals 24.5 GW, divided as:

1) *Region 1:* The Bay Area (also called PGEB[2]), with a total of 10.5 GW of electricity generation capacity installed.
2) *Region 2:* Sacramento (also called SMUD[3]), with a total of 5.4 GW of electricity generation capacity installed.
3) *Region 3:* San Diego (also called SDGE[4]), with a total of 8.6 GW of electricity generation capacity installed.

The 10 power generation technologies are: steam turbines (ST) powered by coal, gas and other fuels, internal combustion engines (ICE) powered by gas, combustion turbines (CT) powered by gas and oil, gas combined-cycle turbines (CC), photovoltaics (referred simply as solar), hydro and biomass generators, and wind turbines.

[2]PGEB stands for Pacific Gas & Electric Bay Area, i.e. PG&E Bay Area.
[3]SMUD stands for Sacramento Municipal Utility District.
[4]SDGE San Diego Gas & Electric.

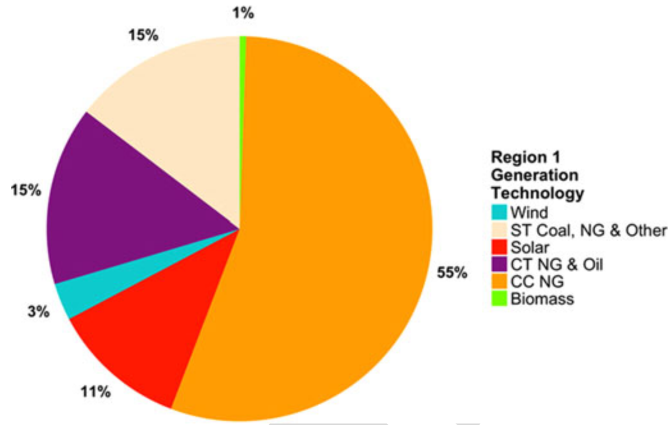

Fig. 4. Share of power generation (MW) in Region 1. The total electricity generation capacity installed is 10.5 GW.

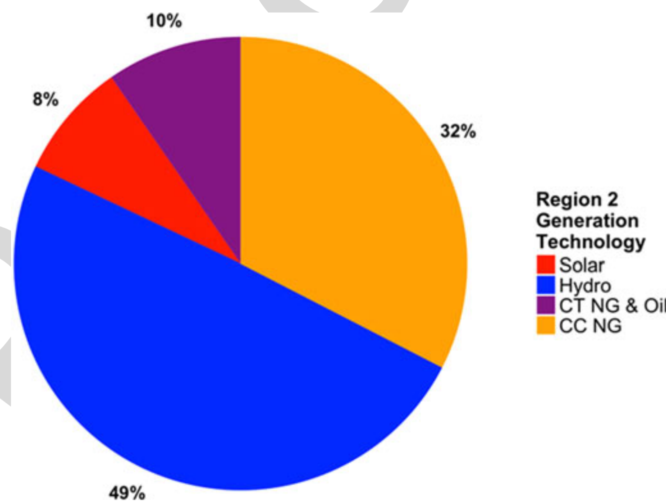

Fig. 5. Share of power generation (MW) in Region 2. The total electricity generation capacity installed is 5.4 GW.

All the generators have the following parameters: maximum capacity (MW), minimum stable level (MW), heat rate base (MMBTU/h), heat rate increment (BTU/kWh), load point (MW), start cost (\$), VO&M charge (\$/MWh), minimum up time (h), minimum down time (h), maximum ramp up (MW/min), maximum ramp down (MW/min). The heat input function (also called fuel rate function) defines heat (i.e. fuel) consumption for the full load domain at which generators operate. The heat input function is modeled as a heat rate base a and a set of linear increments bx, where $b =$ heat rate increment in the middle point of that segment and $x =$ load operation point. The simplest two cases are constant heat rate, equal to the heat rate base $f(x) = a$ and linear heat input function over all the load domain $f(x) = a + bx$. All other cases yield polynomial heat input functions.

The model includes 15 dispatchable and 28 non-dispatchable hydro generators. This means that the dispatch level of 15 hydro units is estimated according to the optimal system operation.

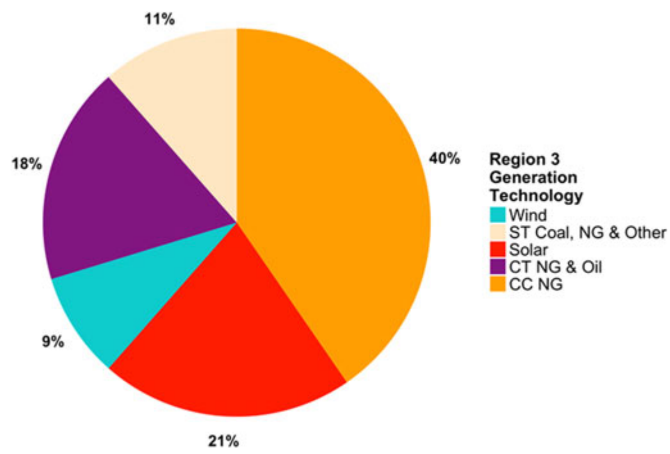

Fig. 6. Share of power generation (MW) in Region 3. The total electricity generation capacity installed is 8.6 GW.

TABLE VIII
BASIC CHARACTERISTICS OF THE NREL-118 TEST SYSTEM DATABASE

Characteristics	Peak Load	Total installed Capacity (MW)	Number of Generators
IEEE 118 IIT 2004	**6,000 MW (One day, hourly)**	**7,220**	**54 generators**
NREL-118 2015	**19,800 MW (annual, hourly)**	**24,600**	**327 generators**
Region 1	*9,700*	*10,523*	*136*
Region 2	*5,200*	*5,443*	*72*
Region 3	*5,500*	*8,600*	*119*

TABLE IX
WIND AND SOLAR CAPACITY GENERATION IN THE NREL-118 TEST SYSTEM

	Wind	Solar
NREL-118 test system	**17 Generators 1,078 MW**	**75 Generators 3,445 MW**
Region 1	*13 Generators 329 MW*	*33 Generators; 1,206 MW (Of which 747 MW are distributed PV)*
Region 2	*0*	*5 Generators; 444 MW (Of which 264 MW are distributed PV)*
Region 3	*4 Generators 749 MW*	*37 Generators; 1,795 MW (Of which 18 MW are distributed PV)*

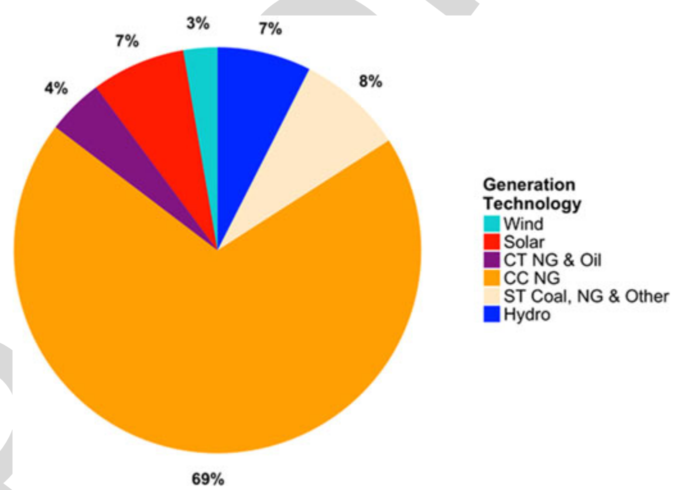

Fig. 7. Results of power dispatch simulation. Share of total annual power generation (MWh) of the full system (three regions combined), by technology.

