GE
Energy Consulting

Pan-Canadian Wind Integration Study (PCWIS)

Section 2: Introduction and Scope

Prepared for: Canadian Wind Energy Association (CanWEA)

Prepared by: GE Energy Consulting

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Legal Notices

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While produced with financial support from Natural Resources Canada, its contents do not necessarily reflect the opinions of the Government of Canada.

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CanWEA is grateful for the support and guidance offered by the TAC, and wishes to thank the members and the organizations they represent for the important contributions they have made to this study. It should be noted that while members of the TAC were instrumental in ensuring the successful delivery of this work, the findings, opinions, conclusions and recommendations presented herein do not necessarily reflect those of the TAC members or the organizations they represent.

Technical Advisory Committee Members:

- Alberta Electric System Operator (AESO)
- BC Hydro
- Hydro Quebec
- Independent Electricity System Operator (IESO)
- ISO-New England (ISO-NE)
- Manitoba Hydro
- Midcontinent Independent System Operator (MISO)
- National Renewable Energy Laboratory (NREL)
- New York Independent System Operator (NYISO)
- SaskPower
- Utility Variable-Generation Integration Group (UVIG)
- Western Electricity Coordinating Council (WECC)

The project team and CanWEA also acknowledge and thank Environment and Climate Change Canada which performed the mesoscale atmospheric modeling and provided raw wind-related data for the wind profiling and forecasting.

Contact Information

The Pan-Canadian Wind Integration Study Report was prepared by General Electric International, Inc. (GEII); acting through its Energy Consulting group (GE) – part of GE Energy Connections - based in Schenectady, NY, and submitted to CanWEA. Technical and commercial questions and any correspondence concerning this document and the study should be referred to:

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Acronyms and Nomenclatures

Base Scenarios

5% BAU	5% Wind Penetration – Business-As-Usual
20% DISP	20% Dispersed Wind Penetration
20% CONC	20% Concentrated Wind Penetration
35% TRGT	35% Targeted Wind Penetration

Unit Types

CC-GAS	Combined Cycle Gas Turbine
COGEN	Cogeneration Plant
DPV	Distributed Photovoltaic
HYDRO	Hydropower / Hydroelectric plant
NUCLEAR	Nuclear Power Plant
OTHER	Includes Biomass, Waste-To-Energy, Etc.
PEAKER	SC-GAS and RE/IC
PSH	Pumped Storage Hydro
PV	Photovoltaic
RE/IC	Reciprocating Engine/Internal Combustion Unit
SC-GAS	Simple Cycle Gas Turbine
SOLAR	Solar Power Plant
ST-COAL	Steam Coal
ST-GAS	Steam Gas
WIND	Wind Power Plant

Canadian Provinces in PCWIS

AB	Alberta
BC	British Columbia

MB	Manitoba
NB	New Brunswick
ON	Ontario
QC	Quebec
MAR	Maritime
NL	Newfoundland and Labrador
NS	Nova Scotia
PE	Prince Edward Island
SK	Saskatchewan

USA Pools in PCWIS

BAS	Basin
CAL	California ISO
DSW	Desert Southwest
FRCC	Florida Reliability Coordinating Council
ISONE	ISO New England
MISO	Midcontinent ISO
NWP	Northwest Power Pool
NYISO	New York ISO
PJM	PJM Interconnection
RMP	Rocky Mountain Pool
SERC-E	SERC Reliability Corporation- East
SERC-N	SERC Reliability Corporation- North
SERC-S	SERC Reliability Corporation- South
SERC-W	SERC Reliability Corporation- West
SPP	Southwest Power Pool Regional Entity

