MN SOLAR PATHWAYS

Solar Potential Analysis – MISO Region

PATHWAYS TO 100% RENEWABLES ACROSS THE MISO REGION: SUMMARY OF FINDINGS
JUNE 30, 2020

PREPARED FOR
MINNESOTA DEPARTMENT OF COMMERCE
AND THE MINNESOTA SOLAR PATHWAYS PROJECT

PREPARED BY
CLEAN POWER RESEARCH
MARC PEREZ

Clean Power Research®

SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Prepared by:
Marc Perez

Clean Power Research, LLC
1541 Third Street
Napa, CA 94559-2808
www.cleanpower.com

Contract Number: 124495

Prepared for Minnesota Department of Commerce, Division of Energy Resources:
Steve Kelley, Commissioner, Department of Commerce
Aditya Ranade, Deputy Commissioner of Energy Resources, Department of Commerce

Lise Trudeau, Project Manager, Department of Commerce, Division of Energy Resources
Phone: 651-539-1861
Email: Lise.Trudeau@state.mn.us

Acknowledgements

This work was funded in part by the U.S. Department of Energy Solar Energy Technologies Office under Award Number DE-EE0007669. The Solar Energy Technologies Office supports early-stage research and development to improve the affordability, reliability, and performance of solar technologies on the grid. Learn more at Energy.gov/solar-office.

Disclaimer

Table of Contents

MN Solar Pathways Overview 4
Introduction 6
Key Findings 7
Constraints of the Solar Potential Analysis for the MISO region 9
Clean Power Transformation (CPT) Model overview 10
Inputs 11
Results 16
Conclusions 24

MN Solar Pathways Overview

Minnesota is a longstanding, nationally recognized leader in energy efficiency and wind development. In recent years, Minnesota has established leadership in solar deployment as well, including hosting the most community solar capacity in the country and a solar electricity standard of 1.5 % as part of the 20 % renewable electricity standard by 2020. The State also adopted a goal of meeting 10 % of the state's electricity needs with solar by 2030.

The Minnesota Solar Pathways (Pathways) initiative, funded by the U.S. Department of Energy Solar Energy Technologies Office (DOE SETO), is a three-year project designed to explore least-risk, best-value strategies for meeting the State of Minnesota's solar goals. As part of this aim, the Pathways Team modeled renewable generation costs, examined ways to streamline interconnection, and evaluated technologies that can increase solar hosting capacity on the distribution grid.

The Pathways Team is comprised of a Core Team and a Technical Committee. The Core Team consists of MN Department of Commerce, Center for Energy and Environment, Clean Energy Resource Teams, Clean Power Research, and the Great Plains Institute. The Technical Committee is the foundation for the project's stakeholder collaboration process and is comprised of 22 organizations. These organizations include cities, corporations, non-profits, consumer representatives, solar installers, and utilities. See Figure 1 below for a list of organizations involved.

Figure 1 : *MN Solar Pathways* team members

Responsibilities of the Core Team and the Technical Committee

To accomplish the Pathways goals, each of the five organizations making up the Core Team took a lead role in various aspects of the project.

- The Minnesota Department of Commerce is the project manager and fiscal agent responsible for reporting to the U.S. Department of Energy.
- The Great Plains Institute (GPI) is the lead facilitator for the Technical Committee and other stakeholder work.
- Clean Power Research (CPR) is responsible for the development of two models and leads all technical work with input from the Technical Committee.
- Center for Energy and Environment (CEE) is the lead on quality control and supports Clean Power Research with data needs.
- Clean Energy Resource Teams (CERTs) is the lead partner responsible for communications, including dissemination of project results and outreach.

Technical Committee members, composed of stakeholders from both the private and public sectors, agreed to several conditions for participation, including meeting bi-monthly throughout the project to inform technical decisions that form the basis of the modeling. Members work collaboratively to make recommendations regarding inputs and variables to strengthen project results. The Technical Committee was instrumental in defining the scenarios and informing the analysis described in this report.

Although the Technical Committee often reached agreement on key project inputs and recommendations, consensus was not a primary goal as modelling allowed for multiple scenarios to be run and compared.

The process for taking input and developing the Solar Potential Analysis (SPA) model was iterative as the Core Team completed work with input from the Technical Committee and reported back. See Figure 2 below for the various roles and structure for completing technical work under Pathways.

