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**

Presentation – January 13, 2015

Presenters:

Minnesota Utilities & Transmission Companies
- Gordon Pietsch (GRE)
- Jared Alholinna (GRE)

GE Energy Consulting
- Richard Piwko

Minnesota Department of Commerce
- Bill Grant
- 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		5,590		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	8,643	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

	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

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

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

American Transmission Company, Dairyland Power Cooperative, Great River Energy, ITC Midwest, Manitoba Hydro, Minnesota Power, Minnkota Power Cooperative, Missouri River Energy Services, MN Department of Commerce, Otter Tail Power, CMMPA, 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

- 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

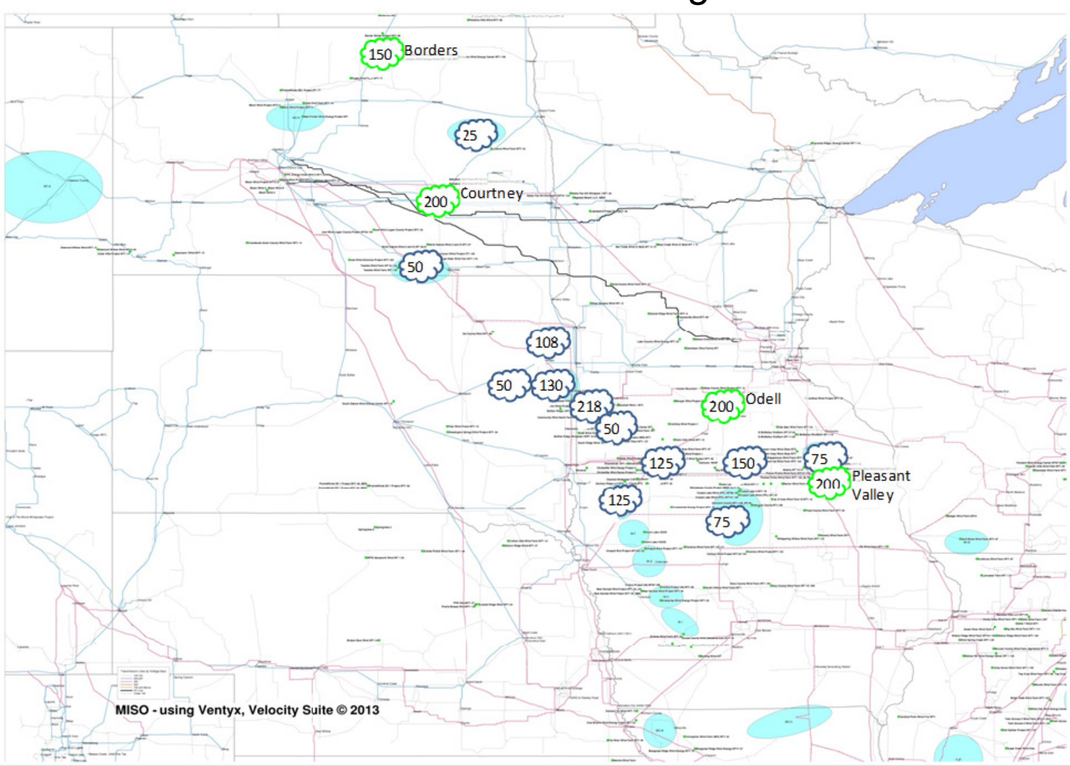
	Minnesota Centric			
	Wind MW	PV MWac		
	Incremental	Incremental		
		Utility PV	Distributed PV	Total Increm. PV
Baseline		361	96	457
Scenario 1	1,931	723	191	914
Scenario 2	610	2,756	430	3186

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



MN Wind Generation Siting – State Locations

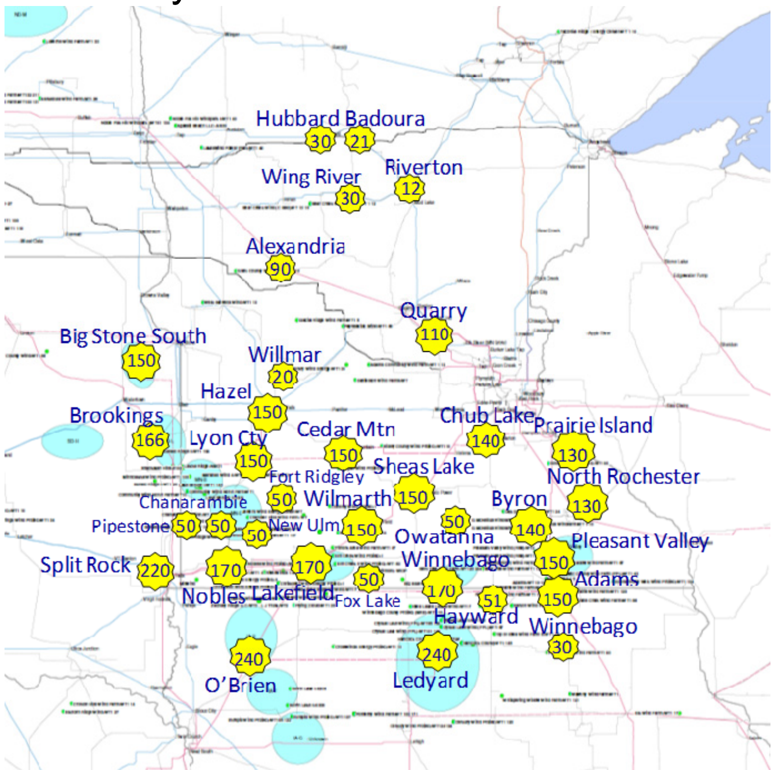
State	Baseline Scenario	Incremental MN Wind gen for Scenario 1	Incremental MN Wind gen for Scenario 2	Total Incremental Wind Scenario 1 & 2
IA %	24.5%	10.4%	9.8%	10.2%
MN %	**43.5%**	**52.7%**	**52.5%**	**52.7%**
ND %	20.9%	22.0%	18.0%	21.1%
SD %	11.1%	14.9%	19.7%	16.1%

