GE
Energy Consulting

PJM Renewable Integration Study

Task 3A Part A

Modeling and Scenarios

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imagination at work

Legal Notices

Contact Information

This report was prepared by General Electric International, Inc. (GEII); acting through its Energy Consulting group (GE) based in Schenectady, NY, and submitted to PJM Interconnection, LLC. (PJM). Technical and commercial questions and any correspondence concerning this document should be referred to:

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Acronyms and Nomenclatures

2% BAU	2% Renewable Penetration – Business-As-Usual Scenario
14% RPS	14% Renewable Penetration – RPS Scenario
20% LOBO	20% Renewable Penetration – Low Offshore Best Onshore Scenario
20% LODO	20% Renewable Penetration – Low Offshore Dispersed Onshore Scenario
20% HOBO	20% Renewable Penetration – High Offshore Best Onshore Scenario
20% HSBO	20% Renewable Penetration – High Solar Best Onshore Scenario
30% LOBO	30% Renewable Penetration – Low Offshore Best Onshore Scenario
30% LODO	30% Renewable Penetration – Low Offshore Dispersed Onshore Scenario
30% HOBO	30% Renewable Penetration – High Offshore Best Onshore Scenario
30% HSBO	30% Renewable Penetration – High Solar Best Onshore Scenario
AEPS	Alternative Energy Portfolio Standard
AGC	Automatic Generation Control
AWS/AWST	AWS Truepower
Bbl.	Barrel
BAA	Balancing Area Authority
BAU	Business as Usual
BTU	British Thermal Unit
CA	Intertek AIM's Cycling⬍Advisor ™ tool
CAISO	California Independent System Operator
CC/CCGT	Combined Cycle Gas Turbine
CEMS	Continuous Emissions Monitoring Systems
CF	Capacity Factor
CO2	Carbon Dioxide
CV	Capacity Value
DA	Day-Ahead
DR	Demand Response
DSM	Demand Side Management
EI	Eastern Interconnection

EIPC	Eastern Interconnection Planning Collaborative
ELCC	Effective Load Carrying Capability
ERCOT	Electricity Reliability Council of Texas
EST	Eastern Standard Time
EUE	Expected Un-served Energy
EWITS	Eastern Wind Integration and Transmission Study
FERC	Federal Energy Regulatory Commission
FLHR	Full Load Heat Rate
FSA	PJM Facilities Study Agreement
GE	General Electric International, Inc. / GE Energy Consulting
GE MAPS	GE's "Multi Area Production Simulation" model
GE MARS	GE's "Multi Area Reliability Simulation" model
GT	Gas Turbine
GW	Gigawatt
GWh	Gigawatt Hour
HA	Hour Ahead
HSBO	High Solar Best Onshore Scenarios
HOBO	High Offshore Best Onshore Scenarios
HR	Heat Rate
HVAC	Heating, Ventilation, and Air Conditioning
IPP	Independent Power Producers
IRP	Integrated Resource Planning
ISA	PJM Interconnection Service Agreement
ISO-NE	Independent System Operator of New England
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour
lbs	Pounds (British Imperial Mass Unit)
LDC	Load Duration Curve

LM	Intertek AIM's Loads Model ™ tool
LMP	Locational Marginal Prices
LNR	Load Net of Renewable Energy
LOBO	Low Offshore Best Onshore Scenarios
LODO	Low Offshore Dispersed Onshore Scenarios
LOLE	Loss of Load Expectation
MAE	Mean-Absolute Error
MAPP	Mid-Atlantic Power Pathway
MMBtu	Millions of BTU
MVA	Megavolt Ampere
MW	Megawatts
MWh	Megawatt Hour
NERC	North American Electric Reliability Corporation
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NWP	"Numerical Weather Prediction" model
O&M	Operational & Maintenance
PATH	Potomac Appalachian Transmission Highline
PJM	PJM Interconnection, LLC.
PPA	Power Purchase Agreement
PRIS	PJM Renewable Integration Study
PRISM	Probabilistic Reliability Index Study Model
PROBE	"Portfolio Ownership & Bid Evaluation Model" of PowerGEM
PSH	Pumped Storage Hydro
PV	Photovoltaic
REC	Renewable Energy Credit
Rest of EI	Rest of Eastern Interconnection
RPS	Renewable Portfolio Standard
RT	Real Time

RTEP	Regional Transmission Expansion Plan
SC/SCGT	Simple Cycle Gas Turbine
SCUC/EC	Security Constrained Unit Commitment / Economic Dispatch
SOx	Sulfur Oxides
ST	Steam Turbine
TARA	"Transmission Adequacy and Reliability Assessment" software of PowerGEM
UCT	Coordinated Universal Time
VOC	Variable Operating Cost
WI	Western Interconnection

1 Project Overview

1.1 Project Objectives

The PJM Renewable Integration Study (PRIS) was initiated at the request of PJM Stakeholders. A team headed by General Electric International, Inc. (GE) was engaged by PJM Interconnection, LLC. (PJM) to perform a comprehensive PJM Renewable Integration Study (PRIS) with focus on wind and solar power in order to investigate and address a range of important and contemporary technical issues to meet the PJM RPS requirement by 2026 which is the selected target Study Year.

The purpose of the study is to assess impacts to the grid if additional wind and solar is connected. It is not an analysis of the economics of those resources, therefore quantifying the capital investment required to construct additional wind and solar is beyond the scope of this study.

The principal objectives of this study are to:

- Determine, for the PJM balancing area, the operational, planning, and market effects of large-scale integration of wind power as well as mitigation/facilitation measures available to PJM
- Make recommendations for the implementation of such mitigation/facilitation measures

The main motivation behind this study is the need to be prepared for the considerably higher penetration of renewable energy into the PJM market by in the next 10 to 15 years. The North American Electric Reliability Corporation (NERC) states that in 2012, renewable generation including hydro made up 15.6% of all on-peak capacity resources and is expected to reach almost 17% in 2022, growing by approximately 60 GW. Of these, 36 GW is expected to be contributed by wind resources, and 13.4 GW by solar resources[1].

Every jurisdiction within the PJM footprint, except for Kentucky and Tennessee, has a renewable portfolio standard (RPS), or Alternative Energy Portfolio Standard (AEPS), or non-binding Renewable Portfolio Goal (RPG)[2].

As reported in the "PJM Regional Transmission Expansion Planning Process" [3] of September 2010, much of the wind potential in PJM is clustered in three areas: along the Appalachian Mountains; in the Midwest, particularly in the Great Plains; and off the East Coast.

[1] NERC 2012 Long-Term Reliability Assessment, November 2012.

[2] www.dsireusa.org

[3] http://www.pjm.com/~/media/documents/reports/20101207-rtep-foldout-921.ashx

Table 1-1 below provides the approximate amounts of wind and solar capacity needed to satisfy PJM's aggregate RPS requirements, in GW of nameplate capacity and percent of PJM load. A renewable energy requirement of about 14% in PJM in 2026 would require approximate 42 GW of wind and 11 GW of solar nameplate capacity. Note that a large portion of NERC's projection of future renewable resources are hydro resources, whereas high penetration scenarios considered in this study are based on addition of only wind and solar resources.

Table 1-1: Estimated Wind and Solar Capacity under RPS

	2021 Nameplate Capacity (GW)	2021 Percent of PJM Load	2026 Nameplate Capacity (GW)	2026 Percent of PJM Load
Wind	32	11.3%	42	13.9%
Solar	7	0.8%	11	1.2%

1.2 Project Team

GE assembled an expert team of partners to address various aspects of renewable integration into PJM grid, collectively referred to as the "GE team". The GE team consists of the following team of consultants:

- GE Energy Consulting
- AWS Truepower (AWST)
- EnerNex
- Exeter Associates
- Intertek Asset Integrity Management (Intertek AIM) – formerly APTECH
- PowerGEM

GE team is shown in Figure 1-1with members of each partner team listed alphabetically by their last names.

To fulfill the objectives of the study, the GE team quantified the impacts of increasing renewable energy penetration on the operation and reliability of the PJM power system, evaluated system performance and operating costs, and identified methods and approaches to mitigate the adverse impacts of renewable energy integration. The results of this study are intended to provide guidance and quantitative metrics to aid PJM in future development decisions.

The GE team has had deep subject matter expertise and experience in assessing the impacts of increased wind and solar generation on power grid operations and markets. For instance:

- GE has conducted similar studies for New York, Ontario, California, Texas, New England, Western USA (WWSIS), and Nova Scotia Power.
- EnerNex has performed similar studies for Minnesota, Colorado, Texas (SPS), Arizona, Oregon, California, New Mexico, Idaho, and Washington.
- AWS Truepower has worked with GE on studies for New York, Ontario, California, Texas, New England, and Nova Scotia Power.
- Intertek AIM is the industry leader in quantifying the impacts of increased cycling on the operation and maintenance of thermal power plants. Intertek AIM has recently assisted Xcel Energy, Arizona Public Service and Tennessee Valley Authority to assess the impacts of increased cycling on their thermal fleet. They have also examined cycling impacts at plants of Allegheny Energy, Constellation Energy and NRG in PJM.
- PowerGEM has tools and experience in simulating the sub-hourly operations and market performance in five ISO markets in the U.S., including PJM.
- Exeter Associates has solid expertise and experience with energy markets and how they are affected by increasing penetration of wind generation. Exeter has published several reports and journal articles on the state of wind integration for the California Energy Commission, the ISO/RTO Council, the National Renewable Energy Laboratory (NREL), and the Electricity Journal.
- EnerNex and AWS Truepower were major contributors to the Eastern Wind Integration and Transmission Study (EWITS), which will be a source of mesoscale wind and solar data for the proposed PJM study.
- GE, EnerNex, AWS Truepower and Exeter have worked with and have extensive experience with NREL.

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Figure 1-1: Project Team

1.3 Project Tasks Overview

To perform a detailed analysis of the operational, planning and market impacts of high penetration of renewable generation on the PJM system, the work was divided into the following four major tasks.

- Task 1: Wind and Solar Profiled Development – This task involved development of wind and solar profiles for the study with sufficient accuracy and flexibility to allow for simulation of power system and renewable generation operation and interaction over the time scales of interest.
- Task 2: Scenario Development and Analysis – This task focused on the development of the study scenarios in consultation with PJM, PJM Stakeholders.
- Task 3: Operational Impact Analysis (3a), and Market Analysis (3b) – This task entailed performing a detailed evaluation of the impact of wind and solar generation variability and uncertainty on PJM's operations and market.
- Task 4: Mitigation, Facilitation, and Report – This task included development of a set of recommendations related to PJM reliability standards, market rules, operating and planning procedures to mitigate the impacts of high wind and solar penetration.

These tasks are described in more detail in the following section.

The key contributions of the GE team members and how they fit together is summarized here:

- *AWS Truepower (AWST):*
    - Developed the detailed wind and solar profiles (actual and forecast values) used in each study scenario reflecting regional attributes of onshore and offshore wind and central and distributed solar power[4] (Task 1).
- GE Energy Consulting:
    - Provided the overall PJM PRIS project leadership and management,
    - Worked with PJM, PJM Stakeholders in developing the scenarios for the study (Task 2).
    - Utilized the GE Multi-Area Production Simulation (GE MAPS) model to simulate the hourly operation of the entire Eastern Interconnection system for the year 2026 (the study year), using production cost data (generator, load and transmission topology) and the regulation and load following requirements

[4] Additional information regarding the development of solar and wind profiles can be found under the Task 1 description.

identified by statistical analysis. The output of the simulation included annual production cost, LMP, congestion, emissions etc. In addition, the GE MAPS simulation was used to identify challenging days for further sub-hourly analysis by PowerGEM using their PROBE software (Task 3a).

  - Employed the GE Multi-Area Reliability Simulation (GE MARS) model to perform Loss of Load Expectation (LOLE) and renewable energy capacity valuation analysis (Task 3a).
  - Developed recommendations on operating and planning procedures to mitigate the impacts of high wind and solar penetration (Task 4)

- *Exeter Associates:*
  - Provided a review of industry experience with integration of wind and solar resources and investigated preferred practices from other markets (Task 3b).
- *EnerNex:*
  - Performed the statistical analysis on the load, wind, and solar data to determine the regulation and load following requirements (Task 3a).
  - Identified challenging time periods for further sub-hourly analysis by the PowerGEM team (Task 3a)
  - Performed additional analysis and developed input data for additional sub-hourly analysis (Task 3b), and provided recommendations on additional operating reserves procedures to mitigate the impacts of higher penetration of renewable energy into PJM grid (Task 3b).
- *PowerGEM:*
  - Performed the “Transmission Overlay Analysis” to identify additional transmission developments and upgrades and their associated costs needed to enable market access to the additional renewable energy and address potential congestion in the transmission grid (Task 3a).
  - Performed a detailed simulation of the challenging days identified by the EnerNex statistical analysis and GE MAPS simulations using the PROBE model. PROBE simulated grid/market operations within the PJM footprint using the boundary conditions from the GE MAPS analysis. PROBE analysis studied shortages in regulation and load-following under PJM’s existing market and operational procedures (Tasks 3a and 3b).

- *Intertek AIM:*
    - Used the hourly generation profiles from GE MAPS and the 10-minute generation profiles from PROBE to determine the impact of additional thermal plant cycling on PJM generators (Task 3a).
    - Conducted "Thermal Plant Emissions Analysis" to evaluate the environmental emissions associated with additional cycling of thermal plants (Task 3a).