On the other side, 28 hydro generators are constrained to a fixed generation. The database includes the time series data of the fixed generation of the non-dispatchable units.

IV. LOAD, WIND AND SOLAR POWER TIME SERIES, AND EMISSION RATES

Table VIII compares the peak load and capacity installed of the IIT model and NREL-118 system. The NREL-118 system includes RT and DA forecast time series for load, as well as wind and solar power time series.

Load data are synthetic load data obtained from neural net regressions with 1980-2012 input weather and load data [24]. Wind data are provided by the Wind Toolkit [27], while solar data is provided by the National Solar Radiation Data Base (NSRDB) [28]. The base year used is 2011. The installed solar power is either distributed PV generation or utility-scale PV, and the majority in the system is utility-scale PV (see Table IX). Both wind and solar locations have been chosen so as to be in close geographic proximity to the load zones where they are connected, ensuring that the meteorological conditions which impact load, wind, and solar are consistent. The aggregated wind and solar profiles are comprised of a number of individual wind or solar plants, each of which has an independent time series of power output whose correlation is dependent on the geographic distance between the plants. For further details on the load, wind, and solar data, including forecasts, please refer to the Western Interconnection Flexibility Assessment study [24].

Table IX summarizes the number of wind and solar generators, by region.

The resulting electricity generation mix (as a share of electricity generation) is shown in Fig. 7.

The database also includes emission rates of carbon dioxide (CO_2), nitrogen oxides (NOx), and sulfur oxides (SOx), for each fuel type. One single value of these gas emissions per fuel type is used across the three regions.

V. UNIT COMMITMENT AND ECONOMIC DISPATCH MODEL

The NREL-118 system's characteristics are explored through a test case, running a unit commitment and economic dispatch model, for DA and RT markets. A commercial production cost modeling tool, Plexos, is used to perform the analysis, using a DC Optimal Power Flow (OPF) model.

The characteristics of each market are provided in Table X. For the DA market, a look-ahead period is included after the 24-hour optimization window. This look-ahead period has a resolution of four hours and is used to include unit commitment constraints of the next 24 hours into the current optimization step. These constraints are mainly minimum up and down up times of the generating units. The amount of look-ahead should

TABLE X
CHARACTERISTICS OF THE ECONOMIC DISPATCH MARKETS RUN USING THE NREL-118 DATABASE

Market Horizon	Time step	Optimization Window	Look ahead*
DA	1 hour	1 day	1 day of 4 hour resolution
RT	1 hour	1 day	Does not apply

*Look ahead is a period after the optimization window, which is included in the DA market. The amount of look-ahead is sufficient to recover start costs or evaluate the longest up or down time constraint.

TABLE XI
TOTAL ANNUAL POWER INTERCHANGES BETWEEN REGIONS

	To R1	To R2	To R3
From R1	-	1,535 GWh	Not connected
From R2	7,553 GWh	-	71 GWh
From R3	Not connected	8.885 GWh	-

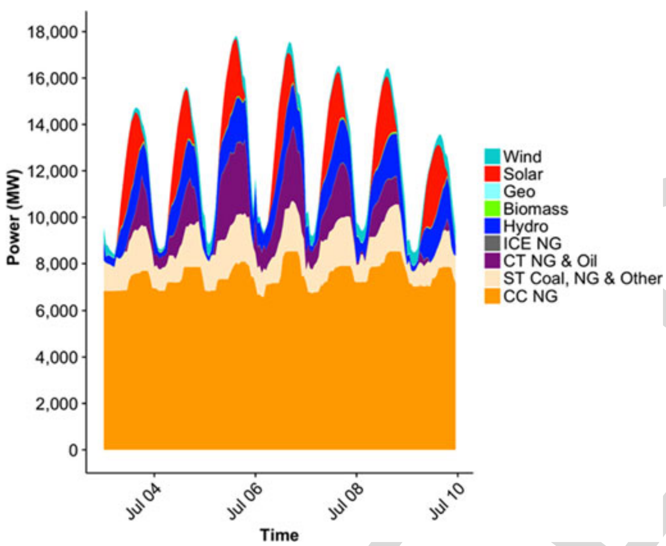

Fig. 8. Power dispatch during week with the annual load peak. Load peak of 17.82 GW happened on July 05, at 3 pm.

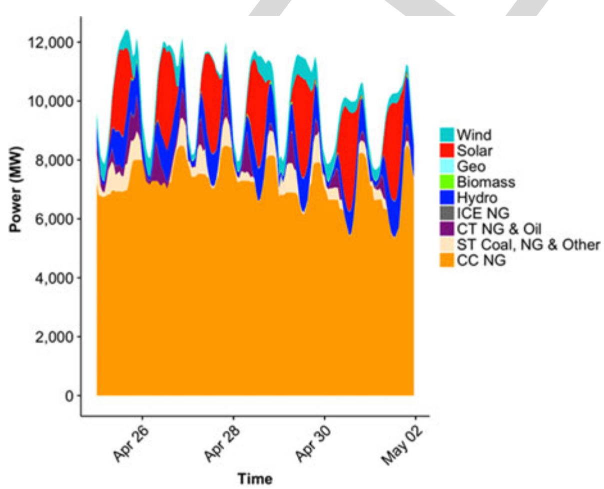

Fig. 9. Power dispatch during week with annual solar peak. Solar peak of 3.4 GW happened on April 30, at 1 pm.

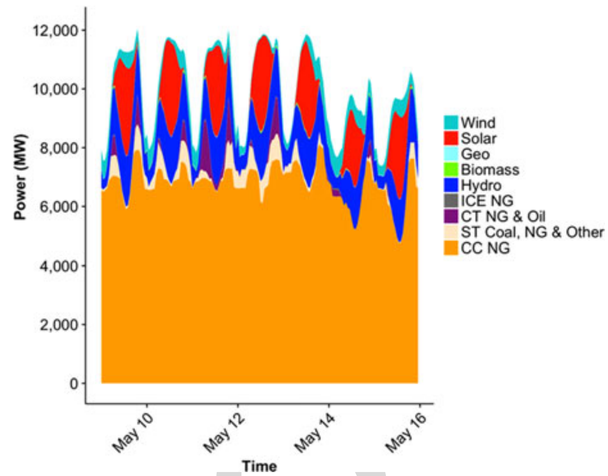

Fig. 10. Power dispatch during week with annual wind peak. Wind peak of 0.8 GW happened on May 13, at 10 pm.

be sufficient to recover start up costs or evaluate the longest up or down time constraint. To replicate these results, it is important to mention that Plexos optimizes monthly hydro budgets to obtain daily hydro budgets for the dispatchable hydro electricity generators.