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

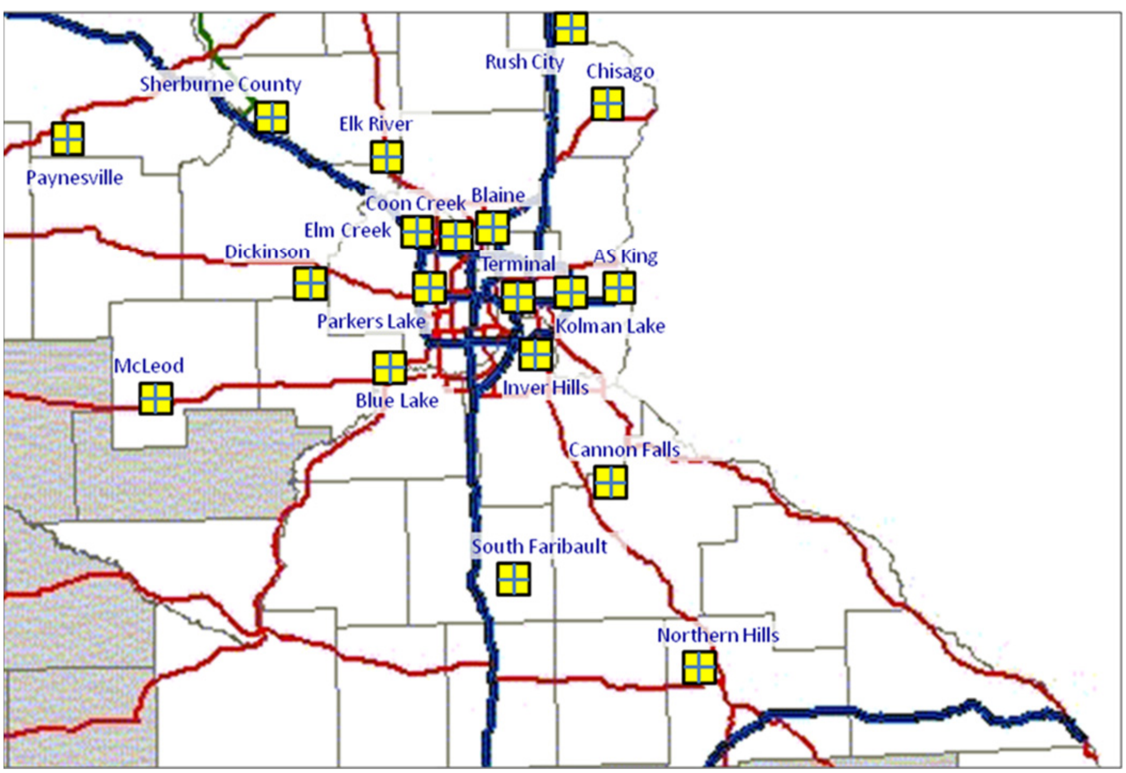
Solar Generation Siting

MN Solar for Utility Locations - All Scenarios



Solar Generation Siting

MN Distributed PV Sites



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%

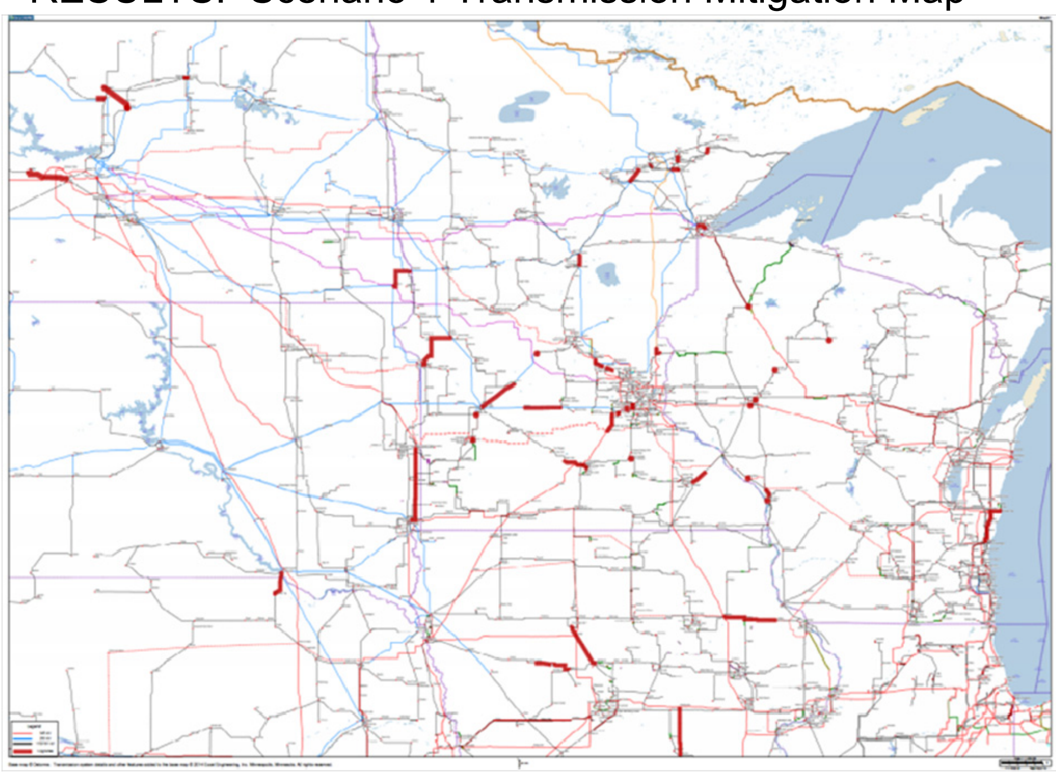
Model Building Steps - conceptual transmission

