GE
Energy Consulting

Pan-Canadian Wind Integration Study (PCWIS)

Section 11: Appendices and References

Prepared for: Canadian Wind Energy Association (CanWEA)

Prepared by: GE Energy Consulting

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imagination at work

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Technical Advisory Committee Members:

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

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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

11 Appendices & References

11.1 Appendix A: GE MAPS Model

Application of GE MAPS

GE's Multi Area Production Simulation (GE MAPS)[1] software program is a transmission based Production cost model to be used for the execution of the wind integration study. This GE proprietary (but commercially available) modeling tool has a long history of governmental, regulatory, independent system operator and investor-owned utility applications. The production cost model provides unit-by-unit production output (MW) on an hourly basis for an entire year of production (GWh) of electricity production by each unit). The results also provide information about the variable cost of electricity production, emissions, fuel consumption, etc.

The overall simulation algorithm is based on standard least marginal cost operating practice. That is, generating units that can supply power at lower marginal cost of production are committed and dispatched before units with higher marginal cost of generation. Commitment and dispatch are constrained by physical limitations of the system, such as transmission thermal limits, minimum spinning reserve, as well as the physical limitations and characteristics of the power plants.

The primary source of model uncertainty and error for production cost simulations, based on the model, consist of:

- Some of the constraints in the model may be somewhat simpler than the precise situation dependent rules used by electricity market operators and utilities.
- Marginal production-cost models consider heat rate and a variable O&M cost. However, the models do not include an explicit heat-rate penalty or an O&M penalty for increased maneuvering that may be a result of incremental system variability due to as-available renewable resources (in future scenarios).
- The production cost model requires input assumptions like forecasted fuel price, forecasted system load, estimated unit heat rates, maintenance and forced outage rates, etc. Variations from these assumptions could significantly alter the results of the study.
- Prices that utilities pays to IPPs for energy are not in general equal to the variable cost of production for the individual unit; nor are they equal to the systemic marginal cost of production. Rather, they are governed by PPAs. The price that utilities pay to

[1] http://www.geenergyconsulting.com/practice-area/software-products/maps

third parties can be reflected in the simulation results insofar as the conditions can be reproduced.

The simulation results provide insight into hour-to-hour operations, and how commitment and dispatch may change subject to various changes, including equipment or operating practices. Since the production cost model depends on fuel price as an input, relative costs and change in costs between alternative scenarios tend to produce better and more useful information than absolute costs. The results from the model approximate system dispatch and production, but do not necessarily identically match system behavior. The results do not necessarily reproduce accurate production costs on a unit-by-unit basis and do not accurately reproduce every aspect of system operation. However, the model reasonably quantifies the incremental changes in marginal cost, emissions, fossil fuel consumption, and other operations metrics due to changes, such as higher levels of wind power.

Unique Features of GE MAPS

GE MAPS is a highly detailed model that calculates hour-by-hour production costs while recognizing constraints on the dispatch of generation imposed by the transmission system. When the program was initially developed over twenty years ago, its primary use was as a generation and transmission planning tool to evaluate the impacts of transmission system constraints on the system production cost. In the current deregulated utility environment, the acronym GE MAPS may more also stand for Market Assessment & Portfolio Strategies because of the model's usefulness in studying issues such as market power and the valuation of generating assets operating in a competitive environment.

The unique modeling capabilities of GE MAPS use a detailed electrical model of the entire transmission network, along with generation shift factors determined from a solved ac load flow, to calculate the real power flows for each generation dispatch. This enables the user to capture the economic penalties of re-dispatching the generation to satisfy transmission line flow limits and security constraints.

Separate dispatches of the interconnected system and the individual companies' own load and generation are performed to determine the economic interchange of energy between companies. Several methods of cost reconstruction are available to compute the individual company costs in the total system environment. The chronological nature of the hourly loads is modeled for all hours in the year. In the electrical representation, the loads are modeled by individual bus.