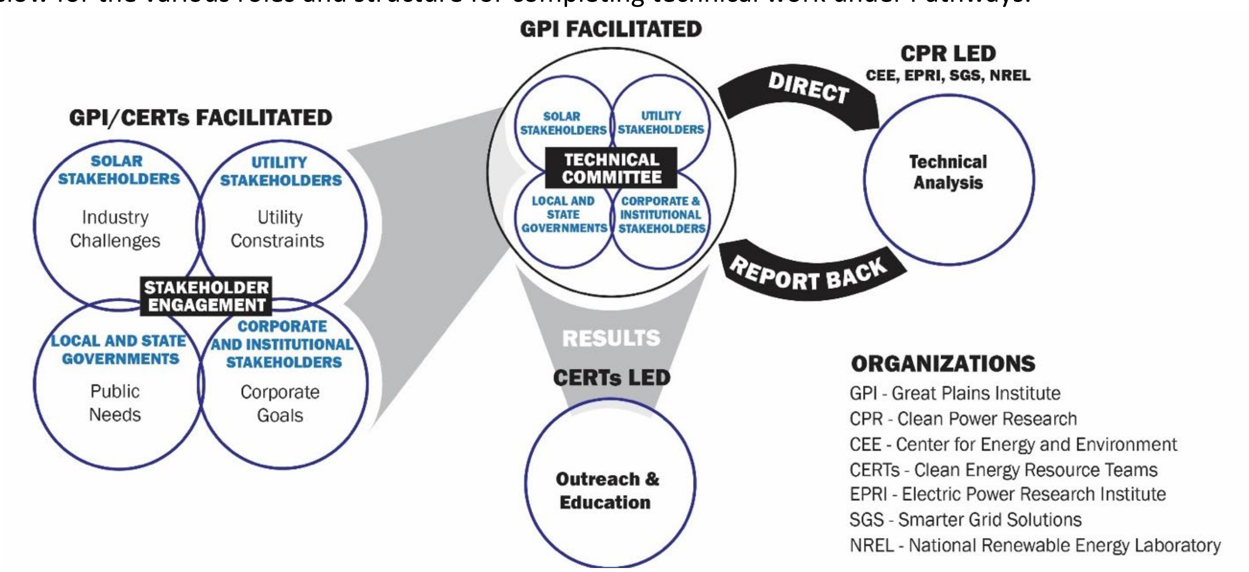


Figure 2 : *MN Solar Pathways* project structure

Introduction

This study attempted to model the generation costs of high penetrations of renewables across the Midcontinent Independent System Operator (MISO) region.

The DOE SETO-funded Minnesota Solar Pathways project began in 2016 and set out to perform a Solar Potential Analysis (SPA). The SPA modeled the cost of generation serving Minnesota's current and future electrical load with high penetrations of renewables. Differing assumptions regarding future costs, electrification and technological diffusion formed 16 unique scenarios across which renewable capacity expansion and dispatch were optimized on a least-cost basis. Upon the conclusion of the Minnesota SPA, the Technical Committee decided to expand the geographic scope of the analysis to study high renewables penetrations across the entirety of MISO, illustrated in Figure 3 below.