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



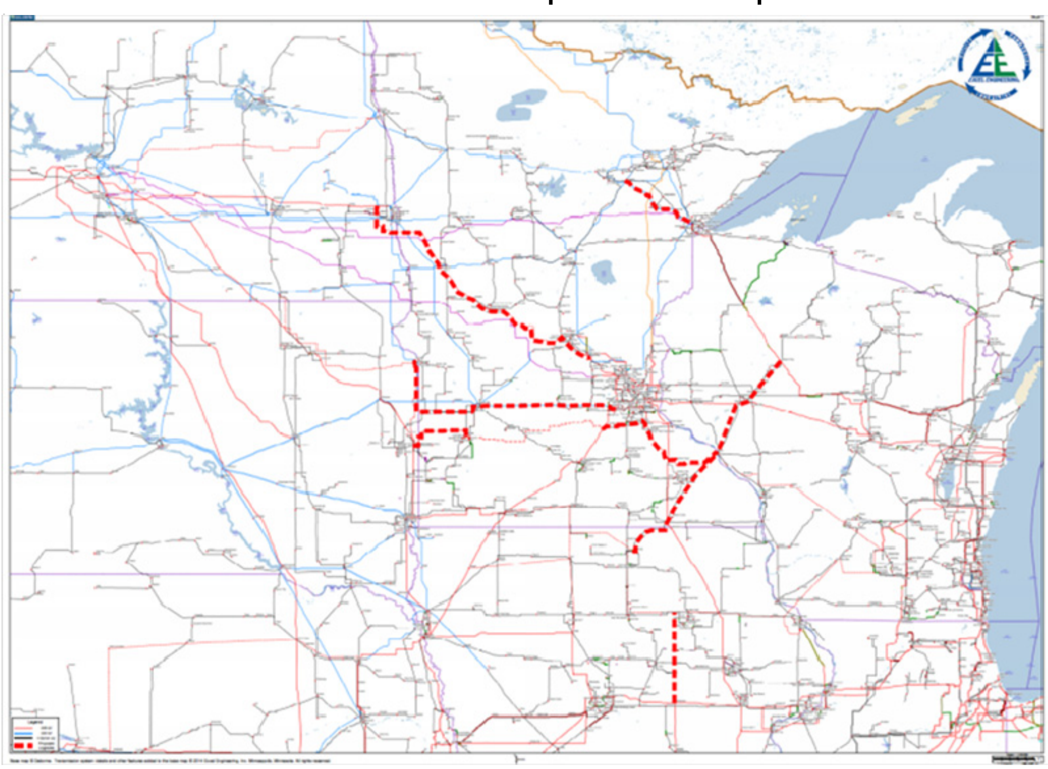
Scenario 1 Conclusions- conceptual transmission

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



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.

Operational Performance and Dynamic Simulations

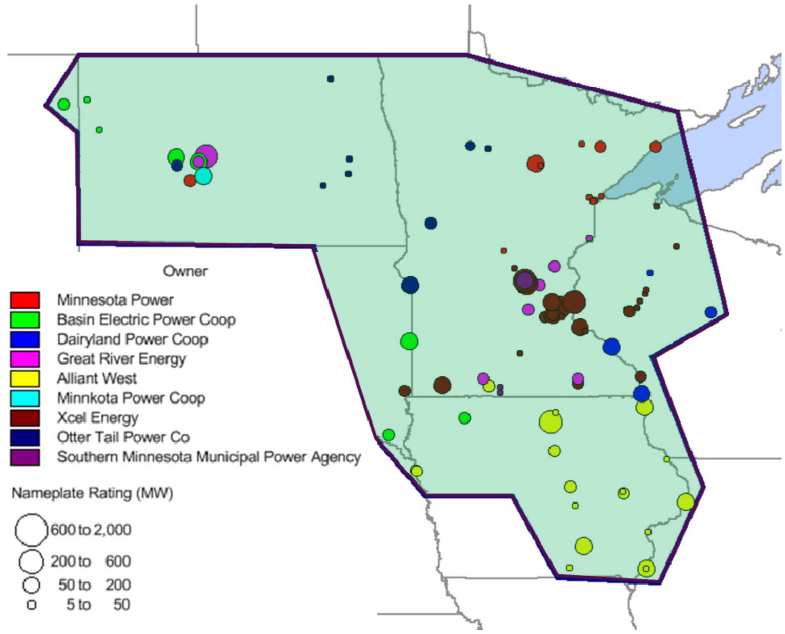
Operational Performance

The operational performance results are 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

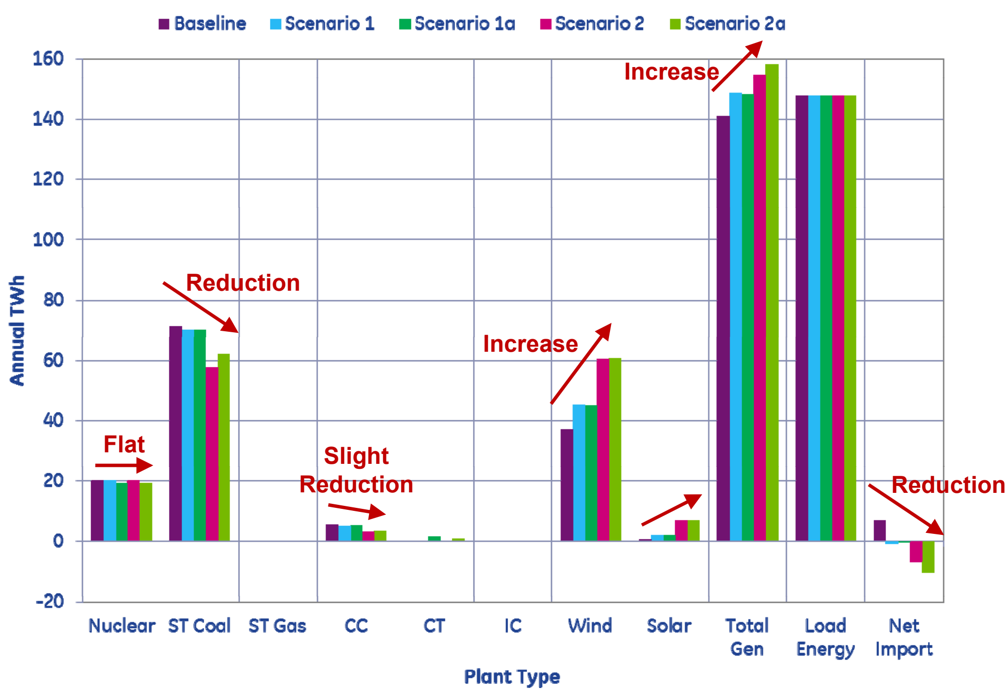
Minnesota-Centric footprint for production simulation analysis