The model includes contingency spinning reserves, and regulation up and down reserves, equal to 3% of load and 1% of load, respectively. These reserve requirements are in line with other production cost models used in renewable integration studies [29], [24]. In total, 234 generators provide reserves –i.e. all generators except wind and solar generators. Each generator participates in the reserve provision of each of the three regions. Energy and reserves are co-optimized in Plexos.

VI. Summary of Results

The NREL-118 test system database includes results for the unit commitment and economic dispatch DA and RT models. The .xml file includes the Plexos model with the system as described, and the following solver settings: integer optimal solution method, solution gap of 0.1 and enforced thermal limits on lines of >69 kV. The aggregated results for the year are described below. Users can run the system with lower optimality gaps to benchmark their models.

Before modifying the database, it is advisable to first run the existing models and compare the results with those included here as a form of model benchmarking.

The power inter-changes across regions of the RT model are depicted in Table XI.

In the three regions there is no generation that has to be curtailed, and load is met at all times, i.e. there is no unserved load. In total there is 0.15 GWh of down regulation reserve shortage, 0.20 GWh of up regulation reserve shortage and 0.32 of contingency spinning reserve shortage. This might be due to renewable forecast errors and modeling rounding limitations, as well as imports that are not modeled or included.

Fig. 8 shows the generation stack of the full system for the week with the peak load (July 5th), while Figs. 9 and 10 show the weeks with the day with peak solar and wind power production respectively (April 30th and May 13th, respectively).

VII. Concluding Remarks

The NREL-118 test system was compiled using transmission grid characteristics of the IEEE 118-bus test system and the generation mix and load profiles of three regions of the WECC 2024 common case database. It consists of three regions, 118 buses, 186 transmission lines and 327 generators. A total of nine generation-technologies are included that represent both fossil fuels and renewables. It includes time-synchronous year-long actual and forecast time series for wind and solar power, as well as for regional electricity load. It also includes detailed generation constraints for the 327 generators (units).

This database is expected to be very valuable to the power system community, providing a standardized database that provides more publically available detail than previous iterations of the IEEE 118-bus system. The complete database can be considered in the community as the standard medium-size IEEE bus-test system, and certain variables, such as generator heat input and ramping functions, emission rates, fuel costs, and transmission line capacities, can be incorporated to other bus-test systems, or can be adjusted as technology performance and costs change in the industry. In addition, new elements, such as demand response mechanisms, electric vehicles, storage capacity and combined-heat power capacity and services, can be included directly, opening the opportunity for further research and collaborations across disciplines.

One immediate gain is the opportunity researchers will have to use this database to conduct renewable integration studies for systems expecting higher renewable penetration rates. This will be possible thanks to the real and forecast time-series data, as well as the level of detail of the system and generators' characteristics that allows tailoring the database to particular case studies. For example, this database can be used to study the impact in system's planning and operation for higher renewable energy scenarios under different climate and energy policy commitments, including increasing cycling of coal and gas power, the role of forecast uncertainty of renewable resources, the expected costs of emissions reduction, the change of locational marginal prices (LMP), the role of specific generator characteristics in the integration of higher renewable energy shares (such as minimum stable level and heat input functions) and the line congestion dynamics.

The new NREL-118 bus-test system database can be used across different research topics allowing for consistency between results from different studies. Such uniformity at this detail level is a tremendous gain and can support further collaboration between research topics.

Acknowledgment

The authors would like to acknowledge the valuable feedback from researchers Anthony Florita, Greg Stark, and Greg Brinkman, from National Renewable Energy Laboratory. Special thanks to Ryan Jones (formerly of E3) for providing the load data.

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An Extended IEEE 118-Bus Test System With High Renewable Penetration

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***Abstract*—This article describes a new publicly available version of the IEEE 118–bus test system, named NREL-118. The database is based on the transmission representation (buses and lines) of the IEEE 118-bus test system, with a reconfigured generation representation using three regions of the US Western Interconnection from the latest Western Electricity Coordination Council (WECC) 2024 Common Case [Transmission expansion planning home and Grid-View WECC database]. Time-synchronous hourly load, wind, and solar time series are provided for one year. The public database presented and described in this manuscript will allow researchers to model a test power system using detailed transmission, generation, load, wind, and solar data. This database includes key additional features that add to the current IEEE 118-bus test model, such as the inclusion of ten generation technologies with different heat rate functions, minimum stable levels and ramping rates, GHG emissions rates, regulation and contingency reserves, and hourly time series data for one full year for load, wind, and solar generation.**

***Index Terms*—Electric grid database, load forecasts, renewable energy data, renewable forecasts, test power system.**

I. Introduction

DETAILED and reliable public databases of test power systems are highly valuable for researchers to conduct studies on new technologies and to test new algorithms. Many researchers use these databases for a number of important areas of power systems operations and planning, including: unit commitment, economic dispatch, congestion management, optimized allocation of distributed generation, fault detection, among many others. However, there are a number of fundamental limitations associated with many current test systems, such as: including only very brief periods of time, having generally smaller systems than those seen in practice, and other aspects that make many practitioners view them as "unrealistic." While test systems have limitations due to assumptions and simplifications, the models can inform electricity planning and market operation stakeholders, as well as policy makers, on the sensitivity of the system to critical variables. For example, some of the limitations of the models can include simplifications of the transmission lines or power generators –e.g. uniform transmission lines' capacities, or generators following linear heat input functions with very low voltage stable levels. Also, assumptions of dispatch modeling design can neglect power purchase agreements or ancillary services incentives. Despite the fact that these shortcomings can lead to errors, the use of reasonable assumptions can reduce the computational resource requirement and provide valid answers.

Test systems have been widely used in the research community because they provide standard public data, valuable for testing new algorithms, technologies, and control schemes. For example, Venkatesh *et al.* [2] test economic load dispatch models in the IEEE 14- [3] 30- [4] and 118-bus [5] systems. Zhao *et al.* [6] apply a stochastic economic dispatch model that includes wind generation and electric vehicles, and Yalcinoz and Short [7] apply a neural network approach to solve an economic dispatch model with transmission capacity constraints, in the IEEE 118-bus test system. Wang *et al.* [8] solve a security-constrained unit commitment problem that takes into account wind power intermittency in a 6-bus test system and in the IEEE 118-bus test system. Happ [9] presents an algorithm to solve a general optimal power dispatch problem using the Jacobian matrix, and applies it in a 9-bus test system and the IEEE 118-bus test system, noting that the results of the latter system are more representative of larger systems. Reid and Hasdorff [10] formulate the economic dispatch model as a quadratic programming problem, solve it using Wolfe's algorithm, and apply it in the IEEE 5-, 14-, 30-, 57- and 118-bus test systems. Fu *et al.* [11] apply an AC corrective/preventive contingency model based on a security-constrained unit commitment model in six case studies, formulated in, among others, the IEEE 118-bus test system and the 1168-bus system.