A high-level overview of the key contributions of the GE team members, the software tools employed and how they fit together is depicted in Figure 1-2.

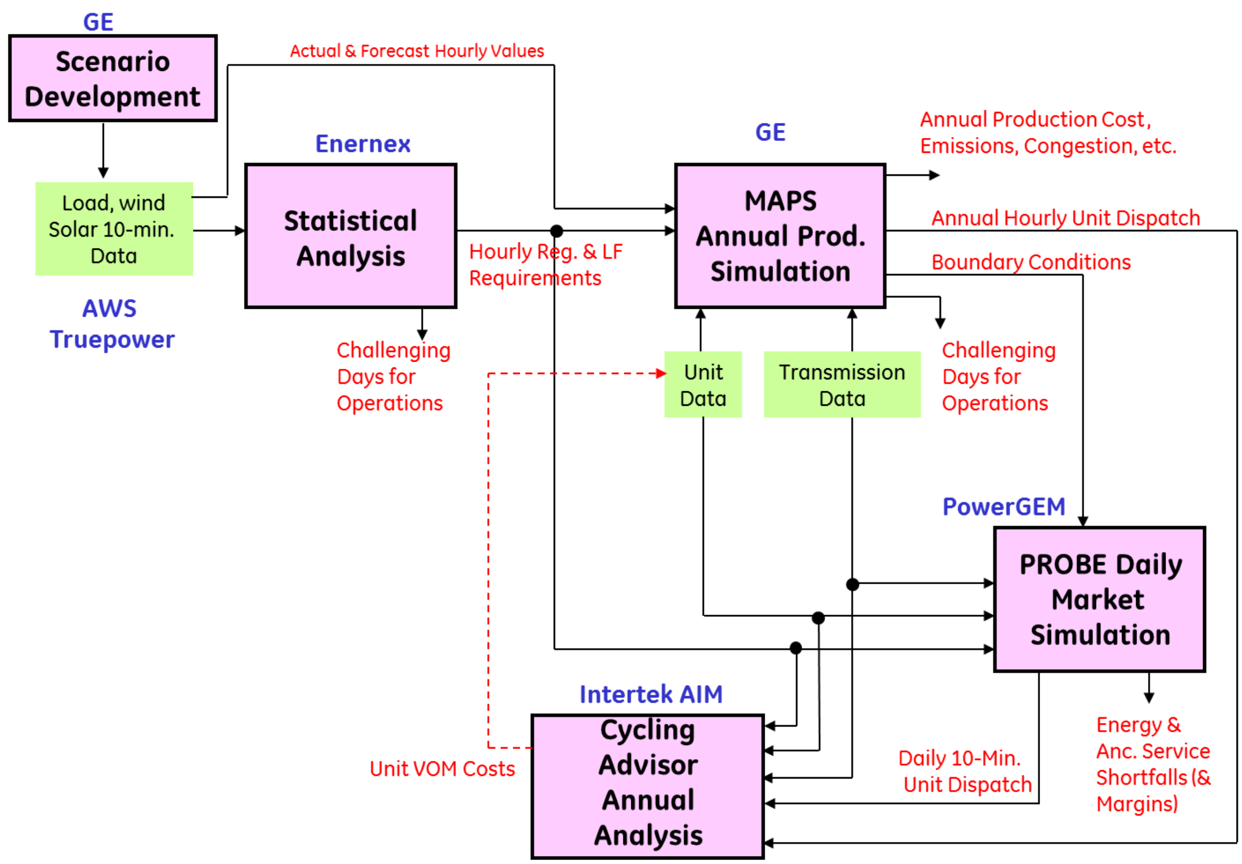

Figure 1-2: Study Process Flowchart

1.4 Analytical Approach

Three primary analytical methods were used to perform the hourly and sub-hourly production costing analysis and the capacity valuation analysis. To provide context for the next sections, a short summary of each is provided here:

- **Hourly Production simulation** analysis with GE's Concorda Suite Multi-Area Production Simulation (GE MAPS) model was used to evaluate hour-by-hour grid operation of each scenario with different wind and load profiles. The production simulation results quantified numerous impacts on grid operation including:
    - Amount of maneuverable generation on-line during a given hour
    - Effects of day-ahead wind forecast alternatives in unit commitment
    - Changes in dispatch of conventional generation resources due to the addition of new renewable generation
    - Changes in emissions (SOx and CO2) due to renewable generation
    - Changes in costs and revenues associated with grid operation, and changes in net cost of energy
    - Changes in intertie loadings
    - Changes in use of hydro resources
    - Number of unit start-ups and hours on line during the year
- **Sub-hourly Simulation** analysis with PowerGEM's Portfolio Ownership & Bid Evaluation (PROBE) model was used to quantify grid performance trends and to investigate potential mitigation measures in the 10-minute time frame. The sub-hourly analysis simulated the operation of dispatchable generation resources as well as variable wind generation in the study footprint using 10-minute time steps for selected days, while enforcing constraints related to unit ramp rates, ramp range, and intertie flow schedules. These simulations enabled examination of the responsiveness of PJM resources in mitigating impact of wind generation in sub-hourly periods.
- **Wind Capacity Valuation** involved loss of load expectation (LOLE) calculations for the study footprint using the GE Concorda Suite's Multi-Area Reliability Simulation (GE MARS) model. The analysis quantified the impact of wind generation on overall reliability measures, as well as the capacity values of the wind generation resources.

Impacts on system-level operating reserves were also analyzed using a variety of techniques including statistics and production simulation. This analysis quantified the effects of variability and uncertainty, and related that information to the system's increased need for operating reserves to maintain reliability and security.

The results from these analytical methods together with the additional analytical work on operating reserve requirements, cycling analysis, and emissions analysis complemented each other and provided a basis for developing observations, conclusions, and recommendations with respect to the successful integration of wind generation into the PJM power grid.

The following section provides an overview of each of the principal tasks.

2 Project Tasks and Modeling Approach

2.1 Task 1: PRIS Wind and Solar Profile Development

Task 1 involved development of wind and solar actual and forecast profiles, and was performed by the AWST team. AWST provided wind and solar power generation profiles and power forecasts within the PJM interconnection region as inputs to hourly and sub-hourly grid simulations. The task required a set of data that captured in a realistic fashion both the temporal and spatial variability of the wind and solar resource and associated power generation of hypothetical and existing renewable energy power plants. These data were based on high-resolution simulations of the historical climate performed by a mesoscale numerical weather prediction (NWP) model covering the period 2004 to 2006.

The work was divided into the following technical tasks:

- Obtaining archived NWP modeled data from the Eastern Wind and Transmission Study (EWITS) previously performed by AWST
- Working with PJM and PJM stakeholders to identify likely renewable energy power plants within the PJM interconnection
- Generating wind power output time series for onshore and offshore EWITS sites
- Generating solar power output time series for commercial, residential, and utility scale sites
- Simulating next-day wind and solar power forecasts for 2004, 2005, and 2006 load and renewable profile years
- Compiling results and reporting on findings

Several assumptions were made in order to facilitate the delivery of the requested datasets. These assumptions were proposed by AWST, presented to project stakeholders, and then applied based on GE and PJM's recommendations.

AWST used the three year meteorological data from the EWITS to produce power output profiles for both wind and solar renewable energy generation facilities. A site selection process was completed for onshore and offshore wind as well as for the centralized and distributed solar sites within the PJM region. The selection was designed to select representative sites that could be installed to meet and exceed renewable portfolio standards for the PJM Interconnection. Using the meteorological data, the power output profiles were developed for each of the hypothetical and planned sites using specifications from the most current power conversion technologies as of July 2011. All of the wind and solar power profiles were validated against surface measurements and were found to be acceptable for use in the PRIS.

Power and energy output were also validated with limited publicly-available generation data and industry-standard software output. Although no model is a perfect reflection of reality, results confirmed that the data represent in a realistic way the averages, seasonal and diurnal patterns, ramping behavior, and power output for wind and solar plants in the PJM region. These data sets are suitable for use in system planning and operating studies.

Task 1 report was issued separately[5].

2.2 Task 2: Scenario Development and Analysis

Task 2 involved development of scenarios for the analysis. The GE team worked together with PJM, stakeholders to develop a set of renewable energy scenarios for analysis. The "base scenarios" were derived from existing state renewable energy mandates for year 2026, with approximately 42 GW wind and 11 GW solar. The locations of these wind and solar facilities were based on proposed wind and solar plants in the PJM generation queue, augmented by additional resources as needed to reach the RPS mandated levels. PJM developed a transmission system model consistent with this level of wind and solar generation, as well as year 2026 loads and other new generation facilities required to meet installed reserve margins.

For the purpose of this proposal, a "scenario" is defined as a specific combination of system topology, generation fleet, and ratings/locations of wind and solar plants. A "sensitivity" is defined as a change to some parameter in a scenario (e.g., fuel cost, carbon pricing, etc.) while keeping the topology, generation fleet, and ratings/locations of wind and solar plants the same. A "scenario" requires significant effort to set up the system configuration, while doing a "sensitivity" analysis requires much less effort as only one (or a few) data items are changed.

Table 2-1 shows the final list of 10 scenarios. It includes:

2% Scenario: This is a reference Business As Usual (BAU) case with the existing level of wind/solar in year 2011. This case served as a benchmark for how operations and market performance will change as wind and solar penetration increases.

14% Scenario: This is the RPS base case with wind and solar generation to meet existing RPS state mandates by 2026.

5 Report: Task 1 Load Profile Data, GE Energy Consulting, September 27, 2011 and AWST Final Report, September 23, 2011

20% Scenarios: This set of scenarios examines system performance with 20% wind and solar penetration in PJM, with four variations on where the wind and solar generation are located and the mix of wind and solar.

30% Scenarios: This set of cases examines system performance with 30% wind and solar penetration in PJM, with four variations on where the wind and solar generation are located and the mix of wind and solar.

Table 2-1: Study Scenario List

Scenario	Renewable Penetration in PJM	Wind/Solar (GWh)	Wind + Solar Siting	Comments
2% BAU	Reference	Existing wind + solar	Existing Plants (Business as Usual)	Benchmark case for measuring changes due to increased wind/solar
14% RPS	Base Case 14%	109 / 11	Per PJM Queue & RPS Mandates	Siting based on PJM generation queue and existing state mandates.
20% LOBO	20%	150 / 29	Low Offshore + Best Onshore	Onshore wind selected as best sites within all of PJM
20% LODO	20%	150 / 29	Low Offshore + Dispersed Onshore	Onshore wind selected as best sites by state or region
20% HOBO	20%	150 / 29	High Offshore + Best Onshore	High offshore wing with best onshore wind
20% HSBO	20%	121 / 58	High Solar + Best Onshore	High solar with best onshore wind
30% LOBO	30%	228 / 48	Low Offshore + Best Onshore	Onshore wind selected as best sites within all of PJM
30% LODO	30%	228 / 48	Low Offshore + Dispersed Onshore	Onshore wind selected as best sites by state or region
30% HOBO	30%	228 / 48	High Offshore + Best Onshore	High offshore wing with best onshore wind
30% HSBO	30%	179 / 97	High Solar + Best Onshore	High solar with best onshore wind

The 14% renewable penetration in the 14% RPS case incudes 1.5% (14,500 GWh) of other non-wind and non-solar types of renewable resources. The total GWh amount of other renewable resources was kept constant across all the scenarios.

PJM was responsible for developing transmission models for each of the scenarios. PJM provided the base power-flow, which PowerGEM then used to develop the transmission model details. The GE team also assisted PJM in identifying additional capacity (type, size and location) that would be required to meet the reserve margin for the various scenarios.

In addition to the different combinations of wind/solar penetration and siting listed in Table 2-1, the analysis considered multiple years of wind/solar/load profiles, i.e., 2004, 2005, and 2006, in addition to a range of sensitivities. One scenario at each penetration level was analyzed with three years of wind/solar/load profiles – these included the 2% BAU, 14% RPS, 20% LOBO, and 30% LOBO scenarios. The other scenarios were analyzed with only the 2006 profile data.

As described later, a number of sensitivity analyses were performed to examine sensitivity of the modeling results to lower load growth, lower natural gas prices, inclusion of carbon pricing, and having perfect forecast of wind and solar energy in selected scenarios.

The entire Eastern Interconnection, with a few exceptions, was modeled in the GE MAPS production simulation. The exceptions were the Canadian Maritime provinces, Manitoba, Saskatchewan, and Quebec, which were modeled as a simpler single energy sources and sinks. The levels of wind and solar generation in the Eastern Interconnection outside of PJM were determined for each scenario as part of Task 2.

Task 2 report was issued separately[6].

2.3 Task 3a: Operational Impact Analysis

2.3.1 Development of Study Scenarios

The study utilized a case-based analysis for examining future growth in renewable energy penetration for the PJM system. After GE performed a number of preliminary model runs based on the initial selected study scenarios and reviewed the results with PJM, a final set of study scenarios were identified by PJM.

A major effort entailed identification of specific wind projects consistent with the scenarios. The locations of these wind facilities were based on proposed wind plants in the PJM generation queue and resource plan, augmented by additional resources as needed to reach the levels listed by PJM, and other forecast changes to the PJM portfolio. The underlying system transmission grid topology was based on transmission system model provided by the PJM transmission team, consistent with this level of wind generation, as well as non-conforming year 2026 loads (i.e. possible large discrete loads that are not typically captured by scaling of historical load profiles) and other planned new generation facilities.