Dots indicate generating plants owned by Minnesota Utilities

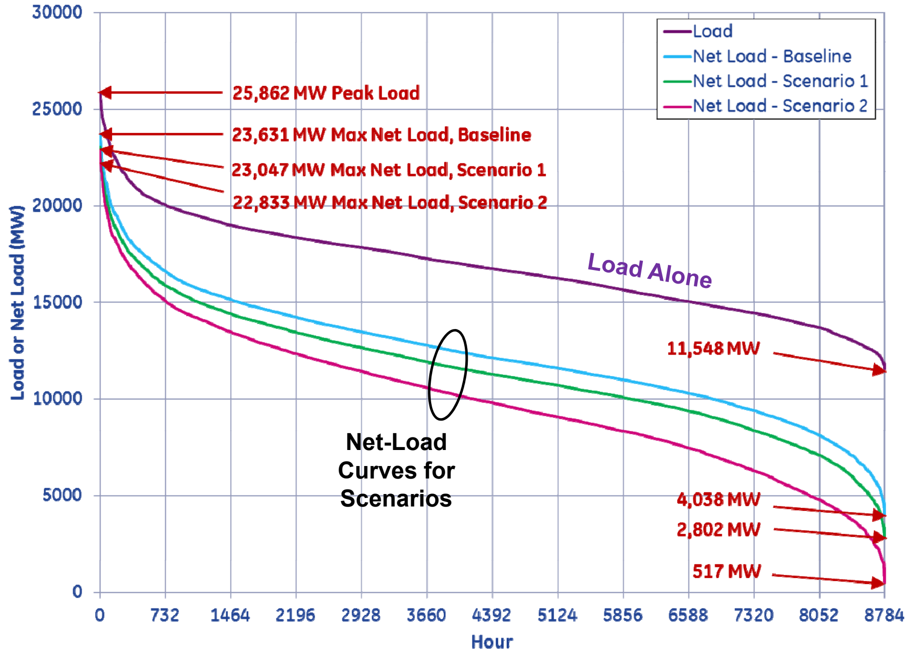
Operational Performance

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



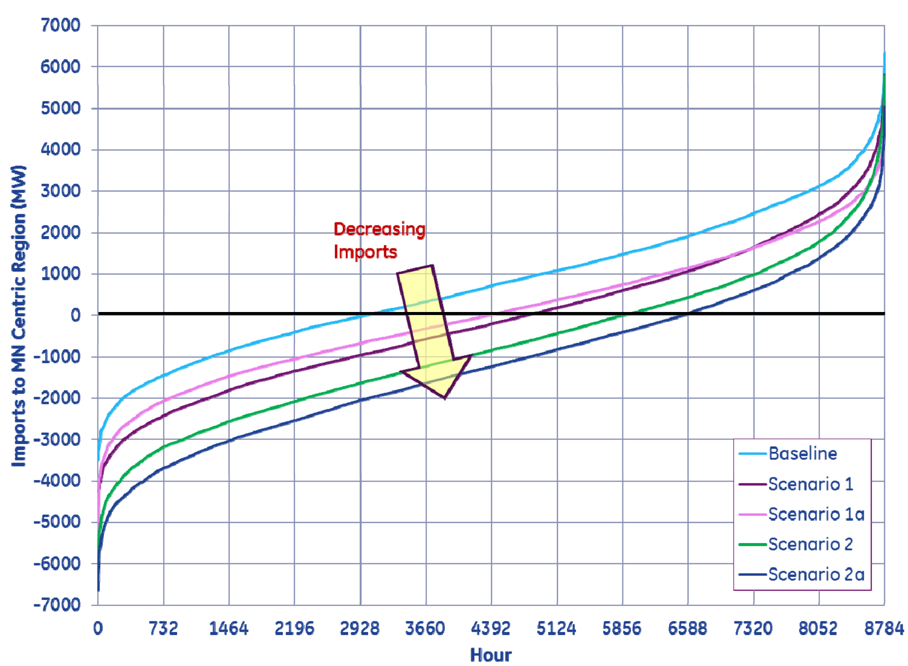
Operational Performance

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



Operational Performance

Annual Duration Curves of Energy Imports for Minnesota-Centric Region



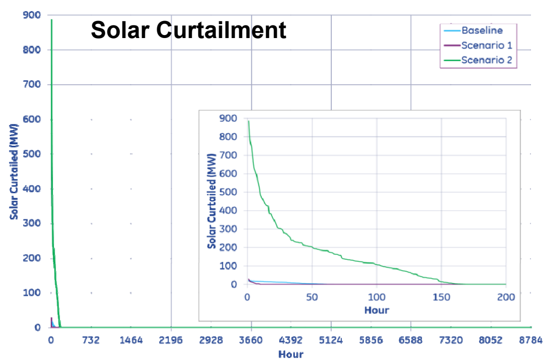
Operational Performance

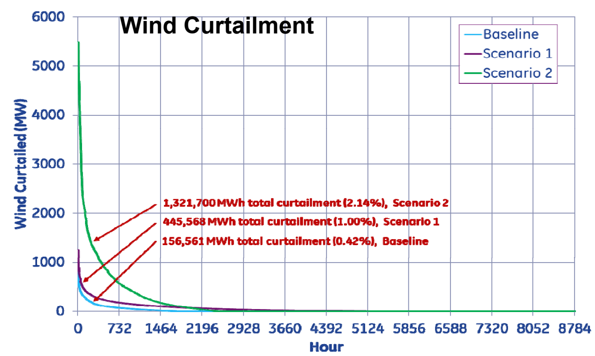
Annual Wind and Solar Energy Curtailment