In addition to the traditional production costing results, MAPS can provide information on the hourly spot prices at individual buses and on the flows on selected transmission lines for all hours in the year, as well as identifying the companies responsible for the flows on a given line.

Because of its detailed representation of the transmission system, GE MAPS can be used to study issues that often cannot be adequately modeled with conventional production costing software. These issues include:

Market Structures – GE MAPS is being used extensively to model emerging market structures in different regions of the United States. It has been used to model the New York, New England, PJM and California ISOs for market power studies, stranded cost estimates, and project evaluations.

Transmission Access – GE MAPS calculates the hour spot price ($/MWh) at each bus modeled, thereby defining a key component of the total avoided cost that is used in formulating contracts for transmission access by non-utility generators and independent power producers.

Loop Flow or Uncompensated Wheeling – The detailed transmission modeling and cost reconstruction algorithms in MAPS combine to identify the companies contributing to the flow on a given transmission line and to define the production cost impact of that loading.

Transmission Bottlenecks – GE MAPS can determine which transmission lines and interfaces in the system are bottlenecks and how many hours during the year these lines are limiting. Next, the program can be used to assess, from an economic point of view, the feasibility of various methods, such as transmission line upgrades or the installation of phase-angle regulators for alleviating bottlenecks.

Evaluation of New Generation, Transmission, or Demand-Side Facilities – GE MAPS can evaluate which of the available alternatives under consideration has the most favorable impact on system operation in terms of production costs and transmission system loading.

Power Pooling – The cost reconstruction algorithms in GE MAPS allow individual company performance to be evaluated with and without pooling arrangements, so that the benefits associated with pool operations can be defined.

Modeling Capabilities of GE MAPS

GE MAPS has evolved to study the management of a power system's generation and transmission resources to minimize generation production costs while considering transmission security. The modeling capabilities of MAPS are summarized below:

Time Frame – One year to several years with ability to skip years.

Company Models – Up to 175 companies.

Load Models – Up to 175 load forecasts. The load shapes can include all 365 days or automatically compress to a typical week (seven different day shapes) per month. The day shapes can be further compressed from 24 to 12 hours, with bi-hourly loads.

Generation – Up to 7,500 thermal units, 500 pondage plants, 300 run-of-river plants, 50 energy-storage plants, 15 external contracts, 300 units jointly owned, and 2,000 fuel types. Thermal units have full and partial outages, daily planned maintenance, fixed and variable operating and maintenance costs, minimum down-time, must-run capability, and up to four fuels at a unit.

Network Model –Includes 50,000 buses, 100,000 lines, 145 phase-angle regulators, and 100 multi-terminal High-Voltage Direct Current lines. Line or interface transmission limits may be set using operating nomograms as well as thermal, voltage and stability limits. Line or interface limits may be varied by generation availability.

Losses - Transmission losses may vary as generation and loads vary, approximating the ac power flow behavior, or held constant, which is the usual production simulation assumption. The incremental loss factors are recalculated each hour to reflect their dependence on the generation dispatch.

Marginal Costs – Marginal costs for an increment such as 100 MW can be identified by running two cases, one 100 MW higher, with or without the same commitment and pumped-storage hydro schedule. A separate routine prepares the cost difference summaries. Hourly bus spot prices are also computed.

Operating Reserves – Modeled on an area, company, pool and system basis.

Secure Dispatch – Up to 5,000 lines and interfaces and nomograms may be monitored. Each study hour considers the effect of hundreds of different network outages.

Report Analyzer – MAPS allows the simulation results to be analyzed through a powerful report analyzer program, which incorporates full screen displays, customizable output reports, graphical displays and databases. The built-in programming language allows the user to rapidly create custom reports.

Accounting – Separate commitment and dispatches are done for the system and for the company own-load assumptions, allowing cost reconstruction and cost splitting on a licensee-agreed basis. External economy contracts are studied separately after the base dispatch each hour.

Bottom Line – Annual fuel plus O&M costs for each company, fuel consumption, and generator capacity factors.

