Minnesota Renewable Energy Integration and Transmission Study

Final Report
October 31, 2014

Prepared for:

The Minnesota Utilities and Transmission Companies
The Minnesota Department of Commerce

Prepared by:

GE Energy Consulting, *with contributions by:*
- The Minnesota Utilities and Transmission Companies
- Excel Engineering, Inc
- MISO

In collaboration with **MISO**

Webinar Presentation – November 6, 2014

Presenters:

Minnesota Utilities & Transmission Companies	GE Energy Consulting	Minnesota Department of Commerce
- Gordon Pietsch (GRE)	- Richard Piwko	- William Grant
- Jared Alholinna (GRE)	- Robert D'Aquila	- Matt Schuerger

Presentation Agenda

- Overview, Scenarios, Scope, Study Team, Review
- Wind and Solar Generation Siting
- Transmission System Conceptual Plans
- Operational Performance Results
- Dynamic Simulation Results
- Key Findings
- Study Contacts

Overview

- In 2013 the Minnesota Legislature adopted a requirement for a Renewable Energy Integration and Transmission Study[1] (MRITS)
- The Minnesota utilities and transmission companies, in coordination with MISO, completed the engineering study
- The Department of Commerce directed the study and appointed and led the Technical Review Committee (TRC)
- MRITS is an engineering study of increasing the Renewable Energy Standard to 40% by 2030, and to higher proportions thereafter, while maintaining system reliability
- The study incorporates and builds upon prior study work

[1] MN Laws 2013, Chapter 85 HF 729, Article 12, Section 4; MPUC Docket No. CI-13-486

Schedule

June – August 2013

Commerce reviewed prior and current studies and worked with stakeholders and study participants to identify key issues, began development of a draft technical study scope, and accepted recommendations of qualified Technical Review Committee (TRC) members

September 2013

Commerce held a stakeholder meeting to discuss the objectives, scope, schedule, and process; Commerce appointed the Technical Review Committee

September / October 2013

Commerce, in consultation with the Minnesota utilities, finalized the study scope

October 2013

The Minnesota utilities, in consultation with Commerce, identified the technical study team

November 2013 – October 2014

The study was completed by the Technical Study Team

Study Scope

MRITS incorporates three core and interrelated analyses:

1) ***Power flow analysis*** – development of a conceptual transmission plan, which includes transmission necessary for generation interconnection and delivery and for access to regional geographic diversity and regional supply and system flexibility;

2) ***Production simulation analysis*** – evaluation of **hour by hour operational performance** of the power system for an entire year (sufficient reserves, load served, wind / solar curtailments, ramp range and rate, and thermal cycling); and

3) ***Dynamics analysis*** – evaluation of **transient stability** (ability of the regional power system to return to steady state following some type of disturbance) and **system strength** (ability of an ac transmission system to support stable operation of large amounts of inverter-based generation).

Study Scenarios

Scenario	Minnesota RE Penetration	MISO Wind & Solar Penetration (including Minnesota)
Baseline	28.5%	14.0%
Scenario 1	40.0%	15.0%
Scenario 2	50.0%	25.0%

- The MRITS study scenarios were developed from statutory guidance, stakeholder input, and technical study team refinement
- **Baseline Scenario:** sufficient renewable energy generation to fully implement the current renewable energy standards and solar energy standards for all states in the study region

  Scenario 1: sufficient renewable energy generation to supply 40% of Minnesota annual electric retail sales from renewables with all regional states at full implementation of their current RESs

  Scenario 2: sufficient renewable energy generation to supply 50% of Minnesota electric retail sales from total renewables *and* to supply 25% of the non-Minnesota MISO North/Central retail electric sales from total renewables (i.e. to increase the MISO North/Central footprint renewables 10% above full implementation the current RESs)
- Scenarios 1 and 2 are built up by adding incremental wind and solar (variable renewables) generation to the corresponding preceding scenario
- The study year of 2028 was selected to help ensure that all models and system data were coordinated with and are consistent with MISO MTEP13 models and databases

Study Scenarios

Wind and Solar Resource Allocations for Study Scenarios

	2013	2028				
MN Retail Sales (GWH)	66,093	71,227				
		Wind MW		**PV MWac**		
Minnesota-centric	**Wind (MW)**	**Total**	**Incremental**	**Total**	**Incremental**	
Existing + signed GIA	8,922				**UPV**	**DPV**
Baseline		5,990		457	361	96
Scenario 1		7,521	1,931	1,371	723	191
Scenario 2		8,131	610	4,557	2,756	430

	2013	2028				
MISO Retail Sales (GWH)	498,000	557,000				
		Wind MW		**PV MWac**		
MISO (includes Minnesota)	**Wind (MW)**	**Total**	**Incremental**	**Total**	**Incremental**	
Existing + signed GIA	15,320				**UPV**	**DPV**
Baseline		22,229	6,900	1509	1,413	96
Scenario 1		24,160	1,931	2,442	723	210
Scenario 2		37,796	13,636	6,201	5,636	565

Study Approach

- All models and system data were coordinated with and consistent with MISO models and databases existing at the time the study began;
- The horizon year for this study was 2028 (to represent 2030 conditions);
- The study is Minnesota centric with a study area focused on Minnesota within the MISO footprint and adjoining neighboring regions;
- All key assumptions and methods were clearly outlined and reviewed during the course of the study and are clearly stated in the report;
- All technical work in this study was reviewed by the Technical Review Committee throughout the study.

Technical Review Committee (TRC)

	Representing
Mark Ahlstrom CEO	**Wind Logics**
Steve Beuning Director Market Operations	**Xcel Energy**
Jeff Eddy Manager Planning	**ITC Holdings**
Brendan Kirby Consultant, grid integration and reliability	**National Renewable Energy Laboratory (NREL)**
Mark Mitchell Director of Operations and COO	**SMMPA**
Michael Milligan Principal Researcher, Grid Integration	**NREL**
Dale Osborn Consulting Advisor, Policy and Economic Studies	**MISO**
Rhonda Peters Principal, InterTran Energy	**Wind on the Wires**
Gordon Pietsch Director Transmission Planning & Operations	**Great River Energy**
Larry Schedin, P.E. Principal, LLS Resources	**MN Chamber of Commerce**
Dean Schiro, P.E. Manager Real Time Planning	**Xcel Energy**
Matt Schuerger, P.E. - TRC Chair Technical Advisor	**Commerce DER**
Glen Skarbakka, P.E. Consultant	**Skarbakka LLC**
Charlie Smith Executive Director	**Utility Variable Generation Integration Group**
George Sweezy Manager System Performance and Planning	**Minnesota Power**
Jason Weiers, P.E. Manager Delivery Planning	**Otter Tail Power**
Terry Wolf Manager Transmission Services	**Missouri River Energy Services**

Observers:

Cezar Panait, P.E., Regulatory Engineer	MN Public Utilities Commission
Lise Trudeau, Engineer	Commerce DER

Study Team (1 of 2)

Jared Alholinna, P.E. (Great River Energy) – technical study team lead

GE Energy Consulting (GE) – operating performance, dynamics, mitigations / solutions

Douglas Welsh	Durga Gautam	Robert D'Aquila
Richard Piwko	Eknath Vittal	Slobodan Pajic
Gary Jordan	Nicholas Miller	

Excel Engineering, Inc. – power flow analysis, transmission conceptual plan

Michael Cronier, P.E.	LaShel Marvig, P.E.

MISO – technical coordination, models, data; production simulation analysis

Jordan Bakke	Brandon Heath	Cody Doll
Aditya Jayam Prabhakar		

Study Team (2 of 2)

Technical Study Team participants – weekly coordination calls, ongoing technical study participation with Excel Engineering, General Electric and MISO.

Kevin Demeny	American Transmission Company
Steve Porter, P.E.	Dairyland Power Cooperative
Jared Alholinna, P.E. - Study Team Lead	Great River Energy
Richa Singhal	Great River Energy
Jeff Eddy	ITC Midwest
David Jacobson	Manitoba Hydro
Scott Hoberg, P.E.	Minnesota Power
Andrew Kienitz	Minnesota Power
George Sweezy, P.E.	Minnesota Power
Christian Winter, P.E	Minnesota Power
Aaron Vander Vorst, P.E.	Minnkota Power Cooperative
John Weber	Missouri River Energy Services
Matt Schuerger, P.E.	MN Department of Commerce
Lise Trudeau	MN Department of Commerce
Michael Riewer	Otter Tail Power
Jason Weiers, P.E.	Otter Tail Power
Andrew Lucero, P.E	Representing CMMPA
Steve Beuning	Xcel Energy
Jarred Cooley	Xcel Energy
Amanda King	Xcel Energy
Dean Schiro, P.E.	Xcel Energy

Task Leads

- *Develop Study Scenarios; Site Wind and Solar Generation*
  Lead contributors: Minnesota Utilities; Minnesota Department of Commerce

- *Perform Production Simulation Analysis*
  Lead Contributor: MISO

- *Perform Power Flow Analysis; Develop Transmission Conceptual Plan*
  Lead Contributors: Minnesota Utilities & Transmission Owners; Excel Engineering Inc

- *Evaluate Operational Performance*
  Lead Contributor: GE Energy Consulting

- *Screen for Challenging Periods*
  Lead Contributor: GE Energy Consulting

- *Evaluate stability related issues, including transient stability performance, voltage regulation performance, adequacy of dynamic reactive support, and weak system strength issues*
  Lead Contributor: GE Energy Consulting

- *Identify and Develop Mitigations and Solutions*
  Lead Contributor: GE Energy Consulting

Wind and Solar Generation Siting

Wind and Solar Generation Siting

- This task focused on selecting sites for wind and solar resources to meet the requirements of the study scenarios.
- Minnesota wind and solar resources were sited in the Minnesota-centric area (MN, ND, SD, northern Iowa)
  - based on existing wind and solar, planned wind and solar (including those with signed Interconnection Agreements, wind sites in MVP portfolio planning), and MN utility announced projects.
- MISO future wind and solar was sited per MTEP guidelines (e.g. at expanded RGOS zones on a pro rata basis).

Wind and Solar Generation Siting

Minnesota-Centric Wind and Solar Amounts to be Sited

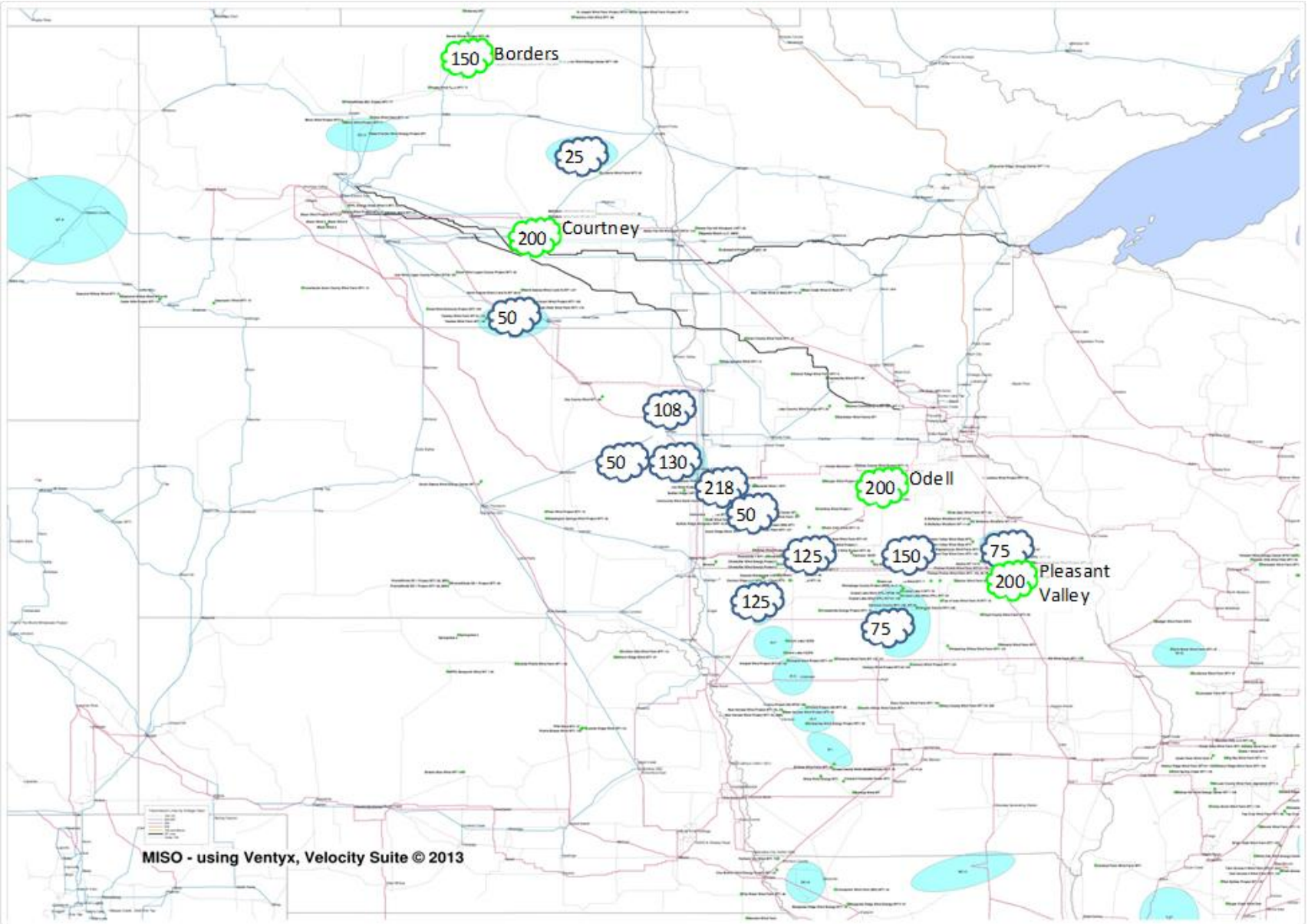
	Minnesota Centric			
	Wind MW	PV MWac		
	Incremental	Incremental		
		Utility PV	Distributed PV	Total Increm. PV
Baseline		361	96	457
Scenario 1	1,931	723	191	914
Scenario 2	610	2,756	430	3186

Non-MN-Centric Wind and Solar Amounts to be Sited

	Non-MN MISO			
	Wind MW	PV MWac		
	Incremental	Incremental		
		Utility PV	Distributed PV	Total Increm. PV
Baseline	6900	1052	0	1052
Scenario 1	0	0	19	19
Scenario 2	13026	2,880	135	3015

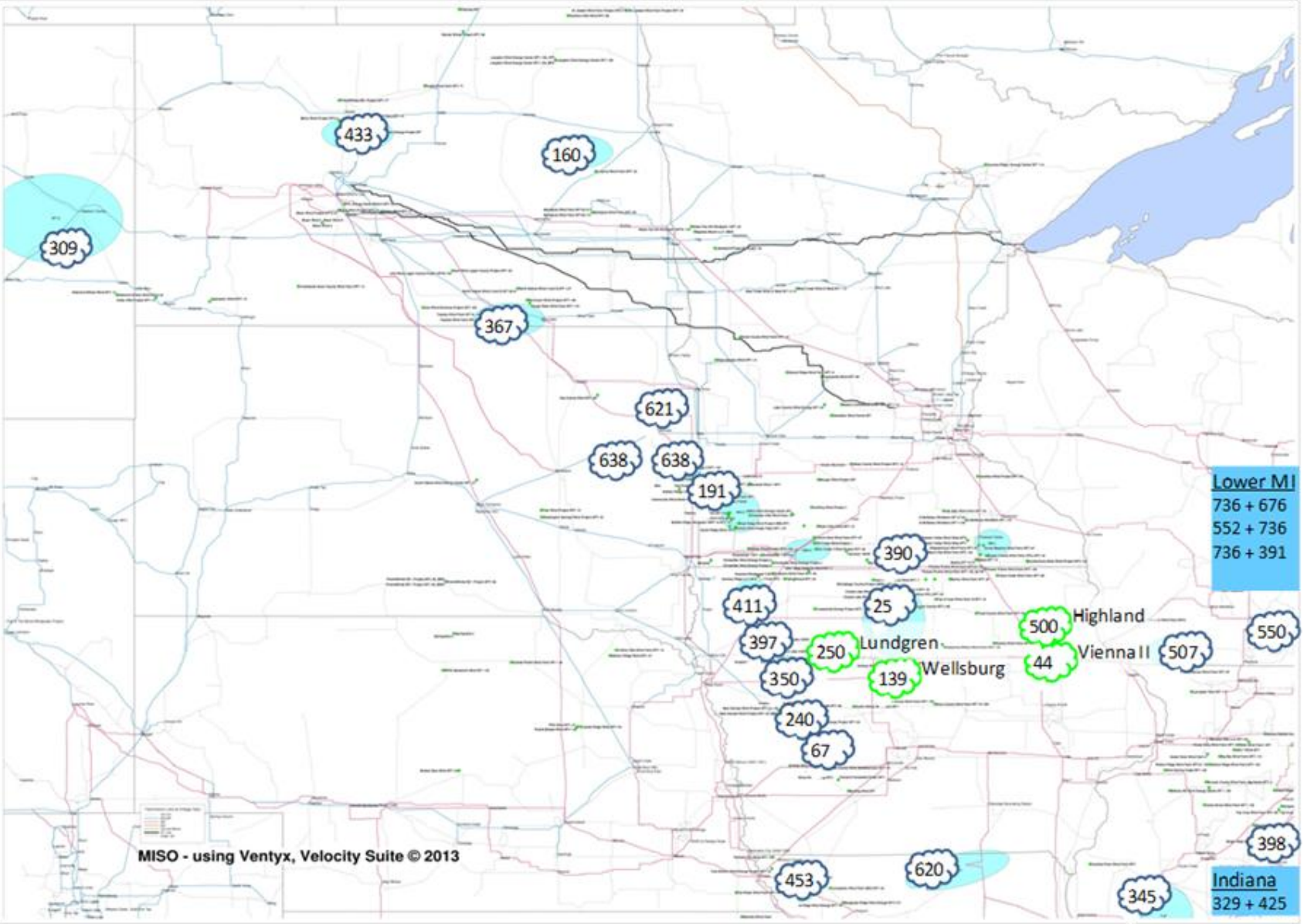
Wind Generation Siting – Scenario 1

MN & Non MN Scenario 1 Wind Siting



Wind Generation Siting – Scenario 2

RGOS Wind Zones w/MN & Non MN Scenario 2



MN Wind Generation Siting – State Locations

State	Baseline Scenario	Incremental MN Wind gen for Scenario 1	Incremental MN Wind gen for Scenario 2	Total Incremental Wind Scenario 1 & 2
IA %	24.5%	10.4%	9.8%	10.2%
MN %	**43.5%**	**52.7%**	**52.5%**	**52.7%**
ND %	20.9%	22.0%	18.0%	21.1%
SD %	11.1%	14.9%	19.7%	16.1%