- 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

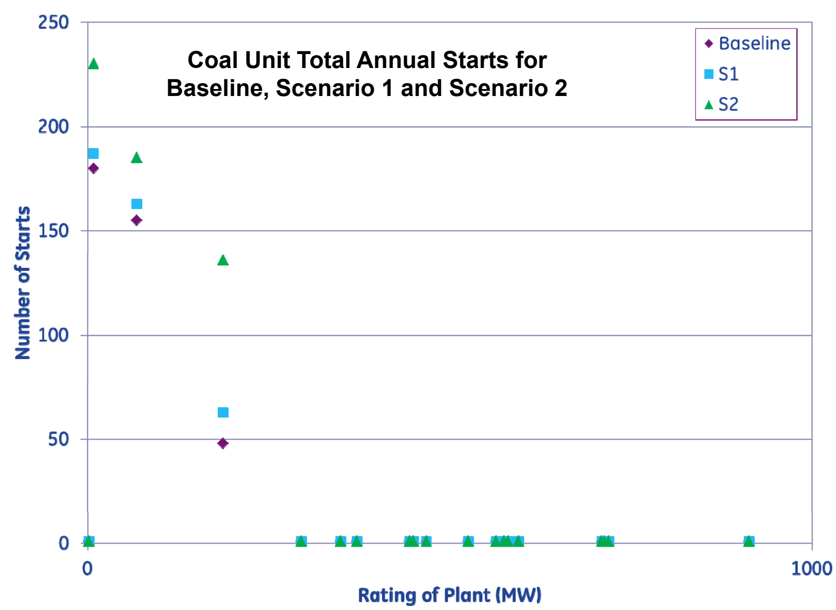




Operational Performance

Thermal Plant Cycling

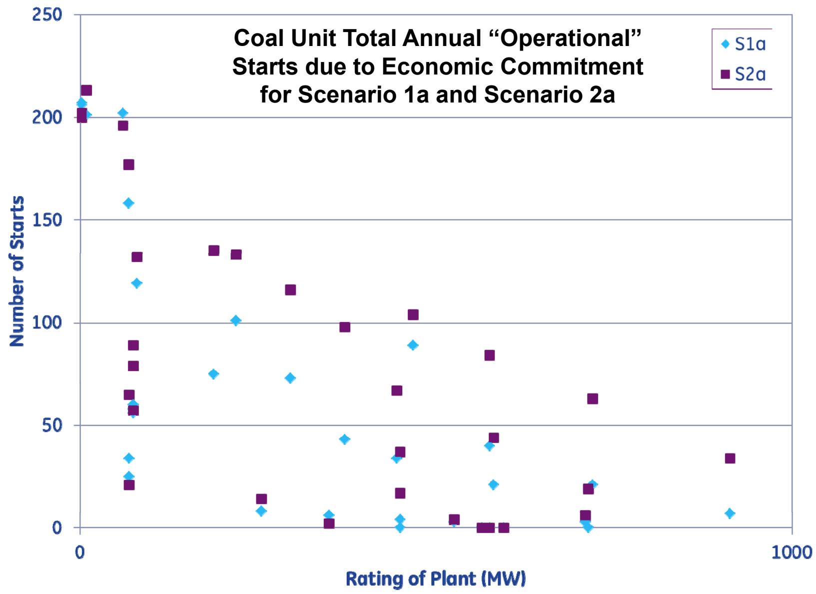
- Baseline, Scenario 1 and Scenario 2 assumed that most coal units would be operated with existing practices (must-run; not decommitted by MISO)
  - Most units have one operational start per year (must-run status)
  - Three units subject to economic commitment
  - These units also show significant cycling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



Operational Performance

Thermal Plant Cycling - continued

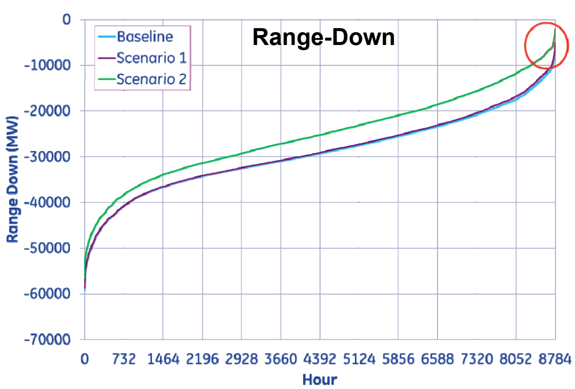
- Scenarios 1a and 2a assumed that the all coal units were subject to Security-Constrained Economic Commitment
  - Most units have a higher number of starts in Scenario 2a (50% MN RE, 25% MISO RE) as compared to Scenario 1a (40% MN RE, 15% MISO RE)
  - Some units have the nearly the same number of starts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

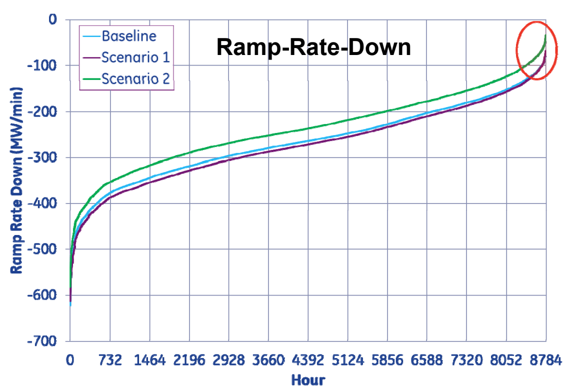


Operational Performance

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/Dynamics Issues

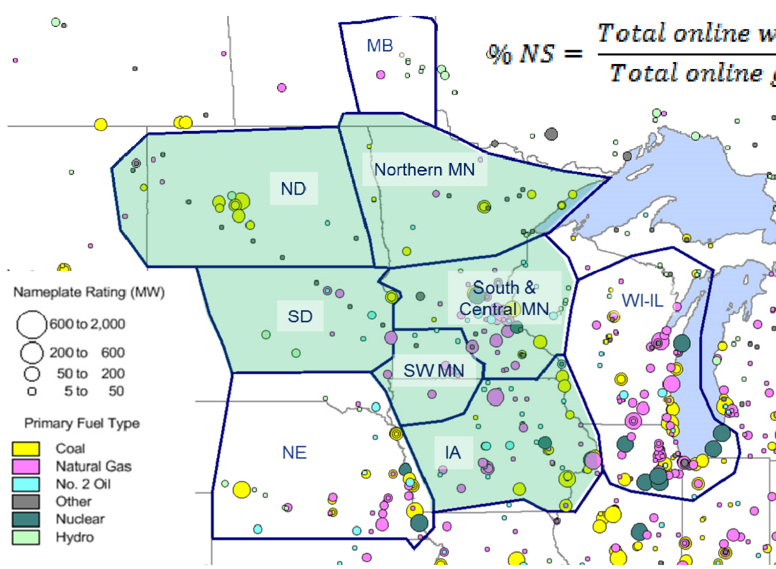
- The results of the production simulation analysis were screened to select challenging operating conditions for dynamic performance, and these operating points were subsequently analyzed with fault simulations in the dynamics task.
  - Percent Non-Synchronous Generation (% NS)
  - Percent Renewable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

