GE
Energy Consulting

Pan-Canadian Wind Integration Study (PCWIS)

Section 9: Sub-Hourly Analysis

Prepared for: Canadian Wind Energy Association (CanWEA)

Prepared by: GE Energy Consulting / EnerNex

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imagination at work

Legal Notices

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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)

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Contact Information

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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

9 Sub-Hourly Analysis

Section Acknowledgement:

This section of the report was written by the EnerNex and GE teams.

9.1 Reserve Adequacy

This section presents a post-simulation analysis of the GE MAPS production cost results to examine whether regulation reserves for each scenarios penetration levels of wind were sufficient to cover sub-hourly variations in load and net load. GE MAPS provided in each hour of the scenario run a resource dispatch that provides sufficient ramping capability of resources to move from one hour to the next. This analysis examines the potential ramping limitations that may occur within the hour due to error in forecasting of load or wind resources. The study looks at the resource ramping limitations, both up and down, that come from the GE MAPS scenario runs. Specifically the total 10-minute up-ramps and down-ramps are provided.

Over the year there are hours when the variability of the intra-hourly wind production could theoretically create a situation where on-line resources may be unable to ramp sufficiently up or down to satisfy the system load requirements. Looking at the sub hourly 10-minute periods there may be times when wind production supports the directional changes in load, for example when load is increasing while wind production is increasing the need for additional ramping generation is not as great than if the wind production moved in the opposite direction. In other intra-hour periods when load is increasing and wind is decreasing the need for additional generating resources would be greater than if wind production was increasing. The up-ramp or down-ramp requirements of generating resources are accounted for in the hour to hour modeling and provide sufficient resource capability to meet regulation requirements. This analysis approximates potential issues that may arise because of inter hour variability of load and wind.

The production cost runs performed in the study provide a solution to the commitment and dispatch of resources in each pool in the Canada system while meeting given constraints on the system for each hour of the year. Given that wind production is variable by its very nature and can move up or down within an hourly period it was decided to examine if the hourly dispatch solution would provide sufficient flexibility to account for the wind resource variability. Having 10-minute actual wind production available provided six periods over the hour for examination. To account for load movement over the hour each 10-minute period was derived by interpolating values over the hour to hour period.

Results for each scenario run provide a value of available dispatched capacity that can move up or down over the hour to satisfy regulating reserves. These values provided included total thermal and hydro up-reg and down-reg amounts. These values were based upon data provided from the TEPPC database[1] and are shown in Table 9-1.

Table 9-1: Average Characteristics Used for Thermal Units in PLEXOS Optimization

Type of Unit	Minimum Generation (as a % of maximum capacity)	Ramp Rate (%/min)	Heat Rate (at full load)	WWSIS-2 Nonfuel Start Cost ($/MW)	TEPPC Nonfuel Start Cost ($/MW)
Coal	40[a]	1.1[a]	10.5	124	11[a]
CC	52[a]	0.9[a]	7.6	81	47[a]
CT	38[a]	4.5[a]	10.7	67	93[a]
Steam	12[a]	1.7[a]	10.7	86	12[a]
Nuclear	95	0.3[a]	11.0	155	_[a]

[a] Denotes an original assumption from the TEPPC database (aggregated for all units of each type). Other information in this table was created for this study as described in Section 2. The TEPPC start costs were not used for this study.

9.2 Sub-Hourly Analysis Methodology

Within every hour of the year, each 10-minute period of wind production and each 10-minute load demand was examined. If the combined change of 10-minute wind production and load demand exceeded either the upward or downward available ramping capability of the committed resources, then this period was noted as having insufficient ramping capacity for the balancing area to satisfy the regulation requirement. This could impact Area Control Error (ACE) and potentially cause a Control Performance Standard 2 (CPS2) violation.