In addition, Hazra *et al.* [12] apply a multi-objective optimization technique for the congestion management problem to the IEEE 30- and 118-bus test systems, and the Northern Region Electricity Board, India (NERB) 390-bus test system. Wang and Nehrir [13] use the IEEE 6-bus test system [14], an IEEE 30-bus test system [4] and a subset of it to verify theoretical optimization methods for placing distributed generation. Zhao and Abur [15] use the IEEE 118-bus test system [5] and the 4520-bus ERCOT system to implement a state estimator for large power systems containing several control areas. Stott and Alsaç [16] test a load-flow solution method in various test systems, in-

Manuscript received July 12, 2016; revised November 11, 2016 and January 16, 2017; accepted February 12, 2017. This work was supported by the U.S. Department of Energy, through the Model & Tool Investment Fund under Contract no. DE_AC36-08-GO28308 from the National Renewable Energy Laboratory. Paper no. TPWRS-01056-2016. *(Corresponding author: Carlo Brancucci Martinez-Anido.)*

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2017.2695963

TABLE I
LOCATION OF NREL-118 SYSTEM DATABASE

	Link
Solar, wind, hydro and load data	http://www.nrel.gov/esif/assets/docs/input-files.zip
System as .csv files and FAQ	http://www.nrel.gov/esif/assets/docs/additional-files-mti-118.zip
Plexos Model as plexos file	http://www.nrel.gov/esif/assets/docs/mti-118-mt-da-rt-reserves-all-generators.xml
Plexos model as .xls file	http://www.nrel.gov/esif/assets/docs/plexos-export.xls

TABLE II
EXAMPLES OF POWER FLOW AND ECONOMIC DISPATCH MODELS THAT COULD USE THE NEW IEEE 118-BUS TEST (NREL-118) SYSTEM

Example of existing research using a bus-test system	**Data added in the NREL-118 relevant to the study and advantage to use NREL-118**
Venkatesh [2] uses economic dispatch and economic emission dispatch to estimate optimal fuel cost and optimal emission of generating units	Data added: -Operation costs by technology -Emissions coefficient and costs. Advantage of using NREL 118-bus system: -Sensitivity of results based on time-series data. -Comparison of the associated results of emission costs by technology. -Inclusion of transmission capacity constraints.
Yokoyama [4], uses a multi-objective formulation to the optimal power flow problem, i.e. minimizing generation cost, total emissions and flow deviation.	Data added: -Generating characteristics -NOx emission characteristics Advantage of using NREL 118-bus system: Sensitivity of results based on time-series data. -Use of a larger system that includes generators with various cost and heat input functions. -Emission results for CO_2.
Yalcinoz, T. and Short, M. J. [7] present a Neural networks approach for solving economic dispatch with transmission capacity constraints	Data added: -Flow limits of transmission lines -Operation costs Advantage of using NREL 118-bus system: -Sensitivity of results based on time-series data. -A three-area system, which can lead to comparison of results with the two-area findings

cluding the IEEE 118-bus test system. Lo *et al.* [17] test a new method for detecting fault locations using the IEEE 118-bus test system. While certainly not an exhaustive listing of all uses of some of the standard test cases, the examples above provide a broad sampling of the various use cases.

While the existing IEEE test systems have thus been utilized to study a broad range of research topics, including economic dispatch models, congestion management and fault location, they often require extensive modifications to do so, and thus are no longer the standard system, and often lose most of their value for making direct comparisons between algorithms. The NREL-118 database presented allows for a broader range of use cases due to its higher data resolution, more detailed system characteristics (including differentiation of three separate regions and heat input functions for 10 power technologies), and time-series data for a full year that includes seasonal variations. It also incorporates many of the challenges of integrating variable and uncertain renewable energy resources, expanding its utility to a new generation of power system problems.

This article presents a modified database, named NREL-118 test system, using the transmission representation (buses and lines) of the IEEE 118-bus test system [18]. Table I provides the links where the database is located. A file with a unit commitment and electricity dispatch model run in Plexos was included, with the intention that users of this test-bed can run the model, compare results and verify that they have set their system appropriately. A user can choose to edit the system components for his/her purpose.

The complete NREL-118 test system database can be considered in the community as a standard medium-size IEEE bus-test system, and certain variables, such as generator heat input and ramping functions, emission rates, fuel costs, and transmission line capacities, can be incorporated in other test systems. The new NREL-118 test system database can be used across different research topics allowing for consistency between results from different studies. Such uniformity at this detail level is a tremendous gain and can support further collaboration between research topics. Table II summarizes some advantages of using the NREL-118 test system proposed database in three studies of power flow and economic dispatch algorithms.

In addition, there is a growing need for large-scale databases of realistic systems. For instance, one of the most common large-scale power system models used by the industry are the databases of The Eastern Interconnection Reliability Assessment Group (ERAG). ERAG creates and maintains a power flow base case series and the System Dynamics Database (SDDB) and dynamic simulation studies, used in the systems of the Eastern Interconnection [19], but these are for use by the regions of the Eastern Interconnection and their member systems [20]. The European Network of Transmission System Operators for Electricity (ENTSO-E) [21] model is accessible [22] but only for the power flow simulation of winter 2009. Some researchers have also proposed virtual power grids for the research community. For instance, Liu *et al.* [23] propose a large-scale system of more than 1,000 generators and 5,000 transmission lines, and with different renewable energy penetration scenarios. While these models intend to test controls for implementation at a regional or national level, they are not widely available and lack long-term, high-resolution time series data.

In particular, the NREL-118 system includes the following information, which is currently not included in other public IEEE bus test systems:

1) Detailed generation constraints (such as upward/downward ramping, minimum generation level, minimum up/down times, heat rate and fuel use at different load levels, start and shutdown costs).
2) Time-synchronous yearlong actual and day-ahead forecast time series for wind and solar power as well as regional electricity load.

3) Results from a unit commitment and economic dispatch model that simulates the operation of the test power system for one year with hourly resolution, including day-ahead unit commitments and real time commitment and dispatch decisions.

Incorporating more details in the generators' models allows performing more realistic unit commitment and economic dispatch studies because operational constraints are defined. One advantage of having these details is that users can adjust the generators' parameters over time or location, as efficiencies improve. Time-synchronous data are critical for renewable integration studies, and one year allows including seasonal variability. Lastly, the results of the unit commitment and dispatch model allow users to benchmark their models.

The presented NREL-118 test database uses the transmission representation (buses and lines) of the IEEE 118-bus test system [18] –scaled up based on the higher installed generation capacity and peak load from three regions of the US Western Interconnection from the latest WECC 2024 Common Case database [1]. One year of time-synchronous hourly actuals (i.e. real time, RT) of wind power, solar power, and load are included. Also, one year of time-synchronous hourly day-ahead (DA) forecasts of wind power, solar power, and load are also provided[1] [24]. The three regions in the test power system are defined to allow for more research applications, such as the assessment of regional power interchanges. The NREL-118 test database does not correspond to an existing real system, but rather each region is a representation of the generation capacity mix of a real power system, using the transmission characteristics of the former IEEE 118-bus test model [18]. The database is made freely and publically available online in comma separated files (.csv) and plexos format (.xml). This manuscript presents how the database can be used to run a unit commitment and an economic dispatch model that includes DA and RT markets. Although not addressed here, this database can be utilized to study the impacts on a system's planning and operations that occur under higher renewable energy scenarios, including increasing cycling of coal and gas power, the role of forecast uncertainty of renewable resources, the expected emissions reductions, the changing of locational marginal prices (LMP), the role of specific generator characteristics in the integration of higher renewable energy shares (such as minimum stable level and heat input functions), and line congestion dynamics. New elements, such as demand response mechanisms, electric vehicles, storage capacity and combined heat and power capacity and services, can be included directly, opening opportunities for further research.