General Glossary

AESO	Alberta Electric System Operator

BAA	Balancing Area Authority
Btu	British thermal unit
CanWEA	Canadian Wind Energy Association
CF	Capacity Factor
CO_2	Carbon Dioxide
DA	Day-Ahead
DNV GL	DNV GL Group
DPV	Distributed PV
DR	Demand Response
EI	Eastern Interconnection
ELCC	Effective Load Carrying Capability
EUE	Expected Un-served Energy
ERGIS	Eastern Renewable Generation Integration Study
EV	Electric Vehicle
EWITS	Eastern Wind Integration and Transmission Study
FERC	Federal Energy Regulatory Commission
FOM	Fixed Operations and Maintenance
GE	GE Energy Consulting
GEII	General Electric International, Inc.
GE EC	GE Energy Consulting
GE MAPS	GE's "Multi Area Production Simulation" Software
GE MARS	GE's "Multi Area Reliability Simulation" Software
GE PSLF	GE's "Positive Sequence Load Flow" Software
GT	Gas Turbine
GW	Gigawatt
GWh	Gigawatt Hour
HA	Hour-Ahead
HR	Heat Rate
IEC	International Electrotechnical Commission

IESO	Independent Electricity System Operator
IPP	Independent Power Producers
IRP	Integrated Resource Planning
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt Hour
lbs.	Pounds (British Imperial Mass Unit)
LDC	Load Duration Curve
LMP	Locational Marginal Prices
LNR	Load Net of Renewable Energy
LOLE	Loss of Load Expectation
MAE	Mean-Absolute Error
MMBtu	Millions of BTU
MMT	Million Metric Tons
MVA	Megavolt Ampere
MW	Megawatts
MWh	Megawatt Hour
NERC	North American Electric Reliability Corporation
NO_X	Nitrogen Oxides
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
O&M	Operational & Maintenance
PCWIS	Pan-Canadian Wind Integration Study
PPA	Power Purchase Agreement
REC	Renewable Energy Credit
RPS	Renewable Portfolio Standard
RT	Real-Time
RTEP	Regional Transmission Expansion Plan
SCUC	Security Constrained Unit Commitment

SCEC	Security Constrained Economic Dispatch
SO_2	Sulfur Dioxide
SO_X	Sulfur Oxides
ST	Steam Turbine
TW	Terawatts
TWh	Terawatt Hour
UTC	Coordinated Universal Time
VOC	Variable Operating Cost
VOM	Variable Operations and Maintenance
WECC	Western Electricity Coordinating Council
WI	Western Interconnection

2 Introduction and Scope

2.1 Project Objectives

The Pan-Canadian Wind Integration Study (PCWIS) was performed to assess the implications of integrating large amounts of wind in the Canadian electrical system: Specifically,

- To develop a consistent database of chronological wind data for potential wind sites across Canada,
- To provide an improved understanding of the operational challenges and opportunities associated with high wind energy penetration in Canada, and
- To provide an improved understanding of the operational and production costs benefits of high wind penetration in Canada.

This study aimed to develop an understanding of the operational implications of how variable wind energy resources would affect the existing and future electricity grid, and what environmental and economic costs and benefits may be associated with integrating large amounts of wind. System operators have a desire to understand how much wind energy can be reliably integrated onto the electricity grid and at what cost. Opportunities for greater penetration and more cost-effective integration are enhanced when these issues are considered on a regional or national basis. While the benefits of wind energy are widely known, the results of this study will help ensure that the benefits of wind energy are most efficiently realized.

It should be noted that the wind penetrating scenarios evaluated in this study (up to 35% nationally) do not represent technical, operational, or economic limits or constraints on wind integration, but represent the study scenarios selected by the Technical Advisory Committee.

2.2 Project Team

The project team, led by GE Energy Consulting, consisted of five companies providing a broad range of technical analysis required for this study.

- GE Energy Consulting - Overall project leadership, production cost simulation and reliability analysis
- Vaisala - Wind profile and forecast data development,
- EnerNex - Wind plant data assembly and management, statistical analysis, regulation/reserve requirements
- Electranix - Transmission reinforcement design

- Knight Piésold - Canadian hydropower resource data and modeling

Project team is shown in Figure 2-1 with members of each partner team listed alphabetically by their last names. In addition to the five company team, other entities supporting the project include DNV GL, acting as advisors to CanWEA, and Environment and Climate Change Canada, which performed the mesoscale atmospheric modeling and provided the raw wind related data to Vaisala.