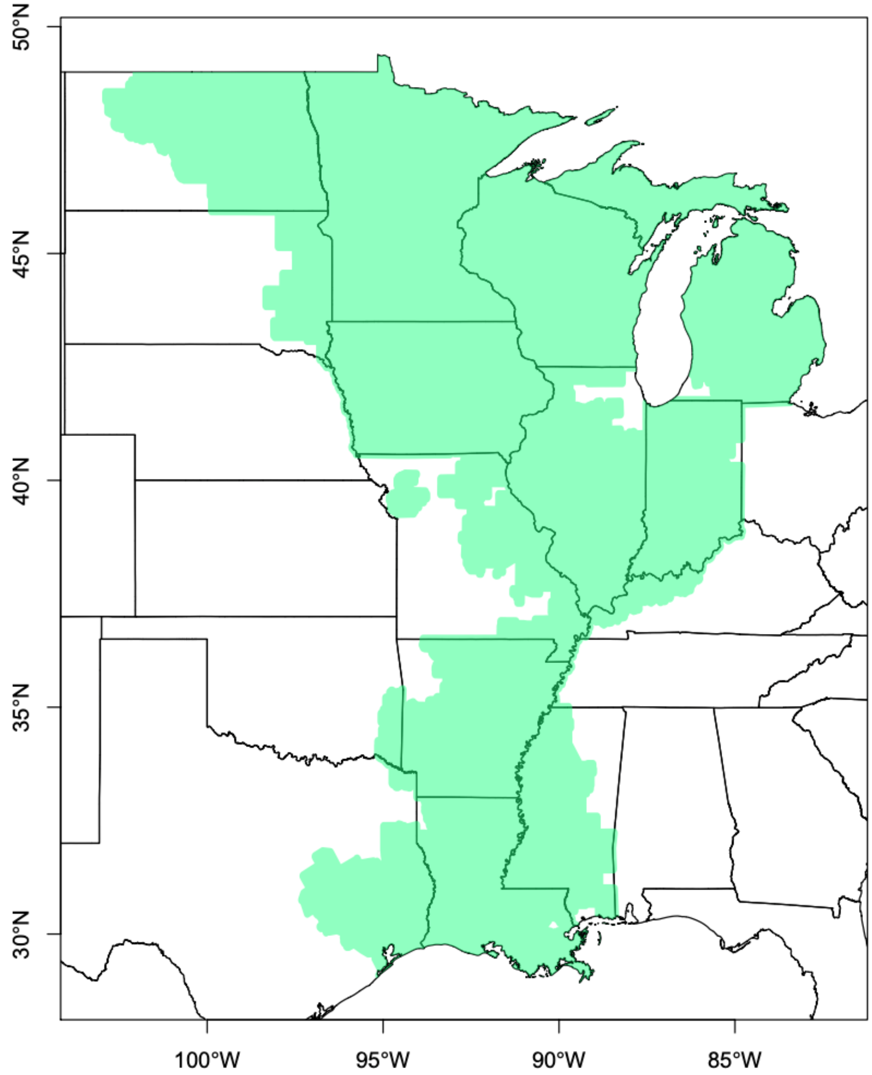


Figure 3: The geographic extents of the MISO region with the continental United States- extending from the Great Lakes region in the North to the Gulf of Mexico in the South.

The project team used the same modeling framework from the Minnesota study to optimize capacity expansion and dispatch of renewables on a Levelized Cost of Electricity (LCOE) basis across 13 distinct geographic regions (10 Load Resource Zones and 3 Regions) that subdivide the MISO system, each with their own unique load and renewable resource characteristics. Capacities of wind, PV and energy storage that together yield the lowest possible electricity generation cost were identified across each of these geographic regions and using four unique technological cost forecasts. More details surrounding the scenario construction can be found in the *Inputs* section.

In addition to this report, interested parties can learn more about the analytical process and dive into the study's outputs through (1) a PowerPoint presentation and webinar, and (2) a dynamic web-tool.[1] Users can thereby learn more about the overall project, modeling approach, and investigate how changing input assumptions (geographic region, cost and dispatchable allowance) affects the least-cost resource mix and dispatch.