The article is structured as follows: Section II describes the existing versions of the IEEE 118-bus test system and the transmission grid characteristics that are included in the NREL-118 database. Section III describes the WECC generators of the three regions that are included in the NREL-118 test system database and Section IV includes a summary of the time series and emission rates. Section IV describes solar, wind and load data used in the database. Sections V and VI present the assumptions and results, respectively, of a unit commitment and economic dispatch model using the NREL-118 test system database. Finally, Section VII includes concluding remarks for further use of the NREL-118 test system database.

[1]The 2024 load, wind and solar power generation data were generated using weather year 2011.

TABLE III
EXISTING VERSIONS OF THE IEEE 118-BUS TEST SYSTEM

	University of Washington	**University of Edinburgh**	**Illinois Institute of Technology. IIT (various researchers), version of 2004**
Regions	1	N/A	3
Number of Buses	118 (32 with installed generation capacity)	118 (19 with installed generation capacity)	118 (54 with installed generation capacity)
Load Data	No Load Participation factors or time series load data available	No Load Participation factors or time series load data available	Load participation: 0.05%-7.4% across 91 buses. Hourly load data for one day available
Number of Generators (MW)	19 (plus 13 compensators) (4,377) (plus - 574 MW of compensators)	19 (4,377)	54 (7,220) SRMC based on heat input function coefficients
Number of Lines	186 lines, with resistance of 0 to 0.099 p.u.; reactance of 0.004 to 0.412 p.u.; and max. flow limit between 140 MW-500 MW (only established by the IIT)		

II. IEEE 118-Bus Test System Characteristics Included in the NREL-118 Database

In 1962, a portion of the U.S. Midwest Interconnect System was made publicly available, which would become known as the IEEE 118-bus test system. In 1993, Richard Christie from the University of Washington [3] edited it into the PECO PSAP format [3], [5]. The original version [5] consists of 118 buses and 186 transmission lines, 19 generators with a total installed capacity of 4,377 MW and 13 compensators with a total installed capacity of 574 MW. Out of the 118 buses, 32 have installed elec-tricity generation capacity, and all buses belong to a single zone. Since the early 2000's, researchers from the Mathematics Department at the University of Edinburgh [25] and the Illinois Institute of Technology (IIT) [18] worked with the system and added line characteristics such as resistance, reactance and maximum flow limits [18]. It is important to note that there are at least two different diagrams of the system published by IIT, mainly differing in the backbone (i.e. high voltage lines). The major difference between these newer versions and the original version is that the newer versions have 54 generators with a larger total installed capacity of 7,220 MW, and the system is divided into three regions.

Table III compares the online publicly available IEEE 118-bus test system versions, while Table IV compile the resistance and reactance of the IIT version of the IEEE 118-bus test sys-

TABLE IV
LINE CHARACTERISTICS FROM THE IIT 2004 VERSION

Line Characteristics	Average	No. Lines	Min	Max
Reactance (p.u.)	0.107	186	0.004	0.412
Resistance (p.u.)	0.027	186	0	0.099

TABLE V
REGIONAL LINE CHARACTERISTICS IN THE NREL-118 SYSTEM

Average Line Characteristics	Region 1 (Zone 1 in Fig. 3)	Region 2 (Zone 2 in Fig. 3)	Region 3 (Zone 3 in Fig. 3)
Reactance (p.u.)	0.0945	0.1133	0.1119
Resistance (p.u.)	0.0226	0.0297	0.03

Reactance and resistance was not modified from the original version. The differences noted in average reactance and resistance is due to reporting regional vs. full system estimates.

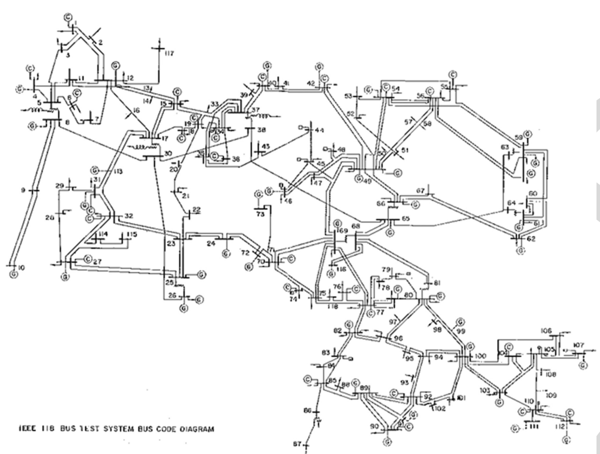

Fig. 1. One-line diagram of the IEEE 118-bus test system, by University of Washington, version of 1993 [5].

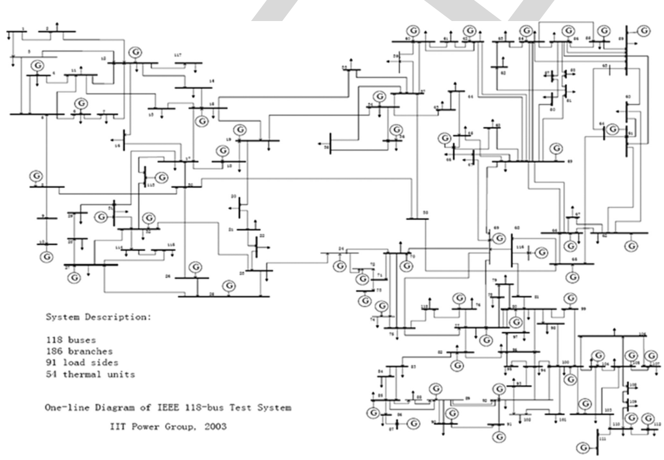

Fig. 2. One-line diagram of the IEEE 118-bus test system, by Illinois Institute of Technology, version of 2003 [18].

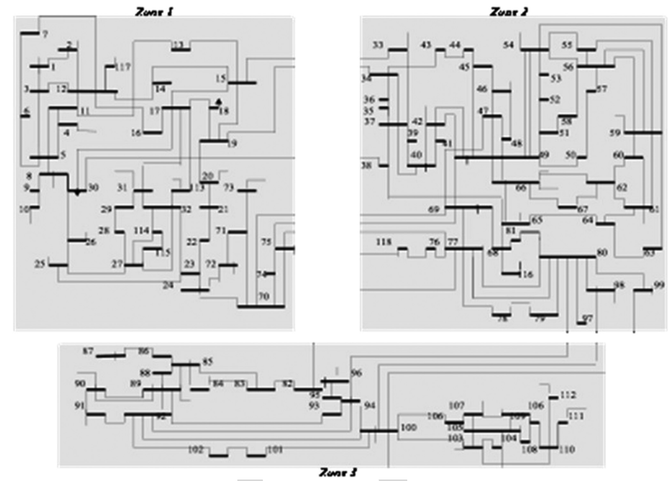

Fig. 3. One-line diagram of the IEEE 118-bus test system, by Illinois Institute of Technology, version of 2004 [18].