11.2 Appendix B: GE MARS Model

The Multi-Area Reliability Simulation software program (GE MARS)[2] enables the electric utility planner to quickly and accurately assess the reliability of a generation system comprised of any number of interconnected areas.

GE Mars Modeling Technique

A sequential Monte Carlo simulation forms the basis for MARS. The Monte Carlo method provides a fast, versatile, and easily-expandable program that can be used to fully model many different types of generation and demand-side options.

In the sequential Monte Carlo simulation, chronological system histories are developed by combining randomly-generated operating histories of the generating units with the inter-area transfer limits and the hourly chronological loads. Consequently, the system can be 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, without the simplifying or idealizing assumptions often required in analytical methods.

Reliability Indices Available From Mars

The following reliability indices are available on both an 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)

The use of Monte Carlo simulation allows for the calculation of probability distributions, in addition to expected values, for all of the reliability indices. These values can be calculated both with and without load forecast uncertainty.

Description of Program Models

Loads - The loads in MARS are modeled on an hourly, chronological basis for each area being studied. The program has the option to modify the input hourly loads through time to meet specified annual or monthly peaks and energies. Uncertainty on the annual peak load forecast can also be modeled, and can vary by area on a monthly basis.

[2] http://www.geenergyconsulting.com/practice-area/software-products/mars

MARS has the capability to model the following different types of resources:

- Thermal
- Energy-limited
- Cogeneration
- Energy-storage
- Demand-side management

An energy-limited unit can be modeled stochastically as a thermal unit with an energy probability distribution (Type 1 energy-limited unit), or deterministically as a load modifier (Type 2 energy-limited unit). Cogeneration units are modeled as thermal units with an associated hourly load demand. Energy-storage and demand-side management are modeled as load modifiers.

For each unit modeled, the user specifies the installation and retirement dates and planned maintenance requirements. Other data such as maximum rating, available capacity states, state transition rates, and net modification of the hourly loads are input depending on the unit type.

The planned outages for all types of units in MARS can be specified by the user or automatically scheduled by the program on a weekly basis. The program schedules planned maintenance to levelize reserves on an area, pool, or system basis. MARS also has the option of reading a maintenance schedule developed by a previous run and modifying it as specified by the user through any of the maintenance input data. This schedule can then be saved for use by subsequent runs.

Thermal Units - In addition to the data described previously, thermal units (including Type 1 energy-limited units and cogeneration) require data describing the available capacity states in which the unit can operate. This is input by specifying the maximum rating of each unit and the rating of each capacity state as a per-unit of the unit's maximum rating. A maximum of eleven capacity states are allowed for each unit, representing decreasing amounts of available capacity as a result of the outages of various unit components.

Because MARS is based on a sequential Monte Carlo simulation, it uses state transition rates, rather than state probabilities, to describe the random forced outages of the thermal units. State probabilities give the probability of a unit being in a given capacity state at any particular time, and can be used if you assume that the unit's capacity state for a given hour is independent of its state at any other hour. Sequential Monte Carlo simulation recognizes the fact that a unit's capacity state in a given hour is dependent on its state in previous hours and influences its state in future hours. It thus requires the additional information that is contained in the transition rate data.

For each unit, a transition rate matrix is input that shows the transition rates to go from each capacity state to each other capacity state. The transition rate from state A to state B is defined as the number of transitions from A to B per unit of time in state A:

$$\textit{TR (A to B)} = \frac{\textit{Number of Transitions from A to B}}{\textit{Total Time in State A}}$$

If detailed transition rate data for the units is not available, MARS can approximate the transitions rates from the partial forced outage rates and an assumed number of transitions between pairs of capacity states. Transition rates calculated in this manner will give accurate results for LOLE and LOEE, but it is important to remember that the assumed number of transitions between states will have an impact on the time-correlated indices such as frequency and duration.

Energy-Limited Units - Type 1 energy-limited units are modeled as thermal units whose capacity is limited on a random basis for reasons other than the forced outages on the unit. This unit type can be used to model a thermal unit whose operation may be restricted due to the unavailability of fuel, or a hydro unit with limited water availability. It can also be used to model technologies such as wind or solar; the capacity may be available but the energy output is limited by weather conditions.