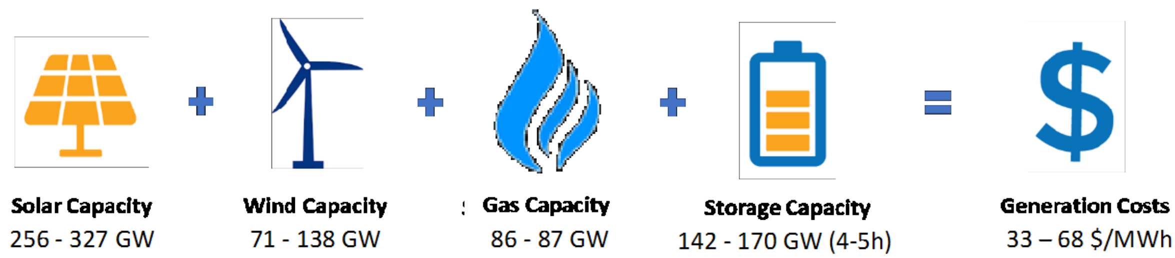
Key Findings

- **Cost of 100% renewable generation by 2050 could be on par with present-day wholesale electricity generation costs in the MISO system ($40/MWh vs. $30/kWh):** Modeling indicates that wind, solar, and storage can firmly serve 100% of load across MISO by 2050 at an LCOE of $40/MWh, comparable to present-day fossil-dominated electricity generation costs ($30/MWh average LMP in MISO).
- **Cost of 95% renewable generation by 2050 could be equivalent to present-day wholesale electricity generation costs across MISO ($20-$30/MWh) :** Generation costs, which in the modeling include the operational and capital costs of electrochemical storage, as well as overbuilding + curtailment (implicit storage) of PV and Wind, can be roughly halved if existing gas or other similarly-priced dispatchable assets are leveraged to provide backup 5% of the time.
- **Overbuilding + curtailment of PV (implicit storage) yields more relative cost savings than the implementation of any other operational strategy studied:** Overbuilding plus curtailment of PV acts as "implicit storage" by providing the same service otherwise provided by energy storage in a high-penetration scenario: assuring supply in otherwise low-yield periods. Because of the corresponding reduction in storage needed to meet demand during these periods, the cost of firm power generation is reduced by nearly a factor of 10. Relative to the cost-reduction from geographic dispersion of renewable generation assets or from the anti-correlation of wind and solar resources, this strategy delivered the most cost-savings.
- **Wind+PV hybridization can reduce costs:** Though not as dramatic a savings as the "implicit storage" scenario, wind + PV complement each other, even in areas where the one resource is dominant over the other. Across the MISO region, the wind tends to blow when the sun isn't shining (and vice-versa). The resources are "anti-correlated" and can deliver cost-savings if optimized.
- **Changing the future cost assumptions for the technologies firmly meeting load (wind, PV, storage) changes the optimal technological mix:**
    - Raising the LCOE of wind relative to PV decreases the cost-optimal wind percentage in MISO.
    - Raising the LCOE of energy storage relative to renewables increases the amount of implicit storage used to achieve minimal cost.
    - Confidence and consensus surrounding LCOE will help solidify understanding surrounding cost-optimal capital outlays when planning for high-penetration renewables.

[1] Each of these items is available at MnSolarPathways.org/MISO-SPA/

- **Because forecasted solar PV costs see a larger decline than wind costs in 2050, PV ends up serving a larger percentage of load than wind across most regions and cost scenarios studied:** In 2050, high technology development scenarios forecast a stronger cost decline for PV than wind. When capacities are optimized to serve load on a cost basis, PV contributes more to load than wind across most of the 14 regions of MISO, despite a very strong wind resource in the northern part of MISO territory. The only exceptions are the Load Resource Zones (LRZ) 3 and 7, where the wind resources are excellent.
- **The MISO Interconnection saves ratepayers money:** Local variability of wind and solar level out in aggregate across MISO's footprint, saving ratepayers in MISO billions of dollars annually relative to the cost of balancing variation with wind, PV and storage in smaller, isolated geographic regions.[2] The caveat is that the transmission and distribution required to support this geographic dispersion will need to be bolstered. Although we did not study the marginal Transmission & Distribution (T&D) upgrades required to support the degree of renewable penetration in this study, our simple calculation indicates that the transmission components would be minimal (a small %) relative to costs resulting from energy supply.[3]
- **95% solar and wind by 2050 could be economic in MISO:** With new-build dispatchable generation supplying 5% of MISO load, modeling indicates that the remaining 95% could be capable of being firmly met by a combination of wind, solar and storage at an LCOE of $33-$68/MWh.

95% Solar and Wind by 2050 across the MISO System



[2] To illustrate this principle, consider the following thought experiment. Take 1kW of PV at put it all in one location: this location will 'see' the passage of intermittent clouds in its output signature. Divide this 1kW of PV between two sites some distance away from each other and while one half of the system 'sees' the cloud, the other half will see sunshine. After passing the first site, it will cloud the other after some time. This de-correlation in the fluctuations across this plant divided in two yields an aggregate reduction in variability. The greater the number of de-correlated sites of this nature (which is more likely to be the case across larger regions) and the lower the aggregate variability of the yield. The example was for PV but the same principle is true for wind production; also at the mercy of stochastic meteorological phenomena.

[3] The Minnesota Renewable Energy Integration & Transmission Study (MRITS) study written by GE Energy in 2014 looked at transmission and distribution costs for significantly increasing renewables in MN and MISO (50% renewables in MN and 25% in MISO.) Capital costs for new and upgraded T&D were nominally large, but when amortized per kWh, they are insignificant compared to the capital outlays for new renewables. An estimated $2.6 B to support this scenario, amortized across 30 years of 666 TWh/yr, is 0.01 cent/kWh. Even if the T&D upgrade costs are 50 times more expensive to support 100% renewables than in the MRITS study, the amortized cost is still only a marginal expense for T&D expansion of 0.05 cent/kWh. https://mn.gov/commerce-stat/pdfs/mrits-report-2014.pdf