To fulfill the objectives of the study, the GE team quantified the impacts of increasing wind energy penetration on the operation and reliability of the Canadian power systems, evaluated system performance and operating costs, and identified methods and approaches to mitigate the potential adverse impacts of renewable energy integration. The results of this study are intended to provide guidance and quantitative metrics to aid Canadian power systems 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 Ontario, Nova Scotia, New England, PJM, New York, California, Texas, Western USA (WWSIS), Hawaii, Barbados, and Vietnam.
- EnerNex has deep experience in methods and tools to quantify the effect of wind resource variability on a system's need for ancillary services, including spinning reserves and regulation.
- The Electranix team, based in Winnipeg, Manitoba, has extensive experience performing analysis and design of transmission systems, both AC and HVDC, including transmission for wind power (including large scale offshore wind).
- The Vaisala team prepared wind power output profiles and wind power forecasts for simulation in the study scenarios. Vaisala is previously developed a similar dataset for NREL for the US.
- The Knight Piésold team contributed hydropower expertise and hydrology analysis to the project to ensure that hydro power is accurately included.

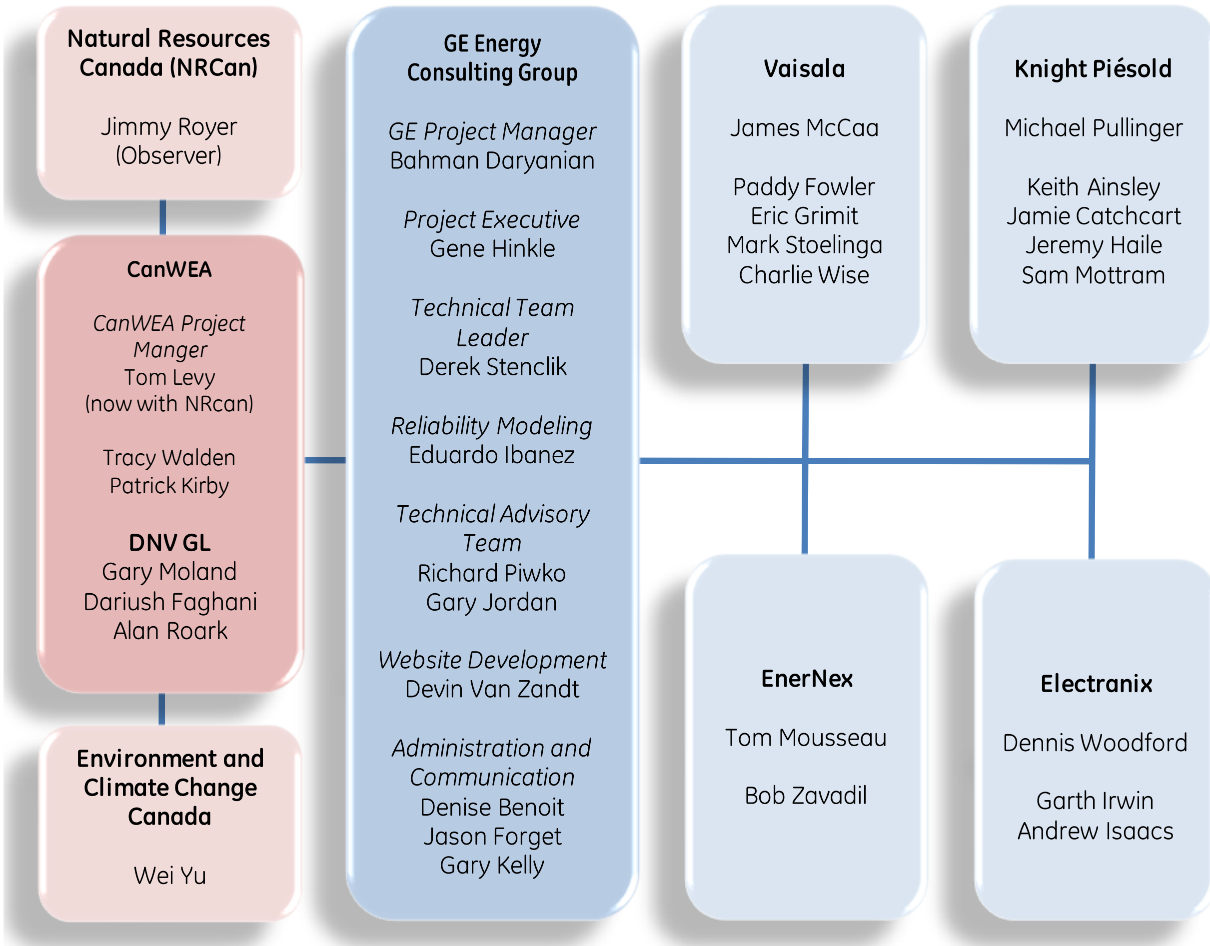

Figure 2-1: Project Team

A Technical Advisory Committee (TAC) provided support and guidance throughout the project, including review of the data and assumptions and the development of study scenarios and selection of sensitivity analyses to be performed. While members of the TAC were instrumental in ensuring the successful delivery of this work, the findings, opinions, conclusions and recommendations presented herein do not necessarily reflect those of the TAC members or the organizations they represent. TAC member organizations are presented in Table 2-1.

Table 2-1: Technical Advisory Committee (TAC) Members

Alberta Electric System Operator (AESO)
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New York Independent System Operator (NYISO)
SaskPower
Utility Variable-Generation Integration Group (UVIG)
Western Electricity Coordinating Council (WECC)

2.3 Project Tasks

2.3.1 Major Tasks

The Study performed a detailed analysis of the operational, planning and market impacts of high penetration of renewable generation on the Canadian power systems. The Study divided the work into 6 major tasks.

> **Task 1** defined 4 study scenarios and developed a generation expansion plan for each scenario.
>
> **Task 2** developed wind 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 3** focused on the development of the transmission reinforcement to support generation expansion.
>