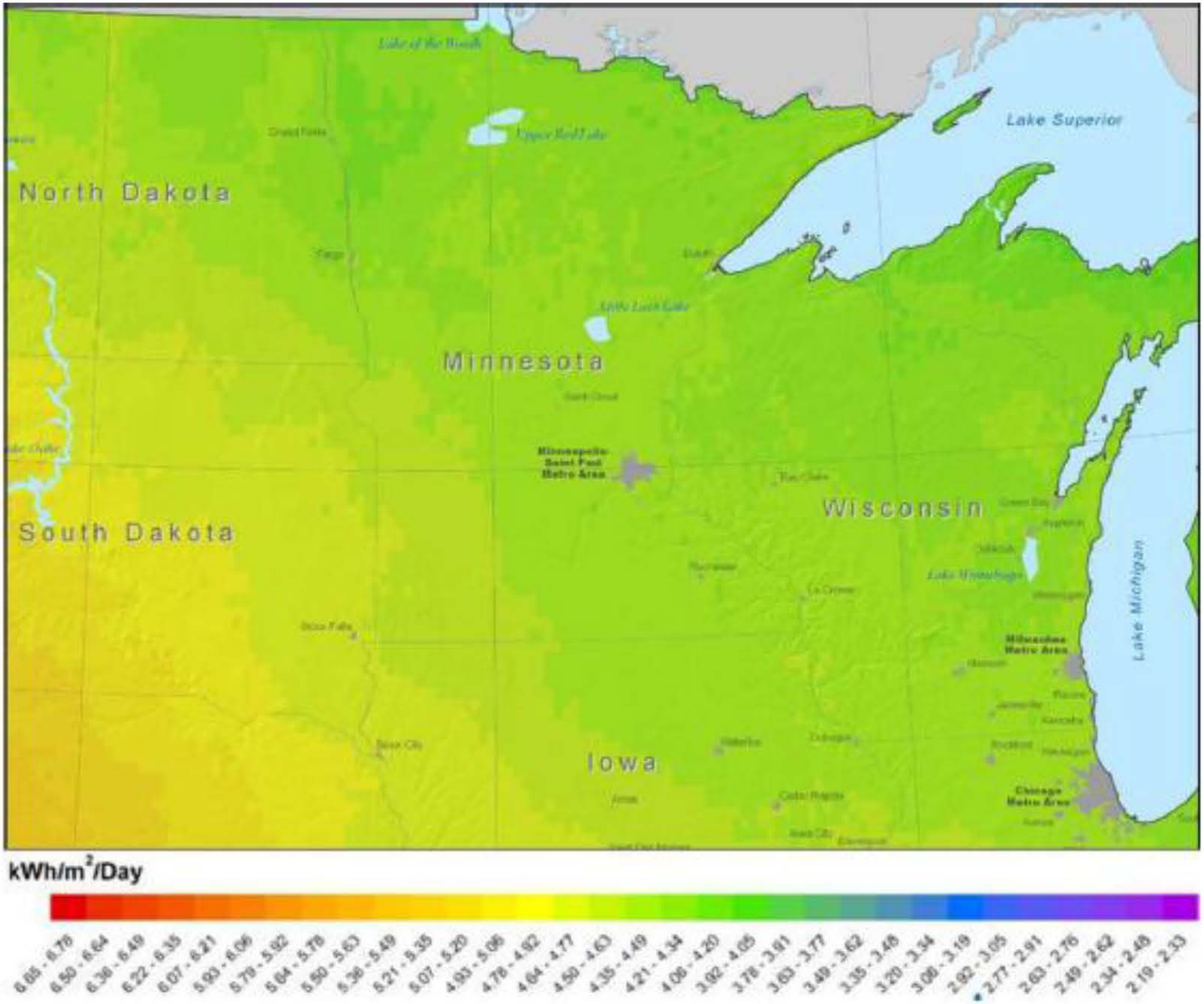
Wind Generation Siting - Reassignment

- The Non-MN MISO wind was sited per as described in the previous section (at RGOS zones on a pro rata basis)
- After the production simulation analysis showed significant amounts of wind congestion at some plants in western MISO, it was decided to relocate some of this congested wind sites to less congested areas.
- A portion of the wind generation was moved from the “Top 4” congested sites and reassigned to the “Bottom 10” least congested sites.
- This reassigned generation only involved the non-MN MISO wind and this generally relocated the wind generation to the south and east locations with lower capacity factor.
- As a result of the placing this generation at sites with lower capacity factors, or reduced average wind speeds, the wind nameplate amounts had to be increased in order to maintain the equivalent wind energy prior to and after the shift.

Solar Generation Siting

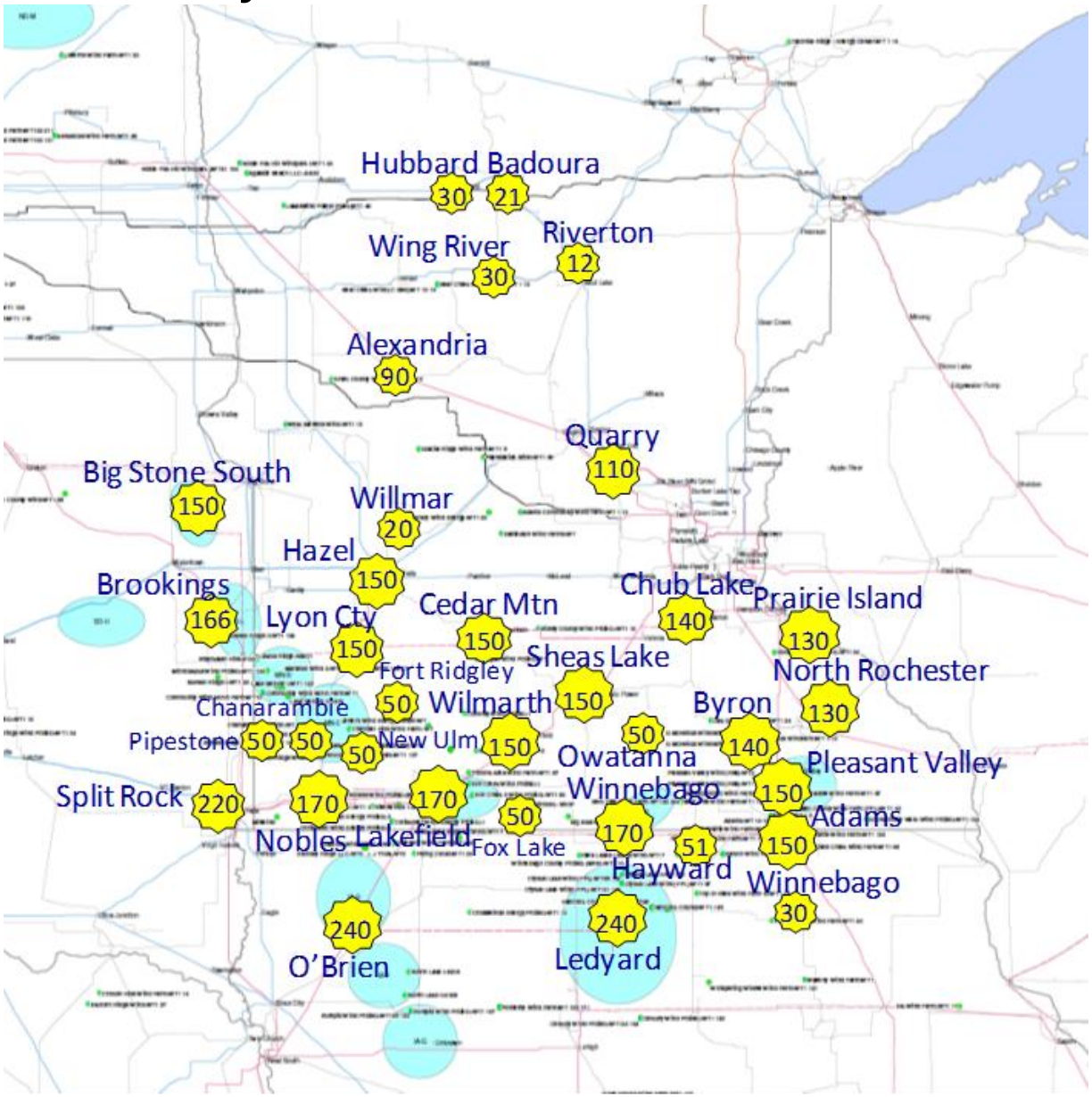
- The solar generation added in the Minnesota-Centric area was split between Distributed PV and Centralized utility scale PV
  - on a 20% / 80% basis for the Baseline and Scenario 1,
  - and a 15% / 85% split for Scenario 2, respectively.
- The distributed PV was assumed to be sited at larger load centers.
- The Centralized utility scale PV was generally spread by solar resource largely over the southern half of Minnesota, however there was some sited in the northern portion of the state

Solar Resource Map



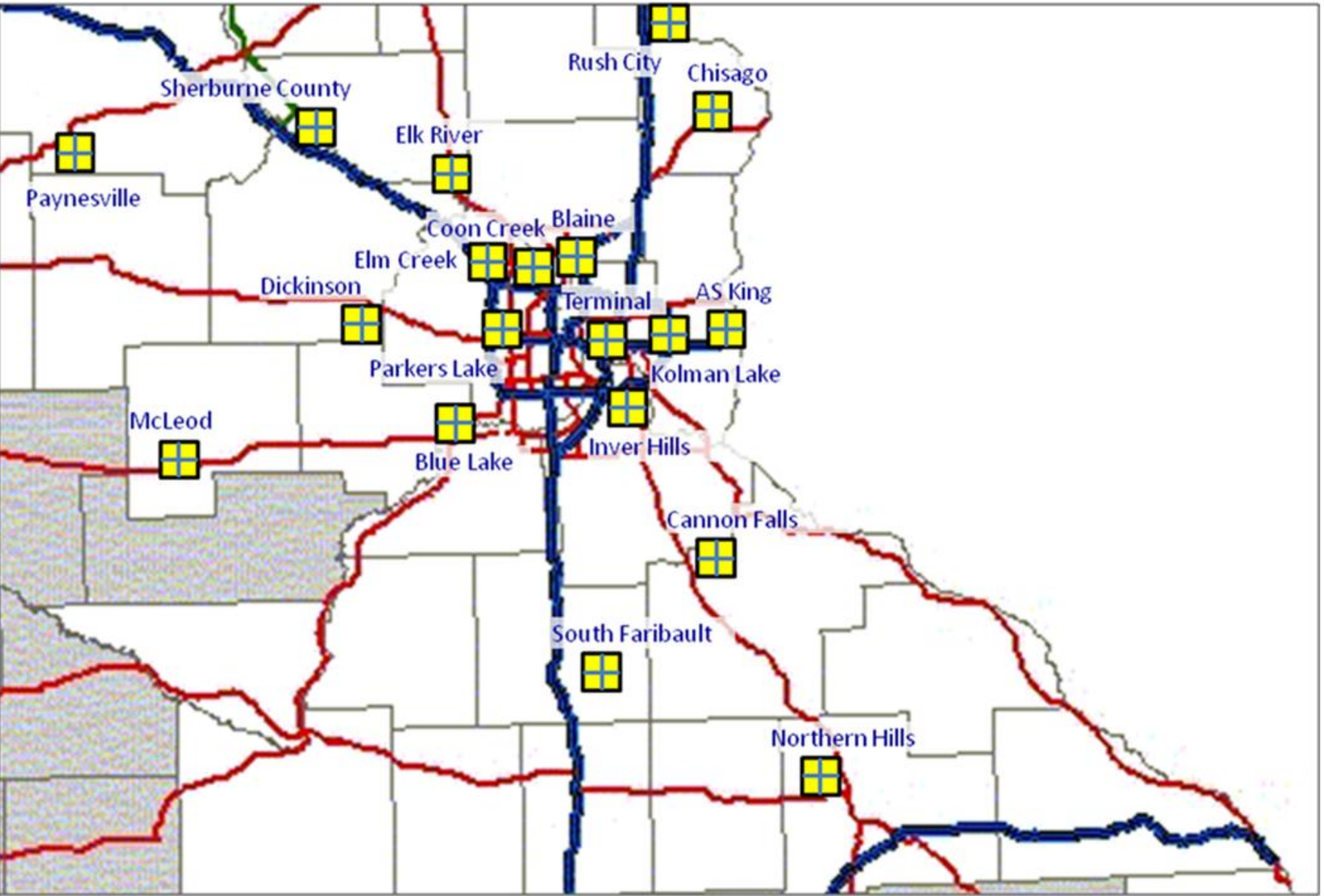
Solar Generation Siting

MN Solar for Utility Locations - All Scenarios



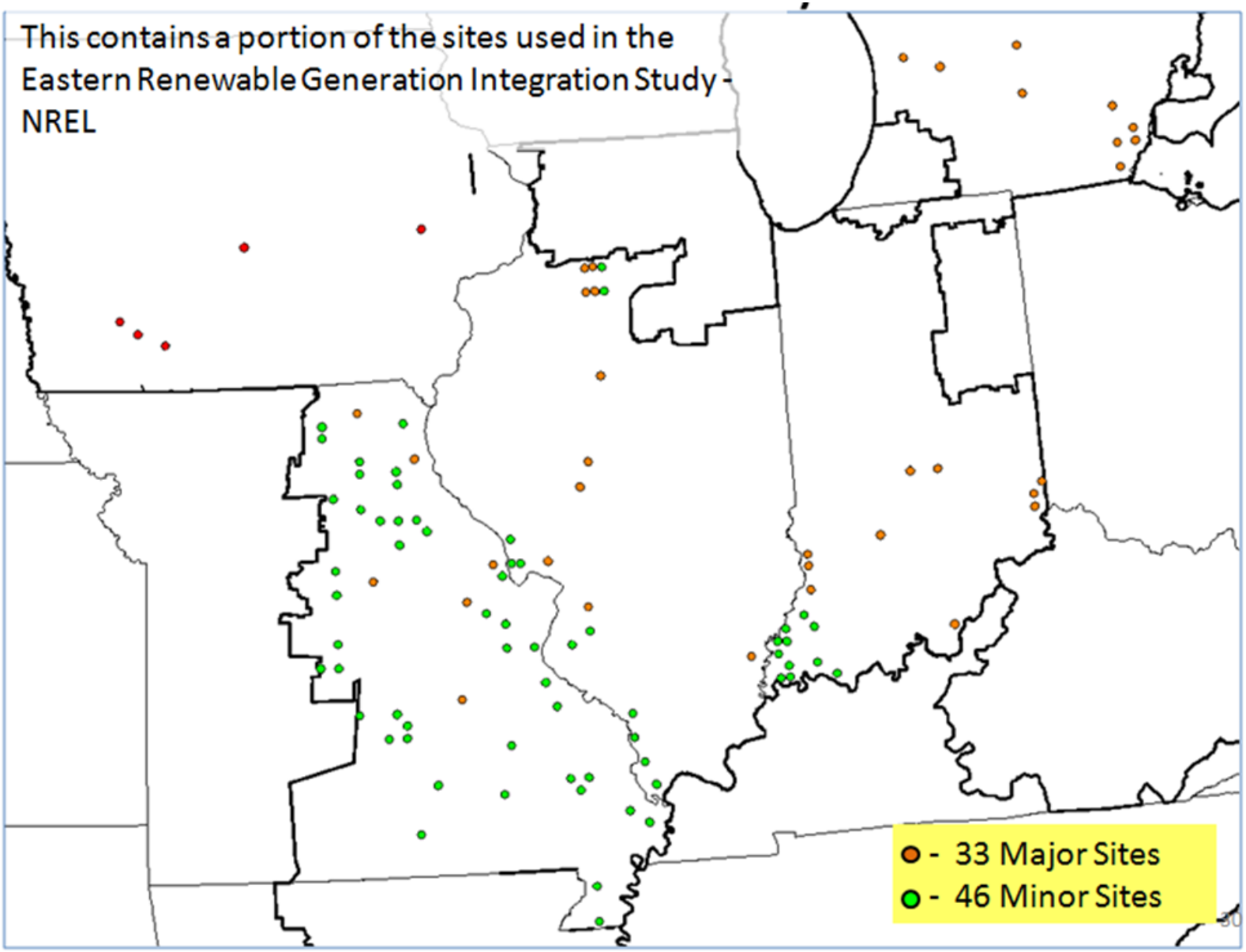
Solar Generation Siting

MN Distributed PV Sites



Solar Generation Siting

Locations of Non-MN Solar - Utility Locations



Transmission Conceptual Plans

Transmission System Conceptual Plans

Assumptions and Methodology

- 2028 Models
- Utilized Powerflow simulation & Contingency Analysis
- MN, ND, SD, Northern IA, WI, Southern Manitoba
- Summer Peak and Summer Off-Peak models
- Wind & Solar Dispatch
  - Summer Peak Model
    - Wind – 20%
    - Solar – 60%
  - Summer Off-Peak Model
    - Wind – 90%
    - Solar – 60%

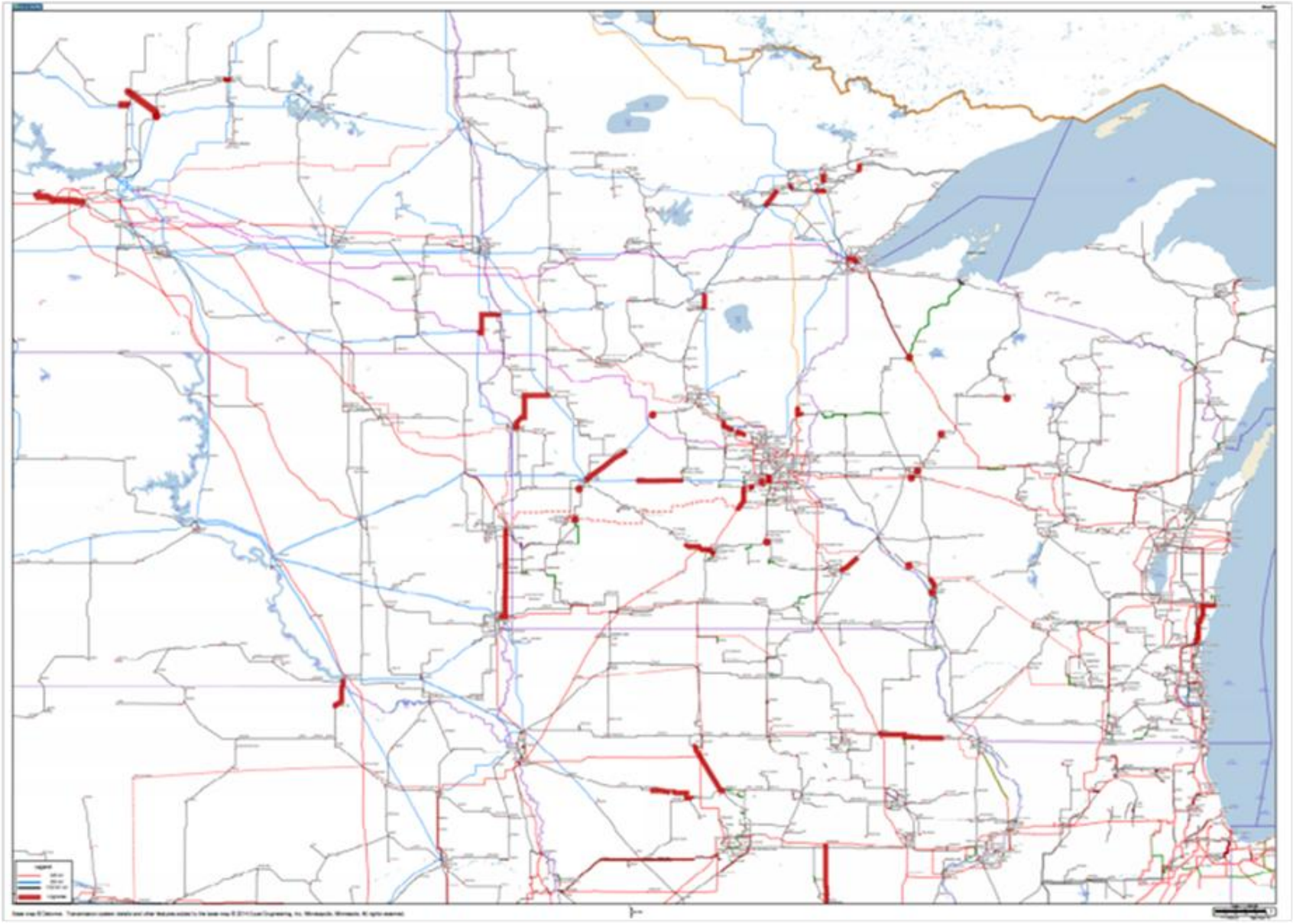
Model Building Steps - conceptual transmission

1. The model building for the steady state thermal analysis involved significant **transmission and generation additions** and **load increases** to reflect the Baseline assumptions of the present MISO state RPSs in a **2028** timeframe.