Insufficient ramping capacity can result in a system frequency variation for the Province if external ramping capacity from transmission interties is not available to compensate for the difference. In other words if there was a period of insufficient ramping capacity it does not necessarily mean the Province has a reliability issue. Reliability standards have been set by NERC that provide guidance to account for periods when a system over or under generates. NERC has set a CPS2 requirement that allows a Balancing Authority to have as many as one violation every other hour over the year. Another measure is that there should be no violations in at least 90% of clock 10-minute periods during a calendar month within a specific limit referred to as L10.

[1] Global CCS Institute Website: https://hub.globalccsinstitute.com/publications/western-wind-and-solar-integration-study-phase-2/32-production-simulation-methodology-and-operational-assumptions

Over the year there are 52,560 ten-minute periods examined in each scenario for each province as well as for all of Canada. Thus the maximum number of periods in a year where ramping limitations may be tolerated is 5,256. Up-ramp and down-ramp limits were tested against the 10-minute change in load. Next, the up-ramp and down-ramp limits were tested against the 10-minute change in net load change, where net load is calculated to be load demand minus wind production. The number of times that ramp capacity did not meet the 10-minute change in load or net load, were counted separately. The results of this analysis indicate that there are only a small number of 10-minute periods when resource ramping fell below the 10-minute variability for load or net load.

In Table 9-2 the percent of periods when a ramping constraint is in violation is shown. Violations were determined for both load and net load. It can be seen that the number of up-ramp and down-ramp violations are very small and fall well within the NERC CSP2 requirements.

Table 9-2: Canada And Province Up-Ramp And Down-Ramp 10-Minute Violations For Each Scenario As A Percent Of All Periods

	Percent of 10-Minute Periods in Year Exceeding Up-Ramp Limits						
	BC	AB	SK	MB	ON	QC	MAR
5% BAU Load	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
5% BAU Net Load	0.000%	0.000%	0.000%	0.000%	0.006%	0.000%	0.000%
20% DISP Load	0.000%	0.000%	0.000%	0.002%	0.011%	0.000%	0.000%
20% DISP Net Load	0.002%	0.023%	0.049%	0.004%	0.093%	0.000%	0.002%
20% CONC Load	0.000%	0.000%	0.000%	0.105%	0.002%	0.000%	0.000%
20% CONC Net Load	0.000%	0.040%	0.004%	0.154%	0.156%	0.000%	0.004%
35% TRG Load	0.000%	0.000%	0.000%	0.025%	0.032%	0.000%	0.000%
35% TRG Net Load	0.002%	0.186%	0.120%	0.038%	0.441%	0.000%	0.006%

	Percent of 10-Minute Periods in Year Exceeding Down-Ramp Limits						
	BC	AB	SK	MB	ON	QC	MAR
5% BAU Load	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
5% BAU Net Load	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
20% DISP Load	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
20% DISP Net Load	0.000%	0.008%	0.051%	0.000%	0.000%	0.000%	0.002%
20% CONC Load	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
20% CONC Net Load	0.000%	0.019%	0.000%	0.000%	0.002%	0.000%	0.086%
35% TRG Load	0.000%	2.367%	0.000%	0.000%	0.000%	0.000%	0.000%
35% TRG Net Load	0.002%	5.953%	0.504%	0.000%	0.002%	0.000%	0.067%

To provide another perspective, the actual count of violations for each province is shown in Table 9-3. Although the number of violations is small, Alberta tends to have periods with many 10-minute up-ramp or down-ramp violations. In the 35% TRGT scenario Alberta has a larger number of violations than the other Provinces. A contributing factor for the large number of down-ramp violations can be that this analysis does not include transmission interchange between Alberta and other pools, a result of the analysis focusing on Provinces without the consideration of transmission interchange. In addition, down ramp limitations in the net load are due to the wind ramping up too fast. This can be easily mitigated by limiting the up ramp of the wind. This will result in slightly more curtailment but will avoid violations. In the 35% TRGT scenario, the high wind penetration levels results in a net-load that is negative for 14% of the 10-minute periods. With the wind rated capacity being over 17 GW, Alberta's minimum load of 11 GW also contributes to the negative net load conditions. In reality, the excess wind generation would be exported or curtailed, thereby avoiding many of the down ramp violations.