> **Task 4** focused on a detailed evaluation of the impact of wind generation variability and uncertainty on Canadian power systems' operations and markets, including a reliability analysis of the affected systems.
>
> **Task 5** considered additional sensitivity analyses determined later in the course of the study.
>
> **Task 6** produced a final report including a set of recommendations based on the results of the study. This task also included development of a study website to provide access to the study reports.

Figure 2-2 shows a flowchart of GE's plan used to execute this study. It identifies the project tasks, primary contributors to each task, and how work product and results flowed from task to task (indicating critical task interdependencies). An overview of the project plan is described below. Details of each task and subtask are presented in Section 3.

Task 1: Generation Expansion

In Task 1, study data assumptions and scenarios were defined by CanWEA, DNV GL, and the TAC, and provided to the GE Team for review and feedback. The GE Team developed a generation expansion methodology, created the generation expansion plan for each scenario, and selected specific locations and ratings for wind resources to build the study scenario datasets.

In addition to Tasks 1.1 through 1.5 specified in the RFP, the proposed scope included Task 1.6. The Knight Piésold team contributed information for the Canadian hydro power database and assisted the GE Team in appropriate modeling of hydro power in the production simulation analysis.

Task 2: Wind Generation

In Task 2, the Vaisala team developed a methodology for developing hourly wind power production data using the data provided by Environment and Climate Change Canada, executed the methodology to generate the wind profiles, and developed hourly wind power forecasts. The wind power output profiles were used in Task 1.5 to select wind locations and build wind generation datasets for each study scenario.

Also in Task 2, EnerNex developed hourly regulation reserve requirements to account for net load (i.e., load minus wind generation) variability based on the developed wind power profiles and load assumptions. These hourly wind variability related regulation reserves were incorporated into the production cost modeling in Task 4.

In addition, EnerNex performed statistical analysis on the load and wind data to characterize wind resources, to provide insights on the load and wind variability and understanding study results obtained in later tasks.

Task 3: Transmission Reinforcements

Task 3 identified the need for additional transmission reinforcements under the study scenarios needed to maintain a reasonable level of congestion caused by higher penetration of wind energy in the system. The size of the transmission reinforcements were determined by the GE MAPS modeling, based on which recommendations and cost estimates for transmission upgrades across modeled transmission interfaces were developed.

