Modernizing Minnesota’s Grid
An Economic Analysis of Energy Storage Opportunities
MISO-wide Electricity Co-Optimized Planning Scenarios

Prepared By:

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Overview

I. Background and the WIS:dom optimization model

II. Main modeling results and analysis

III. Conclusions

IV. Modeling inputs and assumptions
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MISO high penetration renewable energy study for 2050

- In 2016, Vibrant Clean Energy, LLC (VCE) produced a high renewables study for the Midcontinent Independent System Operator (MISO).

- The study found that MISO could reduce emissions by 80% compared with 2005 levels at reasonable cost by expanding generation from wind and solar PV along with complementary natural gas and transmission.

- The present system level analysis is an expanded version of the previous MISO study carried out by VCE.
MISO high penetration renewable energy study for 2050

[Graph showing the expected generation share for different energy sources (Coal, Natural Gas, Nuclear, Hydroelectric, Wind and Solar PV) from 2016 to 2050.]
MISO high penetration renewable energy study for 2050

Including replacement of capacity costs
MISO high penetration renewable energy study for 2050

[Bar chart showing transmission capacity (MW) for different regions and years: 2016, 2030, 2036, 2050. Regions include LRZ 1, LRZ 2, LRZ 3, LRZ 4, LRZ 5, LRZ 6, LRZ 7, N-S Hub, LRZ 8, LRZ 9, LRZ 10. The chart indicates import and export of energy.]
The WIS:dom Optimization Model

- **WIS:dom is the only model to combine:**

i. Continental-scale (globally capable), spatially-determined transmission and generation expansion (3-km, hourly);

ii. Transmission power flow, planning reserves, and operating reserves;

iii. Weather forecasting and physics of weather engines;

iv. Detailed hydro modeling;

v. High granularity for weather-dependent generation;

vi. Large spatial and temporal horizons;

vii. Detailed investment periods (1-year, 2-year, or 5-year) out past 2050.
The WIS:dom Optimization Model

Detailed Input Data

WIS:dom

Numerous Objectives Output

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The WIS:dom Optimization Model
The WIS:dom Optimization Model

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The WIS:dom Optimization Model - MISO
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Key Findings

• Electric Storage in MN reduces the levelized cost of electricity throughout the MISO footprint and is always selected by 2045 when available;

• MISO is capable of reducing GHG emissions by 80% by 2050 without storage; however, with storage as an option, LCOE is reduced and less fossil fuel generation is required;

• The efficacy of electric storage is increased when used in combination with transmission expansion;

• Less transmission expansion is required when storage is selected, when all other considerations are held equal.
Key Findings (continued)

• More storage is selected by the WIS:dom optimization model when the ITC is applied to storage as well as solar PV;

• Findings are consistent and supportive of the MRITS study – MN can support 40%+ variable generation.
  ➢ Current study finds least-cost configurations throughout MISO based upon hourly, high granularity weather data for variable renewables;
  ➢ WIS:dom finds economic and constrained scenarios to determine an agnostic envelope parameter space for role of different technologies;

• Storage provides lower costs, higher resiliency (greater portfolio diversity), reserves, sustainable resource use, and increased transmission efficiency.
### WS:dom Simulation Matrix For Study

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Results archive is found through: [http://www.vibrantcleanenergy.com/media/reports/](http://www.vibrantcleanenergy.com/media/reports/)
J09: No Transmission Expansion, No Storage, No GHG Constraints

![Percentage of 2005 Emissions by Year](chart1)

![LCOE for No Transmission, No Storage, No GHG Constraints Scenario](chart2)

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By allowing storage to participate (along with transmission) the GHG emissions decrease and so does the cost of electricity.
J02: Transmission Expansion, Storage Allowed, No GHG Constraints
J02: Transmission Expansion, Storage Allowed, No GHG Constraints

High Voltage Transmission Capacity between MISO Regions

- 2017
- 2020
- 2025
- 2030
- 2035
- 2040
- 2045
- 2050

LRZ 1 → LRZ 2 → LRZ 3 → LRZ 4 → LRZ 5 → LRZ 6 → LRZ 7 → N-S Hub → LRZ 8 → LRZ 9 → LRZ 10

Export to Hub
Import from Hub
J06: Transmission Expansion, Storage Allowed, GHG Constrained

Storage (with transmission) assist in the reduction of GHGs at lower cost than without storage and facilitate higher amounts of RE
J06: Transmission Expansion, Storage Allowed, GHG Constrained

Wisdom Installed Capacities for Minnesota

Wisdom Installed Capacities for M&O

Wisdom Estimated Electricity Generation By Source (2017)

Wisdom Estimated Electricity Generation By Source (2050)
J06: Transmission Expansion, Storage Allowed, GHG Constrained

Substantially reduces the amount of transmission needed, compared with previous MISO report.
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Conclusions: Summary From Other Cases

- Forced storage scenario results in an increase in LCOE of 0.2% compared with the J09, but with **3% lower GHG emissions**. Forced storage increases by 3 GW each investment period to 24 GW by 2050.