Type 2 energy-limited units are modeled as deterministic load modifiers. They are typically used to model conventional hydro units for which the available water is assumed to be known with little or no uncertainty. This type can also be used to model certain types of contracts. A Type 2 energy-limited unit is described by specifying a maximum rating, a minimum rating, and a monthly available energy. This data can be changed on a monthly basis. The unit is scheduled on a monthly basis with the unit's minimum rating dispatched for all of the hours in the month. The remaining capacity and energy can be scheduled in one of two ways. In the first method, it is scheduled deterministically so as to reduce the peak loads as much as possible. In the second approach, the peak-shaving portion of the unit is scheduled only in those hours in which the available thermal capacity is not sufficient to meet the load; if there is sufficient thermal capacity, the energy of the Type 2 energy-limited units will be saved for use in some future hour when it is needed.

Cogeneration - MARS models cogeneration as a thermal unit with an associated load demand. The difference between the unit's available capacity and its load requirements represents the amount of capacity that the unit can contribute to the system. The load demand is input by specifying the hourly loads for a typical week (168 hourly loads for

Monday through Sunday). This load profile can be changed on a monthly basis. Two types of cogeneration are modeled in the program, the difference being whether or not the system provides back-up generation when the unit is unable to meet its native load demand.

Energy-Storage and DSM - Energy-storage units and demand-side management are both modeled as deterministic load modifiers. For each such unit, the user specifies a net hourly load modification for a typical week which is subtracted from the hourly loads for the unit's area.

Transmission System

The transmission system between interconnected areas is modeled through transfer limits on the interfaces between pairs of areas. Simultaneous transfer limits can also be modeled in which the total flow on user-defined groups of interfaces is limited. Random forced outages on the interfaces are modeled in the same manner as the outages on thermal units, through the use of state transition rates.

The transfer limits are specified for each direction of the interface or interface group and can be input on a monthly basis. The transfer limits can also vary hourly according to the availability of specified units and the value of area loads.

Contracts

Contracts are used to model scheduled interchanges of capacity between areas in the system. These interchanges are separate from those that are scheduled by the program as one area with excess capacity in a given hour provides emergency assistance to a deficient area.

Each contract can be identified as either firm or curtailable. Firm contracts will be scheduled regardless of whether or not the sending area has sufficient resources on an isolated basis, but they can be curtailed because of interface transfer limits. Curtailable contracts will be scheduled only to the extent that the sending area has the necessary resources on its own or can obtain them as emergency assistance from other areas.

Emergency Operating Procedures

Emergency operating procedures are steps undertaken by a utility system as the reserve conditions on the system approach critical levels. They consist of load control and generation supplements which can be implemented before load has to be actually disconnected. Load control measures could include disconnecting interruptible loads, public appeals to reduce demand, and voltage reductions. Generation supplements could include overloading units, emergency purchases, and reduced operating reserves.

The need for a utility to begin emergency operating procedures is modeled in MARS by evaluating the daily LOLE at specified margin states. The user specifies these margin states for each area in terms of the benefits realized from each emergency measure, which can be expressed in MW, as a per unit of the original or modified load, and as a per unit of the available capacity for the hour.

The user can also specify monthly limits on the number of times that each emergency procedure is initiated, and whether each EOP benefits only the area itself, other areas in the same pool, or areas throughout the system. Staggered implementation of EOPs, in which the deficient area must initiate a specified number of EOPs before non-deficient areas begin implementation, can also be modeled.

Resource Allocation among Areas

The first step in calculating the reliability indices is to compute the area margins on an isolated basis, for each hour. This is done by subtracting from the total available capacity in the area for the hour the load demand for the hour. If an area has a positive or zero margins, then it has sufficient capacity to meet its load. If the area margin is negative, the load exceeds the capacity available to serve it, and the area is in a loss-of-load situation.