GE worked with PJM to define all the necessary assumptions for each scenario, including amount of renewable energy (type, rating, and location), energy interchange with neighboring regions, and the starting baseline transmission infrastructure that defined the first scenario.

[6] Report: Task 2 Scenario Development and Analysis, GE Energy Consulting, January 26, 2012.

2.3.2 Analysis of Ancillary Service Requirements

The GE MAPS production simulations employed in this study were conducted chronologically at one-hour time steps. Consequently, the real time adjustments of generation to compensate for variations in the balancing area net demand were not modeled explicitly. Instead, the responsive generation that would be necessary in a given hour to regulate and balance was represented as constraints on the unit commitment and economic dispatch algorithms in the production model. The determination of the appropriate constraints that reflected the additional variability and short-term uncertainty introduced by wind generation was the objective of the statistical analysis.

High-resolution load and wind and solar production data for an extended chronological period (e.g. one or more years) were the primary inputs to this analysis. The pattern that was modeled explicitly in the production simulations, i.e. the average hourly values, was subtracted from the 10-minute values to reveal the intra-hourly requirement. As described in the sections on Statistical Data Analysis and Reserve Analysis, various mathematical and statistical techniques were then applied to characterize this variability and the short-term uncertainty in the case where reserve requirements were determined prior to the operating hour. The statistical characteristics were then used to develop “operating rules” that used current hour values of load and wind generation along with forecasts of those quantities for the next hour as inputs. With these rules, reserve constraints for each hour of the production simulation were pre-computed and entered into the model as profiles for regulation, load following (or implication thereof for sub-hourly market flexibility) and contingency reserves.

2.3.3 Assessment of Correlation of Wind/Solar Generation with System Load

The analysis mentioned above was extended to assess the correlation of renewable generation with the project PJM load in 2026. Simplified methods for estimating capacity value, including those from NREL as well as time-of-day based measures utilized in the electric power industry, were applied to each of the scenarios. These were then compared to results from the more rigorous LOLE analysis. These tasks were performed for the scenarios developed in Task 2 of this project.

2.3.4 Development of List of Constraints

The GE MAPS was used to model the EI transmission in detail. In addition to transmission constraints, GE also modeled other market and operational procedures in the GE MAPS program based on consultation with PJM.

GE suggested and PJM agreed to include a transmission overlay task option in the project. The GE team employed PowerGEM’s Transmission Adequacy and Reliability Assessment (TARA) program to determine the constraints to model for each scenario. The TARA Flowgate

Screening function provides a consistent method to identify all potential N-1 contingency overloads under various generation dispatch scenarios with the primary focus on generation dispatch uncertainties. The unique feature of TARA flowgate screening is that it identifies the list flowgates irrespective of the initial dispatch in the underlining load flow model. Currently, TARA flowgate screening has been in active use at PJM for many applications and is an integral part for the automation of the PJM generator deliverability analysis.

2.3.5 Simulation of PJM Hourly Operations Using GE MAPS

GE used the GE MAPS software to simulate the hourly operation of the entire Eastern Interconnection system for the study year using load and transmission data provided by PJM and the hourly regulation and load following requirements identified in the statistical analysis described earlier. GE MAPS is ideally suited to this study since it simulates a power system from the point of view of a system operator – performing an N-1 security constrained system dispatch with complete and detailed transmission modeling. GE MAPS has been continuously developed, refined and benchmarked for over 30 years and has been applied for system economic analyses for the entire U.S., Canada, and many parts of the world.

The output of the simulation included hourly production costs, Locational Marginal Prices (LMPs), transmission flows and congestion, environmental emissions, and other detailed information. These outputs are discussed in more detail in the discussion of the model results. GE MAPS was also be used to forecast the hourly operation of generators in the PJM, which was used to assess the impact of cycling on thermal units. In addition, the GE MAPS simulation was used to identify challenging days for further sub-hourly analysis using PROBE, along with the boundary conditions (i.e., hourly flows between PJM and its neighbors).

One very important part of the simulation was the treatment of the wind forecast. For each wind plant, two hourly operational profiles were supplied. The first described what the day-ahead wind generation forecast would be, based on the day-ahead weather forecast and state-of-the-art wind generation forecasting models. This established a base line that was used in the unit commitment of the rest of the generation in the system. A second profile defined the actual wind generation that would have occurred based on the actual weather. Options within the GE MAPS model allow consideration of no forecast (i.e., wind generation is ignored in the day-ahead commitment), state-of-the-art mesoscale forecasts, or perfect wind generation forecasts.

2.3.6 GE MAPS Based Hourly Analysis

GE MAPS Model

GE used its proprietary Concorda Suite's Multi-Area Production Simulation (GE MAPS) software to simulate the hourly operation of the PJM system for the study years using load and transmission data provided by PJM and the hourly regulation and load following requirements identified in the statistical analysis. GE MAPS is a chronological hourly security constrained unit commitment and economic dispatch (SCUC/ED) model. GE MAPS is ideally suited to this study since it simulates a power system from the point of view of a system operator – performing an N-1 security constrained system dispatch with complete and detailed transmission modeling. GE MAPS has been continuously developed, refined and benchmarked for over 30 plus years and has been applied for system economic analyses for the entire U.S., Canada, and many parts of the world. Additional information about GE MAPS is provided in the Appendix.

The simulation outputs include, but are not limited to, the following:

- Annual Production Cost (variable operating cost)
- Locational Marginal Prices (LMP)
- Transmission congestion
- Environmental Emissions (SOx, NOx, and CO2)
- Curtailed (i.e., undelivered / spilled) Renewable Energy
- Demand Response (DR) deployed and Un-served Load
- Unit Performance
- Starts, Online Hours, Peaking Unit Utilization, Cycling, etc.
- Impacts of Wind Forecast Error
- Tie-Line Utilization with neighboring system
- Others

PJM Market Database Development

The new solar and wind generation resources were added to the GE MAPS and PROBE production simulation models. These new resources were characterized and modeled as hourly load modifiers, i.e., with fixed generation pattern and not subject to being dispatched by the operator's instructions. It was also assumed that small hydro resources are scheduled "must-take" generation. The curtailments of these resources were set to occur only after solar and wind curtailment.

PJM reviewed the transmission model (with changes in the future) that was built into the GE MAPS database. PJM also reviewed the list of transmission interfaces to monitor (and limit) based on operating experience and present stability constraints. In addition to transmission constraints, GE also modeled other market and operational procedures in the GE MAPS program based on consultation with PJM.

The final scenarios were used to develop a database of profile data for load, wind, and solar generation. The resulting database contained multiple tables of information including:

- Raw profile data at the highest available resolution.
- Average hourly values, computed from the raw profile data.
- Scaling information to project to 2026 and intervening study years load from historical profiles.
- Scenario definitions identifying renewable generation project capacities and corresponding injection bus for the power-flow and production simulations models.
- Any other information, as necessary for constructing the study cases.

PJM Market Simulation

After selection of scenarios, a detailed evaluation of the impact of renewable energy generation variability and uncertainty on PJM's operations for each scenario was performed. The evaluation included extensive GE MAPS simulations for full years of operation as well as more detailed, sub-hourly PROBE examination of challenging periods.

As noted earlier, the GE MAPS production simulations employed in this study were conducted chronologically at one-hour time steps. Hence, the real time adjustments of generation to compensate for variations in the balancing area net demand were not modeled explicitly. Instead, the responsive generation that would be necessary in a given hour to regulate and balance was represented as constraints on the unit commitment and economic dispatch algorithms in the production model. Through statistical analysis, performed by EnerNex, the appropriate constraints that reflect the additional variability and short-term uncertainty introduced by wind generation were determined. Those "operating rules", which used current hour values of load and wind generation along with forecasts of those quantities, were entered into the model as additional reserve constraints (over and above the reserve requirements determined by the current PJM rules) for each hour of the production simulation. The commitment, dispatch and cost implications of those additional reserves were reflected in the GE MAPS results.

GE MAPS was also used to quantify the hourly operation of majority of individual generators in PJM. Combined Cycle Gas Turbines are modeled as a single "unit" regardless of how many generators are present. Smaller hydro plants are aggregated into larger plants. The generation information was fed into the overall analysis of simulation results to help identify and quantify performance that might require or benefit from mitigation options. In addition, the GE MAPS simulation also identified challenging days for further PROBE analysis.

In addition to the detailed representation of the PJM power grid modeled in the GE MAPS, the outside world, covering the rest of the Eastern Interconnection were explicitly represented in GE MAPS, albeit with less level of detail.

2.3.7 Sensitivity Analysis

In addition to the different combinations of renewable energy penetration and siting, the analysis considered a range of sensitivities. As described in more detail later, sensitivity analysis was performed to examine impacts of Lower Load Growth, Lower Natural Gas Prices, including of Carbon Prices, and Perfect Renewable Forecast on system operations and economics. These sensitivities were analyzed across selected study scenarios.

2.3.8 LOLE and Renewable Capacity Valuation Analysis

The objective of this task was to quantify the Capacity Value (CV) of wind generation in PJM using Loss of Load Expectation (LOLE) calculation methods, and to benchmark/calibrate approximate CV calculation methods against the rigorous LOLE method.

GE Energy Consulting used its proprietary Concorda Suite Multi-Area Reliability Simulation Software (GE MARS) to calculate the daily Loss of Load Expectation (LOLE), in days per year, for each scenario for the year 2026. In addition to the daily LOLE, GE MARS also calculated hourly LOLE, in hours per year, and Expected Un-served Energy (EUE), in megawatt hours (MWh) per year.

The reliability indices were calculated for each transmission area, on both an isolated (assuming no ties between areas) and interconnected basis, with weekly and monthly indices also available. The daily LOLE determined the number of days on which an outage is expected to occur. Since typical generation outages are equally likely at any time of the day this index is historically calculated at the time of the system daily peak load. However, wind generation varies throughout the day. Hence, GE employed an expanded version of the GE MARS program to determine the daily LOLE while looking at every hour of the day. In this way any off-peak outages caused by significant drops in the wind generation were fully accounted for.

Based on the ratios of capacity among the areas in the target block, perfect capacity was added to the system to develop a capacity value curve. Perfect capacity is an ideal unit that has a fixed output for all hours of the year, with no outages. An advantage of perfect capacity over other methodologies is that it is independent of forced outage rate, unit size and load profiles which affect other measures. Perfect capacity can be converted into the capacity of a conventional thermal unit based on the forced outage rate of that unit.

Each block was modeled to determine the reliability of the system with that block installed. The equivalent perfect capacity was then determined by finding the amount of added capacity brought the system to the same level of reliability. Further, for most situations analyzed, we determined the amount of perfect capacity that could be needed to meet one-in-ten-year interruption reliability targets.

Since the CV of wind power declines with increasing penetration, the analysis considered several wind penetration levels in PJM based on the study cases. This study considered load, wind and solar profiles for the years 2004, 2005 and 2006. Although total wind and solar generation from a particular plant may not vary too much from year to year, its coincidence with the load, and therefore its reliability value, may shift significantly. All of the scenarios were examined for all three sets of wind and solar profiles.

The LOLE analysis determined the Effective Load Carrying Capability (ELCC) of the incremental wind and solar generation additions. The difference between these cases helped identify the penetration levels at which saturation occurs and no additional benefit is gained due to the transfer limits out of the area. In order to concentrate the analysis on the capacity value of renewable generation within the PJM system it was proposed that the neighboring systems be ignored in this portion of the analysis. In this manner only the PJM load profiles and generation characteristics impacted the capacity value of the renewable generation.

2.3.9 Selection of Potentially Challenging Time Periods

The profile data for PJM load, wind, and solar production were analyzed with a number of mathematical and statistical techniques. In most cases, the characteristics of each scenario were compared to PJM load alone to provide a gauge as to the degree of operational impacts that could be expected for each of the scenarios.

From this backdrop, periods of operational challenge or stress were identified for sub-hourly investigations using the PROBE software. The sufficiency of reserve constraints were explicitly verified by performing a sub-hourly market simulation (Day-Ahead (DA), Hour-Ahead (HA) and Real Time (RT)) of selected days using the PROBE software as described in the Sub-Hourly PROBE Simulation Section.

2.3.10 Simulation of PJM Sub-Hourly Operations Using PROBE for Selected Days

The objective of this sub-task was the development of the process that closely modeled different stages of the PJM market clearance procedure under the current market design. Consequently, PROBE was used to test the impact from increased penetration of renewable resources on market outcomes, since the PROBE software closely models the PJM markets, but on a shorter-term basis than GE MAPS, thus providing capabilities to study selected days in detail by more closely following PJM actual market rules.

PROBE used the same inputs as GE MAPS to simulate challenging days identified by the statistical analysis and the hourly production simulation. The PROBE market simulation analyzed potential short-term operational issues created by each integration scenario, closely following PJM current market rules including detailed modeling of various ancillary market requirements.

The GE MAPS hourly simulations were used to identify challenging days to be analyzed in more detail using PowerGEM's PROBE power system modeling model for sub-hourly simulations. PROBE was used to simulate near real time operations of the PJM system, with 10-minute time-steps, close to the economic dispatch in actual system operations. The PROBE analysis was intended to provide more detailed view of the ability of the PJM system resources to accommodate the variability and uncertainty associated with the levels of wind generation in selected study scenarios.