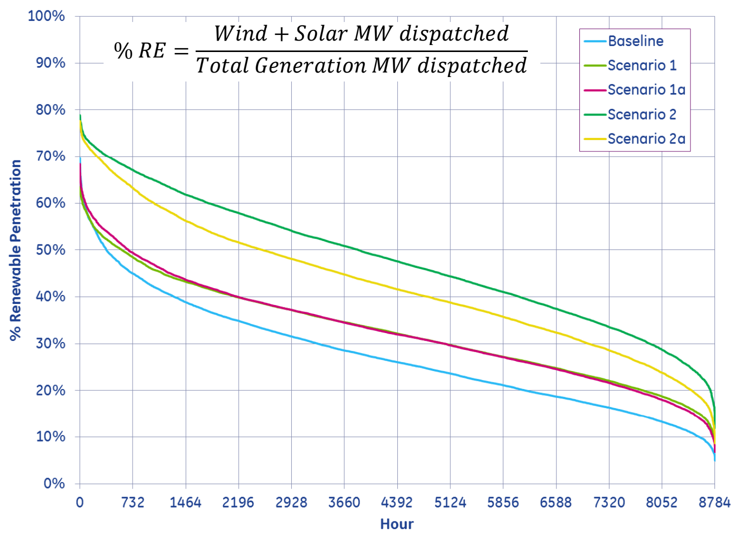
$$\% NS = \frac{Total\ online\ wind + solar\ MW\ rating}{Total\ online\ generation\ MW\ rating}$$



Operational Performance

% Renewable Energy Penetration for the MN-Centric Region

- The % RE metric was 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.

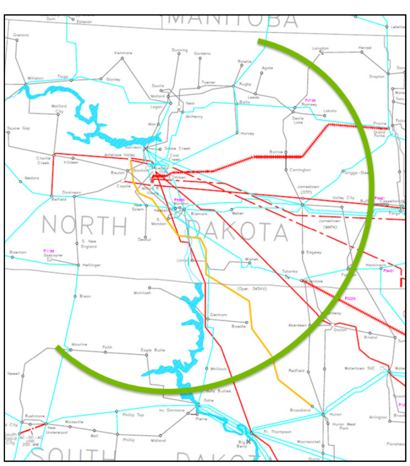


Operational Performance

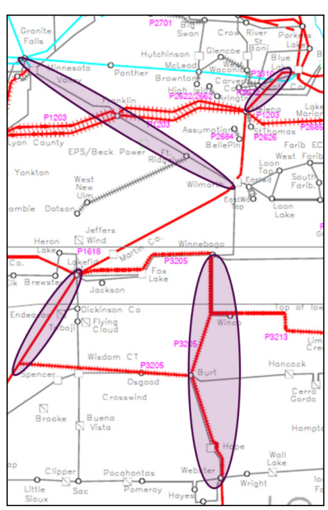
Transmission Interface Loading

- 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.

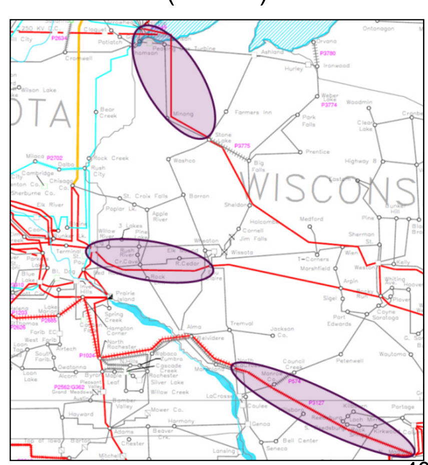
North Dakota Export (NDEX)



Buffalo Ridge Outlet



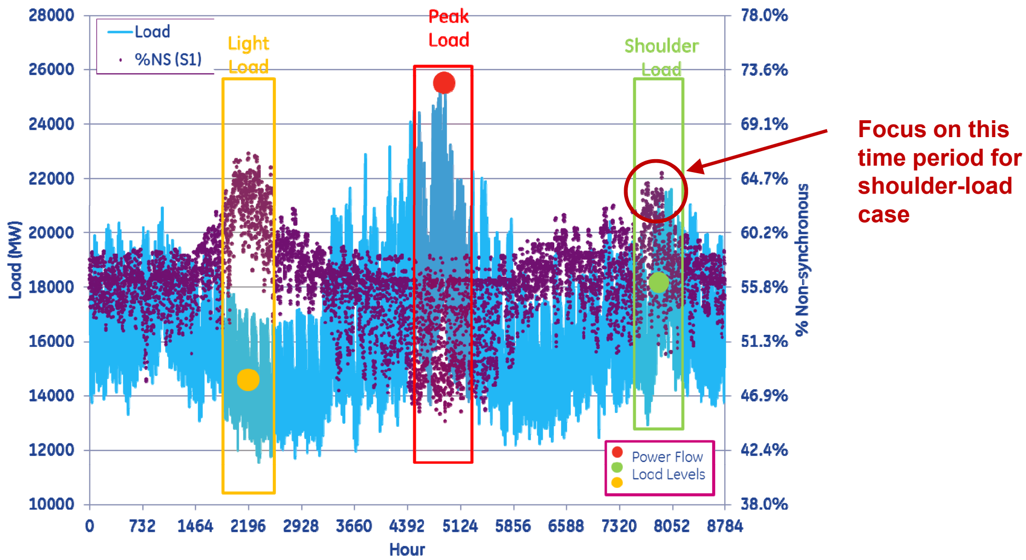
Minnesota-Wisconsin Export (MWEX)