2. The generation dispatch involved a combination of methodologies to best represent the future market which accommodated the **lowest fuel cost generation units** while **maintaining system reliability**.

Transmission System Conceptual Plans

RESULTS: Scenario 1 Transmission Mitigation Map



Transmission System Conceptual Plans

Branch	Possible Mitigation	COST ($M)
Brookings Co-White 345 kV line	WAPA terminal equipment- 1800 MVA	0.50
Cedarsauk-Edgewater 345 kV line	ATC uprate- 750 MVA	1.00
Helena-Scott Co. 345 kV line	XEL rebuild as double circuit	30.00
Ottumwa-Montezuma 345 kV line	ITC uprate- 956 MVA	1.00
Split Rock-White 345 kV line	WAPA terminal equipment- 1195 MVA	1.00
Riverton-Mud Lake 230 kV line	GRE uprate- 383MVA	9.00
98L Tap-Hilltop 230 kV line	MP rebuild - 400 MVA	11.20
Panther-Mcleod 230 kV line	XEL uprate- 391	0.20
Willmar-Granite Falls 230 kV line	GRE rebuild 391MVA	50.00
Hankinson-Wahpeton 230 kV line	OTP uprate- 361 MVA	0.30
Briggs Road-Mayfair 161 kV line	XEL rebuild- 400 MVA	10.00
Drager-Grand Junction 161 kV line	CBPC rebuild- 326 MVA	37.50
Boone Jct-Fort Dodge 161 kV line	MEC / CIPCO rebuild- 326 MVA	62.50
Hazleton-Dundee 161 kV line	ITC terminal equipment- 326 MVA	0.20
Liberty-Dundee 161 kV line	ITC rebuild- 326 MVA	6.50
Wabaco-Rochester 161 kV line	DPC rebuild - 400 MVA	10.90
43L Tap-Laskin 138 kV line	MP rebuild - 200 MVA	3.00
Wilmarth-Swan Lake 115 kV line	XEL terminal equipment- 144 MVA	0.20
Wilmarth-Eastwood 115 kV line	XEL uprate- 310 MVA	3.00
Souris-Velva Tap 115 kV line	XEL terminal equipment- 144 MVA	0.20
Monticello-Oakwood 115 kV line	XEL rebuild- 310 MVA	12.00
Black Dog-Wilson 115 kV line	XEL terminal equipment- 310 MVA	0.20
Chisago-Lindstrom 115 kV line	XEL upgrade- 400 MVA	0.50
Scott Tap-Scott Co. 115 kV line	XEL Rebuild- 310 MVA	2.00
Hassan-Oakwood 115 kV line	XL rebuild- 310 MVA	7.00
Velva Tap-McHenry 115 kV line	XEL terminal equipment- 144 MVA	0.20
Hibbard-Winter St 115 kV line	MP rebuild - 240 MVA	3.00
Etco-Forbes 115 kV line	MP rebuild - 200 MVA	3.00
Forbes-Iron Tap 115 kV line	MP rebuild - 200 MVA	3.00
Hibbing-44L Tap 115 kV line	MP terminal equipment- 80 MVA	0.20
Iron Tap-Tbird 115 kV line	MP rebuild - 200 MVA	3.00
Tbird-37L Tap 115 kV line	MP rebuild - 200 MVA	3.00
Blackberry-Panasa Naswak 115kV	MP upgrade- 240 MVA	2.16

Rugby OTP-Rugby CPC 115 kV line	OTP rebuild - 200 MVA	1.00
Halliday-Beulah 115 kV line	WAPA terminal equipment- 144 MVA	0.20
Rugby-Rugby CPC 115 kV line	BEPC rebuild - 200 MVA	1.00
Johnson Jct-Morris 115 kV line	GRE terminal equipment- 99 MVA	0.20
Johnson Jct-Ortonville 115 kV line	OTP/MRES rebuild - 200 MVA	16.00
Fort Randall-Spencer 115 kV line	WAPA terminal equipment 144 MVA	0.20
Blaisdell-Palermo 115 kV line	BEPC rebuild - 200 MVA	8.00
Logan-SW Minot 115 kV line	BEPC rebuild - 200 MVA	7.00
Hazel Creek 345/230 kV Tx #6	XEL add 2nd 336 MVA transformer	6.00
Stone Lake 345/161 kV Tx #9	XEL replace with 448 MVA transformer	7.50
Eau Claire 345/161 kV Tx #9 & 10	XEL replace BOTH with 448 MVA transformers	15.00
Lyon Co 345/115 kV Tx #1	XEL add 2nd 448 MVA transformer	7.50
McHenry 230/115 kV Tx #1	GRE replace with 187 MVA transformer	2.00
LaCrosse 161/69 kV Tx #1 & 2	XEL replace BOTH with 112 MVA transformers	3.20
Marshland 161/69 kV Tx #1 & 2	XEL replace BOTH with 112 MVA transformers	3.20
Gravel Isle 161/69 kV Tx #5 & 6	XEL replace BOTH with 112 MVA transformers	3.20
West Faribault 115/69 kV Tx #1 & 2	XEL replace BOTH with 140 MVA transformers	3.60
Paynesville 115/69 kV Tx #1 & 2	XEL replace with 70 MVA transformer	2.80
Prentice 115/69 kV Tx #5	XEL replace with 70 MVA transformer	1.40
Holcombe 115/69 kV Tx #1	DPC replace with 70 MVA transformer	1.40
Glendale 115/69 kV Tx #1 & 2	GRE replace Both with 112 MVA BOTH transformers	3.20
	Add breakers at Arrowhead 115kV bus*	2.00
	Total Cost	**373.06**

Scenario 1

54 Transmission Mitigations

≈ $373M

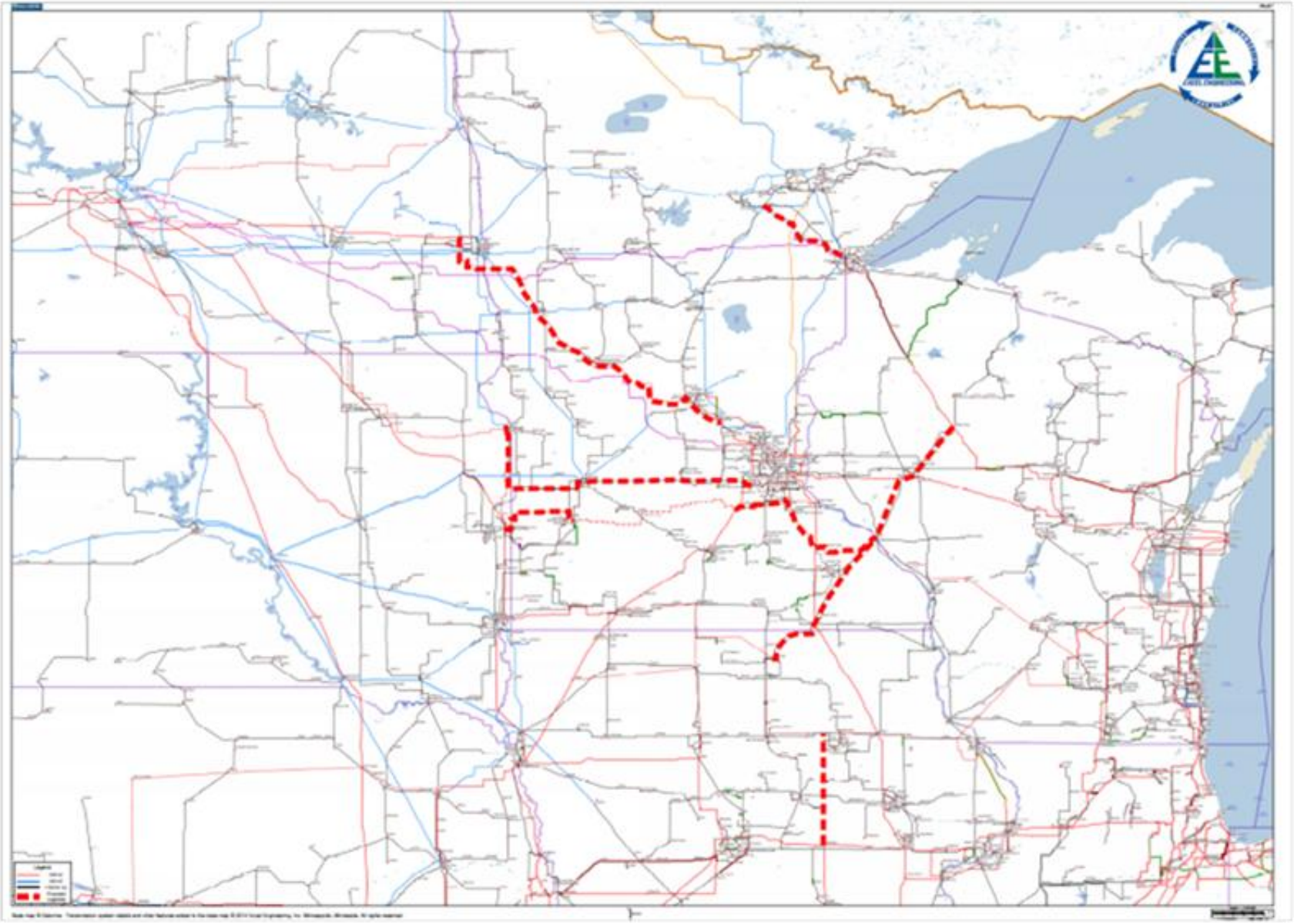
Scenario 1 Conclusions- conceptual transmission

1. The Scenario 1 Transmission Mitigations, as identified with steady state thermal powerflow analysis, to accommodate an increase wind and solar generation necessary to increase the MN RES to 40% involved ***54 facilities*** *(upgrades to existing transmission lines) with a total estimated cost of* ***$373M****.*

2. The Scenario 1 mitigations
   - Are considered conceptual at this point
   - Have not been optimized
   - Further study would be required for the upgrades/mitigations
   - These 54 mitigations could create a challenge in scheduling and coordinating outages for the construction time necessary to upgrade the facilities.

Transmission System Conceptual Plans

Scenario 2 Transmission Expansion Map



Transmission System Conceptual Plans

Scenario 2 Transmission Expansion

Branch	COST ($M)
Corridor Project (rebuilding existing 230 kV line to 345 kV) Hazel Creek-Panther-Mcleod-Blue Lake double circuit 345 kV line	466.00
Iron Range-Arrowhead 345 kV line	182.00
Sheldon-Eau Claire-Alma-Adams-Killdeer 345 kV line	700.00
Blackhawk-Montezuma 345 kV line	196.00
Big Stone South-Hazel Creek 345 kV line	200.00
Bison-Alexandria-Quarry-Monticello 345 kV line #2(dbl circuit CapX2020)	204.10
Brookings Co-Lyon Co 345 kV line #2(dbl circuit CapX2020)	58.00
Helena-Chub Lake-Hampton 345 kV line #2(dbl circuit CapX2020)	47.00
Hampton-North Rochester-Alma 345 kV line #2(dbl circuit CapX2020)	75.00
Total Cost	**$2,128.10**

Scenario 2 Conclusions- conceptual transmission

1. To alleviate widespread system issues, Transmission Expansions were identified and involved ***nine facilities*** *(5 new lines & 4 second circuits to planned lines) with a total* ***estimated cost of $2,128M****.*

2. The Transmission Mitigations, as identified with steady state thermal powerflow analysis, ***23 facilities*** *with a total estimated cost of* ***$351M****.*

3. Even with the expansions and mitigations, there was numerous facility overloads and market congestion causing wind curtailment. It was decided that the top 4 congested sites would have generation reduced and moved to the bottom 10 least congested sites (T4B10). This generation siting shift assisted in resulting in a more reliable and efficient market system.

Scenario 2 Conclusions- conceptual transmission

4. The Production Modeling Analysis showed a number of market congestions caused by the overload of several facilities. These congestion mitigations involved **seven facilities** with a total estimated cost of **$88M**.

5. The **total** Scenario 2 expansions and upgrades involved **39 projects** at an **estimated cost of $2,567M**

6. The transmission expansions and mitigations:
   - Are considered high-level and conceptual, yet representative of transmission solutions
   - Have not been intensively analyzed nor optimized
   - further study would be required for most practicable expansion/upgrade.
   - Require coordination with MISO and other utilities.
   - These expansions and mitigations could create a challenge in scheduling and coordinating outages for the construction time necessary to upgrade and build the facilities.

Scenario 2 Conclusions- conceptual transmission

7. A HVDC alternative was tested as a sensitivity.
   - The modeled 600 kV HVDC line was about 800 miles long and with converter buses located at southeastern **South Dakota** and northwest Iowa and two inverter buses located northern and southern **Indiana**.
   - The estimated cost of this HVDC project was approximately **$3B** and still required **26 mitigations** with an estimate cost of approximately $631M.

Operational Performance

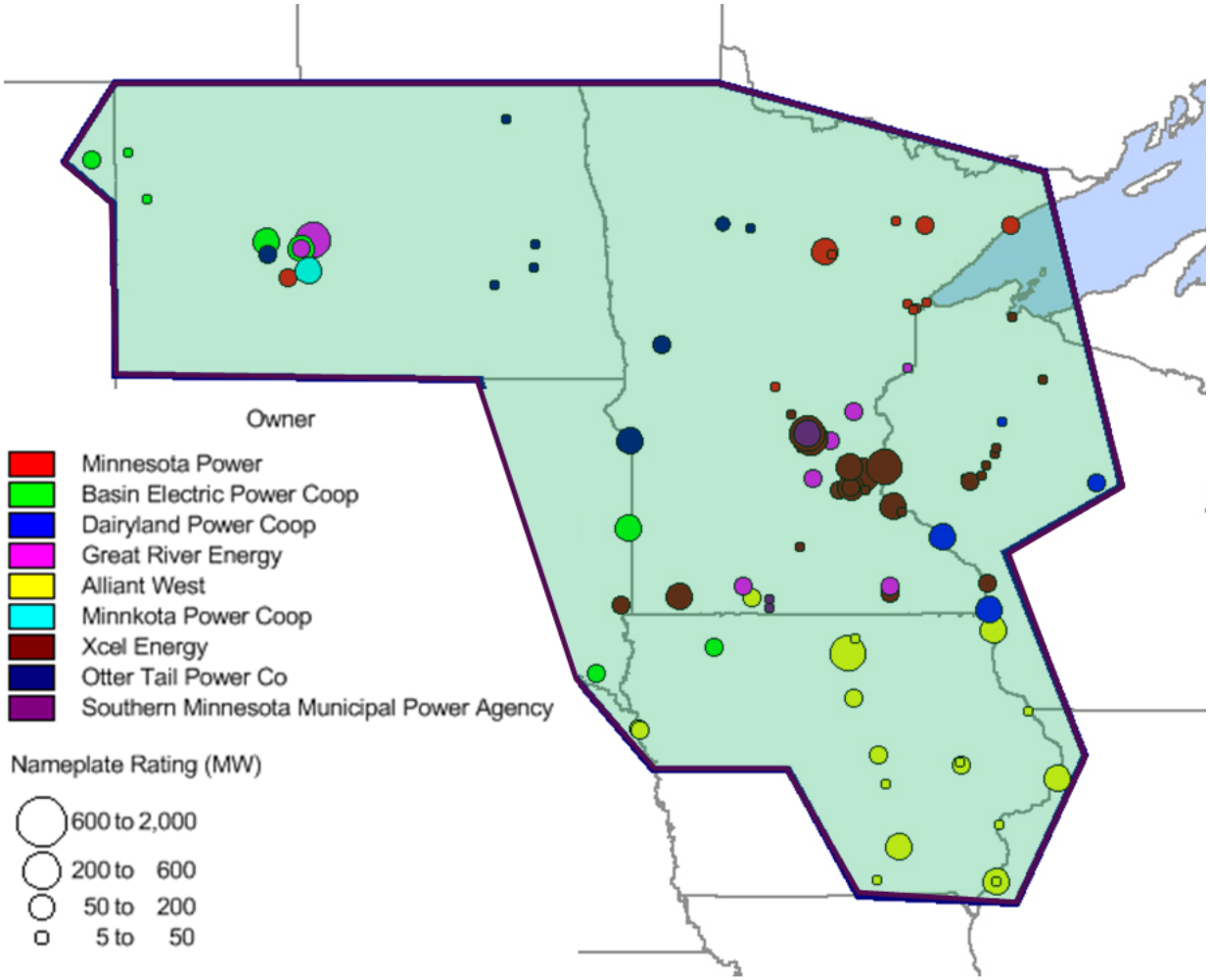
Operational Performance

All of these results were obtained from hourly production simulations (one year duration) for the study scenarios

- Annual energy production and generation fleet utilization
- Wind and solar curtailment
- Thermal plant cycling
- MISO ramp-rate and ramp-rate capability
- Challenging time periods for stability & control issues
  - Screening metrics included % non-synchronous generation, % renewable generation penetration, transmission interface loading

Operational Performance

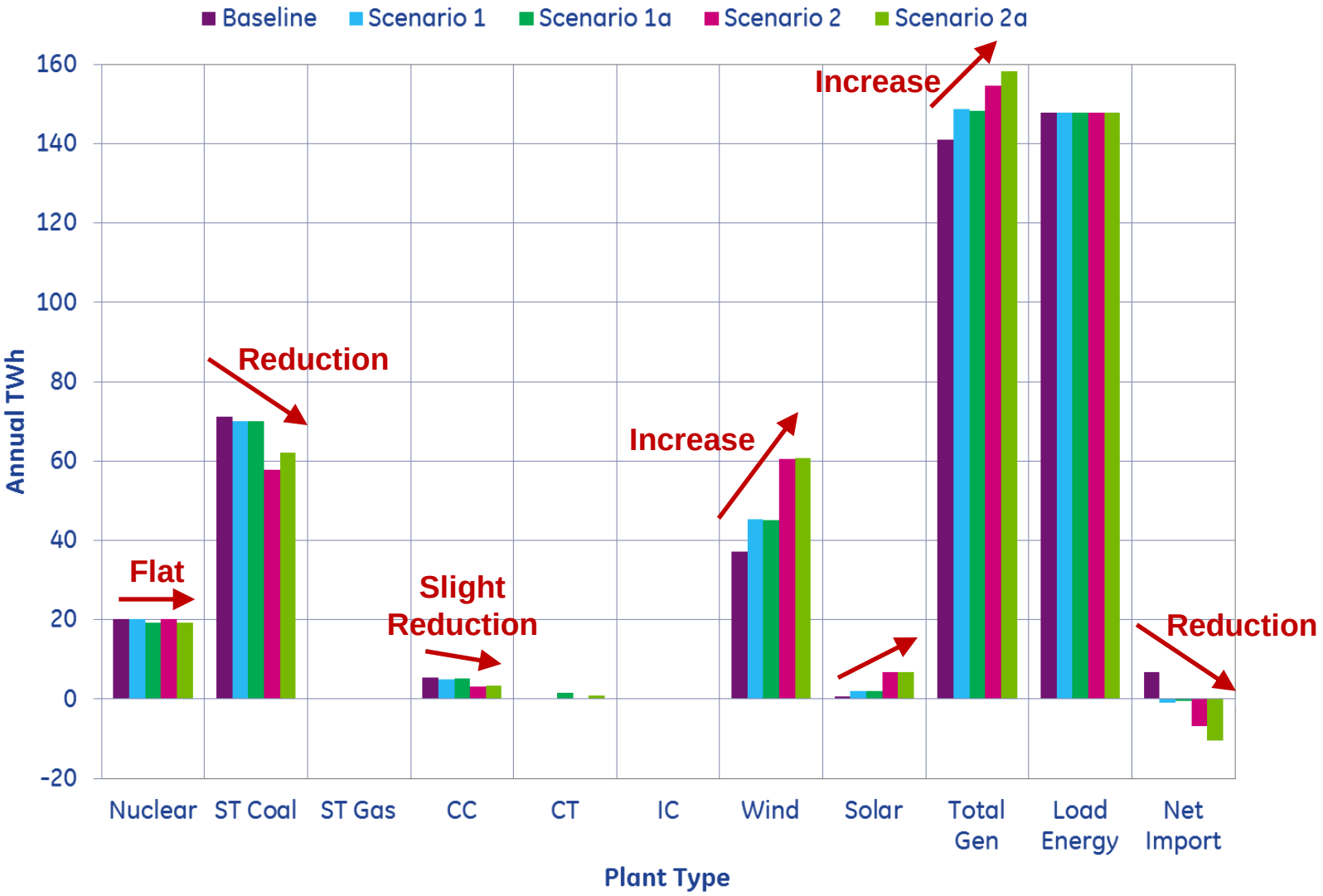
Minnesota-Centric footprint for production simulation analysis