The maintenance, wind and hydro schedules from the GE MAPS simulation were entered into the PROBE model for the selected days of interest in selected study cases. The PROBE simulation analyzed sub-hourly thermal dispatch and potential short-term operational issues in the selected case.

2.3.11 Assessment of Unit Cycling Impacts

The Intertek AIM's proprietary unit commitment model – Cycling⬍Advisor ™ (CA)[7] - was used to assess impacts of unit cycling. CA was used to derive the incremental variable O&M costs of power plant operation by utilizing its ability to model unit cycling damage. CA used the hourly MW dispatch and other inputs such as fuel costs, variable O&M costs, equipment damage costs, unit startup costs, and emission amounts, from GE MAPS. The Loads Model ™ (LM)[8] was also utilized to evaluate the damage and damage cost due to cycling at an hourly and a 10 min operating profile.

The objective of this task was to provide estimates of cycling related wear-and-tear costs and variable O&M costs. Results of the investigation are reported in the section on "Power Plant Cycling Analysis".

[7] CA Code remains the sole property of Intertek AIM

[8] Intertek AIM's Loads Model includes the methodology and software Intertek AIM has been developing since the late 1980s to quantify cycling intensity from hourly generation, reliability data, and background information, such as thermal signature and remaining useful life data. Loads Model software is simplified and converted to subroutines within the CA computer program, ensuring that our best cycling models are simulated.

2.4 Task Flow Diagrams

Further details of each task are illustrated in the following diagrams.

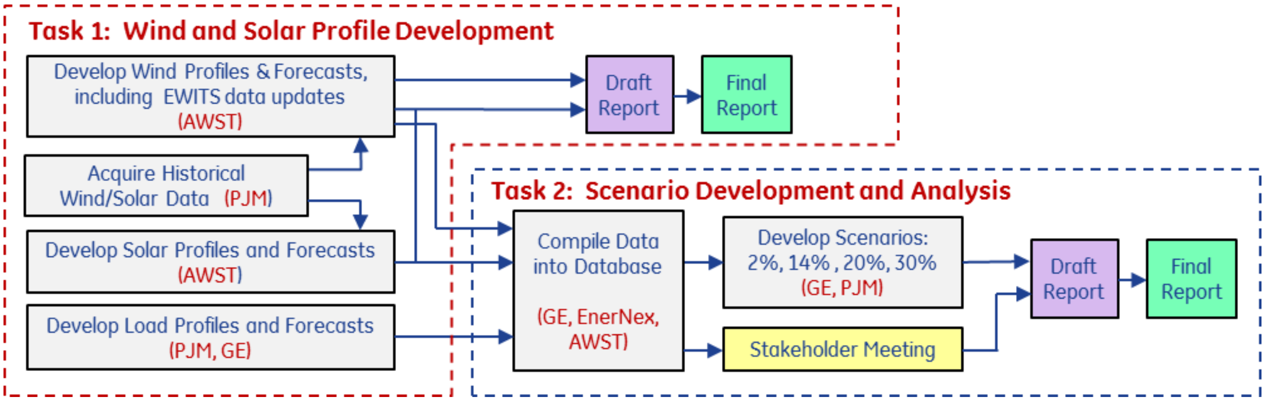

Figure 2-1: Task 1 and 2 Details

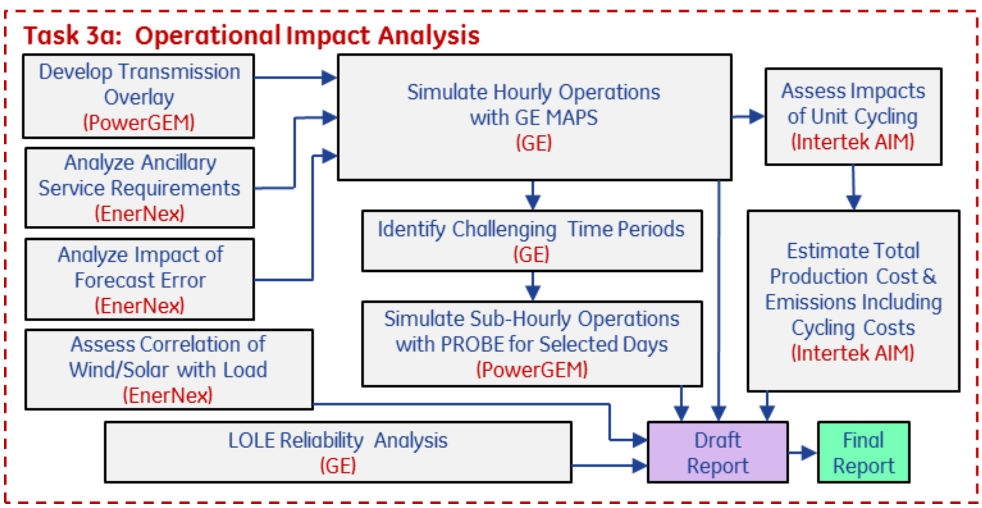

Figure 2-2: Task 3a Details

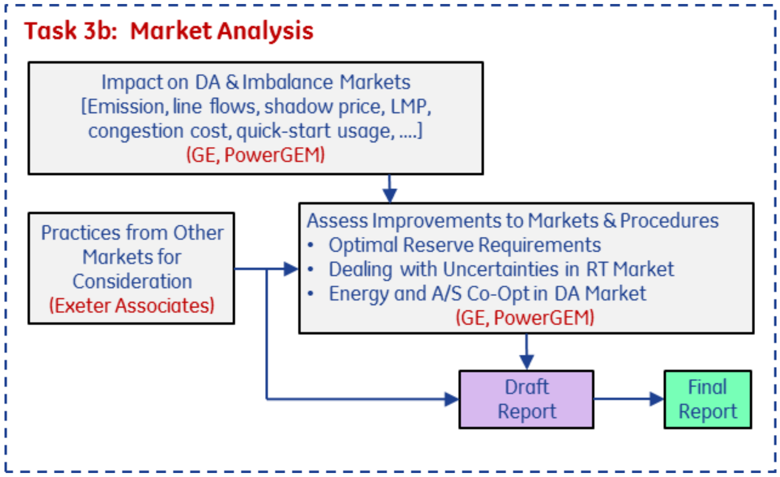

Figure 2-3: Task 3b Details

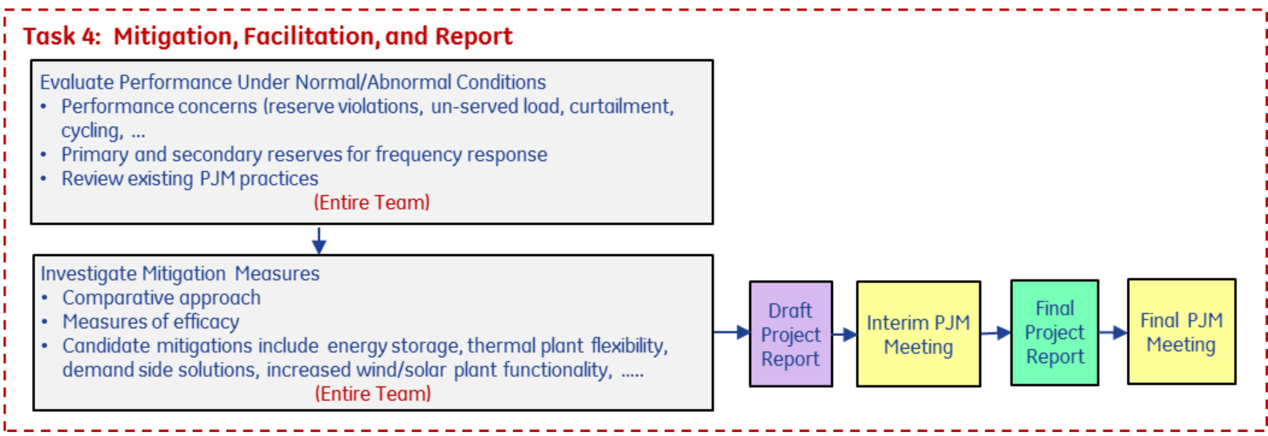

Figure 2-4: Task 4 Details

3 Modeling Assumptions

3.1 PJM Power System Overview

PJM Interconnection[9] is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of 13 states and the District of Columbia. As shown in Figure 3-1, the territories covered include all or parts of states of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia.

PJM acts as a neutral, independent party in operating a competitive wholesale electricity market and managing the high-voltage electricity grid to ensure reliability for more than 60 million people. PJM's long-term regional planning process provides a broad, interstate perspective that identifies the most effective and cost-efficient improvements to the grid to ensure reliability and economic benefits on a system wide basis.

PJM began in 1927 when three utilities, realizing the benefits and efficiencies possible by interconnecting to share their generating resources, formed the world's first continuing power pool. Additional utilities joined in the following years.

In 1997, PJM became a fully independent organization. At that time, membership was opened to non-utilities and an independent Board of Managers was elected.

On April 1, 1997, PJM opened its first bid-based energy market. Later that year the Federal Energy Regulatory Commission (FERC) approved PJM as the nation's first fully functioning independent system operator (ISO). ISOs operate, but do not own, transmission systems in order to provide open access to the grid for non-utility users.

Later, the FERC encouraged the formation of regional transmission organizations (RTOs) to operate the transmission system in multi-state areas and to advance the development of competitive wholesale power markets. PJM became the nation's first fully functioning RTO in 2001.

A view to the overall size of PJM is provided in Table 3-1.

[9] www.pjm.com

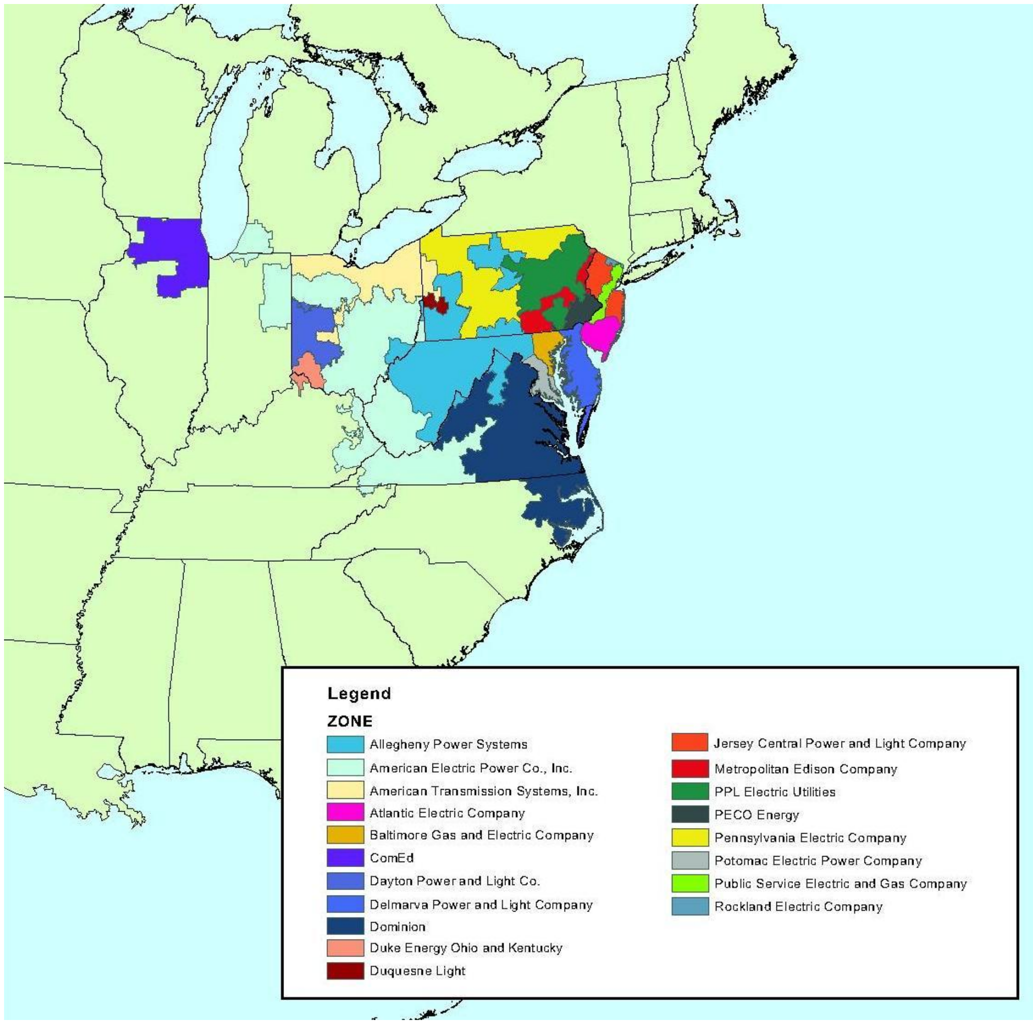

Figure 3-1: PJM Interconnection

[Source: www.pjm.com]

Table 3-1: PJM at a Glance in 2012

Membership	800+
Generating Capacity	185,600 MW
Peak Demand	163,848 MW
Annual Energy	832,331 GWh
Transmission Lines	59,750 Miles
Annual Billings	$29.18 billion
Territories Served	13 States + D.C.
Area Covered	214,000 Square Miles
Population Served	60 million

[Source: PJM 2012 Annual Report]

3.2 PJM and Renewable Energy

Eleven of the thirteen states within PJM and the District of Columbia have renewable portfolio standard (RPS) requirements, which are legislative or administrative requirements in each state to procure, or generate, a specified about of power from renewable energy sources such as wind, solar, biomass, and/or geothermal. Definitions of renewable energy and target amounts and years of achieving them are not consistent across the states, as shown in Figure 3-2. The other two states, Virginia and West Virginia, have renewable portfolio goal (RPG), but not mandatory requirements to achieve the set goals.