TABLE VI
CHANGES INTRODUCED IN LINE CHARACTERISTICS IN THE NREL-118 SYSTEM

	Line Flow Limits Levels (MW)
IEEE 118 IIT 2004	175, 200, 500, 1,000
NREL-118 2015	600, 700, 1,700, 3,500 Inter-regional lines: Region 1 to Region 2: Lines 44, 45, 54, 108, 116, 120, 185. Total flow limit: 6,400 MW Region 2 to Region 3: Lines 128, 148, 157, 158, 159. Total flow limit: 3,100 MW Region 1 to Region 3: No connections

The new Line Flow Limits were multiplied by the factor (3.5) by which total capacity installed increased

tem. Fig. 1 through Fig. 3 show the different existing diagrams. The University College of Dublin has also made available a visualization of the system showing the effective impedance of the branches [26].

A. NREL-118 Test System Characteristics

This database was based on the IIT 2004 transmission representation, the diagram and line characteristics are shown in Fig. 3 (see in reference [18], the "JEAS" files). The IIT IEEE 118-bus test system consists of a single region, where the load is defined for the entire system and for only one week. The NREL-118 system consists of three regions, each of which has a different load profile, and the resolution of the data is hourly for one full year.

B. NREL-118 Test System Line Characteristics

The line characteristics taken from the IIT 2004 version are the reactance and resistance (p.u.) (Table V). IIT lines' maximum flow levels were multiplied by the factor by which total system's installed capacity increased (x 3.5) and rounded for convenience, as shown in Table VI.

C. NREL-118 Test System Bus Characteristics

The total electricity generation capacity installed was increased 3.5 times compared to the original IEEE 118 system,

TABLE VII
BUS CHARACTERISTICS OF THE IIT IEEE 118-BUS TEST SYSTEM AND THE NREL-118 SYSTEM

Characteristics	Bus Load Participation factor	Number of buses with load	Number of buses with installed capacity	Number of buses with no load and no generation capacity
IEEE 118 IIT 2004	**0.05-7.4%**	**91**	**54 buses**	**10**
NREL-118 2015	**0.2-15%**	**91**	**54 buses**	**10**
Region 1 (Zone 1 in Fig. 3)	*0.6-8.3%*	*30*	*136*	*0*
Region 2 (Zone 2 in Fig. 3)	*0.6-15%*	*37*	*72*	*6*
Region 3 (Zone 3 in Fig. 3)	*0.2-10%*	*24*	*119*	*4*

but the generation distribution throughout the buses was maintained, after normalizing the participation factors by region. The load participation factors were also taken from the IIT 2004 system and normalized by region (i.e. summing to one in each region, instead of summing to one in the entire system). Thus, the buses that have no capacity installed or zero load in the IIT system were left with no allocation. Table VII summarizes the load participation factors by region and the number of buses with capacity installed. The foundational elements of the electricity system representation needed for advanced dynamic studies are provided in the database though additional generator information may be required for some specific applications, such as advanced power control from wind turbines.

III. POWER CAPACITY INCLUDED IN THE NREL-118 TEST SYSTEM

The IEEE 118-bus test system only includes the generators' capacity and the bus number where they connect. It does not have details of generators' characteristics. In contrast, the new database includes characteristics of generators located in three existing regions. These regions and its generators were obtained from the WECC 2024 Common Case database [1], and their generation mixtures are shown in Fig. 4 through Fig. 6, respectively.

The total new installed capacity equals 24.5 GW, divided as:

1) *Region 1:* The Bay Area (also called PGEB[2]), with a total of 10.5 GW of electricity generation capacity installed.
2) *Region 2:* Sacramento (also called SMUD[3]), with a total of 5.4 GW of electricity generation capacity installed.
3) *Region 3:* San Diego (also called SDGE[4]), with a total of 8.6 GW of electricity generation capacity installed.

The 10 power generation technologies are: steam turbines (ST) powered by coal, gas and other fuels, internal combustion engines (ICE) powered by gas, combustion turbines (CT) powered by gas and oil, gas combined-cycle turbines (CC), photovoltaics (referred simply as solar), hydro and biomass generators, and wind turbines.

[2]PGEB stands for Pacific Gas & Electric Bay Area, i.e. PG&E Bay Area.
[3]SMUD stands for Sacramento Municipal Utility District.
[4]SDGE San Diego Gas & Electric.

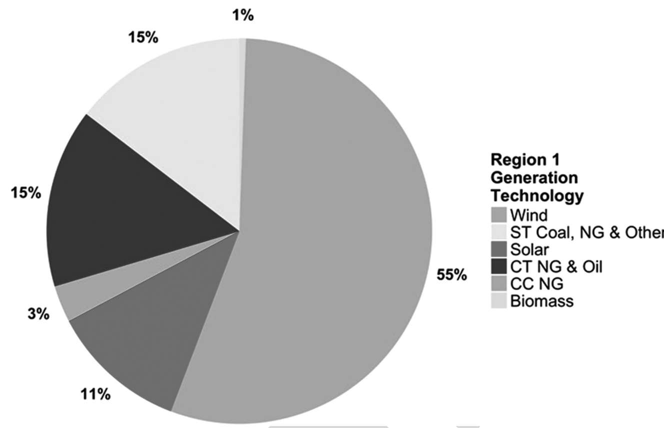

Fig. 4. Share of power generation (MW) in Region 1. The total electricity generation capacity installed is 10.5 GW.

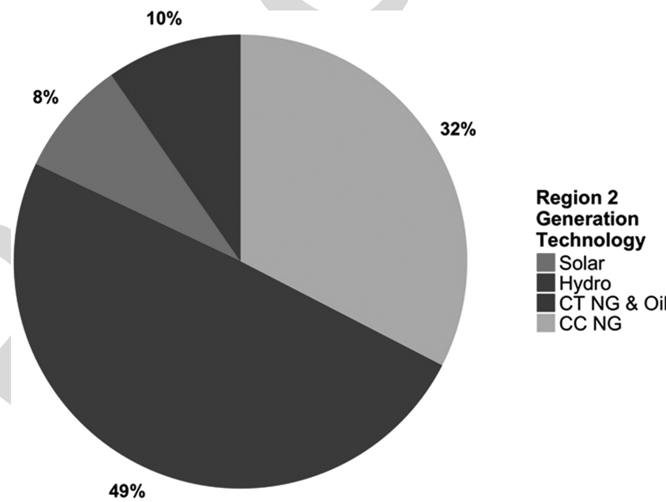

Fig. 5. Share of power generation (MW) in Region 2. The total electricity generation capacity installed is 5.4 GW.