Dots indicate generating plants owned by Minnesota Utilities

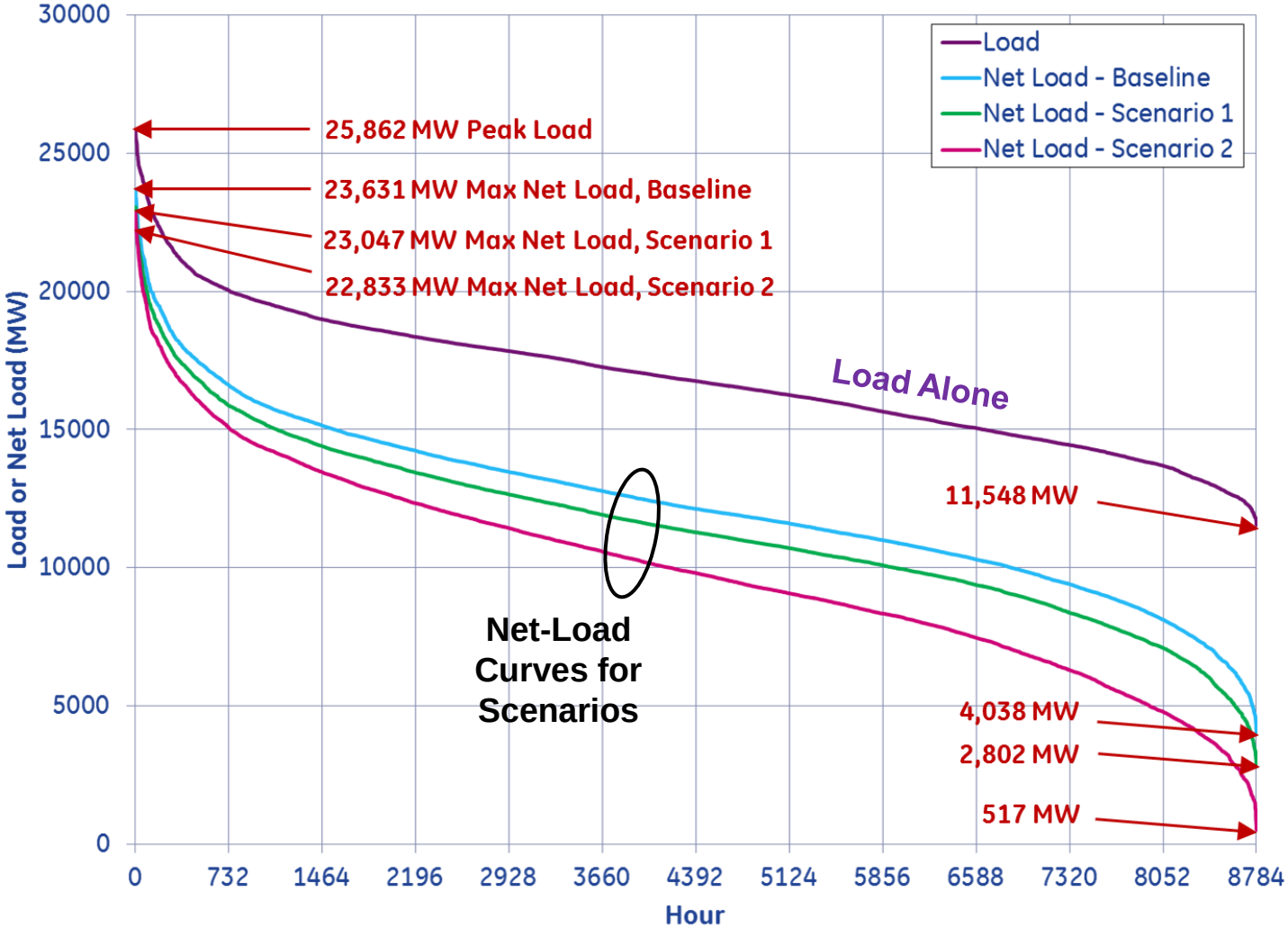
Operational Performance

Annual generation in TWh by unit type for Minnesota-Centric region



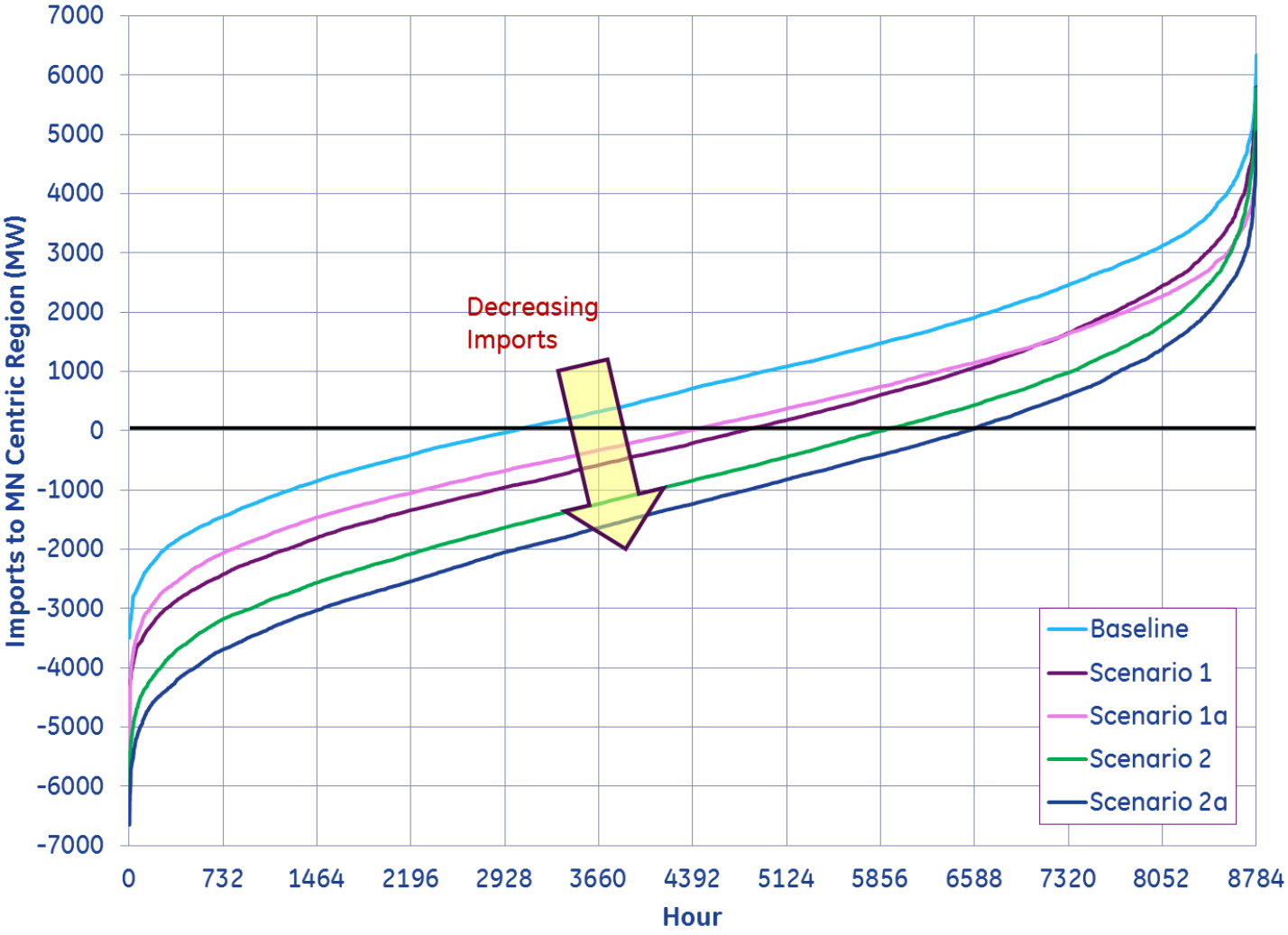
Operational Performance

Annual Load and Net-Load Duration Curves for Minnesota-Centric Region



Operational Performance

Annual Duration Curves of Energy Imports for Minnesota-Centric Region



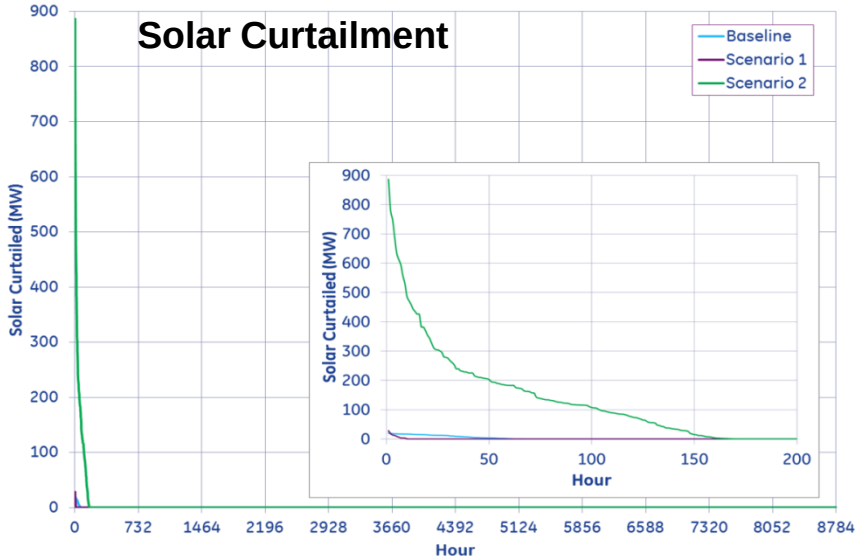
Operational Performance

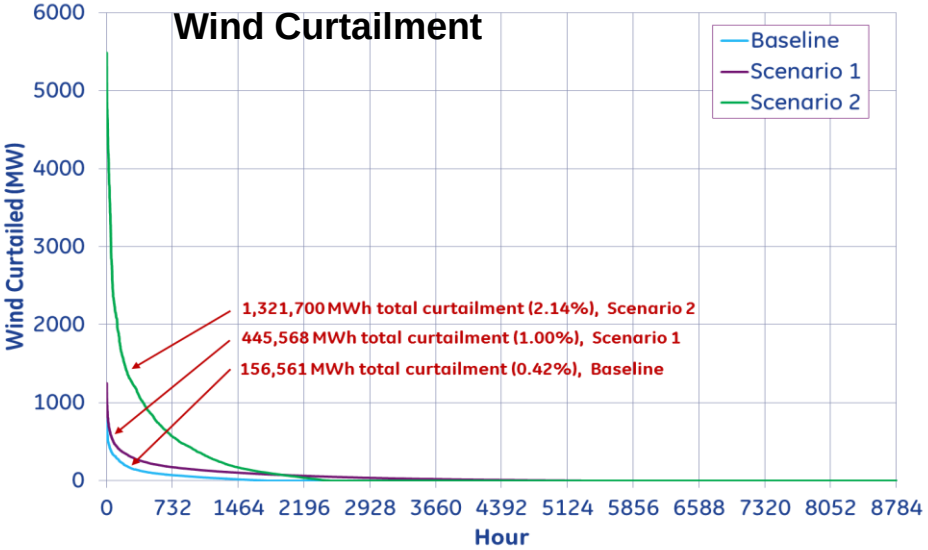
Annual Wind and Solar Energy Curtailment

- In general, there is very little curtailment (a reasonable amount)
- Curtailment caused by mix of local congestion and system-wide minimum generation conditions

	Baseline	Scenario 1	Scenario 1a	Scenario 2	Scenario 2a
Wind Curtailment	0.42%	1.00%	1.59%	2.14%	1.60%
Solar Curtailment	0.09%	0.00%	0.23%	0.42%	0.24%

Annual Duration Curves for Solar and Wind Curtailment

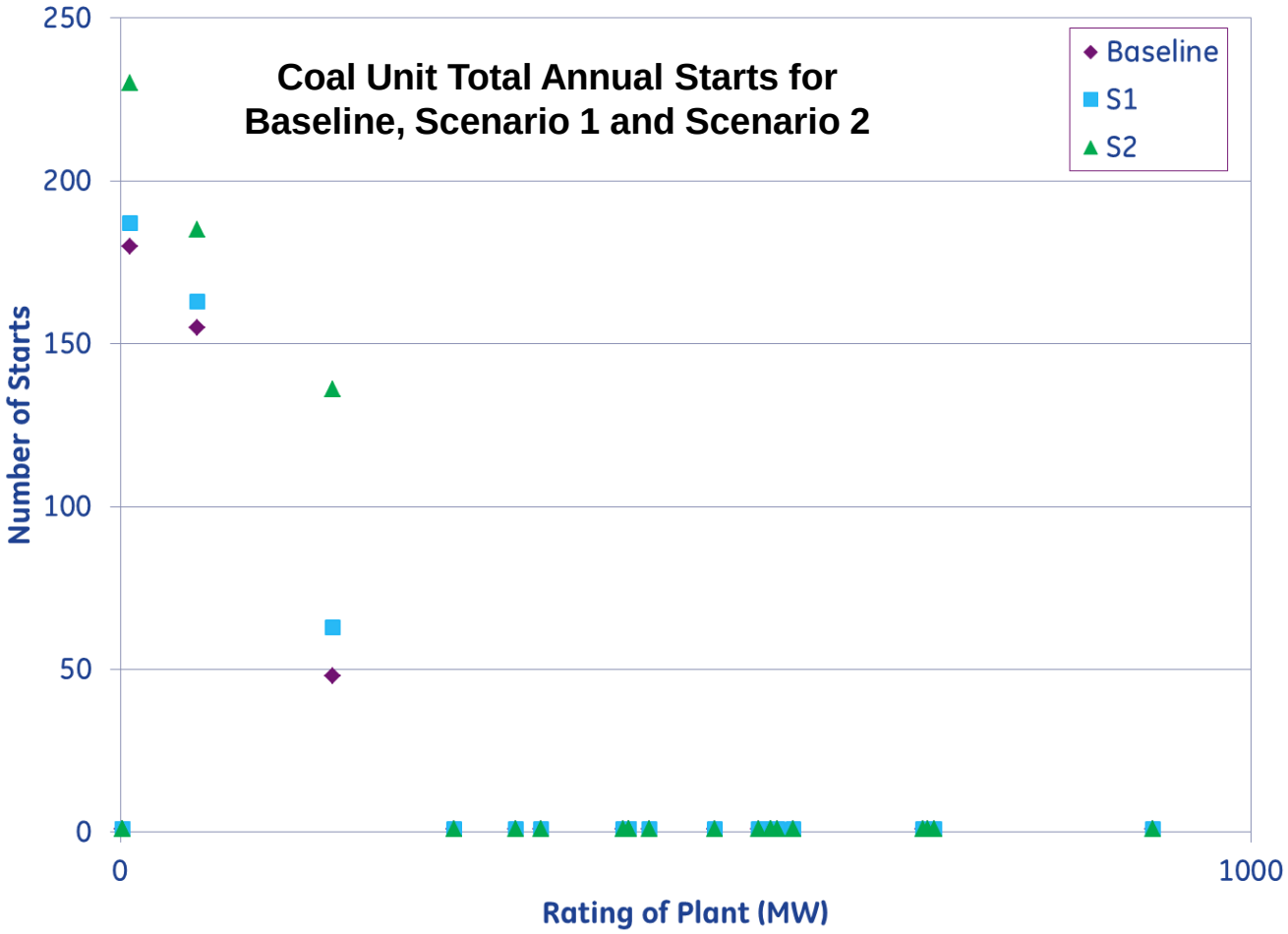




Operational Performance

Thermal Plant Cycling

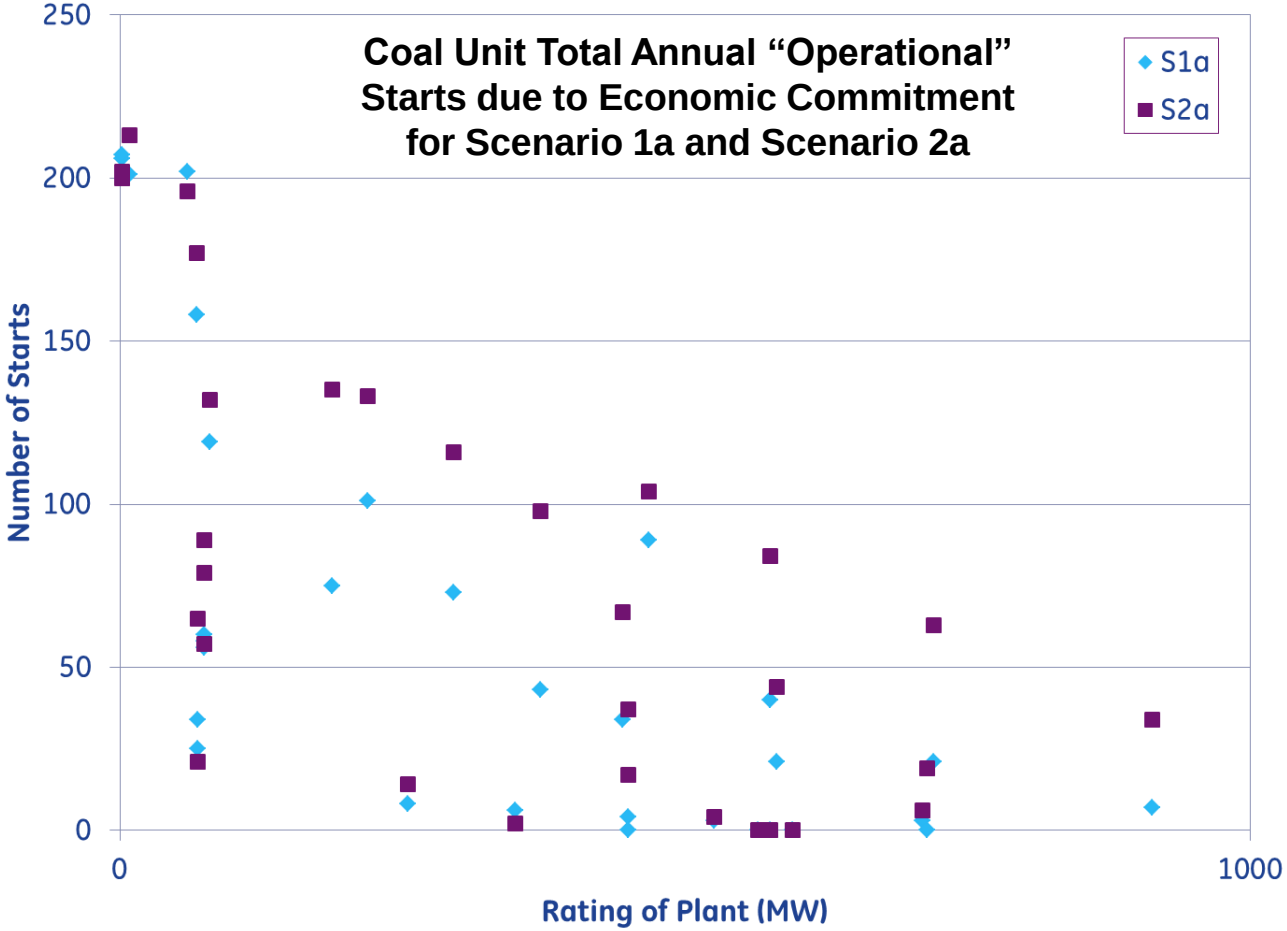
- Baseline, Scenario 1 and Scenario 2 assumed that most coal units would be operated with existing practices (must-run; not decommitted by MISO)
  - Most units have one operational start per year (must-run status)
  - Three units subject to economic commitment
  - These units also show significant cycling in the Baseline scenario
  - These units also show increased number of starts with increased wind/solar penetration