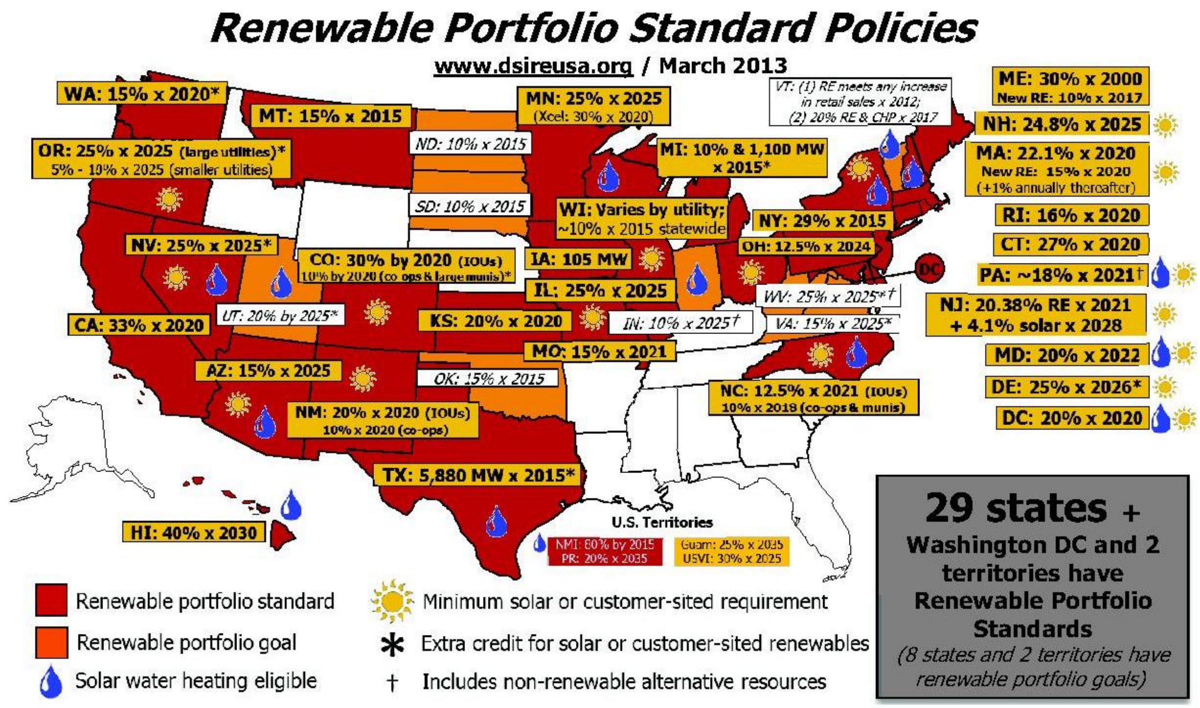

Figure 3-2: Renewable Portfolio Standard Policies

[Source: www.dsireusa.org – with written permission from NC Solar Center / DSIRE]

In 2011, renewable generation provided 3.5% of total electricity used in the PJM region. PJM works with state and federal officials to facilitate their goals for new renewable generation. PJM uses the Generation Attribute Tracking System (GATS), developed by PJM affiliate, PJM-EIS[10], to track the generation of renewable resources by producing a renewable energy credit (REC) certificate for each one-megawatt of renewable power produced, and also to

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[10] PJM-EIS is a wholly owned subsidiary of PJM that developed the GATS, and provides the reporting and data tracking services of both emissions and renewable energy credits.

track the retirement of each certificate by an electric utility to demonstrate RPS compliance. A REC represents the environmental and other non-power attributes created when renewable energy is generated. A certificate can be traded in REC markets with others in order to meet RPS requirements.

3.3 General Modeling Assumptions

The analysis of the PJM system with different levels of wind and solar energy penetration are based on basic set of assumptions about the PJM power system which represent the current and future state of the system, such as load, generation makeup, fuel costs, and transmission system.

This section lists the pertinent modeling assumptions used throughout this study. GE started with the GE MAPS model of the North America's Eastern Interconnect, which included the underlying transmission grid and a database of the generation resources, and projection of fuel and load data. The PJM portion of the model was then revised by the more detailed data in various stages during the project, and generally encompassing all aspects of the PJM power system, including detailed information on transmission, generation, load, fuel prices, and the relevant operational constraints.

The following list includes the basic features and assumptions used in the modeling of the PJM Power system:

- The year of the analysis is 2026, reflecting load energy and peak demand in 2026 based on the annual growth assumptions for energy; however, the hourly load shape is based on the historical years of the hourly patterns of the renewable energy, which for all the base scenarios is based on the year 2006.
- Entire Eastern Interconnect system is simulated – a capability provided by the GE MAPS model.
- Renewable plants are connected to higher voltage busses – this facilitates the locating of the renewable resources in GE MAPS which does model distribution level systems and makes the available transmission capacity accessible to renewable generation.
- Unless otherwise specified, PJM coal plants are assumed to have emissions control technology.
- Renewable resources are curtailed when dispatch will impact nuclear operation.
- Although GE MAPS has the capability, for simplicity, only primary fuel is modeled.

- Existing operating reserve practice is used for reference case, but statistical analysis is used to modify reserves for other scenarios with higher penetration of renewable energy.
- 2026 data are updated based on PJM input on coal retirement / gas repower and new builds
- Inflation rate is 2% per year (applied to inputs such as Variable Operations and Maintenance (VOM) costs, Fixed Operations and Maintenance (FOM) costs, etc.)
- PJM is represented as one power pool (PJM), modeled as a nodal market, with a number of areas or zonal pricing zones.
- Summer season is from May 1st to September 30st, and during this period thermal units have a capacity derate.
- Winter season is from October 1st to April 30th, and during this time thermal units have full capacity.
- For the hourly simulation, GE MAPS can directly model the hourly reserves (i.e., Spinning Reserve in GE MAPS terminology). The hourly reserves modeled in PRIS consist of:
  a) A constant Contingency Reserve reflecting the largest contingency in the system, and
  b) An hourly variable operating reserve, which in his study is determined by the statistical analysis of 10-minute solar, wind, and load data.
- The GE MAPS hourly reserve is also used in the sub-hourly PROBE simulations.
- The production simulation analysis assumed that all units were economically committed and dispatched while respecting existing and new transmission limits, generator cycling capabilities, and minimum turndowns, with exceptions made for any must-run unit or units with operational constraints.
- Increased O&M of conventional generators due to increased ramping and cycling are not included in the base scenario runs.
- Renewable energy plant O&M costs are not included. Renewable energy is considered to be a price-taker.
- The hydro modeling does not reflect the specific climatic patterns of 2004, 2005, and 2006, but rather a 10-year long-term average flow per month.
- The sub-hourly modeling assumed a 10-minute economic dispatch.

The following sections provide further detail on various PJM power system modeling assumptions.

3.4 Thermal Resources

3.4.1 Capacity Mix

The starting generation capacity mix excluding wind and solar is based on the existing installed generation – the 2% renewable penetration business as usual (2% BAU) scenario.

Figure 3-3 shows a pie chart of the starting 2% BAU scenario winter capacity mix in 2026 with the exclusion of the wind and solar capacities. In addition to the "existing" PJM generation, Figure 3-3 includes "new" ISA/FSA qualified plants in the PJM queue, plus additional "generic" SCGT and CCGT plants added to the PJM and Rest of EI systems in the 2% BAU scenario to meet the pool reserve margin targets in 2026 consistent with the assumed load growth. For instance, there is currently approximately 30 GW of SCGTs in PJM. The addition of PJM queue and needed generic capacity to meet the 2026 installed reserve margins brings up the total SCGT capacity to about 65 GW. The thermal and hydro generation and other renewable resources, excluding wind and solar plants, remain unchanged across all the scenarios studied.

As shown in Figure 3-3, gas based generation capacity accounts for close to 49 percent of PJM total generation mix. Next is coal based generation with 29 percent of the total capacity, and then nuclear power with 16 percent of the total capacity. The generation capacity mix excluding wind and solar plants remains unchanged across all the scenarios studied.

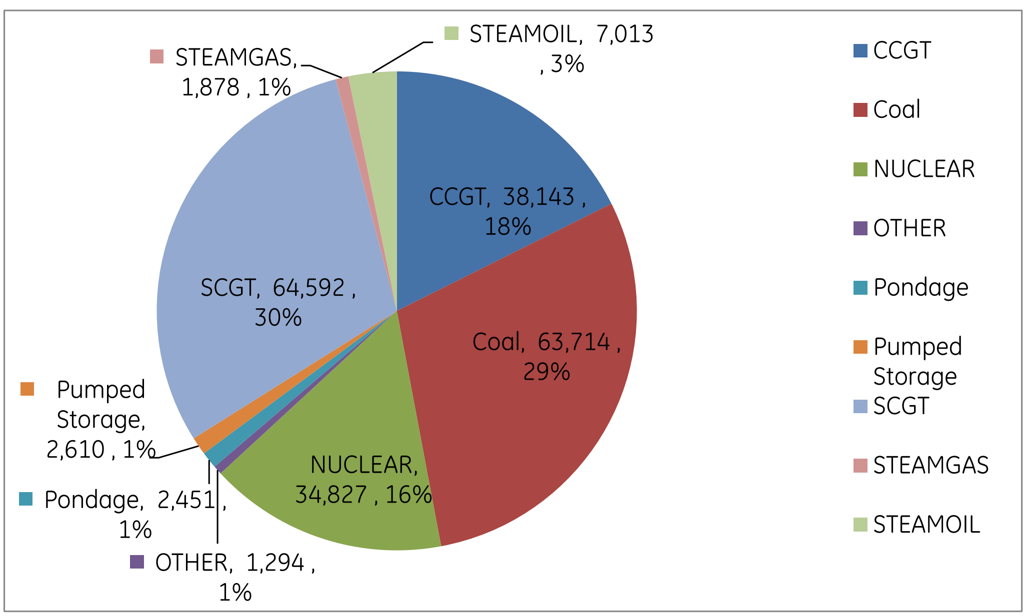

Figure 3-3: Starting 2% BAU Scenario Capacity Mix without Wind and Solar (MW)

3.4.2 Additions and Retirements

The PJM thermal generator additions for modeling are based on what is on PJM queue plus future generic power plants that are added in GE MAPS to maintain the PJM reserve margin target. Generic additions are added in future years only if the starting installed capacity falls below the PJM reserve margin target in the 2% BAU case. These generic units are retained in the higher penetration scenarios. The PJM Queue has 31.5 GW of generation qualified under PJM Facilities Study Agreement and Interconnection Service Agreement (FSA/ISA).

Thermal generator additions in the Rest of the Eastern Interconnect are based on the Ventyx Velocity Suite data for new power plants under construction, plus future generic power plant additions in GE MAPS to maintain the reserve margin targets at the pool level. Generic additions are split between Single Cycle Gas Turbines (SCGTs) and Combined Cycle Gas Turbines (CCGTs) depending on regional needs.

The coal plant retirements were based on forecasts provided by PJM. Other plant type retirements are based on announcements compiled by Ventyx. For the Rest of Eastern Interconnection, retirements of all plant types are based on the announcements compiled by Ventyx.

All nuclear plants, with the exception of those that have announced plans to shut down such as Oyster Creek, are assumed to continue to extend their operating licenses and remain in operation by 2026.

3.4.3 Plant Characteristics

Individual thermal plants are represented in GE MAPS as multi-block units with constant heat rates for each block. Other parameters that define thermal plants in GE MAPS include the following:

- Start Cost – Based on GE engineering; by size, by type
- Economic Max/Min – Set to operating Max/Min
- Ramp Rate – Only applied in production cost simulation when looking at spinning reserve capability
- Minimum Down Time – Based on CEMS data analysis; by type, by size
- Minimum Run Time – Not currently specified
- Full Load Heat Rates – Based on GE review of multiple sources including CEMS
- Environmental Emissions/Effluent Removal Rates – Net emission rates based on CEMS data analysis from Ventyx Velocity Suite

- OM Cost – Based on data from Ventyx Velocity Suite

Start Costs are included in the total costs in the unit commitment process; but only variable costs - which include fuel costs, OM costs, and emissions costs - are taken into account in hourly economic dispatch. Full load heat rates (FLHRs) in GE MAPS are translated into constant block heat rates for each defined capacity block of the thermal unit.

A unit designated as “Must-Run” is always committed, but its loading point above its minimum load is determined by the security constrained economic dispatch algorithm.

Operating reserve capability of each thermal unit is based on the unit’s ramp rate and its type, and is equal to some fraction of its total capacity.