If there are any areas that have a negative margin after the isolated area margins have been adjusted for curtailable contracts, the program will attempt to satisfy those deficiencies with capacity from areas that have positive margins. Two methods are available for determining how the reserves from areas with excess capacity are allocated among the areas that are deficient. In the first approach, the user specifies the order in which an area with excess resources provides assistance to areas that are deficient. The second method shares the available excess reserves among the deficient areas in proportion to the size of their shortfalls.

The user can also specify that areas within a pool will have priority over outside areas. In this case, an area must assist all deficient areas within the same pool, regardless of the order of areas in the priority list, before assisting areas outside of the pool. Pool-sharing agreements can also be modeled in which pools provide assistance to other pools according to a specified order.

Output Reports

The following output reports are available from MARS. Most of the summaries of calculated quantities are available for each load forecast uncertainty load level and as a weighted-average based on the input probabilities.

- Summary of the thermal unit data.
- Summary of installed capacity by month by user-defined unit type.
- Summary of load data, showing monthly peaks, energies, and load factors.
- Unit outage summary showing the weeks during the year that each unit was on planned outage.

- Summary of weekly reserves by area, pool, and system.
- Annual, monthly, and weekly reliability indices - by area and pool, isolated and interconnected.
- Expected number of days per year at specified margin states on an annual, monthly, and weekly basis.
- Annual and monthly summaries of the flows, showing for each interface the maximum and average flow for the year, the number of hours at the tie-line limit, and the number of hours of flow during the year.
- Annual summary of energy and hours of curtailment for each contract.
- Annual summary of energy usage for the peaking portion of Type 2 energy-limited units.
- Replication year output, by area and pool, isolated and interconnected, showing the daily and hourly LOLE and LOEE for each time that the study year was simulated. This information can be used to plot distributions of the indices, which show the year-to-year variation that actually occurs.
- Annual summary of the minimum and maximum values of the replication year indices.
- Detailed hourly output showing, for each hour that any of the areas has a negative margin on an isolated basis, the margin for each area on an isolated and interconnected basis.
- Detailed hourly output showing the flows on each interface.

Program Dimensions

All of the program dimensions in MARS can be changed at the time of installation to size the program to the system being studied. Among the key parameters that can be changed are the number of units, areas, pool, and interfaces.

11.3 Appendix C: GE PSLF Model

Effective power system analysis often requires large-scale simulations and manipulation of large volumes of data. When performing these analyses, efficient algorithms are just as important as the engineering models in which the data is used. GE Energy recognizes these imperatives, and has developed Concorda Positive Sequence Load Flow (GE PSLF)[3] model.

The algorithms in the GE PSLF suite have been developed to handle large utility-scale systems of up to 80,000 buses.

A complete set of tools allows the user to switch smoothly between data visualization, system simulation, and results analysis.

GE PSLF Features & Benefits

- Comprehensive System Modeling: provides precise models for lines, transformers, generators, and other components, at a nameplate level
- Highly Accurate: enabling more detailed system and modeling capabilities
- Efficient Data Management: full-screen data editor, tools for searching, sorting and selecting data, numerous reports which facilitate system planning
- Customizable: extendable data records, user defined data tables
- Enhanced Graphics: allow the user to inspect power system models, select, display, and edit components; view the system from a specific component.
- Dynamic Model Library: generators, turbines, excitation controls, governors, power system stabilizers, loads, relays and other power system components
- Renewable Generation Models: detailed dynamic models of GE wind turbine generators, a GE PV solar plant, and a suite of generic wind and solar models.
- Automation and Scripting: Engineer Program Control Language (EPCL), provides detailed access to internal data, internal commands and math functions.

GE PSLF Applications

Concorda GE PSLF is a comprehensive system modeling tool which can be used for many aspects of system planning and analysis

- steady state, load flow simulation
- short circuit analysis
- dynamic simulation

[3] http://www.geenergyconsulting.com/practice-area/software-products/pslf

- identifying system bottlenecks
- identify grid code violations

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