All the generators have the following parameters: maximum capacity (MW), minimum stable level (MW), heat rate base (MMBTU/h), heat rate increment (BTU/kWh), load point (MW), start cost ($), VO&M charge ($/MWh), minimum up time (h), minimum down time (h), maximum ramp up (MW/min), maximum ramp down (MW/min). The heat input function (also called fuel rate function) defines heat (i.e. fuel) consumption for the full load domain at which generators operate. The heat input function is modeled as a heat rate base a and a set of linear increments bx, where $b =$ heat rate increment in the middle point of that segment and $x =$ load operation point. The simplest two cases are constant heat rate, equal to the heat rate base $f(x) = a$ and linear heat input function over all the load domain $f(x) = a + bx$. All other cases yield polynomial heat input functions.

The model includes 15 dispatchable and 28 non-dispatchable hydro generators. This means that the dispatch level of 15 hydro units is estimated according to the optimal system operation.

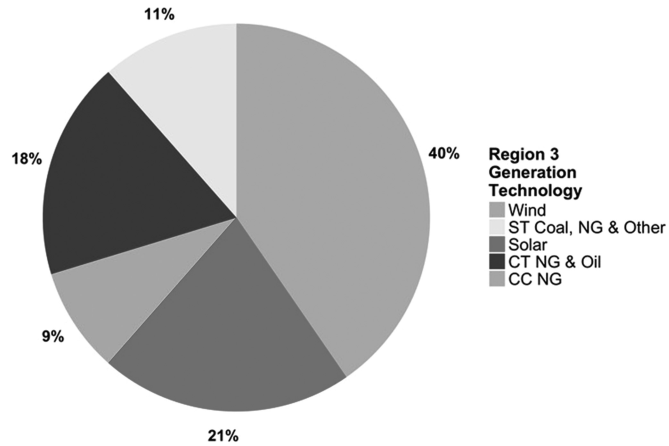

Fig. 6. Share of power generation (MW) in Region 3. The total electricity generation capacity installed is 8.6 GW.

TABLE VIII
BASIC CHARACTERISTICS OF THE NREL-118 TEST SYSTEM DATABASE

Characteristics	Peak Load	Total installed Capacity (MW)	Number of Generators
IEEE 118 IIT 2004	**6,000 MW (One day, hourly)**	**7,220**	**54 generators**
NREL-118 2015	**19,800 MW (annual, hourly)**	**24,600**	**327 generators**
Region 1	*9,700*	*10,523*	*136*
Region 2	*5,200*	*5,443*	*72*
Region 3	*5,500*	*8,600*	*119*

On the other side, 28 hydro generators are constrained to a fixed generation. The database includes the time series data of the fixed generation of the non-dispatchable units.

IV. LOAD, WIND AND SOLAR POWER TIME SERIES, AND EMISSION RATES

Table VIII compares the peak load and capacity installed of the IIT model and NREL-118 system. The NREL-118 system includes RT and DA forecast time series for load, as well as wind and solar power time series.

Load data are synthetic load data obtained from neural net regressions with 1980-2012 input weather and load data [24]. Wind data are provided by the Wind Toolkit [27], while solar data is provided by the National Solar Radiation Data Base (NSRDB) [28]. The base year used is 2011. The installed solar power is either distributed PV generation or utility-scale PV, and the majority in the system is utility-scale PV (see Table IX). Both wind and solar locations have been chosen so as to be in close geographic proximity to the load zones where they are connected, ensuring that the meteorological conditions which impact load, wind, and solar are consistent. The aggregated wind and solar profiles are comprised of a number of individual wind or solar plants, each of which has an independent time series of power output whose correlation is dependent on the geographic distance between the plants. For further details on the load, wind, and solar data, including forecasts, please refer to the Western Interconnection Flexibility Assessment study [24].

TABLE IX
WIND AND SOLAR CAPACITY GENERATION IN THE NREL-118 TEST SYSTEM

	Wind	Solar
NREL-118 test system	**17 Generators 1,078 MW**	**75 Generators 3,445 MW**
Region 1	*13 Generators 329 MW*	*33 Generators; 1,206 MW (Of which 747 MW are distributed PV)*
Region 2	*0*	*5 Generators; 444 MW (Of which 264 MW are distributed PV)*
Region 3	*4 Generators 749 MW*	*37 Generators; 1,795 MW (Of which 18 MW are distributed PV)*

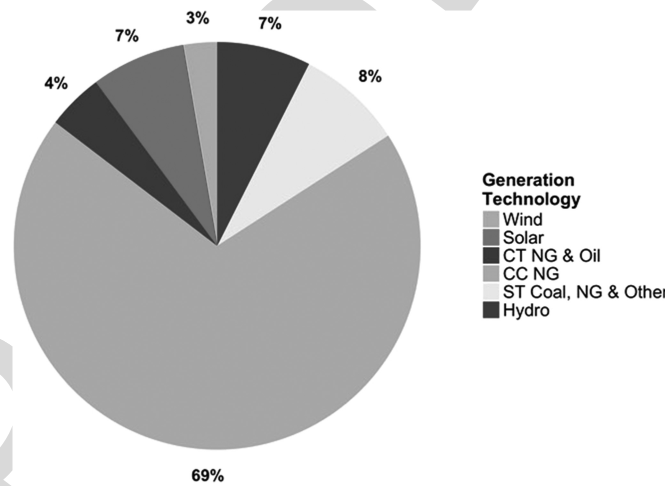

Fig. 7. Results of power dispatch simulation. Share of total annual power generation (MWh) of the full system (three regions combined), by technology.

Table IX summarizes the number of wind and solar generators, by region.

The resulting electricity generation mix (as a share of electricity generation) is shown in Fig. 7.

The database also includes emission rates of carbon dioxide (CO_2), nitrogen oxides (NOx), and sulfur oxides (SOx), for each fuel type. One single value of these gas emissions per fuel type is used across the three regions.

V. UNIT COMMITMENT AND ECONOMIC DISPATCH MODEL

The NREL-118 system's characteristics are explored through a test case, running a unit commitment and economic dispatch model, for DA and RT markets. A commercial production cost modeling tool, Plexos, is used to perform the analysis, using a DC Optimal Power Flow (OPF) model.

The characteristics of each market are provided in Table X. For the DA market, a look-ahead period is included after the 24-hour optimization window. This look-ahead period has a resolution of four hours and is used to include unit commitment constraints of the next 24 hours into the current optimization step. These constraints are mainly minimum up and down up times of the generating units. The amount of look-ahead should

TABLE X
CHARACTERISTICS OF THE ECONOMIC DISPATCH MARKETS RUN USING THE NREL-118 DATABASE

Market Horizon	Time step	Optimization Window	Look ahead*
DA	1 hour	1 day	1 day of 4 hour resolution
RT	1 hour	1 day	Does not apply

*Look ahead is a period after the optimization window, which is included in the DA market. The amount of look-ahead is sufficient to recover start costs or evaluate the longest up or down time constraint.