Operational Performance

Thermal Plant Cycling - continued

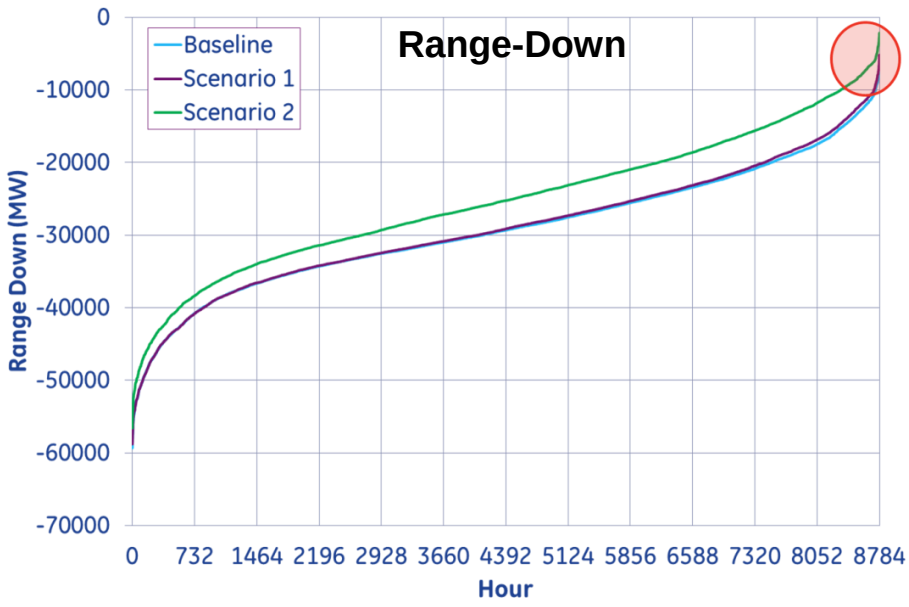
- Scenarios 1a and 2a assumed that the all coal units were subject to Security-Constrained Economic Commitment
  - Most units have a higher number of starts in Scenario 2a (50% MN RE, 25% MISO RE) as compared to Scenario 1a (40% MN RE, 15% MISO RE)
  - Some units have the nearly the same number of starts in both scenarios

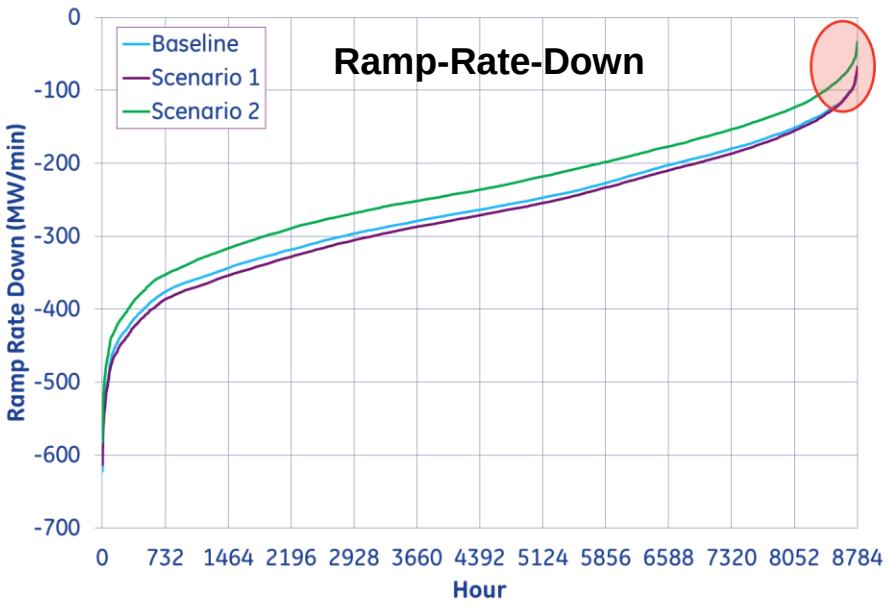


Operational Performance

Annual Duration Curves of Range-Down and Ramp-Rate-Down Capability for Conventional Generation within MISO Central-North

- Range-Down capability of conventional generation fleet in MISO decreases for all hours of the year as Wind and Solar penetration increases
- Wind and Solar Plants could contribute Range-Down and Ramp-Rate-Down during periods when additional capability is needed in MISO (via existing DIR Program)





Operational Performance

Screening Metrics for Stability/Control Issues

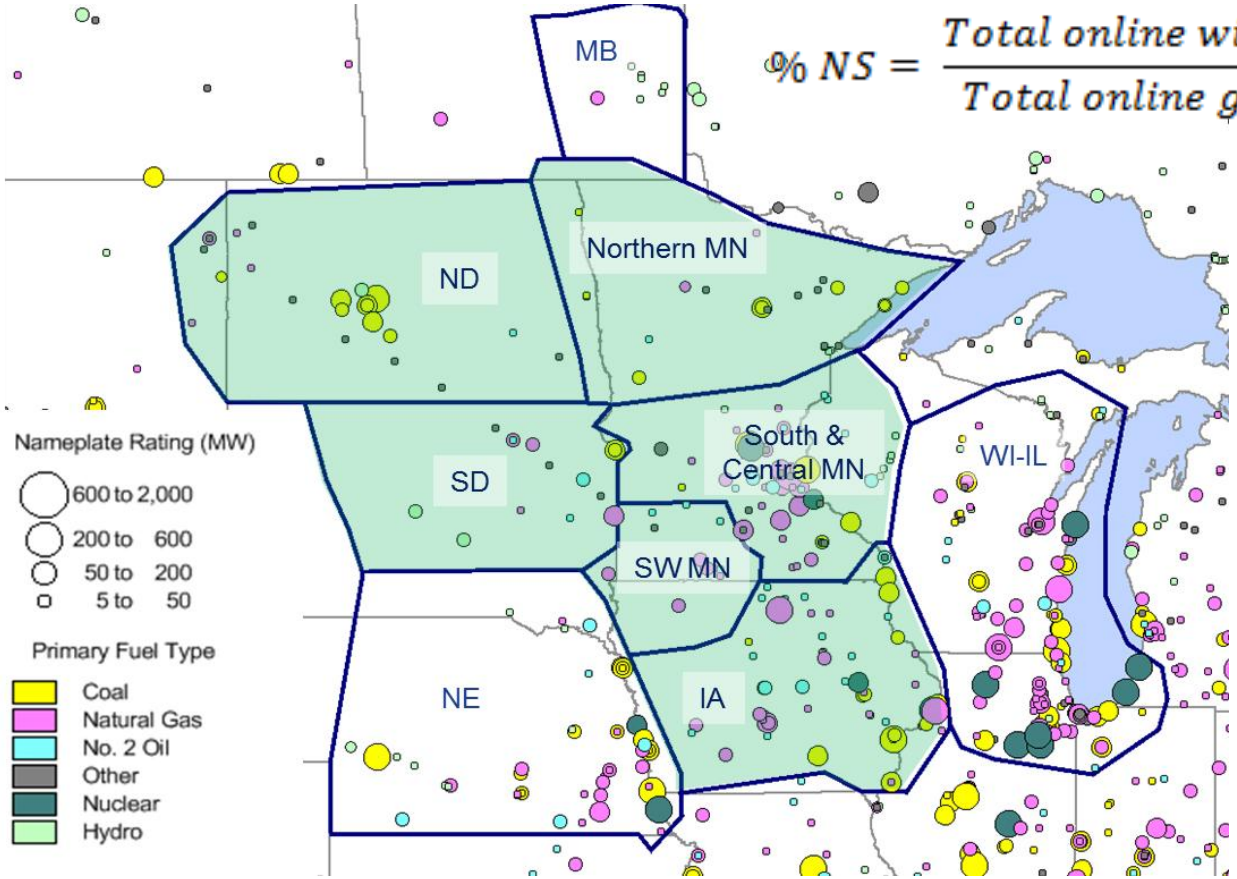
- The results of the production simulation analysis were screened to select challenging operating conditions for dynamic performance, and these operating points were subsequently analyzed with fault simulations in the dynamics task.
  - Percent Non-Synchronous Generation (% NS)
  - Percent Renewable Penetration (% RE)
  - Transmission Interface Loading

Operational Performance

Geographic Footprint of Minnesota-Centric Region for % Non-Synchronous Generation Metric (% NS)

- The % NS metric is the ratio of non-synchronous inverter-based generation (i.e. wind and solar) MW rating to the total generation (i.e. wind, solar and all conventional generation) MW rating within a given geographic boundary.
- This metric is an indicator of ac system strength or weakness.

$$\% NS = \frac{Total\ online\ wind + solar\ MW\ rating}{Total\ online\ generation\ MW\ rating}$$



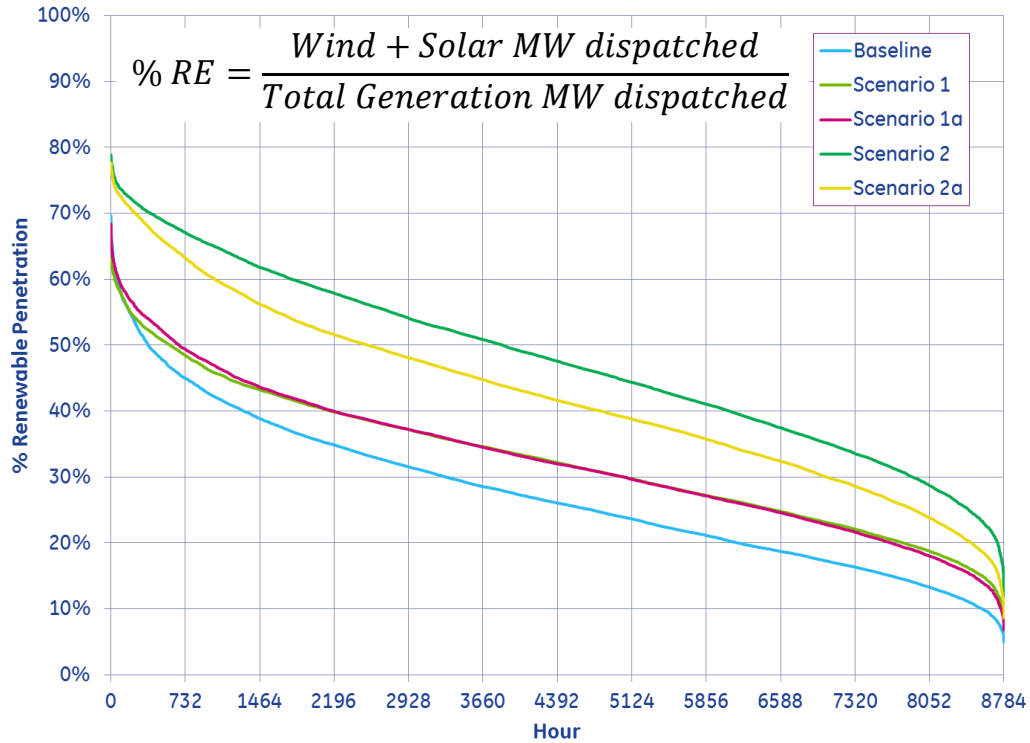
Operational Performance

% Renewable Energy Penetration for the Minnesota-Centric Region (% RE)

- The % RE metric is the ratio of all wind and solar generation MW output to the total MW output of all generation (including wind and solar) within a given geographic boundary
- The % RE metric was selected as it is one of the traditional metrics used to identify periods of the year where there are high levels of renewable generation supplying the load in the system, and where the dynamic performance of the overall system is more dependent on the dynamic performance of the wind and solar resources.

  - Plot shows duration curve of % RE for Minnesota-centric region for all study scenarios

$$\% RE = \frac{Wind + Solar\ MW\ dispatched}{Total\ Generation\ MW\ dispatched}$$

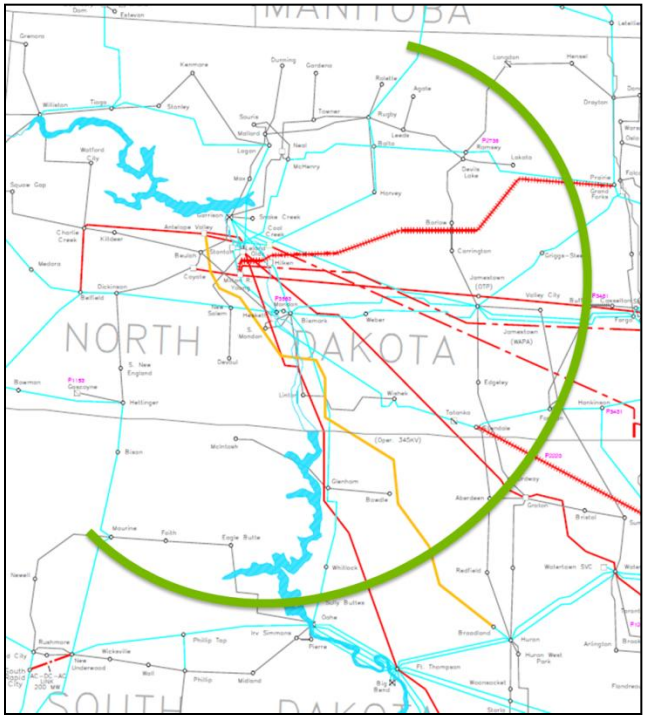


Operational Performance

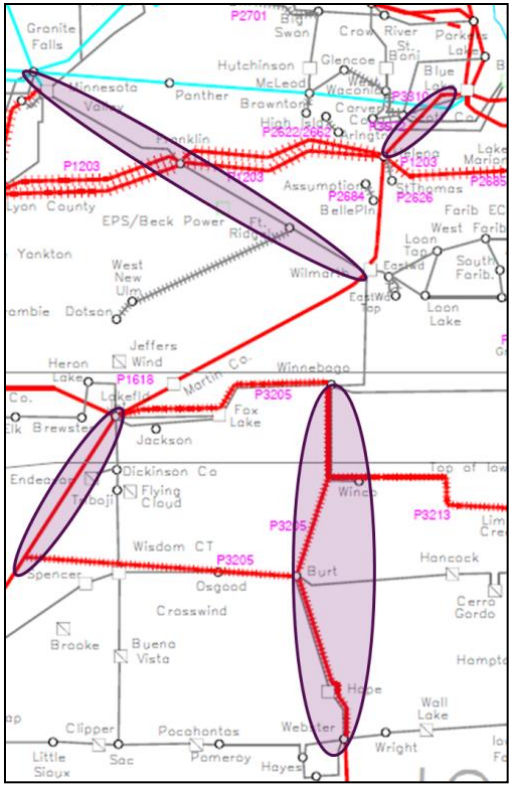
Transmission Interface Loading

- This metric was used to identify periods of high loading on three interfaces that are important to the dynamic performance of the Minnesota region. High loading on these interfaces stresses the overall transmission system, and provides appropriate operating conditions for testing system resilience to transmission system faults.