Table 9-3: Count of all Canada and Province Up-Ramp and Down-Ramp Violations in each Scenario

	Number of 10-Minute Periods in Year Exceeding Up-Ramp Limits						
	BC	AB	SK	MB	ON	QC	MAR
5% BAU Load	0	0	0	0	0	0	0
5% BAU Net Load	0	0	0	0	3	0	0
20% DISP Load	0	0	0	1	6	0	0
20% DISP Net Load	1	12	26	2	49	0	1
20% CONC Load	0	0	0	55	1	0	0
20% CONC Net Load	0	21	2	81	82	0	2
35% TRG Load	0	0	0	13	17	0	0
35% TRG Net Load	1	98	63	20	232	0	3

	Number of 10-Minute Periods in Year Exceeding Down-Ramp Limits						
	BC	AB	SK	MB	ON	QC	MAR
5% BAU Load	0	0	0	0	0	0	0
5% BAU Net Load	0	0	0	0	0	0	0
20% DISP Load	0	0	0	0	0	0	0
20% DISP Net Load	0	4	27	0	0	0	1
20% CONC Load	0	0	0	0	0	0	0
20% CONC Net Load	0	10	0	0	1	0	45
35% TRG Load	0	1,244	0	0	0	0	0
35% TRG Net Load	1	3,129	265	0	1	0	35

Table 9-4 shows the resulting maximum MW exceeding up-ramp and down-ramp limits. A few data points were removed due to discontinuities in the raw data. The values shown represent the largest violations in each province; and therefore, they represent the very extreme 10-minute up-ramp and down-ramp violation hours during the year.

Table 9-4: Maximum MW Exceeding Up-Ramp and Down-Ramp Limits in Each Scenario

	Maximum Additional MWs Needed to Meet Up-Ramp Requirements						
	BC	AB	SK	MB	ON	QC	MAR
5% BAU Load	0	0	0	0	0	0	0
5% BAU Net Load	0	0	0	0	0	0	0
20% DISP Load	0	0	0	0	42	0	0
20% DISP Net Load	0	213	251	0	229	0	0
20% CONC Load	0	0	0	34	0	0	0
20% CONC Net Load	0	693	0	163	290	0	0
35% TRG Load	0	0	0	18	100	0	0
35% TRG Net Load	0	1,653	404	44	410	0	15

	Maximum Additional MWs Needed to Meet Down-Ramp Requirements						
	BC	AB	SK	MB	ON	QC	MAR
5% BAU Load	0	0	0	0	0	0	0
5% BAU Net Load	0	0	0	0	0	0	0
20% DISP Load	0	0	0	0	0	0	0
20% DISP Net Load	0	160	145	0	0	0	0
20% CONC Load	0	0	0	0	0	0	0
20% CONC Net Load	0	629	0	0	0	0	238
35% TRG Load	0	89	0	0	0	0	0
35% TRG Net Load	0	1,469	517	0	0	0	140

Alberta has the largest ramp-up and ramp-down violations in the 35% TRGT scenario. Again, it should be noted that these values represent extreme cases in the year and may occur during a tiny fraction of the 10-minute intervals in the year.

The up-ramps can be managed by applying wind curtailment. However, to deal with severe ramp-down violations, other mitigation options can be considered, including, but not limited to, improved wind ramp forecasts, demand response, energy storage, pre-contingency curtailment of wind, and use of transmission interties.

To get a better perspective, the magnitude and number of ramp violations in Alberta for the 35% TRGT scenario can be seen in Figure 9-1. The underlying data is shown in Table 9-5. It can be shown that:

- In the 35% TRGT scenario, 76.3% of the net load ramp violations in Alberta (out of the total of 8.6% of the 10-minute periods with violations) are less than 100 MW.
- In the 35% TRGT scenario, 99.7% of the net load ramp violations in Alberta (out of the total of 8.6% of the 10-minute periods with violations) are less than 500 MW.
- In the 35% TRGT scenario, 0.22% of net load violations in Alberta (out of the total of 8.6% of the 10-minute periods with violations) require more than 500 MW of additional up-ramp capability to meet the up-ramp requirements.
- In the 35% TRGT scenario, 0.09% of net load violations in Alberta (out of the total of 8.6% of the 10-minute periods with violations) require more than 500 MW of additional down-ramp capability to meet the down-ramp requirements.