Based on the analysis of Task 4 (described below) GE determined the additional modeling based transmission reinforcements needed to keep the transmission congestion at a reasonable level at different wind penetration levels. Electranix used that information to develop the actual new physical transmission elements that would provide the additional transmission capacity identified by the model. Electranix also provided a high level estimate of the cost of additional transmission.

Task 4: Scenario Analysis

In Task 4, the GE Energy Consulting team performed production simulations of hourly operation of the Canadian and the U.S. interconnected systems for each of the 4 scenarios. The output of the simulation provided generation dispatch, annual production cost, locational marginal prices (LMP), congestion, emissions etc.

Also as part of Task 4, GE used the GE Multi-Area Reliability Simulation (GE MARS) model to evaluate resource adequacy, reliability, LOLE and wind capacity value for each of the study scenarios.

Task 5: Sensitivity Analysis

GE performed additional Sensitivity Analysis in Task 5, based on new objectives and issues that were raised over the course of the initial work, which were determined based on inputs from CanWEA, GL GH, and the Technical Advisory Committee.

Task 6: Reporting and Website Development

Finally in Task 6, the entire project team worked on preparing the presentation material for the later Technical Advisory Committee meetings and drafting of the final report. GE worked with CanWEA to develop a website for distributing the study findings that can be accessed and downloaded for review and further studies.

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 2-2.