Operational Performance

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

Selection of Operating Conditions for Dynamic Analysis

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

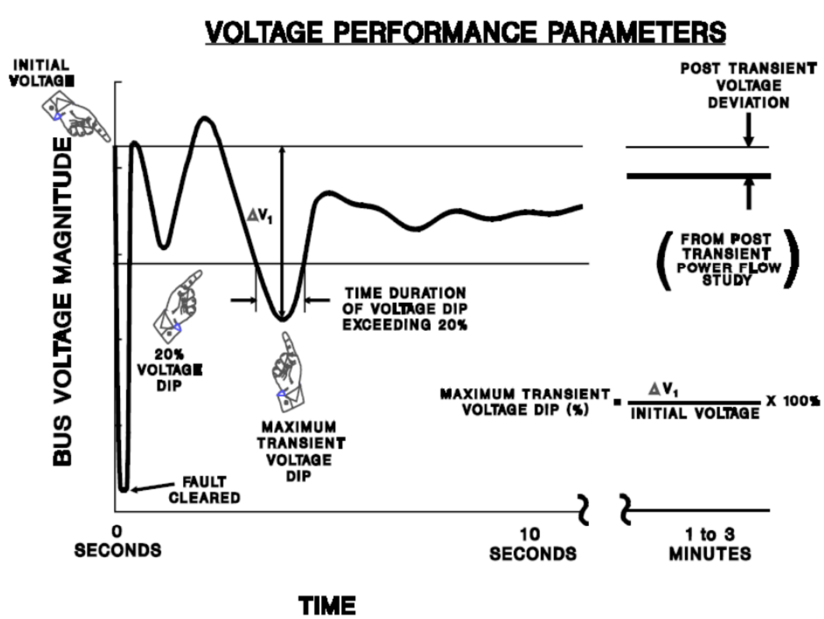
Dynamic Simulations

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



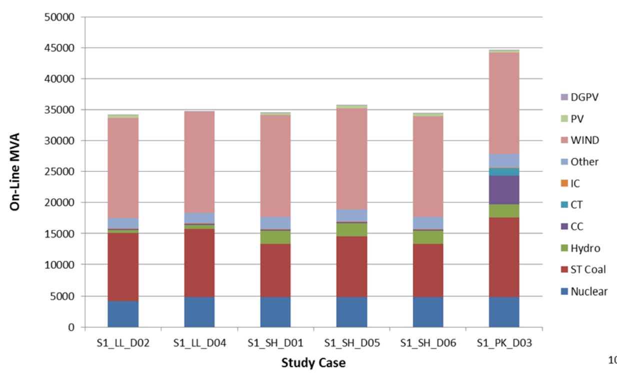
Dynamic Simulations

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

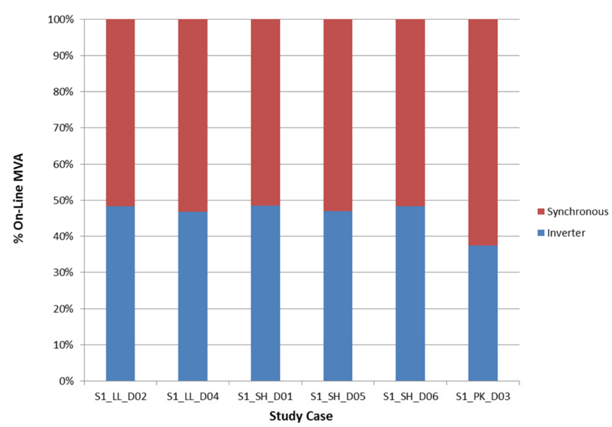
*** Note:** Case 4 has MWEX loading above 1400 MW (max value from production simulation). The impact of MWEX loading was tested using this case, subject to additional contingencies on MWEX lines.

Dynamic Simulations



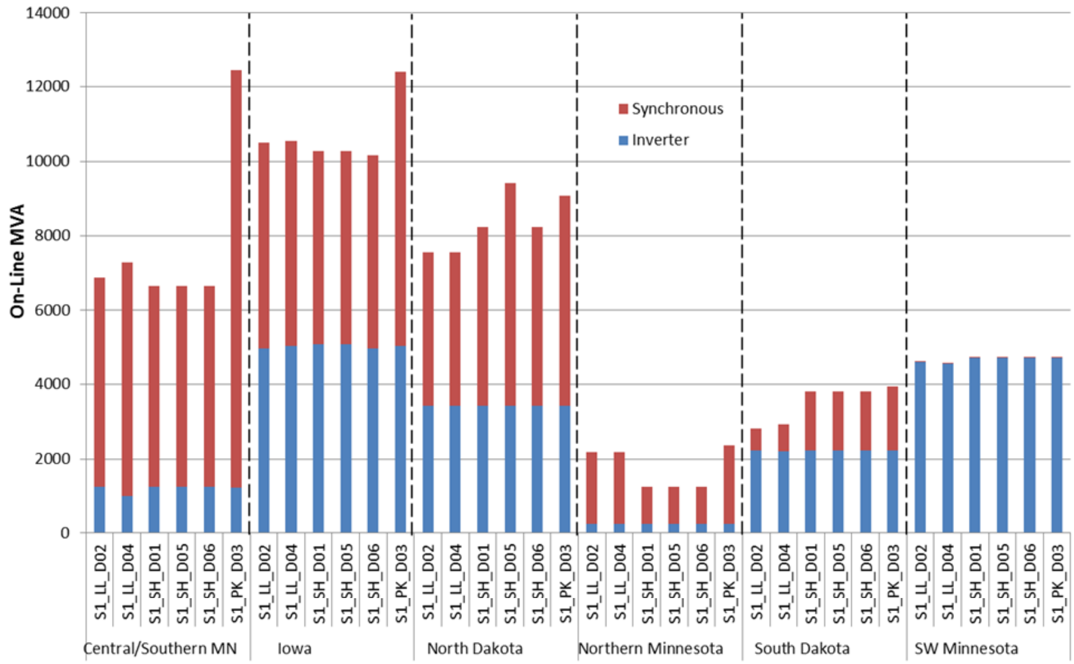
Minnesota Centric Commitment by Unit Type (MVA)