TABLE XI
TOTAL ANNUAL POWER INTERCHANGES BETWEEN REGIONS

	To R1	To R2	To R3
From R1	-	1,535 GWh	Not connected
From R2	7,553 GWh	-	71 GWh
From R3	Not connected	8.885 GWh	-

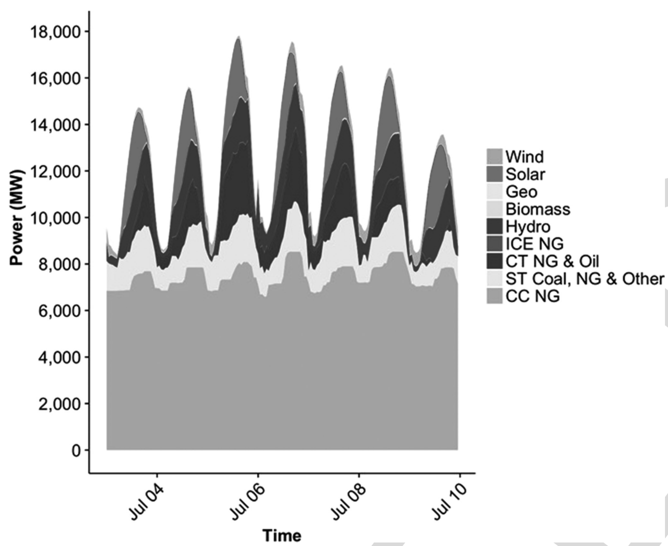

Fig. 8. Power dispatch during week with the annual load peak. Load peak of 17.82 GW happened on July 05, at 3 pm.

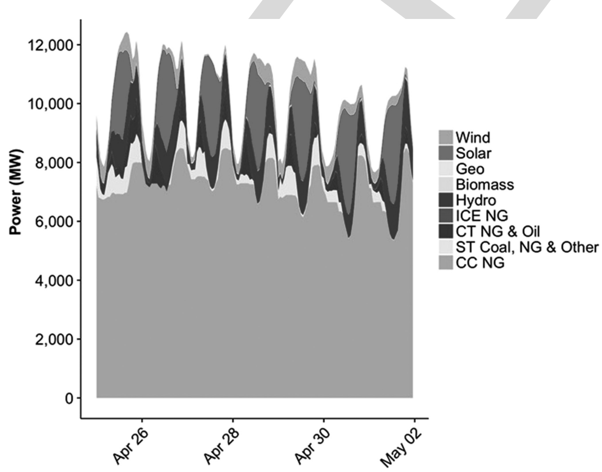

Fig. 9. Power dispatch during week with annual solar peak. Solar peak of 3.4 GW happened on April 30, at 1 pm.

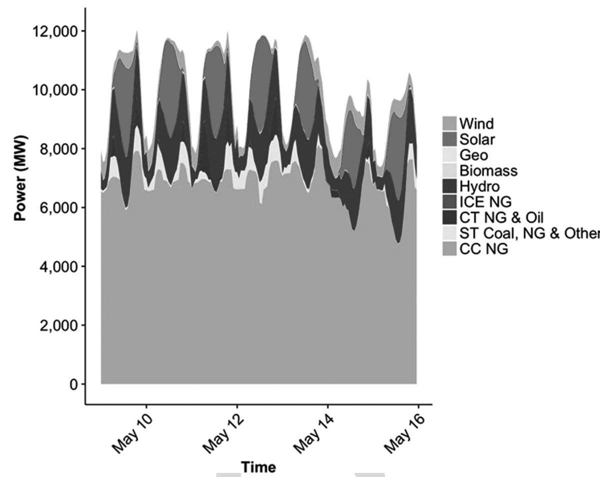

Fig. 10. Power dispatch during week with annual wind peak. Wind peak of 0.8 GW happened on May 13, at 10 pm.

be sufficient to recover start up costs or evaluate the longest up or down time constraint. To replicate these results, it is important to mention that Plexos optimizes monthly hydro budgets to obtain daily hydro budgets for the dispatchable hydro electricity generators.

The model includes contingency spinning reserves, and regulation up and down reserves, equal to 3% of load and 1% of load, respectively. These reserve requirements are in line with other production cost models used in renewable integration studies [29], [24]. In total, 234 generators provide reserves –i.e. all generators except wind and solar generators. Each generator participates in the reserve provision of each of the three regions. Energy and reserves are co-optimized in Plexos.

VI. SUMMARY OF RESULTS

The NREL-118 test system database includes results for the unit commitment and economic dispatch DA and RT models. The .xml file includes the Plexos model with the system as described, and the following solver settings: integer optimal solution method, solution gap of 0.1 and enforced thermal limits on lines of >69 kV. The aggregated results for the year are described below. Users can run the system with lower optimality gaps to benchmark their models.

Before modifying the database, it is advisable to first run the existing models and compare the results with those included here as a form of model benchmarking.

The power inter-changes across regions of the RT model are depicted in Table XI.

In the three regions there is no generation that has to be curtailed, and load is met at all times, i.e. there is no unserved load. In total there is 0.15 GWh of down regulation reserve shortage, 0.20 GWh of up regulation reserve shortage and 0.32 of contingency spinning reserve shortage. This might be due to renewable forecast errors and modeling rounding limitations, as well as imports that are not modeled or included.

Fig. 8 shows the generation stack of the full system for the week with the peak load (July 5th), while Figs. 9 and 10 show the weeks with the day with peak solar and wind power production respectively (April 30th and May 13th, respectively).

VII. Concluding Remarks

The NREL-118 test system was compiled using transmission grid characteristics of the IEEE 118-bus test system and the generation mix and load profiles of three regions of the WECC 2024 common case database. It consists of three regions, 118 buses, 186 transmission lines and 327 generators. A total of nine generation-technologies are included that represent both fossil fuels and renewables. It includes time-synchronous year-long actual and forecast time series for wind and solar power, as well as for regional electricity load. It also includes detailed generation constraints for the 327 generators (units).

This database is expected to be very valuable to the power system community, providing a standardized database that provides more publically available detail than previous iterations of the IEEE 118-bus system. The complete database can be considered in the community as the standard medium-size IEEE bus-test system, and certain variables, such as generator heat input and ramping functions, emission rates, fuel costs, and transmission line capacities, can be incorporated to other bus-test systems, or can be adjusted as technology performance and costs change in the industry. In addition, new elements, such as demand response mechanisms, electric vehicles, storage capacity and combined-heat power capacity and services, can be included directly, opening the opportunity for further research and collaborations across disciplines.

One immediate gain is the opportunity researchers will have to use this database to conduct renewable integration studies for systems expecting higher renewable penetration rates. This will be possible thanks to the real and forecast time-series data, as well as the level of detail of the system and generators' characteristics that allows tailoring the database to particular case studies. For example, this database can be used to study the impact in system's planning and operation for higher renewable energy scenarios under different climate and energy policy commitments, including increasing cycling of coal and gas power, the role of forecast uncertainty of renewable resources, the expected costs of emissions reduction, the change of locational marginal prices (LMP), the role of specific generator characteristics in the integration of higher renewable energy shares (such as minimum stable level and heat input functions) and the line congestion dynamics.

The new NREL-118 bus-test system database can be used across different research topics allowing for consistency between results from different studies. Such uniformity at this detail level is a tremendous gain and can support further collaboration between research topics.

Acknowledgment

The authors would like to acknowledge the valuable feedback from researchers Anthony Florita, Greg Stark, and Greg Brinkman, from National Renewable Energy Laboratory. Special thanks to Ryan Jones (formerly of E3) for providing the load data.

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