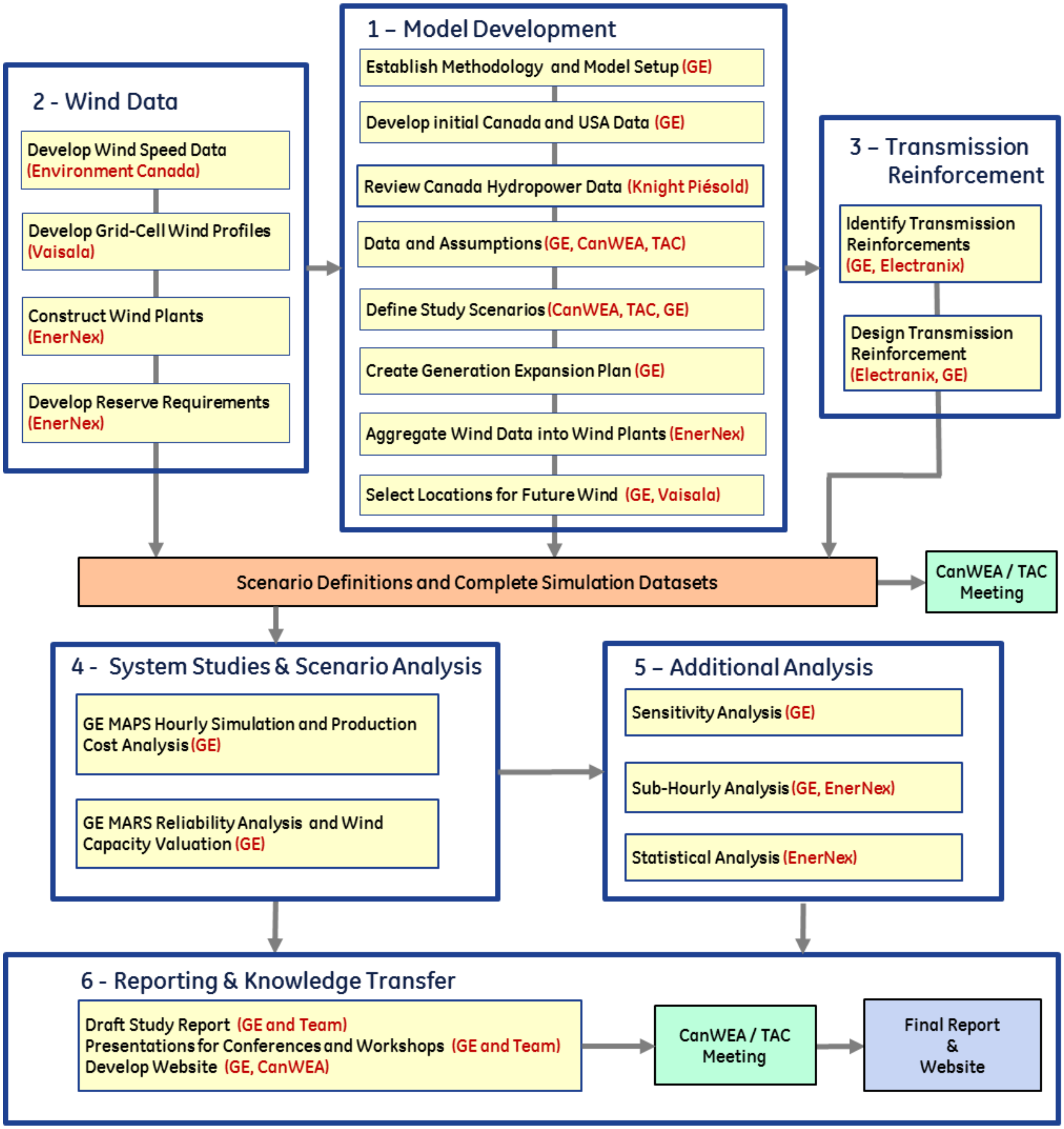

Figure 2-2: Study Process Flowchart

2.3.2 Additional Analysis

Statistical and Reserve Analysis

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 Canadian power grid.

Sub-Hourly Analysis

Additional analysis included analysis of sub-hourly reserve by quantifying the adequacy of available capacity of dispatchable generation resources to cover 10-minute variability of wind generation and load in the study footprint subject to unit ramp rates and ramp range constraints.

2.4 Analytical Approach

2.4.1 Methodology and Modeling Tools

The core analysis of this study required detailed production simulation analysis and reliability analysis. The study utilized the GE Concorda Suite Multi-Area Production Simulation (GE-MAPS) model for production costing analysis, and the GE Multi-Area Reliability Simulation (GE-MARS) model for reliability analysis and wind capacity valuation. Brief overviews of these models are presented below, and more extensive descriptions are presented in the Appendix.

The power grids represented in this study are extremely large and complex systems, covering most of North America. The underlying model included representation of both the entire Eastern Interconnection (EI) and the Western Interconnection (WI). In other words, the representation of the power systems was not limited just to the Canadian provinces, and included the entire U.S. regions, other than ERCOT – covering most of Texas – which is an isolated interconnection and not synchronized with either EI or WI. Simulation of hourly nodal security constrained unit commitment and economic dispatch of the entire North American power system was made possible by GE's High-Performance Cluster Computing capability. This was an important asset to enable full nodal simulation of the combined US and Canada power grids.

2.4.2 Hourly Production Cost Analysis (GE MAPS)

The GE team utilized GE Concorda Suite Multi-Area Production Simulation (GE MAPS) model to perform simulation of the selected four scenarios and the requisite sensitivities. GE MAPS is a proven tool that has been used in previous renewable (wind and solar) integration studies performed by GE and its partners in the course of the last 10 years. GE MAPS is a nodal, security-constrained, unit commitment and economic dispatch model with detailed realistic representation of all generation types and the underlying transmission grid. Generation of all types, including existing and future thermal, hydro, wind, and solar plants were represented as connected to nodes or buses (substations) on the grid. The model provided detailed hourly outputs of operational and economic performance of all generation units. The modeling results also provided hourly information on transmission flows, binding transmission constraints, shadow prices, and congestion costs.

For the purposes of this study, the GE MAPS model covered both U.S. and Canadian interconnections. Hence, the modeling provided detailed information on inter-country power flows, based on a nodal based realistic representation of the neighbouring power systems in the U.S. The model was run for each modeled interconnection (i.e., both EI and WI), with the degree of detail based on additional information that the GE team was able to collect and incorporate in the existing GE MAPS database of U.S. and Canada.

The production simulation results quantified numerous impacts on grid operation under different scenarios on an hourly basis, including, but not limited to:

- Electricity generation by each defined generation resource and unit type
- Operational performance of generation resources
- Curtailed energy due to higher penetration of wind and congestion
- Environmental emissions (SO2, NOX, and CO2)
- System-wide operational costs (so-called production costs)
- Power flows and congestion on monitored transmission tie-lines

2.4.3 Reliability Analysis and Wind Capacity Valuation (GE MARS)

The GE team utilized the GE Concorda Suite Multi-Area Reliability Simulation (GE MARS) model to perform reliability analysis (loss of load expectation, LOLE) and wind capacity valuation (effective load carrying capability, ELCC).