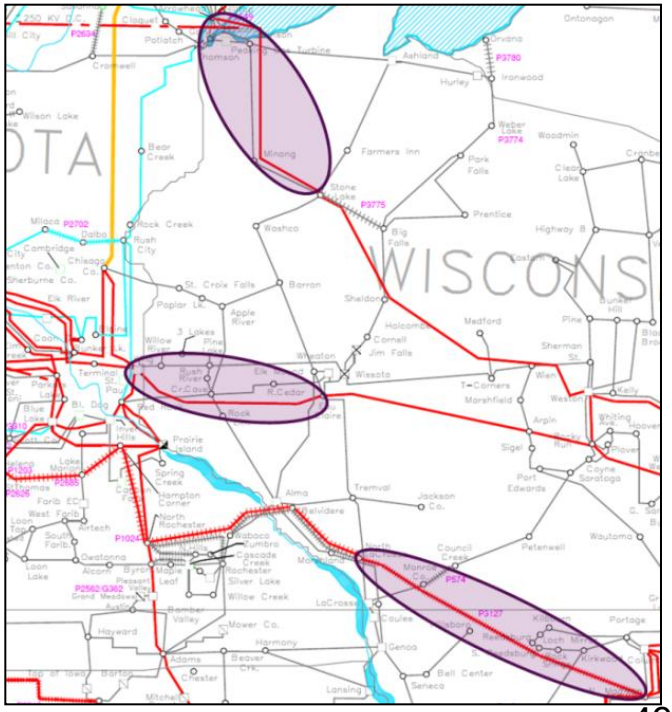
North Dakota Export (NDEX)



Buffalo Ridge Outlet



Minnesota-Wisconsin Export (MWEX)



Operational Performance

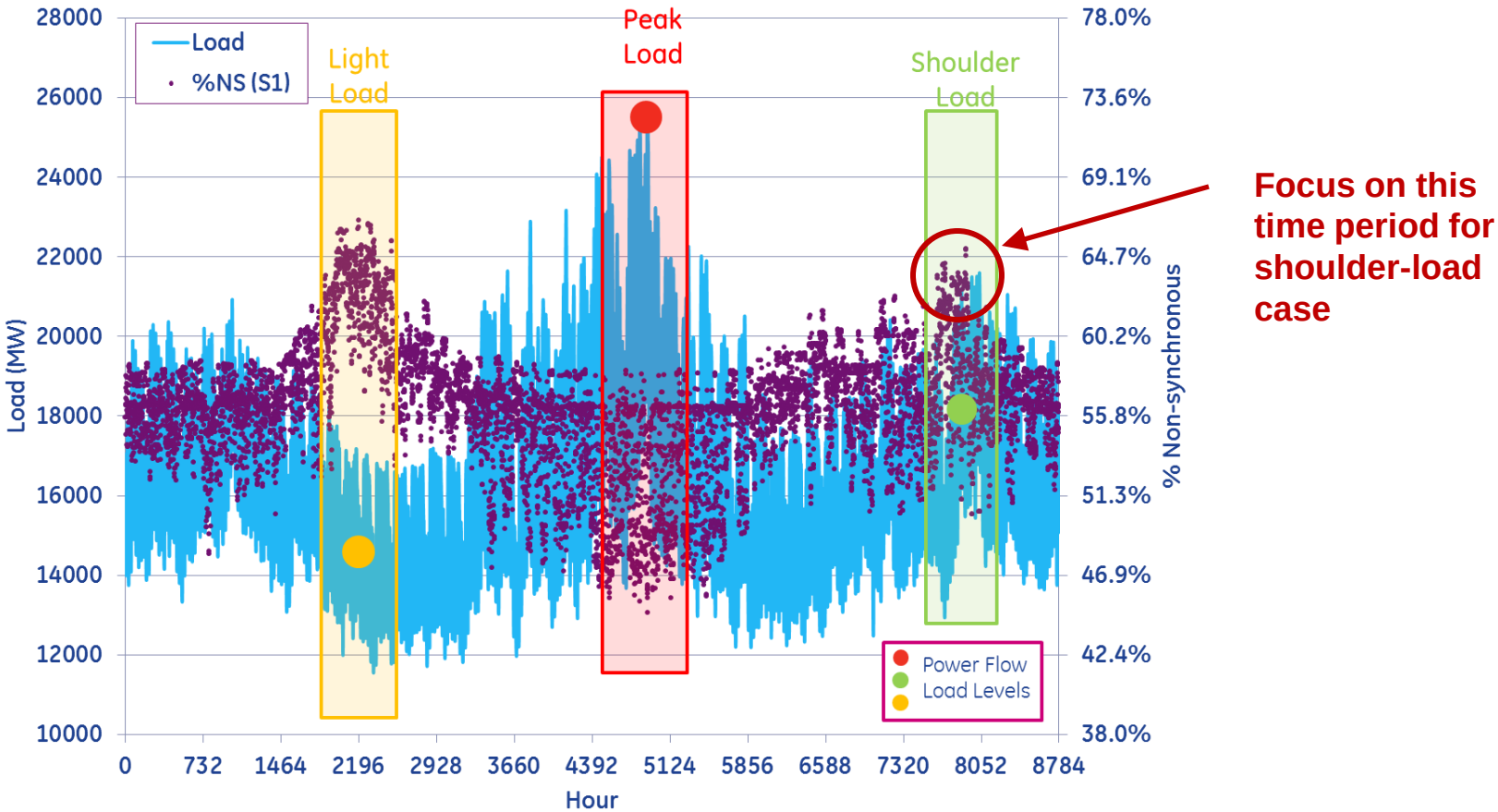
Selection of Operating Conditions for Dynamic Analysis

- Using the three metrics described in the previous section, seven stability cases were selected for each of the two studied scenarios, Scenario 1 and Scenario 1a, for a total of 14 cases
  - The first metric used to screen for stability cases was the % NS measure.
  - Next, the load and corresponding hourly % NS values were plotted chronologically
  - To identify a group of hours with similar operating conditions, the data was then filtered by time of year (fall), system load level (shoulder) and highest % NS (>55%); The result was 118 hours that satisfied the criteria
  - These 118 hours were then sorted by time of day to ensure that the hours with online solar (daytime hours) were captured and allowed for consistent hours in the commitment and dispatch; This resulted in 15 hours where the commitment and dispatch had very high % NS levels during a very small window
- The goal of the screen process was to filter down the 8784 hours of operation from the production simulation results into small groups of hours with common operating conditions that would facilitate in building a commitment and dispatch in the appropriate power flow case

Operational Performance

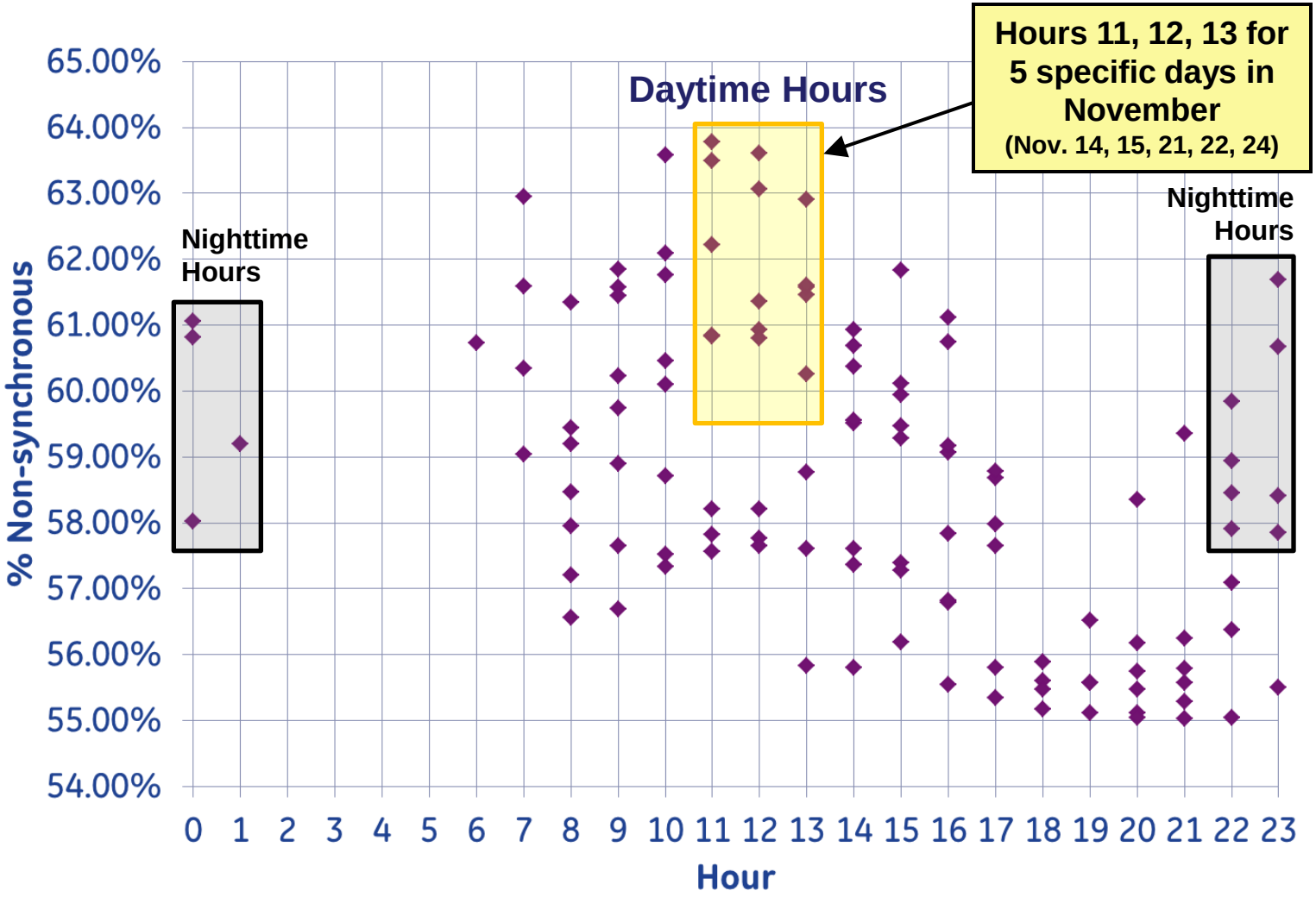
Chronological Load and % NS for the Minnesota-Centric Region

- As part of the multi-step screening process, the load and corresponding hourly % NS values were plotted chronologically; loading levels that corresponded to the power flow cases (peak, shoulder, light) were identified and used to refine the loading windows in hours with similar characteristics.



Operational Performance

Narrowing selection window to a group of consecutive hours with similar operating conditions (load, commitment, dispatch)



Operational Performance

Similar process followed for all three screening criteria . . .

- Percent Non-Synchronous Generation (% NS)
- Percent Renewable Penetration (% RE)
- Transmission Interface Loading

And for different system loading levels

- Peak Load
- Shoulder Load
- Light Load

Resulting in 7 different powerflow conditions in two study scenarios

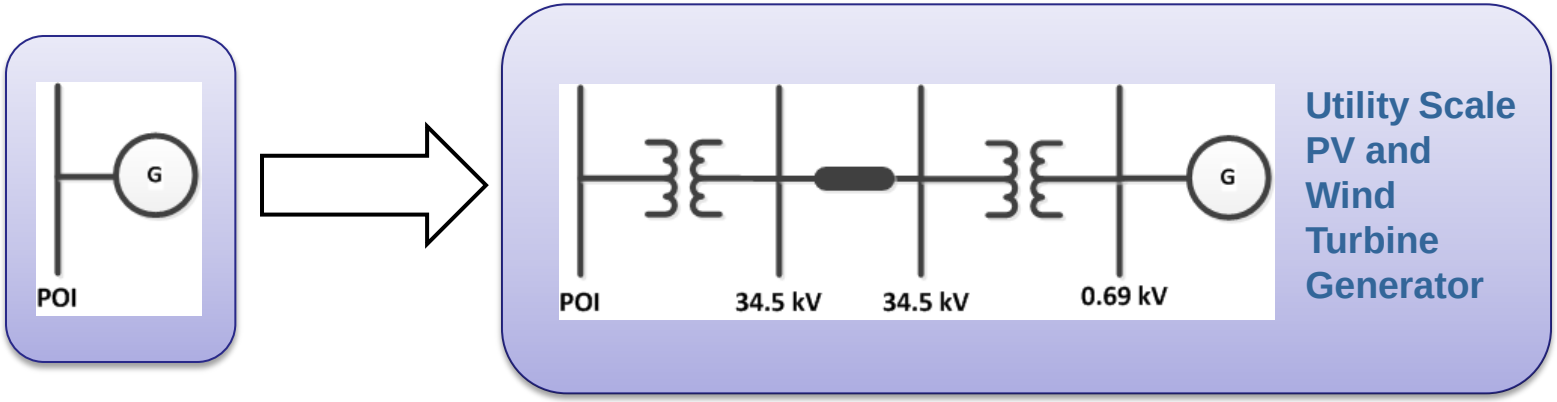
Dynamic Simulations

Dynamic Simulations

Existing wind plants modeled per supplied dynamic data (most plants regulating low voltage side of POI transformer)

Dynamic Models of New Wind and Solar Resources

- Wind plants split 50/50 between Type 3 and Type 4
- Wind turbines and PV Inverters have the NERC required zero voltage ride-through
- Wind and PV modeled with ±0.90 PF reactive at inverter transformer terminals
- Wind and PV regulate terminal voltage, not at the point of interconnection (high or low side of step up transformer)
- No coordinated plant wide control or coordination between plants
- No inertial response



Dynamic Simulations

Overview of Simulation Process / Steps

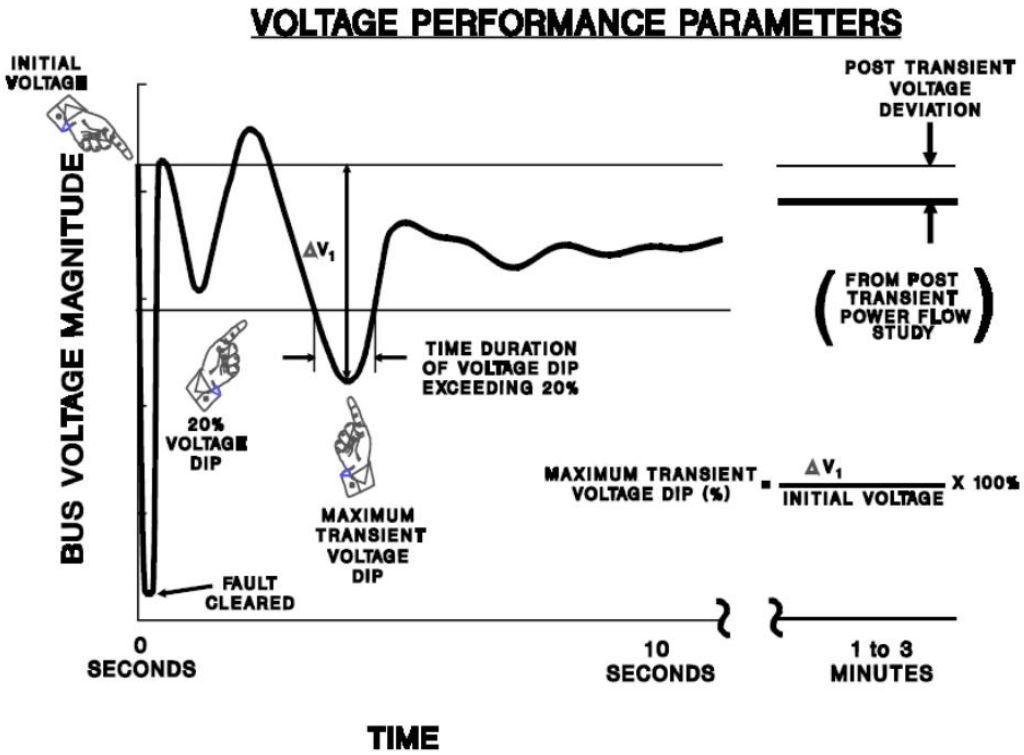
- Set up powerflow for operating conditions selected from production simulation screening process
- Quantify dynamic reactive reserves (indicator of ability to survive transient system disturbances)
- Simulate system response to a selected set of disturbances
  - Traditional disturbances, new disturbances in high-renewable locations, new disturbances from screening criteria (e.g., high interface flows)
- Examine “weak system” issues by calculating Composite Short-Circuit Ratio (CSCR) for selected buses and regions
- Explore possible mitigations

Analysis of Dynamic Performance

- Plots of stability results, including regional metrics
- Monitor generic impedance relay action and sequence of events report

Voltage Recovery:

- Test ΔV at all 220 kV & higher throughout MISO
- Dip below 20% of initial value for more than 20 cycles
- Dip below 0.70 pu after fault clearing (0.15sec after fault application time)



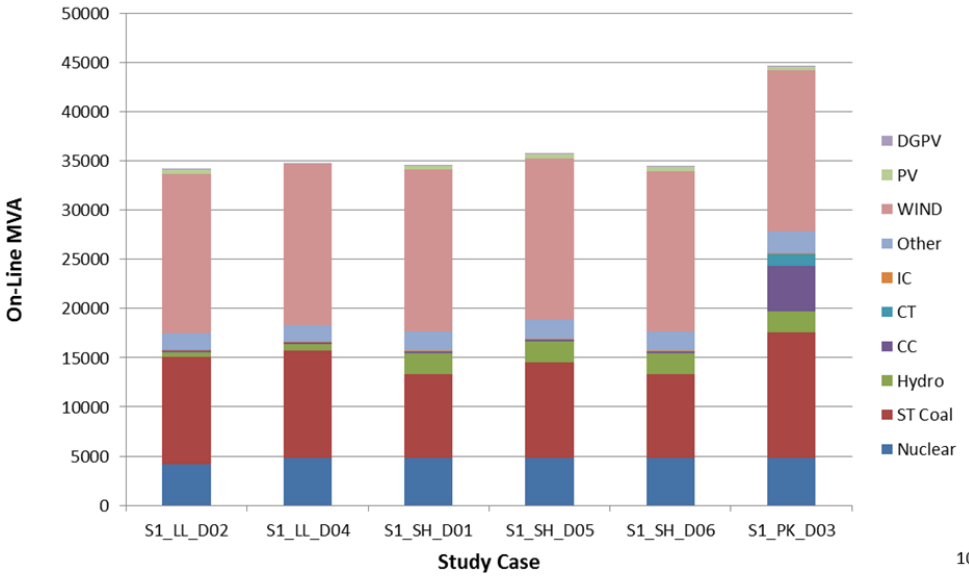
Dynamic Simulations

Stability Case Descriptions

Case	Name	Criteria	Load	Notes
1	S1_SH_D01	High % NS	Shoulder	49% NS Generation 37% Renewable Energy
2	S1_LL_D02	High % NS	Light	48% NS Generation 36% Renewable Energy
3	S1_PK_D03	High % NS	Peak	37% NS Generation 21% Renewable Energy
4	S1_LL_D04	High % RE Penetration	Light	47% NS Generation 40% Renewable Energy
5	S1_SH_D05	High Transmission Loading NDEX	Shoulder	47% NS Generation 37% Renewable Energy 2334 MW NDEX Loading
6	S1_SH_D06	High Transmission Loading Buffalo Ridge Outlet	Shoulder	48% NS Generation 41% Renewable Energy SW Minn Renewables at 95% Pmax
7	S1_LL_D04*	High Transmission Loading MWEX	Light	47% NS Generation 40% Renewable Energy 2424 MW MWEX Loading

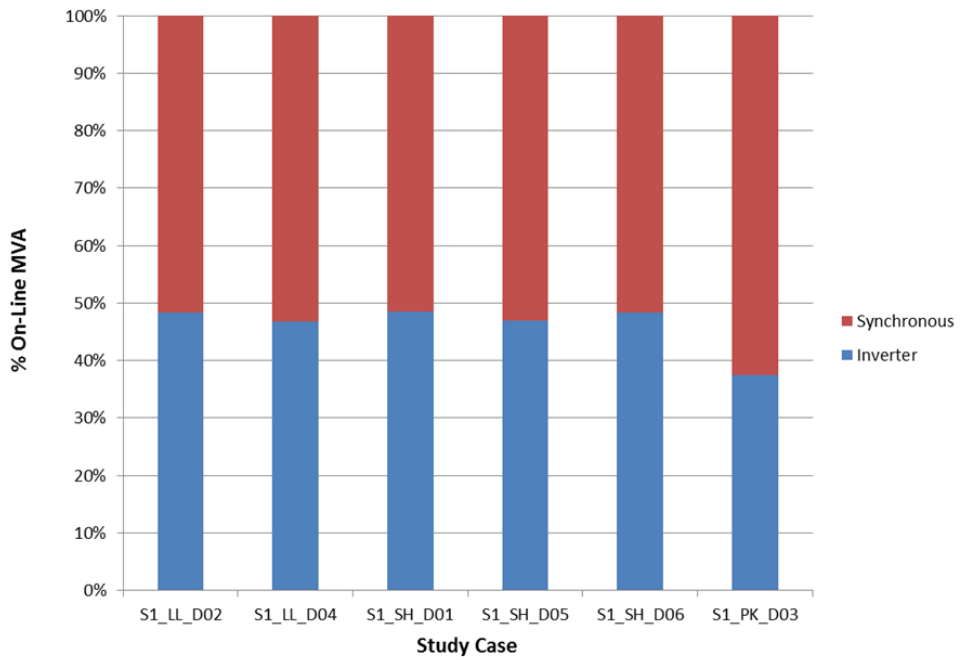
*** Note:** Case 4 has MWEX loading above 1400 MW (max value from production simulation). The impact of MWEX loading was tested using this case, subject to additional contingencies on MWEX lines.