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



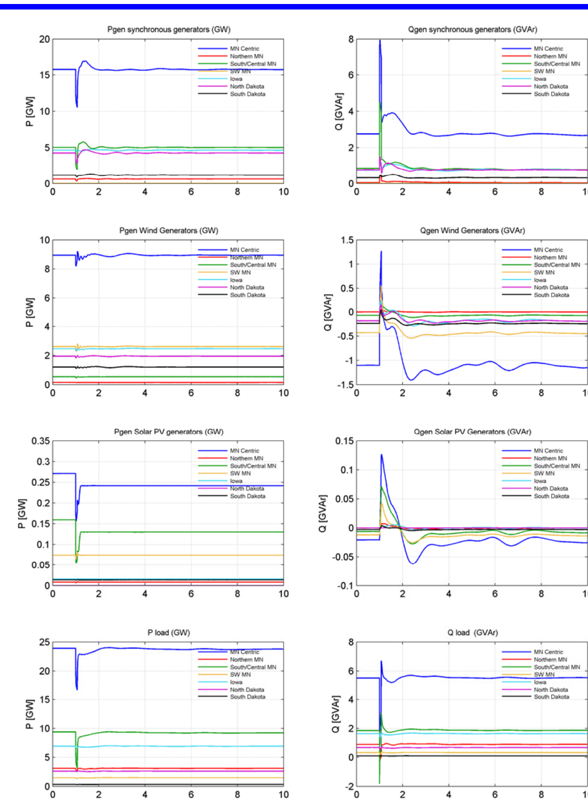
Dynamic Simulations

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**

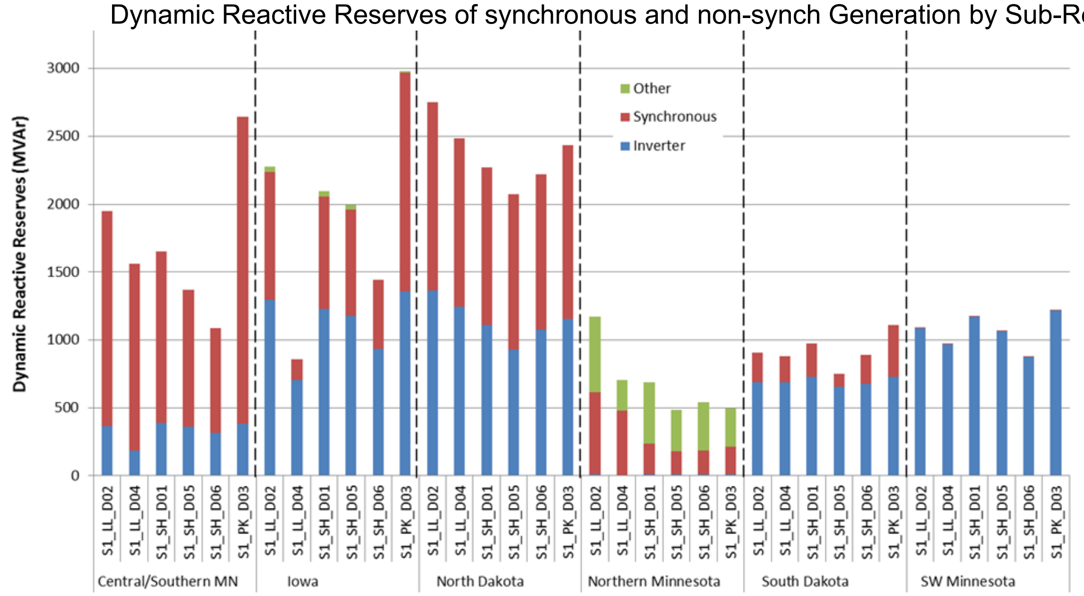
No	Fault Name	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
1	EI2	stable	stable	stable	stable	stable	stable	stable
2	AG1	stable	stable	stable	stable	stable	stable	stable
3	AG3	stable	stable	stable	stable	stable	stable	stable
4	NAD	stable	stable	stable	stable	stable	stable	stable
5	PCS	stable	stable	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

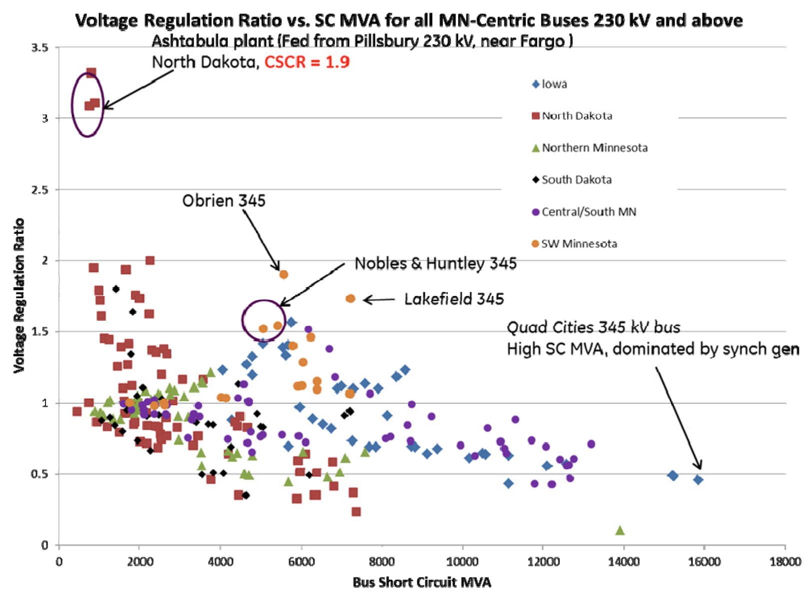
- Composite Short-Circuit Ratio (CSCR) is an indicator of the ability of an ac transmission system to support stable operation of inverter-based generation
- Low CSCR operating conditions can lead to control instabilities in inverter-based equipment (Wind, Solar PV, HVDC and SVC)
- Synchronous machines (either generators or synchronous condensers) contribute short-circuit strength to the transmission system and therefore increase CSCR.

Dynamic Simulations

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



Dynamic Simulations

Weak System Issues

- **Mitigation through Wind/PV Inverter Controls**
  - Standard inverter controls and setting procedures may not be sufficient for weak system applications.
  - 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

The approaches are complementary, so the ultimate solution for a particular region would likely be a combination.

Key Findings

Key Findings

General Conclusions for 40% Renewable Energy in Minnesota

Production simulation analysis results:

- **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 (continued)

General Conclusions for 40% Renewable Energy in MN

Dynamic simulation results:

- **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 (doubly-fed induction) and Type 4 turbines (full converter) 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 (continued)

General Conclusions for 50% Renewable Energy in Minnesota

Production simulation results:

- **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 50% renewable energy in Minnesota** (and with current renewable energy standards in neighboring MISO North/Central states increased by 10%)
  - Assumes significant upgrades and expansions to the transmission system 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 (continued)

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 (continued)

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).
- 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.

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