A sequential Monte Carlo simulation formed the basis for GE MARS. Chronological system histories were developed by combining randomly-generated operating histories of the generating units, with inter-area transfer limits and hourly chronological loads. Consequently, the system was modeled in great detail with accurate recognition of random events, such as equipment failures, as well as deterministic rules and policies which govern system operation. GE MARS does not require simplified or idealized assumptions often required for other analytical methods.

The following reliability indices were produced on both isolated (zero ties between areas) and interconnected (using the input tie ratings between areas) basis:

- Daily LOLE (days/year)
- Hourly LOLE (hours/year)
- LOEE (MWh/year)
- Frequency of outage (outages/year)
- Duration of outage (hours/outage)
- Need for initiating emergency operating procedures (days/year)

2.4.4 High Performance Computing Facility

The GE team leveraged its High Performance Computing (HPC) Center capabilities to perform the analysis in a timely and efficient manner using parallel computing techniques. GE Energy Consulting uses a Linux-based High Performance Cluster to significantly reduce runtimes of the GE MAPS and GE MARS models. Each of these programs is highly suited for parallel processing and the GE Energy Consulting software team has developed customized code to maximize the HPC benefit.

2.5 Study Limitations

Heuristic-Based Generation Expansion Plan

The focus of this project was to determine the various impacts of wind energy additions in Canada. It was not intended to be an overall integrated resource plan (IRP). The study makes no effort to establish the overall adequacy of the Canadian power grid, nor does it attempt to determine exactly what resources are necessary to meet system performance and reliability objectives.

Although full integrated resource planning (IRP) type analysis was beyond the scope of this study, a heuristic generation expansion planning approach was used to add enough new generation capacity so that all of the balancing areas would meet their installed reserve margin requirements with anticipated 2025 system load levels in the 5% BAU scenario.

Transmission Reinforcements in lieu of Long-Term Regional Transmission Expansion Planning

In addition, this study is not meant to be a long-term regional transmission expansion plan. The approach used in this study is adequate for determining the appropriate levels of transmission reinforcements. Doing a more complex long-term regional transmission expansion planning study was beyond the scope of this project.

Limited Focus of the Economic Analysis

The study scope did not include evaluation of the economic viability of the generation resources that would be significantly impacted by the higher penetration of wind and their downward pressure on electricity costs caused by displacement of fossil fuel based generation. Economic viability of generation resources needed to meet the required installed reserve margins may require additional sources of revenue (such as those from ancillary services and capacity markets) to compensate for revenue short falls due to lower utilization and downward pressure on prices caused by additional wind in the system.

Furthermore, the production cost simulations quantify variable operating costs only. These are the costs that determine which units, of the ones available to the system operator, should be utilized to serve load in a least cost manner. These costs include fuel consumption, variable operations & maintenance, and unit startup. The production cost analysis does not include costs related to new capital expenditures required for new wind additions or fixed operations & maintenance or power purchase agreements for new generation resources.

Production/Reliability Simulation

The modeling used is highly sophisticated, and the tools (GE MAPS and GE MARS) are industry standards - widely used for economic and operational evaluation of power systems. Nevertheless, they are still simulations. Reality is even more complex, and successful grid operation includes the action of experienced human operators. There are limits to our ability to exactly replicate present, and even more so, to accurately predict possible future operations of the Canadian grid. GE has extensive experience and has exercised care and applied engineering judgment to make sure that the simulations are reasonably accurate, and that they provide the quantitative insight necessary for Canadian stakeholders to make good investment and operational decisions. Perfect accuracy is neither possible nor necessary.

Engineering Analysis

This study included a technical evaluation of the economics, operations, and reliability of increased renewable penetration, but it did not include an evaluation of system stability associated with those changes. Technical engineering analysis related to dynamic frequency response, grid strength, power-swing stability, and transmission related interconnection studies and transfer analyses should be evaluated in future study work.

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