Dynamic Simulations



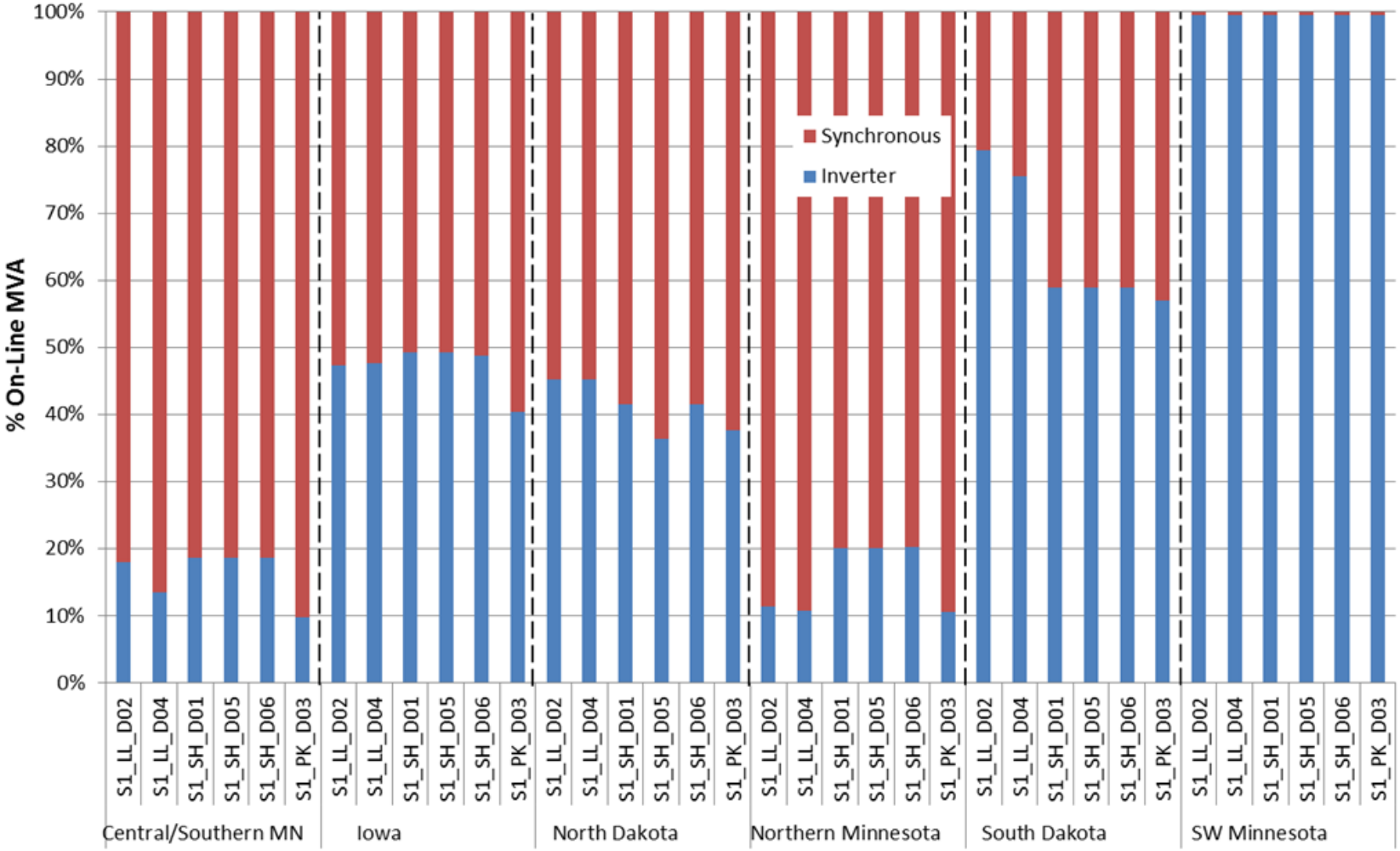
Minnesota Centric Commitment by Unit Type (MVA)

Percentage of On-line Non- vs Synchronous (MVA)



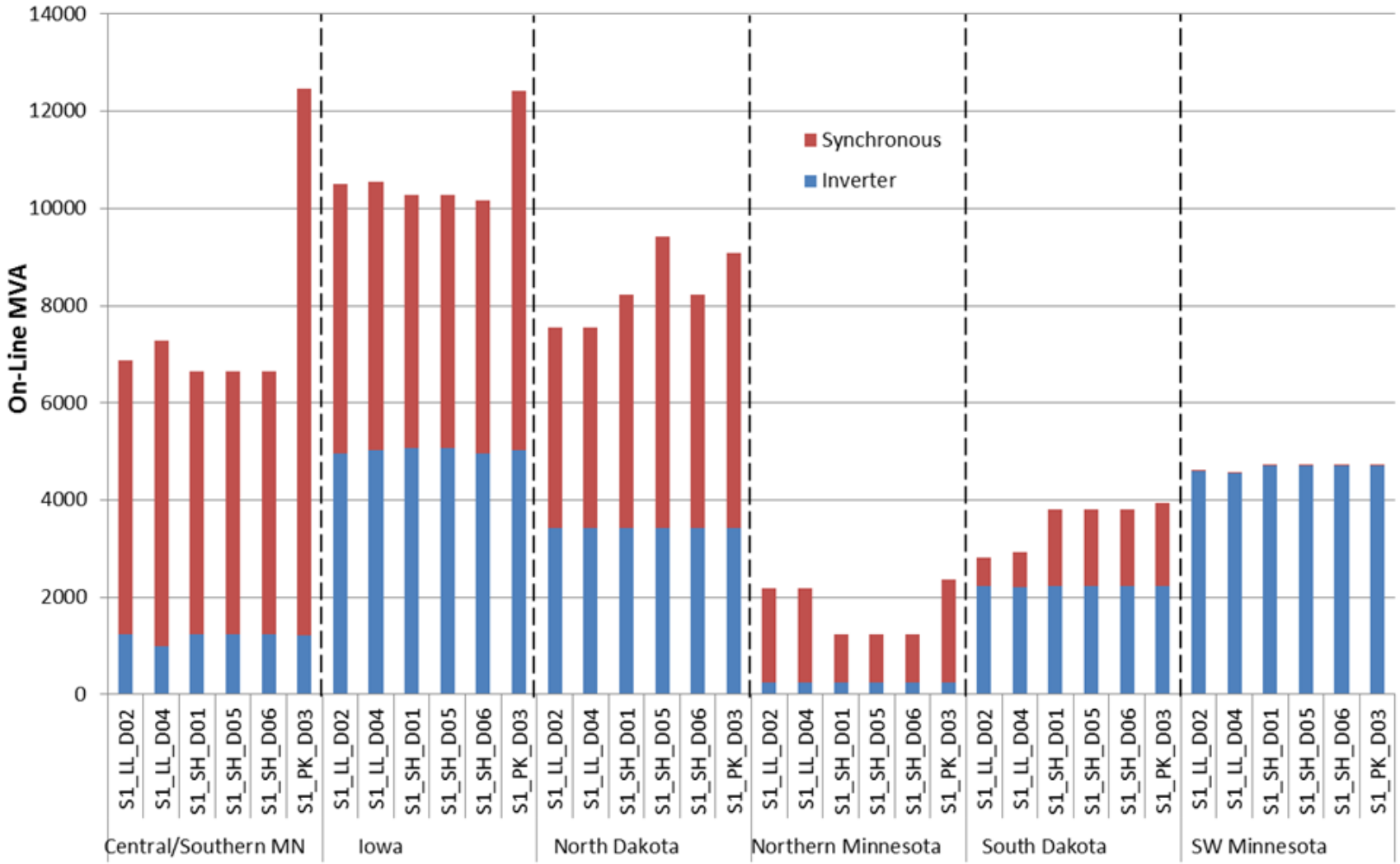
Dynamic Simulations

Percentage of online, non- and synchronous MVA by Sub-Region



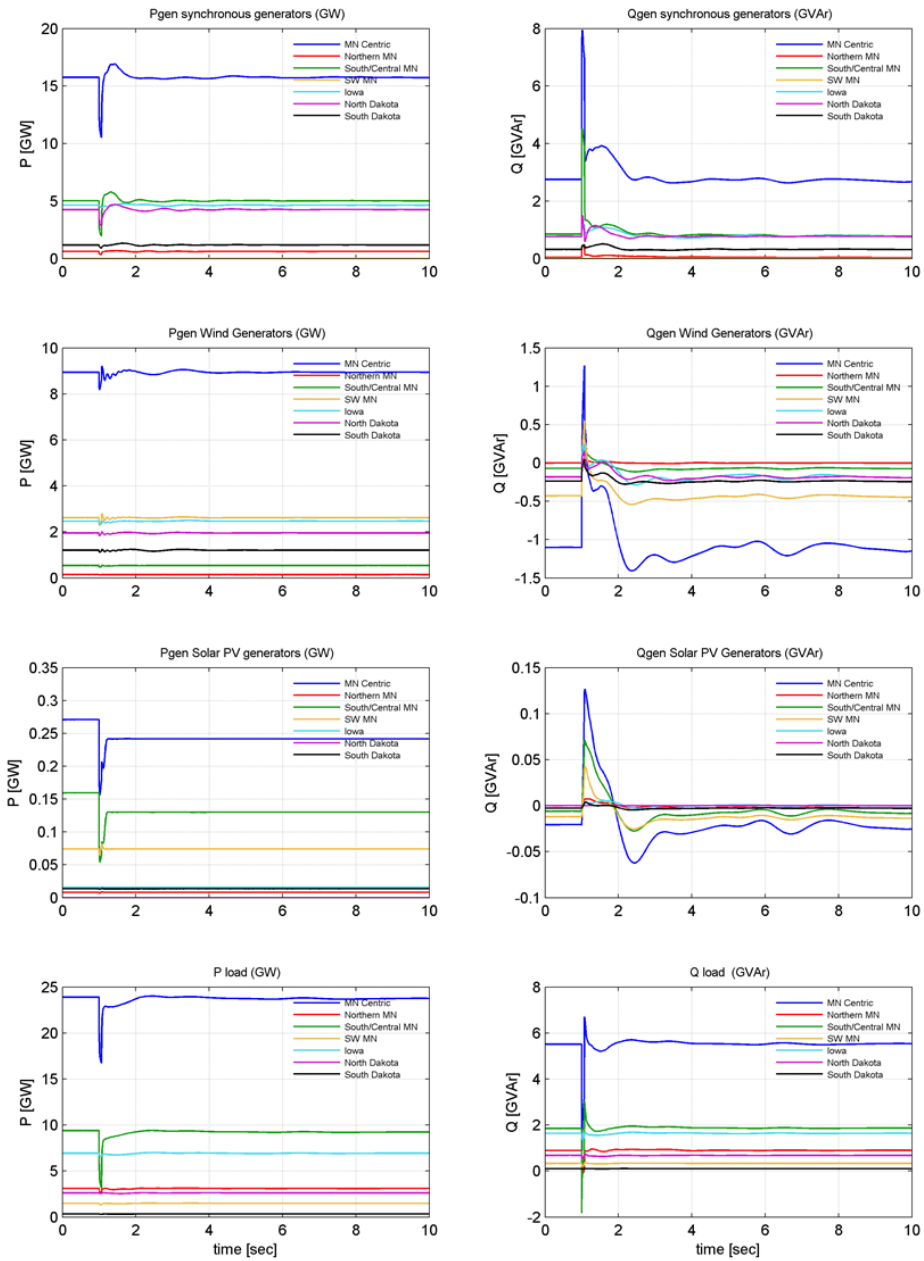
Dynamic Simulations

Online MVA of synchronous and non-synch Generation by Sub- Region



Dynamic Simulations

Example case for high percentage of non-synchronous in the Minnesota footprint



Dynamic Simulations

Stability & Voltage Recovery Analysis

- Transient stability analysis evaluated system response to a range of system faults
- The faults tested cover reference disturbances, disturbances in areas with low short circuit strength and faults along transmission interfaces
- All stability simulations were evaluated using the criteria describe previously
- All tested scenarios produce transiently stable response with acceptable voltage recovery.

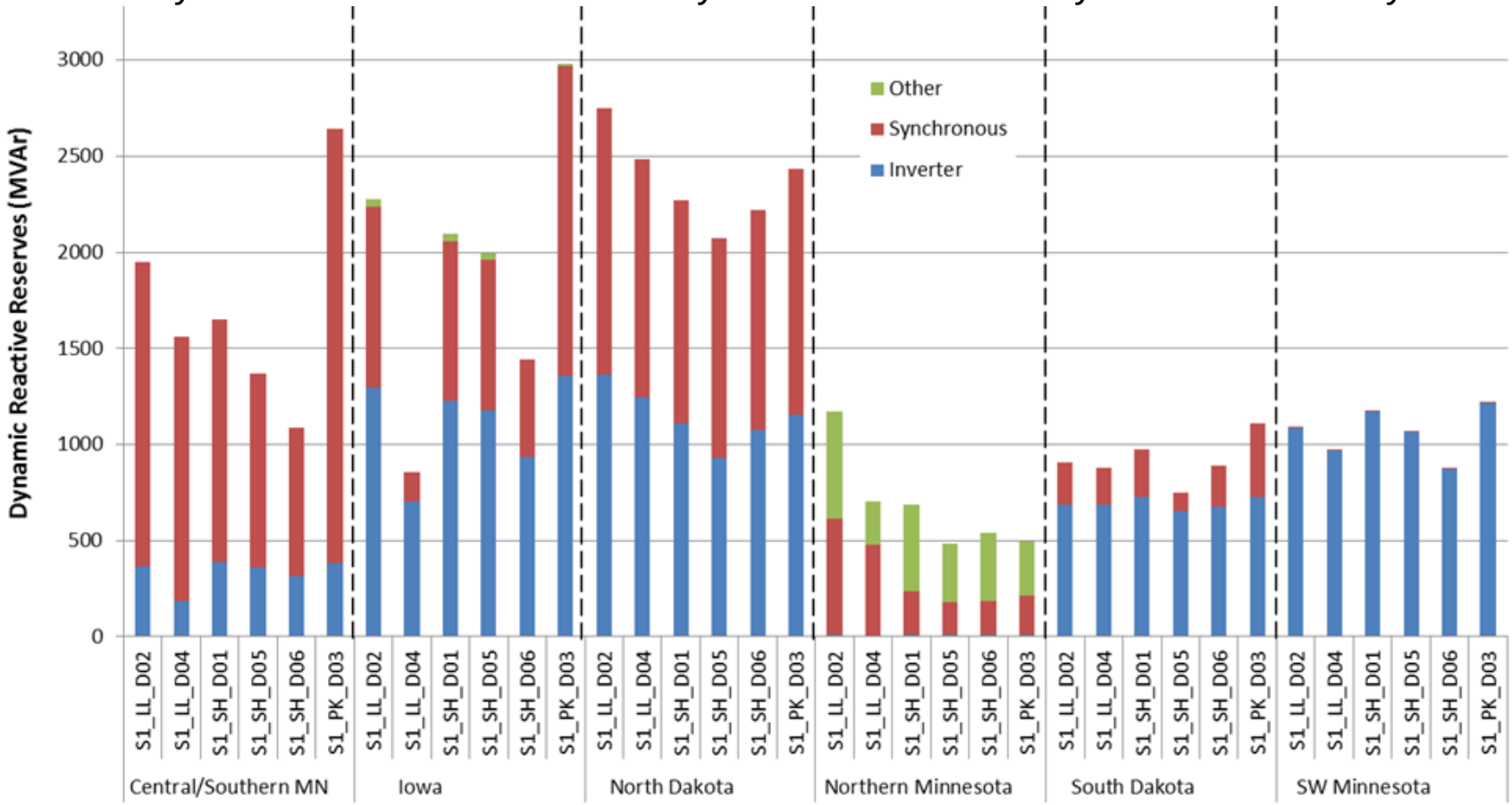
No	Fault Name	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
1	EI2	stable	stable	stable	stable	stable	stable	stable
2	AG1	stable	stable	stable	stable	stable	stable	stable
3	AG3	stable	stable	stable	stable	stable	stable	stable
4	NAD	stable	stable	stable	stable	stable	stable	stable
5	PCS	stable	stable	stable	stable	stable	stable	stable
6	LSC1	stable	stable	stable	stable	stable	stable	stable
7	LSC2	stable	stable	stable	stable	stable	stable	stable
8	LSC3	stable	stable	stable	stable	stable	stable	stable
9	LSC4	stable	stable	stable	stable	stable	stable	stable
10	LSC5	stable	stable	stable	stable	stable	stable	stable
11	Trip_DEERCK	stable	stable	stable	stable	stable	stable	stable
12	Term_King	stable	stable	stable	stable	stable	stable	stable
13	AG1_v2	NT	NT	NT	NT	stable	NT	NT
14	AG3_v2	NT	NT	NT	NT	stable	NT	NT
15	briggs	NT	NT	NT	NT	NT	NT	stable
16	sheas	NT	NT	NT	NT	NT	stable	NT

Dynamic Simulations

Reactive Reserves

- The dynamic reactive reserves for all test cases were sufficient to maintain system stability and allow for acceptable voltage recovery
- Both the transient voltage dip and post-transient voltages recovered met all screening criteria

Dynamic Reactive Reserves of synchronous and non-synch Generation by Sub-Region



Dynamic Simulations

Weak System Issues

- Composite Short-Circuit Ratio (CSCR) is an indicator of the ability of an ac transmission system to support stable operation of inverter-based generation
  - A system with a higher CSCR is considered strong and a system with a lower CSCR is considered to be weak
  - CSCR is calculated as the ratio of the composite short-circuit MVA at the points of interconnection (POI) of all wind/solar plants in a given area to the combined MW rating of all those wind and solar generation resources
- Low CSCR operating conditions can lead to control instabilities in inverter-based equipment (Wind, Solar PV, HVDC and SVC)
  - This is a relatively new area of concern within the industry
  - Understanding of the fundamental stability issues is rapidly growing as more wind plants are being installed in regions with weak ac systems
  - Equipment vendors, transmission planners and consultants are all working to gain a better understanding of the issues; Modeling and simulation tools have already been developed to enable detailed analysis of the phenomena. Wind and solar inverter control systems are being modified to improve weak system performance
- Synchronous machines (either generators or synchronous condensers) contribute short-circuit strength to the transmission system and therefore increase CSCR.
  - System operating conditions with more synchronous generators online will have higher CSCR.
  - Stronger transmission ties (additional transmission lines or transformers, or lower impedance transformers) between synchronous generation and regions of wind and solar generation will increase CSCR