3.5 Hydro Resources

Three types of hydro resources are modeled in GE MAPS: pondage hydro, pumped storage hydro (PSH), and fixed hourly pattern hydro (the so-called “Hourly Modifiers” in GE MAPS).

Key features of pondage hydro include the following:

- Monthly minimum hourly generation in MW (which sets the “run-of-the-river” generation)
- Monthly maximum hourly generation in MW (which set the maximum MW generation during each month)
- Total monthly energy generation limit in MWh
- Within the bounds of min hourly generation and max hourly generation and the total monthly energy generation, the pondage hydro units are dispatched by GE MAPS as peak shaving resources against any defined hourly load pattern.

Key features of PSH include the following:

- Total energy storage size in MWh
- Total charging capacity in MW
- Total discharging capacity in MW
- Roundtrip efficiency in percent (a number between 0 and 1)
- PSH units dispatch schedule are determined during unit commitment to take advantage of system variable cost differentials between charge and discharge periods.

Key features of the hourly modifier hydro include the following:

- Fixed hourly generation levels in MW (or MWh/Hour)

- This kind of hydro is not dispatchable since its hourly value is fixed. As such, it acts to lower or modify the original load; the reason it is classified as hourly modifier resources.

Fuel and O&M costs of hydro resources are assumed to be zero since water is assumed to be a renewable and freely available resource. The fixed and capital costs are not taken into account since these costs do not impact economic dispatch.

3.6 Wind and Solar Resources

All wind and solar units are modeled as hourly load modifiers in GE MAPS and follow a pre-defined hourly generation pattern. Wind and solar resources are assumed to have zero fuel and O&M costs, and hence are assumed to be available at no cost in the dispatch stack. The model does not take into account any power purchase agreement (PPA) based prices of independent power producers (IPP) in dispatch of wind and solar resources. However payments to IPPs can be post-processed.

Wind and solar shapes used throughout the study were provided by AWST and represent modeled wind and solar generation patterns based on meteorological data from the years 2004, 2005, and 2006. AWST provided two shapes for each wind and solar site location in the province. One shape represents a Day-Ahead renewable forecast that is used only during the GE MAPS unit commitment process, while the other shape represents a real time wind availability that is used during the GE MAPS economic dispatch process. Each wind and solar plant is assigned to a unique AWST pattern based on its geographic location and scaled according to the MW rating of the plant.

It is important to note that the inputs into GE MAPS are hourly wind *availability* patterns only. The hourly generation however is an output from the GE MAPS algorithm that takes into account any necessary curtailment. Wind and solar generation are the last resources to be curtailed (i.e., spilled) during the low load and high supply periods. In such times, GE MAPS uses a priority order, whereby the more expensive thermal unit operations are curtailed, but only up to their minimum load (they are still kept online if already committed). If no more thermal generation is available for curtailment, then GE MAPS uses an assigned priority order to curtail the remaining wind and solar resources. The last in the priority order is typically non-grid scale distributed solar generation, assumed to be not responsive to system operators' curtailment commands.

3.7 Fuel and Emission Price Projections

3.7.1 Natural Gas Prices

Monthly natural gas prices are based on the Henry Hub prices from the EIA Annual Energy Outlook 2012 Report. The starting price is the price at Metropolitan Edison Company Ventyx Natural Gas Region projected to the 2026 study year, which is $8.02/MMBtu (in nominal dollars).

Prices in other PJM regions reflect the additional "basis differentials" reflecting the time and location dependent variations in the cost of natural gas relative to the Metropolitan Edison Company price. Basis differentials are shown in Figure 3-4. These basis differentials were provided by PJM, but originated from Ventyx Velocity Suite database. As can be seen, the highest basis differentials are in the Mid-Atlantic and VACAR regions of PJM, and with January being the month where prices are highest. The resulting monthly natural gas prices are shown in Table 3-3 and Figure 3-4.

Table 3-2: Monthly PJM Basis Differentials Relative to the Metropolitan Edison Company Natural Gas Price

Ventyx Gas Pricing Region	MidAtl - E	MidAtl - W	Ohio	VACAR	MO-IL	West VA	Indiana	Kentucky
Jan-2026	119.61%	107.08%	104.93%	113.61%	103.73%	106.40%	104.42%	104.31%
Feb-2026	117.18%	106.83%	104.80%	112.41%	103.56%	106.15%	104.28%	104.24%
Mar-2026	113.12%	106.53%	104.64%	111.15%	103.24%	105.83%	104.12%	104.07%
Apr-2026	111.93%	106.14%	104.48%	111.03%	102.79%	105.42%	103.93%	104.18%
May-2026	111.97%	105.92%	104.36%	110.84%	102.76%	105.19%	103.81%	104.12%
Jun-2026	111.92%	105.81%	104.29%	110.66%	102.76%	105.09%	103.75%	104.04%
Jul-2026	112.30%	105.90%	104.33%	110.28%	102.83%	105.18%	103.79%	104.04%
Aug-2026	112.25%	105.93%	104.34%	110.19%	102.84%	105.21%	103.80%	104.11%
Sep-2026	111.80%	105.65%	104.18%	109.87%	102.47%	104.94%	103.65%	104.05%
Oct-2026	111.71%	105.71%	104.21%	110.10%	102.63%	105.00%	103.68%	103.93%
Nov-2026	112.38%	105.94%	104.31%	110.48%	103.03%	105.25%	103.79%	104.02%
Dec-2026	115.39%	106.62%	104.65%	111.44%	103.48%	105.95%	104.15%	104.15%

Table 3-3: Monthly PJM Natural Gas Prices in Nominal Dollars) ($/MMBtu)

Natural Gas Prices in 2006 ($/MMBtu)	MidAtl - E	MidAtl - W	Ohio	VACAR	MO-IL	West VA	Indiana	Kentucky
Jan 2026	9.59	8.59	8.42	9.11	8.32	8.53	8.37	8.37
Feb 2026	9.40	8.57	8.40	9.02	8.31	8.51	8.36	8.36
Mar 2026	9.07	8.54	8.39	8.91	8.28	8.49	8.35	8.35
Apr 2026	8.98	8.51	8.38	8.90	8.24	8.45	8.34	8.36
May 2026	8.98	8.49	8.37	8.89	8.24	8.44	8.33	8.35
Jun 2026	8.98	8.49	8.36	8.87	8.24	8.43	8.32	8.34
Jul 2026	9.01	8.49	8.37	8.84	8.25	8.44	8.32	8.34
Aug 2026	9.00	8.50	8.37	8.84	8.25	8.44	8.32	8.35
Sep 2026	8.97	8.47	8.36	8.81	8.22	8.42	8.31	8.35
Oct 2026	8.96	8.48	8.36	8.83	8.23	8.42	8.31	8.34
Nov 2026	9.01	8.50	8.37	8.86	8.26	8.44	8.32	8.34
Dec 2026	9.25	8.55	8.39	8.94	8.30	8.50	8.35	8.35

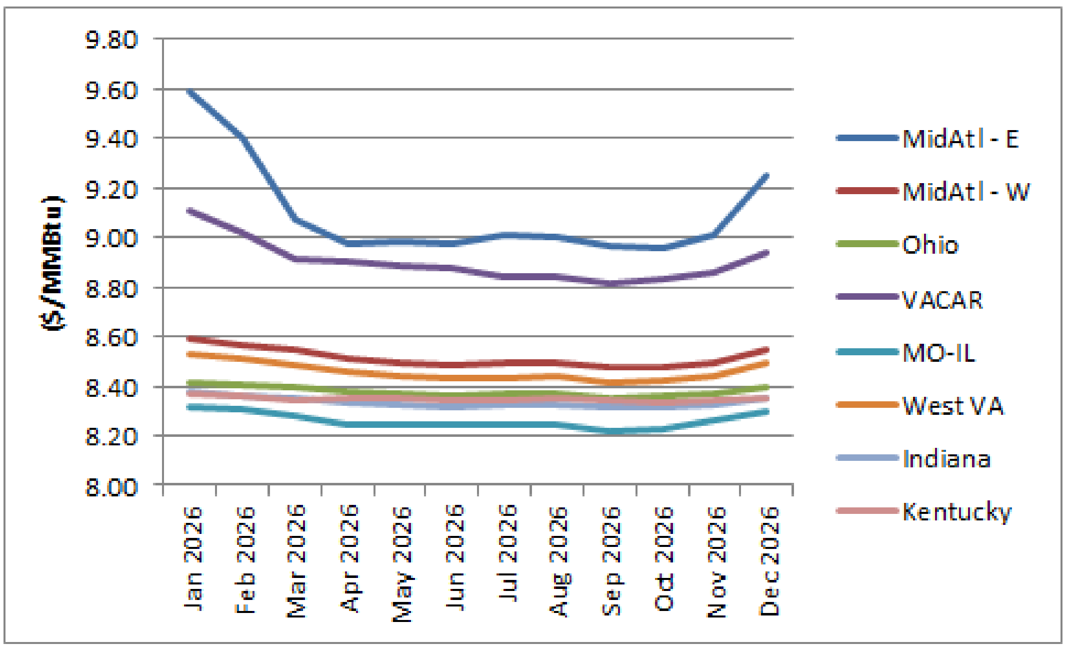

Figure 3-4: Monthly PJM Natural Gas Prices in Nominal Dollars ($/MMBtu)

3.7.2 Coal Prices

Annual coal prices are based on data from the EIA Annual Energy Outlook 2012 Report. The 2026 average U.S. delivered price used for the analysis is $3.51/MMBtu (in nominal dollars). The blended plant prices were developed from Ventyx average historic coal usage (2009-2011). The 2026 coal prices by coal region are provided in Table 3-4.

Table 3-4: Regional Coal Prices

Coal Region	2026 Price ($/MMBtu)
Central Appalachia	4.79
Central Interior	2.54
Gulf Lignite	6.08
Illinois Basin	2.12
Indonesia	2.20
Lignite	4.32
Northern Appalachia	1.55
Powder River Basin	3.31
Rocky Mountain	4.05
Southern Appalachia	1.15

Plant transportation costs are based on historic 3-year averages from 2009 to 2011, as shown in Table 3-5 for different exporting coal regions.

Table 3-5: Coal Transportation Costs by Coal Region

Coal Region	2026 Average Transportation Cost ($/MMBtu)
Central Appalachia	0.77
Central Interior	0.34
Gulf Lignite	0.07
Illinois Basin	0.55
Indonesia	0.14
Lignite	0.52
Northern Appalachia	0.14
Powder River Basin	1.25
Rocky Mountain	1.52
Southern Appalachia	0.37

The resulting average coal transportation cost by PJM plants based on their coal source is shown in Figure 3-5.

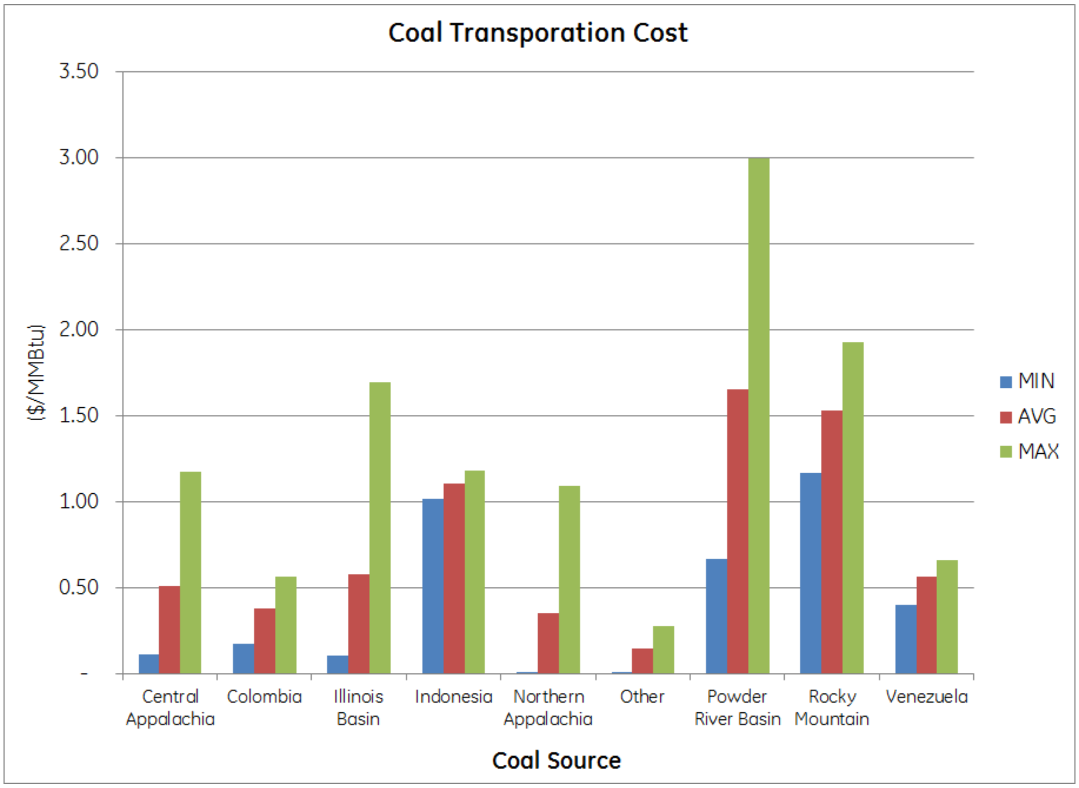

Figure 3-5: Coal Transportation Costs by Plant

3.7.3 Oil Prices

Oil price projections are based on Ventyx Velocity Suite NYMEX Forecast. Table 3-6 presents the projected monthly oil and other fuel prices. As seen, the 2026 months with highest projected oil prices are November and December.