Constraints of the MISO Solar Potential Analysis

Three factors that could affect the cost of high-penetration renewables were not researched as part of this study at the direction of the Technical Committee (TC):

- **Electrification:** Unlike the MN SPA, this project did not investigate changes in future load shape if electrification of the heating and transport sectors increases in MISO. Assuming driving behavior does not drastically change, the MN SPA showed that electrified transportation loads would not alter the load's seasonal shape, just its magnitude. Heating electrification was shown to alter the seasonality of MN's load shape given that heating demand occurs during the winter. Under the MN SPA, meeting future loads with electrified heating shifts the optimized wind/PV balance-point further towards wind. This was reflective of the better seasonal match between winter loads and the winter wind resource in Minnesota. Solar, being a summer-peaking renewable resource has a better seasonal match with air-conditioning loads. In the MN SPA, we saw LCOEs for meeting MN load increase by 5% when the heating sector was fully electrified. The expectation that a similar relative increase when heating loads across MISO are electrified is reasonable.
- **T&D costs**: As with the MN SPA, the project stakeholders made a decision to only investigate *generation* costs associated with reaching high penetration renewables futures. For an assessment of costs linked to increased renewables' penetration across this region, the MRITS study provides good context, albeit at lower penetration.[3]
- **Load Shifting:** The MISO SPA did not look at demand-side load shifting. Reductions in LCOE from shifting newly electrified (water and space) heating and transportation loads were discussed in the MN SPA and the lessons learned regarding the magnitude of generation-cost reduction could certainly be applied across the MISO region. For reference, load-shifting of Domestic Hot Water (DHW) and Electric Vehicle (EV) loads was found to reduce LCOEs a further 10-20% under the MN SPA.

Clean Power Transformation (CPT) Model overview

The CPT model used in the MISO SPA work is a techno-economic optimized capacity expansion and dispatch model capable of identifying how to guarantee load in the most cost-effective manner across regions small and large with diverse demand and resource characteristics. The load to be guaranteed can be utility- or ISO-wide demand, or the demand of an individual industrial service like an electrolysis or desalination facility. The team has successfully used the CPT model to perform studies for subtropical island grids[4,5], states[6,7,8,9,10] (Minnesota and New York), the national power grid in Italy[11,12] and others.

The CPT model ingests detailed demand data, future electrification plans, and technology costs and characteristics. It evaluates combinations of technologies and renewable penetration levels under each user-defined scenario and produces the optimum deployment of technologies at the lowest cost. The model ensures that scenario constraints are observed and that all forecasted loads are met.

The CPT model has the capability to consider various types of storage (electrochemical, physical, etc.), solar and wind capacities and detailed performance characteristics, the degree of transportation and building electrification, energy efficiency and the implementation of flexibility strategies on both demand- and supply-sides.

A 100% renewable-powered system—be it a continent-spanning system the size of the MISO or a system reflecting the demand of an individual server farm—typically results in a mismatch between supply and demand. This mismatch can occur on a daily basis (excess solar energy during the day and insufficient energy at night), a multi-day basis (insufficient energy due to several cloudy days in a row) and a seasonal basis (excess energy in the summer and insufficient energy in the winter). The most challenging and costly issue is the seasonal mismatch.

There are three ways to address a seasonal mismatch. One option is to use very long-duration storage to move energy from one season to another. The second option is to increase supply during the supply-constrained season. The third option is to use energy efficiency to reduce demand during the supply-constrained season. The CPT model develops solutions that optimize across all three options. Simultaneously considering all three options (long-duration storage, supply increases via implicit storage, and demand reductions) will advance the scientific understanding of how to construct the optimal portfolio of resources.

In the MISO SPA work, the CPT model was used to optimize across the supply-side interventions: long-duration storage and implicit storage.

---

[4] Tapaches, E., R. Perez, P. Lauret, M. Perez & M. David, (2019): Mitigation of the Variability of a PV Fleet via Geographical Dispersion and Energy Storage Systems on the Reunion Island - Proc. 46th IEEE PV Specialists Conference (oral), Chicago, Il

[5] Tapaches, E., R. Perez, M. Perez, T. Chamarande, P. Lauret & M. David, (2020): Rapport Technique Projet PEPS Réunion – Rapport du Laboratoire PIMENT de l'Université de la Réunion, Mai 2020.