Dynamic Simulations

Weak Grid Analysis – Composite Short-Circuit Ratio, CSCR

Control Stability with Regard to CSCR Levels

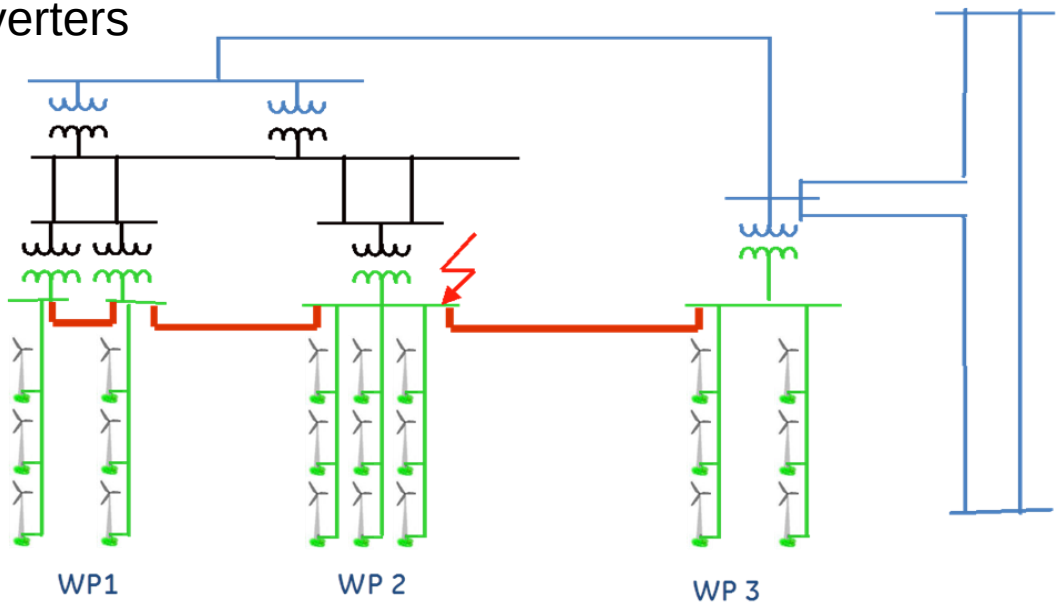
<1.0 1.5 1.7 2.0 2.5 3.0

- In general, CSCR > 2.5 to 3 is "Safe" or Stable

Example of CSCR analysis for multiple wind plants

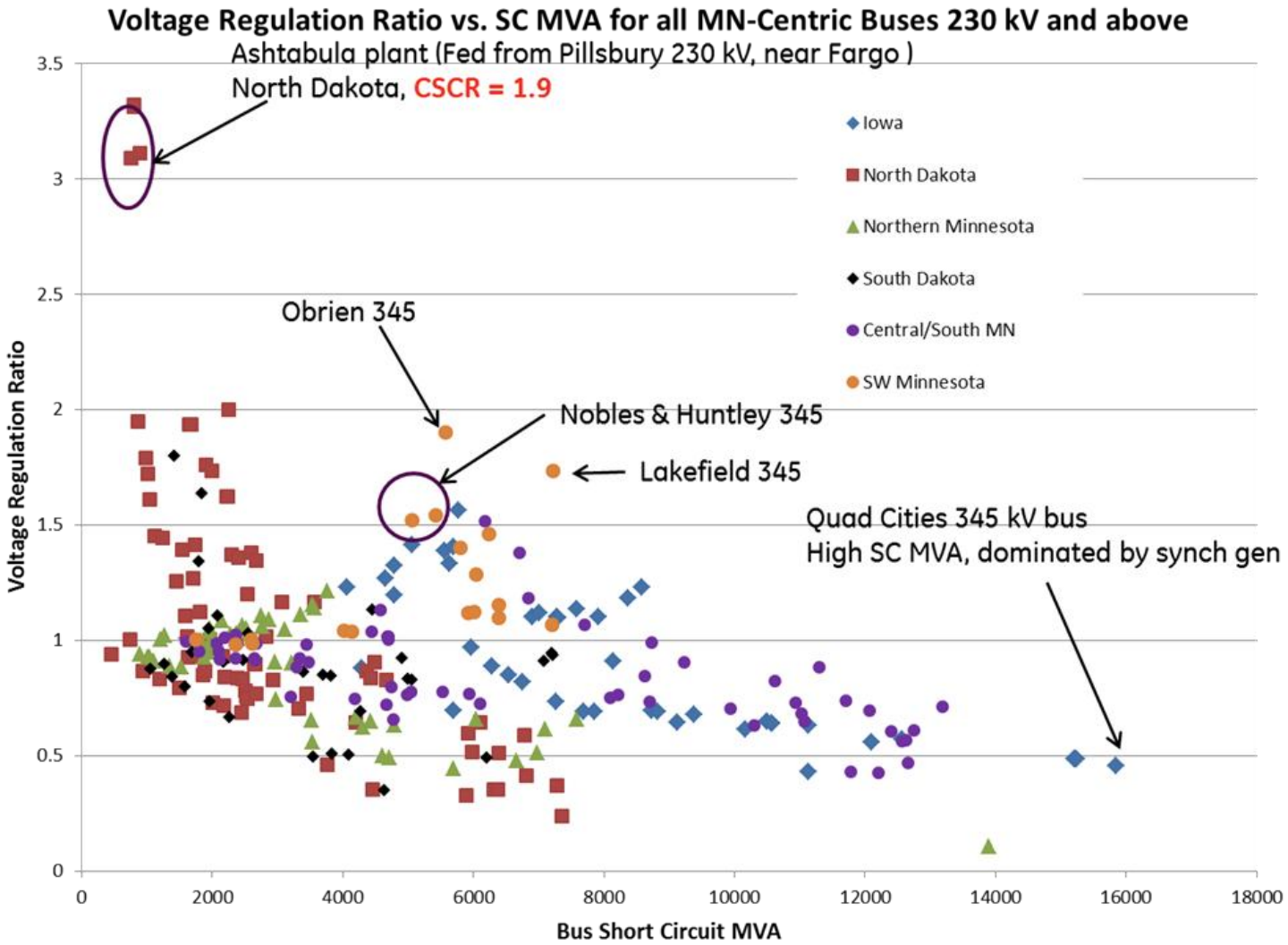
- 3-Phase short circuit at 34.5 KV buses - all interconnected
- No current contribution from converters

$$CSCR = \frac{Composite\ SC\ MVA}{\sum converter\ MW\ rating}$$



Dynamic Simulations

SC MVA vs. Voltage Regulation Ratio for Minnesota-Centric Transmission Buses → identified buses/regions to examine



Dynamic Simulations

Weak System Issues

- Two regions studied:
  - Local pockets of a wind plants in North Dakota fed from Pillsbury 230 kV near Fargo).
  - Minnesota (Buffalo Ridge area) with a very high concentration of wind and solar plants and no nearby synchronous generation
  - CSCR calculated for normal and emergency conditions, variation in generation commitment
  - Stability simulations shows acceptable system response but both regions have CSCR approaching the weak region
- Results of weak system analysis and mitigation approaches are presented in the following section (Key Findings)

Key Findings

Key Findings – 1 of 9

General Conclusions for 40% Renewable Energy in Minnesota

- Production simulation and transient/dynamic stability analysis results indicate that ***the system can be successfully operated for all hours of the year*** with no unserved load, no reserve violations, and minimal curtailment of renewable energy ***with wind and solar resources increased to achieve 40% renewable energy for Minnesota***, and with current renewable energy standards fully implemented in neighboring MISO North/Central states
  - Assumes upgrades to existing transmission to accommodate the additional wind and solar resources
  - Is operationally achievable with most coal plants operated as baseload must-run units, similar to existing operating practice; Is also achievable if all coal plants are economically committed per MISO market signals, but additional analysis would be required to better understand implications, tradeoffs, and mitigations related to increased cycling duty

Key Findings – 1 of 9 (continued)

General Conclusions for 40% Renewable Energy in MN

- Dynamic simulation results indicate that ***there are no fundamental system-wide dynamic stability or voltage regulation issues introduced with wind and solar resources increased to achieve 40% renewable energy for Minnesota***

  This assumes:

  - New wind turbine generators are a mixture of Type 3 and Type 4 turbines with standard controls
  - The new wind and utility-scale solar generation is compliant with present minimum performance requirements (i.e. they provide voltage regulation/reactive support and have zero-voltage ride through capability)
  - Local-area issues are addressed through normal generator interconnection requirements

Key Findings – 2 of 9

General Conclusions for 50% Renewable Energy in Minnesota

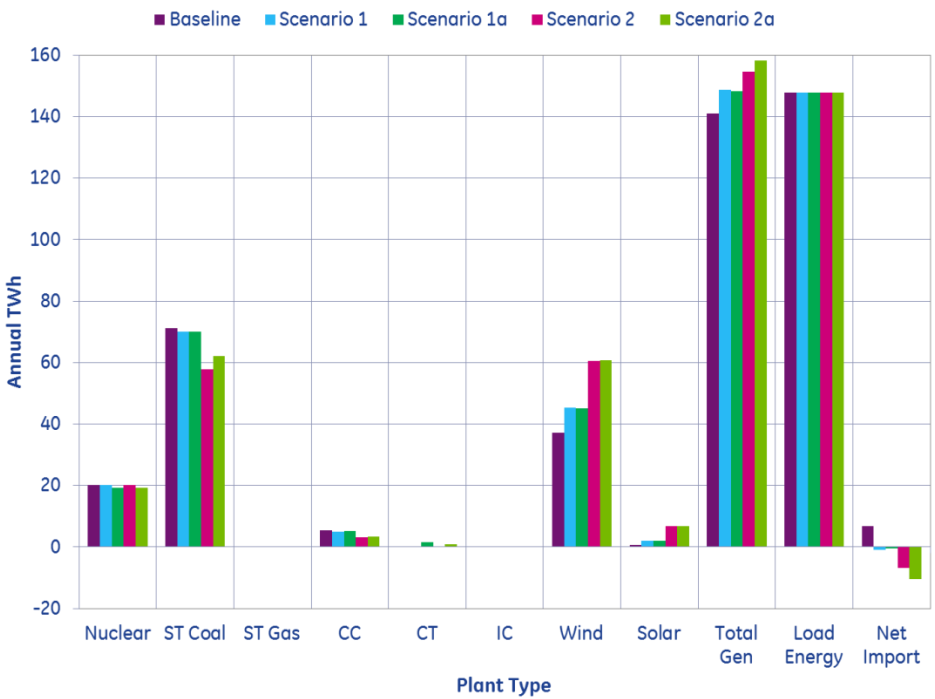
- With wind and solar resources increased to achieve ***50% renewable energy in Minnesota and 25% renewable energy in MISO*** *(North/Central)*, production simulation results indicate that ***the system can be successfully operated for all hours of the year*** with no unserved load, no reserve violations, and minimal curtailment of renewable energy. This assumes sufficient transmission upgrades, expansions and mitigations to accommodate the additional wind and solar resources.
  - Assumes upgrades to existing transmission to accommodate the additional wind and solar resources
  - Is operationally achievable with most coal plants operated as baseload must-run units, similar to existing operating practice; Is also achievable if all coal plants are economically committed per MISO market signals, but additional analysis would be required to better understand implications, tradeoffs, and mitigations related to increased cycling duty
  - No dynamic analysis was performed for the study scenarios with 50% renewable energy for Minnesota (Scenarios 2 and 2a) due to study schedule limitations and this analysis is necessary to ensure system reliability

Key Findings – 3 of 9

Annual Energy in the Minnesota-Centric Region

- Comparing Scenarios 1 and 1a (40% MN renewables) with the Baseline
  - Wind and solar energy increases by 8.5 TWh, all of which contributes to bringing the State of Minnesota from 28.5% RE penetration to 40% RE penetration
  - There is very little change in energy from conventional generation resources
  - Most of the increase in wind and solar energy is balanced by a decrease in imports. The Minnesota-Centric region goes from a net importer to a net exporter.

- Comparing Scenario 2 with Scenario 1
  - Wind and solar energy increases by 20 TWh. Of this total, 4.8 TWh brings the State of Minnesota from 40% to 50% RE penetration and the remainder contributes to bringing MISO from 15% to 25% RE penetration
  - Most of the increase in wind and solar energy in the Minnesota-Centric region is balanced by a decrease in coal generation and an increase in net exports to neighboring regions
  - Gas-fired, combined-cycle generation declines from 5.0 TWh in Scenario 1 to 3.0 TWh in Scenario 2.



Key Findings – 4 of 9

Cycling of Thermal Plants

- Most coal plants were originally designed for baseload operation; Increased cycling duty could increase wear and tear on these units
  - Many coal plants in MISO presently are designated by the plant's owner to operate as "must-run" in order to avoid start/stop cycles that would occur if they were economically committed by the market
- Scenarios S1 and S2 assumed coal plants would continue to operate as they do today
  - Coal units were on-line all year (except for scheduled maintenance periods) and were not decommitted during periods of low market prices
  - Results of these scenarios confirmed that the coal units could remain must-run with minor impacts on overall operation of the Minnesota-Centric region
- Scenarios S1a and S2a assumed that all coal plants in MISO are subject to economic commitment/dispatch (i.e., not must-run)
  - Results of these scenarios show a high number of start/stop cycles of coal plants
  - Small coal units (below 300 MW rating) could have an additional 100 to 200 starts per year, beyond those due to forced or planned outages
  - Large coal units (above 300 MW) could have an additional 20 to 100 starts per year
- Cycling of combined-cycle (CC) plants declines slightly as wind and solar penetration increases
  - Primarily due to a decrease in CC plant utilization as wind and solar energy increases

Key Findings – 5 of 9

Curtailment of Wind and Solar Energy

- In general, a small amount of curtailment is to be expected in any system with a significant level of wind and solar generation.
- Overall curtailment in the Minnesota-Centric region is relatively small in all study scenarios
  - Wind energy curtailment: 0.42% in Baseline, 1.00% in Scenario 1, 2.14% in Scenario 2
  - Solar energy curtailment: 0.09% in Baseline, none in Scenario 1, 0.42% in Scenario 2
- Wind curtailment in Baseline and Scenario 1 is primarily due to local transmission congestion at a few wind plants
  - Could be mitigated by transmission modifications, if economically justifiable
- Wind curtailment in Scenario 2 is due to system-wide operational limits during nighttime hours, when many baseload generators are dispatched to their minimum output levels
  - Could be reduced by decommitting some baseload generation via economic market signals
- Comparing Scenario 2 (coal units must-run) with Scenario 2a (economic coal commitment):
  - Wind curtailment decreases from 2.14% to 1.60%
  - Solar curtailment decreases from 0.42% to 0.24%

Key Findings – 6 of 9

Other Operational Issues

- Ramp-range-up and ramp-rate-up capability of the MISO conventional generation fleet increases with increased penetration of wind and solar generation
  - Conventional generation is generally dispatched down rather than decommitted when wind and solar energy is available, which gives those generators more headroom for ramping up if needed
- Ramp-range-down and ramp-rate-down capability of the MISO conventional generation fleet decreases with increased penetration of wind and solar generation
  - In Scenario 2, there are 500 hours when ramp-rate-down capability of the conventional generation fleet falls below 100 MW/minute
  - Periods of low ramp-down capability coincide with periods of high wind and solar generation
  - Wind and solar generators are capable of providing ramp-down capability during these periods
  - MISO's existing Dispatchable Intermittent Resource (DIR) process already enables this for wind generators
- No significant transmission system congestion was observed in any of the study scenarios with the assumed transmission upgrades and expansions
  - Transmission contingency conditions were considered in both the powerflow analysis used to develop the conceptual transmission system and the security-constrained economic dispatch in the production simulation analysis

Key Findings – 7 of 9

System Stability, Voltage Support, Dynamic Reactive Reserves

- With wind and solar resources increased to achieve 40% renewable energy in Minnesota, no angular stability, oscillatory stability or wide-spread voltage recovery issues were observed over the range of tested study conditions.
  - The 16 dynamic disturbances used in stability simulations included key traditional faults/outages as well as faults/outages in areas with high concentrations of renewables and high inter-area transmission flows.
  - System operating conditions included light load, shoulder load and peak load cases, each with the highest percent renewable generation periods in the Minnesota-Centric region.
- Southwest Minnesota, South Dakota and at times Iowa get a significant portion of dynamic reactive support from wind and solar resources.
  - Wind and Solar resources contribute significantly to voltage support/dynamic reactive reserves. The fast response of wind/solar inverters helps voltage recovery following transmission system faults. However, these are current-source devices with little or no overload capability. Their reactive output decreases when they reach a limit (low voltage and high current).
- Synchronous machines (either generators or synchronous condensers), on the other hand, are voltage-source devices with high overload capability.
  - This characteristic will strengthen the system voltage, allowing better utilization of the dynamic capability of renewable generation. The mitigation methods discussed below, namely strengthening the ac system through new transmission or synchronous machines, will also address this concern.

Key Findings – 7 of 9 (continued)

System Stability, Voltage Support, Dynamic Reactive Reserves

- Overall dynamic reactive reserves are sufficient and all disturbances examined for Scenarios 1 and 1a show acceptable voltage recovery.
  - The South & Central and Northern Minnesota regions get the majority of their dynamic reactive support from synchronous generation. Maintaining sufficient dynamic reserves in these regions is critical, both for local and system-wide stability.
- Local load areas, such as the Silver Bay and Taconite Harbor area, require reactive support from synchronous machines due to the high level of heavy industrial loads.
  - If all existing synchronous generation in this region is off line (i.e. due to retirement or decommitment), reinforcements such as new transmission or synchronous condensers would be required to support the load.
- Dynamic simulation results indicate that it is critical to maintain sufficient system strength and dynamic reserves to support high flows on the Northern Minnesota 500 kV lines and Manitoba high-voltage direct-current (HVDC) lines.
  - Insufficient system strength and reactive support will limit Manitoba exports to the U.S. Existing transmission expansion plans, as modeled in this analysis, address these issues and are sufficient for the anticipated levels of Manitoba exports.

Key Findings – 8 of 9

Weak System Issues

- There are two general situations where weak system issues generally need to be assessed:
  - Local pockets of a few wind and solar plants in regions with limited transmission and no nearby synchronous generation (e.g. plants in North Dakota fed from Pillsbury 230 kV near Fargo).
  - Larger areas such as Southwest Minnesota (Buffalo Ridge area) with a very high concentration of wind and solar plants and no nearby synchronous generation
- This study examined the sensitivity of weak system issues in Southwest Minnesota. Observations are as follows:
  - The trouble spots identified in this analysis are not very sensitive to existing synchronous generation commitment. While there is very little synchronous generation within the area, the region is supported by a strong networked 345 kV transmission grid. Primary short circuit strength is from a wide range of base-load units in neighboring areas, and interconnected via the 345 kV transmission network. Commitment, decommittment or outages of individual synchronous generators do not have significant impact on CSCR in these identified areas.
  - Transmission outages will lower system strength and make the issue worse. When performing CSCR and weak system assessments as wind and solar penetration increases, it will be prudent to consider normal and design-criteria outages at a minimum (i.e, outage conditions consistent with MISO reliability assessment practices).

Key Findings – 9 of 9

Mitigation of Weak System Issues

- There are two approaches to improving wind/solar inverter control stability in weak system conditions:
  - To improve the inverter controls, either by carefully tuning the equipment control functions or modifying the control functions to be more compatible with weak system conditions. With this approach, wind/solar plants can tolerate lower CSCR conditions.
  - To strengthen the ac system, resulting in increased short-circuit MVA at the locations of the wind/solar plants. This approach increases CSCR.
- The approaches are complementary, so the ultimate solution for a particular region would likely be a combination of both.

Key Findings – 9 of 9 (continued)

Mitigation of Weak System Issues

- **Mitigation through Wind/PV Inverter Controls**
  - Standard inverter controls and setting procedures may not be sufficient for weak system applications. Loop gains of internal control functions inherently increase when system impedance increases, thereby reducing the stability margin of the controllers.
  - Developers and equipment vendors must be made aware when new plants are being proposed for weak system regions so they can design/tune controls to address the issue. Wind plant vendors have made significant progress in designing wind and solar plant control systems that are compatible with weak system applications.
- **Mitigation by Strengthening the AC System**
  - CSCR analysis of the Southwest Minnesota region shows that synchronous condensers located near the wind and solar plants would be a very effective mitigation for weak system issues.
    - Synchronous condensers are synchronous machines that have the same voltage control and dynamic reactive power capabilities as synchronous generators. Synchronous condensers are not connected to prime movers (e.g. steam turbines or combustion turbines), so they do not generate power.
  - Other approaches that reduce ac system impedance could also offer some benefit:
    - Additional transmission lines between the wind/solar plants and synchronous generation plants
    - Lower impedance transformers, including wind/solar plant interconnection transformers

Thank you!

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The full study is posted on the Minnesota Department of Commerce web site.