Table 3-6: Projected Oil Prices

Month in 2026	WTI	Gulf Coast Residual (No. 6 Oil) ($/bbl.)	Gulf Coast LS Diesel (No.2 Distillate Oil) ($/bbl.)	Gulf Coast Residual (No. 6 Oil) ($/MMBtu)	Gulf Coast LS Diesel (No.2 Distillate Oil) ($/MMBtu)
1	112.52	93.89	130.43	14.93	22.39
2	112.48	93.86	130.38	14.93	22.38
3	112.43	93.81	130.32	14.92	22.37
4	112.74	94.07	130.68	14.96	22.43
5	113.65	94.83	131.73	15.08	22.61
6	113.58	94.77	131.65	15.07	22.60
7	113.51	94.71	131.57	15.06	22.59
8	113.43	94.65	131.48	15.05	22.57
9	113.34	94.57	131.38	15.04	22.55
10	113.66	94.84	131.74	15.08	22.62
11	114.54	95.57	132.76	15.20	22.79
12	114.53	95.56	132.75	15.20	22.79

3.7.4 Nuclear Fuel Prices

Projected nuclear fuel prices are from Ventyx Energy Velocity™, shown in the Table 3-7.

Table 3-7: Projected Nuclear Fuel Price

Date	Nuclear Fuel Price ($/MMBtu)
2026	0.75

3.7.5 Summary of Fuel Price Assumptions

Table presents a summary of the fuel price assumptions used for production cost simulations.

Table 3-8: Forecasted Fuel Prices for Study Year 2026

Fuel Type	Nominal Price	Source	Comments
Natural Gas	$8.02/MMBtu	EIA 2012 Energy Outlook	At Henry Hub; Regional basis differentials provided by PJM
Coal	$3.51/MMBtu	EIA 2012 Energy Outlook	Adjusted to reflect regional price differences ($1.15 to $6.08) per Ventyx historical usage data.
Nuclear	$0.75/MMBtu	Ventyx Energy Velocity Forecast	
Residual No.2 Oil	$15.04/MMBtu	Energy Velocity NYMEX Forecast	Adjusted to include monthly variation patterns ($14.92 to $15..20)
LS No.2 Diesel	$22.56/MMBtu	Energy Velocity NYMEX Forecast	Adjusted to include monthly variation patterns ($22.37 to $22.79)

3.7.6 Emission Prices

It is assumed that in our base scenarios, all operating plants will have appropriate control technology, i.e., compliance by all plants, and hence, all emission prices are assumed to be $0/ton for criteria pollutants such as SOx and NOx, and for greenhouse gases (GHG) such as CO2. A sensitivity case described later considers a non-zero CO2 (carbon) price.

3.8 Load Projections

PJM load projections are based on PJM's 2011 load forecast report. Since the historical wind and solar data from 2004, 2005, and 2006 are used for the analysis, for consistency, the load shapes used are also from the same years (i.e., 2004, 2005, and 2006). The load shapes are then energy-scaled to the 2026 annual energy for each zone. The load scaling methodology is discussed in Task 1 Report.

Load for the Rest of Eastern Interconnection is based on the Ventyx Velocity Suite's "Historical and Forecast Demand by Zone", aggregated to the GE MAPS Pool levels, which are roughly equivalent to the NERC sub-regions. Individual control area historical load shapes were then energy-scaled using a pool level scaling factor. The resulting load projections by GE MAPS Pool are provided in Table 3-9.

Table 3-9: Eastern Interconnection Load Projections for 2026

MAPS Pool	Ventyx 2026 Forecasted Energy GWh	2010 Energy GWh	Average Annual Growth Rate
PJM	969,596	810,811	1.1%
MISO	605,177	531,156	0.8%
Southern	305,497	250,284	1.3%
FRCC	279,147	229,783	1.2%
SPP	275,816	236,717	1.0%
VACAR	261,710	226,514	0.9%
Central / TVA	255,532	229,162	0.7%
Delta / Entergy	180,012	156,808	0.9%
NYISO	174,383	163,505	0.4%
ISONE	157,208	128,660	1.3%
IESO	142,080	141,897	0.0%
OVEC	231	495	-4.6%
EI	3,606,390	3,105,792	0.9%

PJM Load is depicted in the following figures. The first figure shows the 2026 PJM Load Duration Curve (LDC), which is the sorted hourly PJM load from highest to lowest. The second figure shows the 2026 PJM load in the form of monthly energy and monthly peak. As can be seen, June, July, and August are high load months reflecting high HVAC usage, with the annual peak occurring in July.

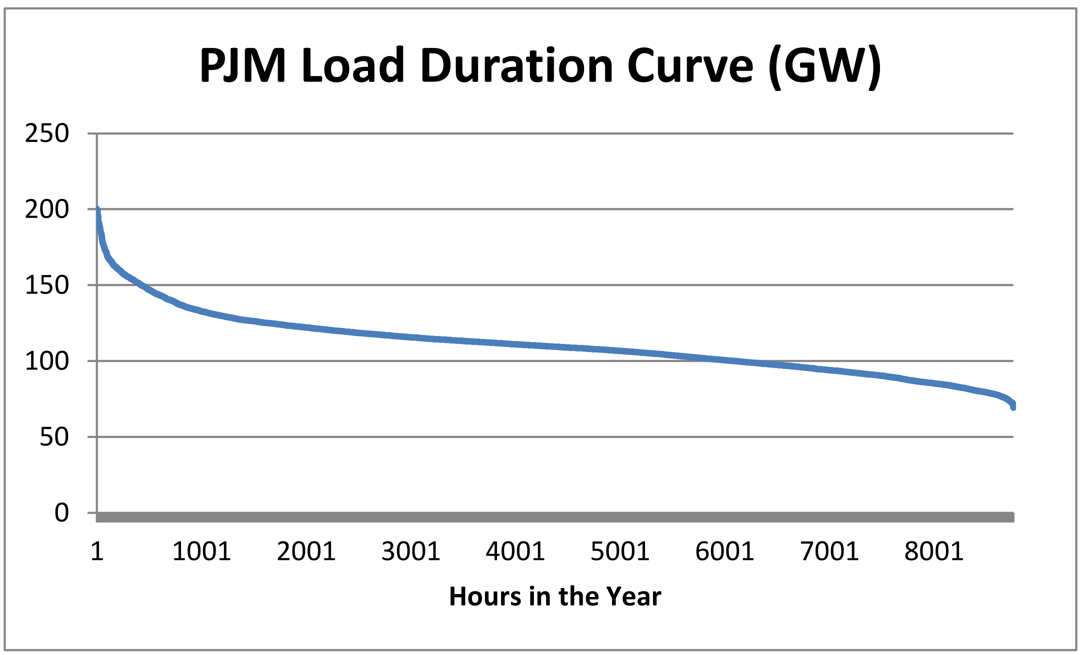

Figure 3-6: PJM 2026 Load Duration Curve

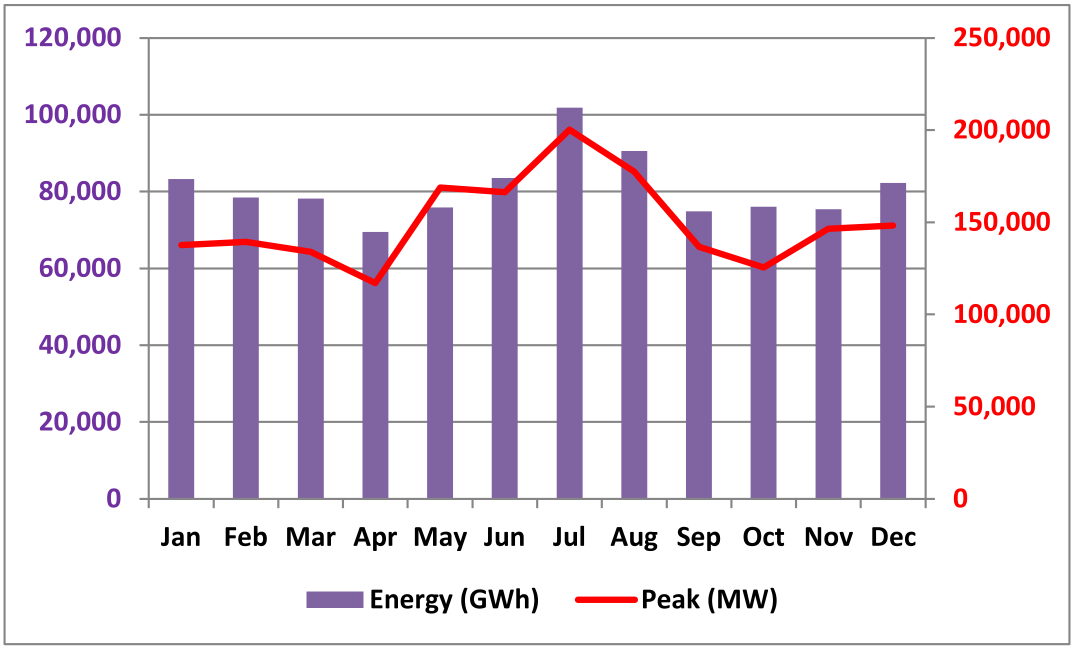

Figure 3-7: PJM 2026 Monthly Energy and Peak

3.9 Transmission

GE used the 2019 EI solved power flow data provided by PJM as input into the GE MAPS model. GE MAPS model includes the full configuration of the EI transmission grid including all the major transmission lines and transmission system buses and line constraints. Also included are all the major thermal and contingency constraints with summer and winter ratings applied, and other operational constraints that can be represented by nomograms in GE MAPS.

For load and generation bus assignments:

- All load buses are assigned to the appropriate areas.
- All large generation units are assigned to the correct generation bus.
- Some small wind and hydro units with unknown bus locations are assigned to the large transmission node in the corresponding area.

For inter-regional transmission, we assumed transmission "hurdle rates" based on Eastern Interconnection Planning Collaborative (EIPC) study[11]. Following table shows the assumed hurdle rates between connecting regions.

[11] Source: Future 1 Modeling Assumptions, http://www.eipconline.com/uploads/Future_1_Modeling_Assumptions_Master_9-24-11.xls

Table 3-10: Interregional Hurdle Rates

From	To	Total Hurdle 2010 $/MWh
PJM	MISO	2
MISO	PJM	2
PJM	NY	6
NY	PJM	8
PJM	Non RTO Midwest	6
PJM	TVA	6
PJM	VACAR	6
VCAR	PJM	7
TVA	PJM	9

4 Study Scenarios

4.1 Selected Scenarios

The 10 scenarios of Table 2-1 are reproduced again below in Table 4-1. These scenarios represent different levels of renewable energy penetration and different mixes of central, commercial, and residential solar, best sites and dispersed onshore wind, and offshore wind resources.

Table 4-1: Summary of the Study Scenarios

Scenario	Renewable Penetration Level	Wind/Solar (GWh)	Wind + Solar Siting
2% BAU	2%	Existing W+ S	Existing Plants (Business as Usual - Reference Case)
14% RPS	14%	109/11	PJM Queue & Mandates (RPS Compliance – Base Case)
20% LOBO	20%	150/29	Low Offshore, Best Onshore
20% LODO	20%	150/29	Low Offshore, Dispersed Onshore
20% HOBO	20%	150/29	High Offshore, Best Onshore
20% HSBO	20%	121/58	High Solar, Best Onshore
30% LOBO	30%	228/48	Low Offshore, Best Onshore
30% LODO	30%	228/48	Low Offshore, Dispersed Onshore
30% HOBO	30%	228/48	High Offshore, Best Onshore
30% HSBO	30%	179/97	High Solar, Best Onshore

4.2 Scenario Descriptions

- 2% BAU Scenario represents the PJM system in its current state, i.e., “Business-As-Usual” (BAU) scenario, which has 2% renewable penetration, and as such, serves as the “Reference” scenario.
- 14% RPS Scenario represents 14% of renewable penetration and is in compliance with the Renewable Portfolio Requirement (RPS) targets for states within the PJM footprint, and serves as the “Base Case” scenario.

- 20% HOBO Scenario represents a renewable penetration of 20%, with high offshore wind, and best sites onshore wind ("Best Sites" selections are described in Task 2 Report[12]).
- 20% LOBO Scenario represents a renewable penetration of 20%, with low offshore wind, and best sites onshore wind.
- 20% LODO Scenario represents a renewable penetration of 20%, with high offshore wind, and dispersed sites onshore wind.
- 20% HSBO Scenario represents a renewable penetration of 20%, with high solar penetration, and best sites onshore wind.
- 30% HOBO Scenario represents a renewable penetration of 20%, with high offshore wind, and best sites low onshore wind.
- 30% LOBO Scenario represents a renewable penetration of 30%, with low offshore wind, and best sites low onshore wind.
- 30% LODO Scenario represents a renewable penetration of 30%, with low offshore wind, and dispersed sites low onshore wind.
- 30% HSBO Scenario represents a renewable penetration of 30%, with high solar penetration, and best sites onshore wind.