- Storage including ITC results in earlier adoption by the WIS:dom model of storage. It facilitates a reduction in LCOE of 0.5% and an additional **6 GW** of storage by 2050.

- Whenever transmission expansion is allowed, WIS:dom selects more storage than when it is not allowed.

- More solar PV is selected by WIS:dom when more storage is available.

- Storage competes with and reduces CTs in some regions of MISO as storage becomes economical. Particularly in the “forced storage” scenario.

- All other results are consistent with those shown; more transmission results in more storage deployed, emission targets increase storage deployment, increased storage promotes more solar PV deployment.
Conclusions

- Adopting storage now adds no significant cost or risk to the MN energy portfolio; rather it facilitates a more diverse future portfolio.

- Storage assists with reaching RPS goals/targets and can lower the cost of energy across MN and MISO.

- Storage helps reduce the burden on transmission when high renewables exist.

- Storage replaces CTs on a cost basis by (at least) 2040, much earlier if ITC is included.

- Storage is a useful tool in providing a “least-regrets, least-cost” energy transition strategy.
Thank You

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Modeling Inputs and Assumptions

Capital Costs for Conventional Generation

- Coal: $3,470
- Combined Cycle: $977
- Combustion Turbine: $829
- Nuclear: $5,325
- Hydro: $2,483
Modeling Inputs and Assumptions

Capital Costs for Renewable Generation

- Storage
- Wind - Onshore
- Solar PV - Utility
- Solar PV - Residential

Year

Cost ($/kW)

2015 2020 2025 2030 2035 2040 2045 2050 2055

1,800 1,408 1,101 995 899 813 735 895 852 664
1,449 1,404 1,104 1,041 1,487 1,558 1,551 1,553 1,547 1,536
2,254 2,215 1,745 1,583 1,376 1,376 1,376 1,376 1,376 1,376
2,759 2,759 2,759 2,759 2,759 2,759 2,759 2,759 2,759 2,759

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Modeling Inputs and Assumptions

Fuel Costs for Thermal Generation

- Natural Gas
- Coal
- Uranium

Cost ($/MWh) vs. Year

Year: 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050, 2055

Cost: 3.89, 4.62, 5.23, 5.06, 5.19, 5.16, 5.16, 5.16

Energy and Utility Costs

Cost: 2.08, 2.26, 2.33, 2.41, 2.51, 2.60, 2.60, 2.60

Year: 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050, 2055

Cost: 0.71, 0.71, 0.71, 0.71, 0.71, 0.71, 0.71, 0.71

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Fixed Operation and Maintenance Cost of Each Technology

- Coal: $28.75
- Combined Cycle: $14.75
- Combustion Turbine: $10.30
- Nuclear: $92.05
- Hydroelectric: $14.00
- Wind - Offshore: $29.50
- Solar PV - Utility: $14.75
- Solar PV - Residential: $17.70
- Storage: $16.00

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Modeling Inputs and Assumptions

Variable Operation and Maintenance Cost of Each Technology

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost ($/per megawatt hour MWh)</th>
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<td>Storage</td>
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</tbody>
</table>

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Modeling Inputs and Assumptions

Heat Rates for Thermal Generators

- Coal: 10,300 Btu/kWh
- Combined Cycle: 6,430 Btu/kWh
- Combustion Turbine: 9,750 Btu/kWh
- Nuclear: 10,700 Btu/kWh
Modeling Inputs and Assumptions

Economic Lifetime of Each Technology

- Coal: 53 years
- Combined Cycle: 38 years
- Combustion Turbine: 30 years
- Nuclear: 60 years
- Hydroelectric: 75 years
- Wind - Onshore: 30 years
- Solar PV - Utility: 30 years
- Solar PV - Residential: 30 years
- Storage: 20 years
- Transmission: 75 years
Modeling Inputs and Assumptions

WIS:dom Weighted Average Cost of Capital (WACC)

- Coal: 6.78%
- Combined Cycle: 6.78%
- Combustion Turbine: 6.78%
- Storage: 6.78%
- Nuclear: 6.78%
- Hydroelectric: 6.78%
- Wind: 6.78%
- Offshore Wind: 6.78%
- Solar PV - R: 6.78%
- Solar PV - U: 6.78%
- CSP: 6.78%
- Geothermal: 6.78%
Modeling Inputs and Assumptions

Capacity of transmission lines by voltage and length (SIL method)