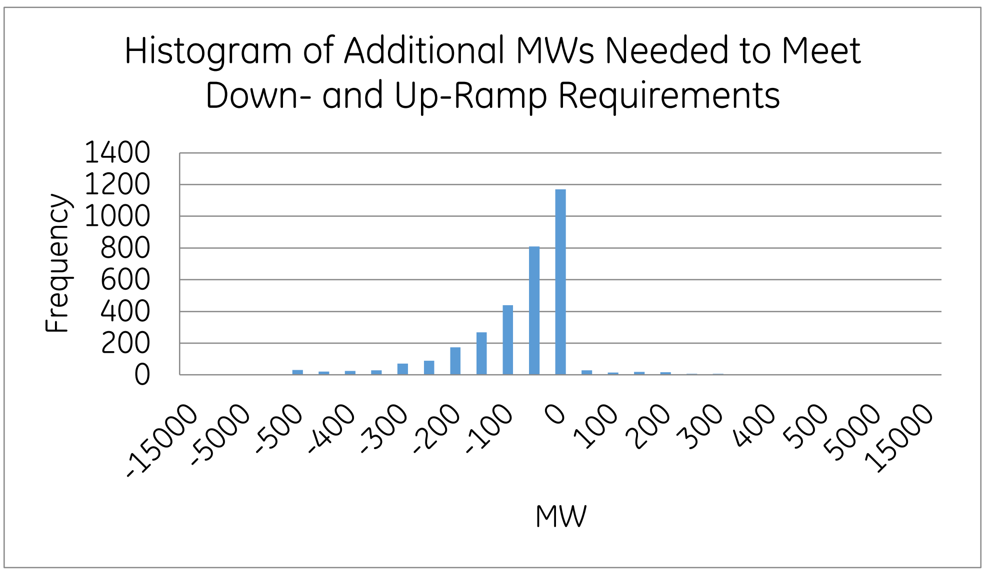

Figure 9-1: Number and Magnitude of 10-Minute Ramp Violations in Alberta for 35% TRGT Scenario

Table 9-5: Data for Histogram of Additional MW Needed to Meet the 10-Minute Net Load Up-Ramp and Down-Ramp Requirements in Alberta in the 35% TRGT Scenario

Bin	*Frequency*	*Percent*
-15000	0	0.0%
-10000	1	0.0%
-5000	0	0.0%
-1000	2	0.1%
-500	31	1.0%
-450	21	0.7%
-400	24	0.7%
-350	28	0.9%
-300	71	2.2%
-250	90	2.8%
-200	174	5.4%
-150	268	8.3%
-100	439	13.6%
-50	810	25.1%
0	1170	36.3%
50	28	0.9%
100	15	0.5%
150	18	0.6%
200	16	0.5%
250	6	0.2%
300	6	0.2%
350	1	0.0%
400	0	0.0%
450	0	0.0%
500	1	0.0%
1000	3	0.1%
5000	2	0.1%
10000	2	0.1%
15000	0	0.0%
TOTAL	**3227**	**100.0%**

9.3 Key Finding and Conclusion

In conclusion the regulation reserve requirements provided in each scenario provide sufficient operating capacity to meet 10-minute up-ramp and down-ramp constraints more than 99% of the time in all provinces in Canada, except Alberta.

The up-ramps can be managed by applying wind curtailment. However, to deal with more severe sub-hourly ramp-down violations in Alberta and to a lesser extent in Saskatchewan and Maritime provinces, other mitigation measures can be considered. These include, but are not limited to, improved wind ramp forecasts, demand response, fast ramping energy storage, pre-contingency wind curtailment, and use of transmission interties.