4.3 Wind and Solar Split and Capacities

Table 4-2 presents the proportion of onshore versus offshore wind and centralized versus distributed solar resources in the scenarios. Distributed solar is assumed to be a mix of residential (20%) and commercial (80%) photovoltaic (PV) solar power.

Table 4-2: Onshore/Offshore Wind and Wind/Solar Split

Scenario	Onshore Wind	Offshore Wind	Centralized Solar	Distributed Solar
14% RPS Base	86%	14%	50%	50%
Low Offshore	90%	10%	50%	50%
High Offshore	50%	50%	50%	50%
High Solar	90%	10%	50%	50%

The total solar and wind capacity for each scenario are provided in Table 4-3.

12 Report: Task 2 Scenario Development and Analysis, GE Energy Consulting, January 26, 2012.

Table 4-3: The Total Capacity by Wind/Solar For Each Scenario

Scenario	Onshore Wind (MW)	Offshore Wind (MW)	Centralized Solar (MW)	Distributed Solar (MW)	Total (MW)
2% BAU	5,122	0	72	0	5,194
14% RPS	28,834	4,000	3,254	4,102	40,190
20% LOBO	39,452	4,851	8,078	10,111	62,492
20% LODO	40,942	4,851	8,078	10,111	63,982
20% HOBO	21,632	22,581	8,078	10,111	62,402
20% HSBO	32,228	4,026	16,198	20,294	72,746
30% LOBO	59,866	6,846	18,190	16,907	101,809
30% LODO	63,321	6,846	18,190	16,907	105,264
30% HOBO	33,805	34,489	18,190	16,907	103,391
30% HSBO	47,127	5,430	27,270	33,823	113,650

4.4 Renewable Energy Penetration in the Rest of EI

The Eastern Wind Integration and Transmission Study (EWITS) Scenario 2 (20% Hybrid with Offshore) was used as guide to determine allocations to other NERC Regions. It was assumed that the Rest of EI does not grow its overall renewable penetration as quickly as PJM. The EWITS data is shown in the following table.

The resulting PJM and Rest of EI renewable penetration are provided in Table 4-5.

TABLE 1. TOTAL AND OFFSHORE WIND IN THE SCENARIOS								
Region	Scenario 1 20% High Capacity Factor, Onshore		Scenario 2 20% Hybrid with Offshore		Scenario 3 20% Local, Aggressive Offshore		Scenario 4 30% Aggressive On- and Offshore	
	TOTAL (MW)	Offshore (MW)	Total (MW)	Offshore (MW)	Total (MW)	Offshore (MW)	Total (MW)	Offshore (MW)
MISO/ MAPP[a]	94,808		69,444		46,255		95,046	
SPP	91,843		86,666		50,958		94,576	
TVA	1,247		1,247		1,247		1,247	
SERC	1,009		5,009	4,000	5,009	4,000	5,009	4,000
PJM	22,669		33,192	5,000	78,736	39,780	93,736	54,780
NYISO	7,742		16,507	2,620	23,167	9,280	23,167	9.280
ISO-NE	4,291		13,837	5,000	24,927	11,040	24,927	11,040
TOTAL	**223,609**	**0**	**225,902**	**16,620**	**230,299**	**64,100**	**337,708**	**79,100**

Table 4-4: Wind Renewable Allocation for the Eastern Wind and Transmission Study (EWITS) Scenarios

[Source: Eastern Wind Integration and Transmission Study (EWITS) Executive Summary and Project Overview, Table 1[13]]

Table 4-5: PJM and Rest of EI Renewable Energy Penetration for Each Scenario

Scenario	PJM % RE	EI % RE
Base	14%	10%
Low Offshore	20%	15%
High Offshore	20%	15%
High Solar	20%	15%
Low Offshore	30%	20%
High Offshore	30%	20%
High Solar	30%	20%

4.5 Process Flow for Analysis of One Scenario

The diagram in Figure 4-1 illustrates the process flow for analysis of one scenario, including sub-tasks and contributions of each member of GE team. , various analytical elements and data generated in different sub-tasks come together and processed in steps, in order to simulate each study scenario.

13 http://www.nrel.gov/docs/fy11osti/47078.pdf

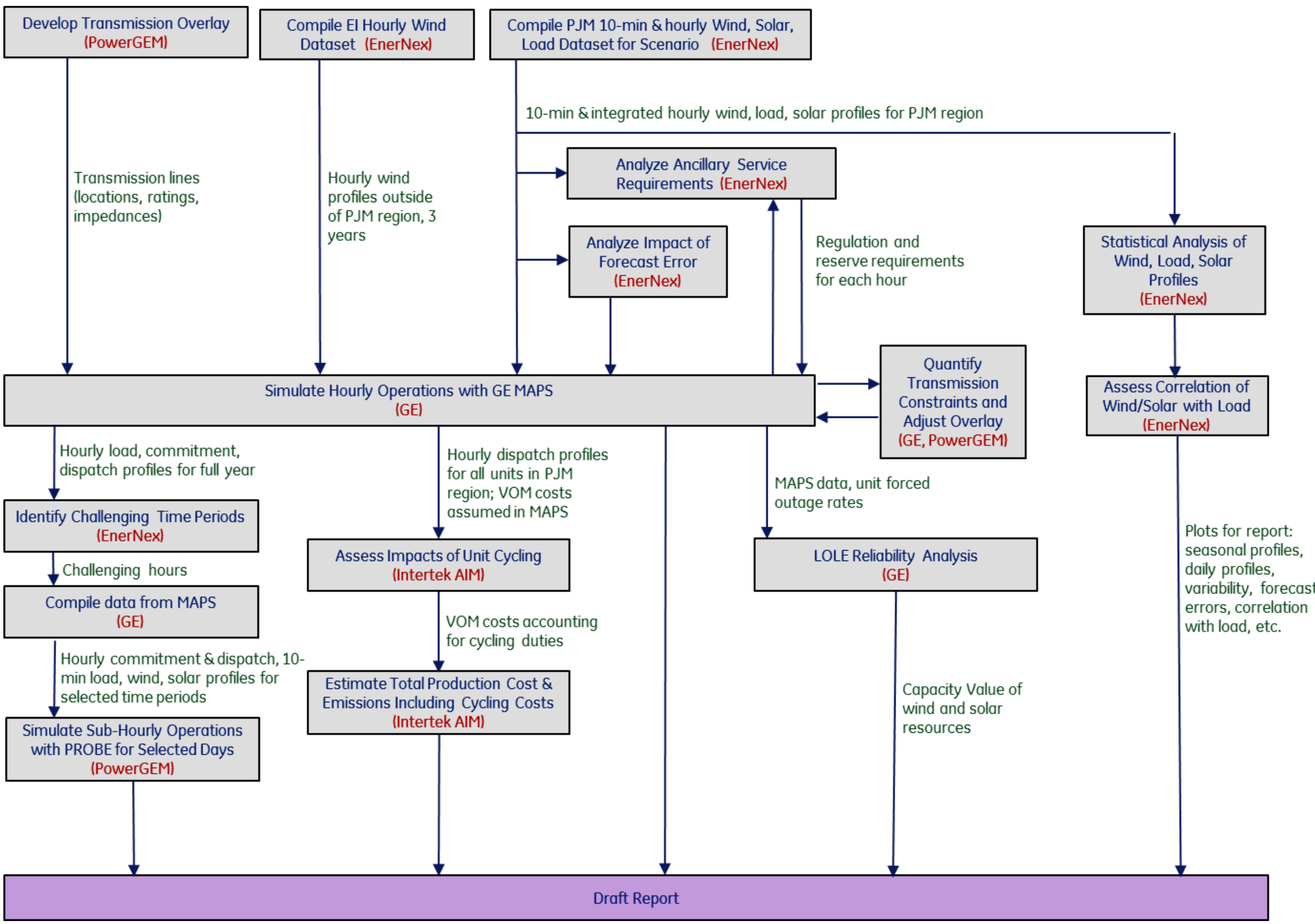

Figure 4-1: Process Flow for Analysis of One Scenario

5 References

Reference for reserves and statistics

1. E. Ela, M. Milligan, B. Kirby, " Operating Reserves and Variable Generation", NREL/TP-5500-51978, Aug 2011
2. Electrical Reliability Council of Texas, "Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements": http://www.ercot.com/news/presentations/2008/Wind_Generation_Impact_on_Ancillary_Services_-_GE_Study.zip

Reference for plant requirements, and for export of power

3. New England ISO "New England Wind Integration Study":

   http://www.iso-ne.com/committees/comm_wkgrps/prtcpnts_comm/pac/reports/2010/newis_report.pdf
4. NERC Integration of Variable Generation Task Force (IVGTF): "Special Assessment 2012 – Requirements for Interconnection of Variable Generation", September 2012

   http://www.nerc.com/files/IVGTF_Task_1-3.*pdf*

Reference on demand response, and on forecast use and discounting

5. NREL, "Western Wind and Solar Integration Study":

   http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf
6. NREL, "Western Wind and Solar Integration Study: Executive Summary

   http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_executive_summary.pdf

Reference on minimum load problems in small systems

7. Hawaiian Electric Company, Hawaii Natural Energy Institute, "Oahu Wind Integration Study":

   www.hnei.hawaii.edu/PDFs/Oahu_Wind_Integration_Study.pdf

Reference on plant requirements and on plant dynamics

8. California ISO, "Frequency Response Study" Oct, 2011:

   http://www.caiso.com/Documents/Report-FrequencyResponseStudy.pdf

NERC references

9. NERC Integration of Variable Generation Task Force (IVGTF), http://www.nerc.com/filez/Archive_IVGTF.htm

10. IVGTF Accommodating High Levels of Variable Generation Report, 5/5/2008 (first report)

Reference for operational flexibility discussion…probably in section with new generation, lower minimums, storage…

11. Special Report: Potential Reliability Impacts of Emerging Flexible Resources November 2010:

    http://www.nerc.com/files/IVGTF_Task_1_5_Final.pdf

Reference to go along with the ISO-NE requirements document

12. Task Force 1-3 - Interconnection Requirements Enhanced Draft Special Reliability Assessment: Interconnection Requirements for Variable Generation, 03/02/12:

    http://www.nerc.com/filez/ivgtf_Interconnection.html

Reference for forecasting discussion

13. Task Force 2-1 - Operator Survey NERC IVGTF Task 2.1 Report: Variable Generation Power Forecasting for Operations, 02/23/09:

    http://www.nerc.com/filez/ivgtf_Operation.html

14. Alberta Electric System Operator: “Wind Power Forecasting Services”

    http://www.aeso.ca/gridoperations/18286.html

References for demand response and storage discussion

15. Task Force 1-5 - Reliability Impacts of Storage and Demand Response Potential Reliability Impacts of Emerging Flexible Resources

References for HVDC availability

16. CIGRE 2012 B4-113-2012 “A Survey of the Reliability of HVDC Systems Throughout the world during 2009-2010”, MG Bennett, NS Dhaliwal, A Leirbukt.

Reference for capacity valuation/MARS section

17. Methods to Model Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning 3/14/11

    http://www.nerc.com/filez/ivgtf_Probabilistic.html

Western Wind and Solar Study – Phase II Results

18. Sub-hourly Impacts of High Solar Penetrations

    www.nrel.gov/docs/fy12osti/56171.pdf<http://www.nrel.gov/docs/fy12osti/56171.pdf

19. The Western Wind and Solar Integration Study Phase 2

    www.nrel.gov/docs/fy12osti/56217.pdf<http://www.nrel.gov/docs/fy12osti/56217.pdf

Cycling (Wear and Tear) Cost Analysis

20. NREL report: "Analysis of Cycling Costs in Western Wind and Solar Integration Study",

http://www.nrel.gov/docs/fy12osti/54864.pdf

Forecast Errors

21. NREL Preprint "A Comparison of Wind Power and Load Forecasting Error Distributions)

    http://www.nrel.gov/docs/fy12osti/54384.pdf

Reserves

22. NREL Preprint: "A Solar Reserve Methodology for Renewable Energy Integration Studies Based on Sub-Hourly Variability Analysis"

    http://www.nrel.gov/docs/fy12osti/56169.pdf

ERCOT Primary Reserves from Wind Generation

23. ERCOT , "Protocol Revision Requests (PRR833) - Primary Frequency Response Requirement from Existing WGRs" Sep 22, 2009

References for Major Wind Integration Studies

24. Ontario Power Authority, Independent Electricity System Operator, Canadian Wind Energy Association's "Ontario Wind Integration Study": http://www.powerauthority.on.ca/Storage/28/2321_OPA_Report_final.pdf
25. California Energy Commission's Intermittency Analysis Project Study "Appendix B - Impact of Intermittent Generation on Operation of California Power Grid"

    http://www.energy.ca.gov/2007publications/CEC-500-2007-081/CEC-500-2007-081-APB.PDF
26. New York State Energy Research and Development Authority's "The Effects of Integrating Wind Power on Transmission System Planning, Reliability, and Operations": http://www.nyserda.org/publications/wind_integration_report.pdf
27. Independent System Operation, New England, "New England Wind Integration Study "

    http://www.iso-ne.com/committees/comm_wkgrps/prtcpnts_comm/pac/reports/2010/newis_report.pdf
28. Hawaiian Electric Company, Hawaii Natural Energy Institute, "Oahu Wind Integration Study"

    www.hnei.hawaii.edu

imagination at work