[6] Perez, M.J.R., Putnam, M. (Minnesota Department of Commerce), (2018): Solar Potential Analysis Report

[7] Perez, M.J.R., R. Perez, K. R. Rábago & M. Putnam, (2018): Overbuilding & curtailment: The cost-effective enablers of firm PV generation. Solar Energy 180, 412-422

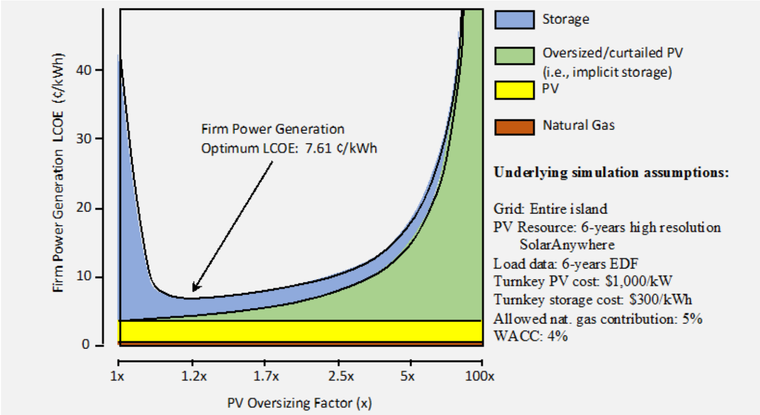
[8] Perez, M.J.R., R. Perez, K. R. Rábago & M. Putnam, (2019): Achieving 100% renewables: supply-shaping through curtailment. PV Tech Power 19, 56-61

[9] Perez R., et al. (2019): Operationally Perfect Solar Power Forecasts: A Scalable Strategy to Lowest-Cost Firm Solar Power Generation - Proc. 46th IEEE PV Specialists Conference (oral), Chicago, Il

[10] Perez R., et al. (2019): Perfect Operational Solar Forecasts – A scalable strategy toward firm power generation- International Energy Agency Solar World Congress, Santiago, Chile

[11] Pierro M., R. Perez, M. Perez, D. Moser & Cristina Cornaro, (2019): From Day-Ahead PV Forecast to PV Regulation: Imbalance Mitigation Strategies for the Italian Coi43ase Study - Proceeding EU PVSEC 2019 (oral), 6CO.16.2

[12] Pierro M., R. Perez, M. Perez, D. Moser & Cristina Cornaro, (2019): La transizione solare della produzione elettrica Italiana, sogno o realtà? QualeEnergia, January 2019



Comparative contributions of storage, PV, natural gas and implicit storage to firm power generation LCOE for the grid of La Reunion

Figure 4: Comparative contributions of storage, PV, natural gas and implicit storage to firm power generation LCOE for the grid of La Réunion.

Comments on Implicit Storage

Implicit Storage is a term used here to comprise the concept of overbuilding + curtailment. Its implementation increases supply in the winter by oversizing the renewables (PV and/or wind). This requires curtailing excess renewable energy at times when oversized supply exceeds demand but correspondingly requires significantly less storage because production increases during low-yield periods where storage or other backup would otherwise be required. Thereby, *Implicit Storage* can replace a large fraction of physical storage while achieving the same firm high penetration objective. But, it does so at a greatly reduced cost. Implicit Storage embraces overgeneration rather than always avoiding curtailment.[13] As evidenced in Figure 4, an optimum exists at the point where the marginal addition of implicit storage adds more cost to delivering firm power than it reduces from displaced conventional storage.

Inputs

Like the MN SPA, the MISO SPA used two types of data inputs: (1) hourly-interval time series data representing the MISO load from 13 distinct sub-regions and the wind and solar resources within each region, and (2) techno-economic data for each of the technologies under consideration.

Techno-economic data

Four unique cost scenarios were developed from the 2019 NREL ATB and are highlighted in Table 1 below. These scenarios are tied to (1) two specific forecast horizons (2025, 2050) and (2) two specific degrees of technological development (High, Low). *High* technological development yields lower costs and *Low* technological development yields higher costs. The thesis behind optimizing across different cost regimes is to understand the degree to which the relative costs of storage, wind and PV affect optimal capacity outlays. Building consensus around these costs will help planners better frame the future and the optimal capacities of these technologies to target from a regulatory perspective. A discount rate or weighted average cost of capital of 4% and cash-flow length of 30 years was chosen for

[13] Perez, M. J. R. (2014). A model for optimizing the combination of solar electricity generation, supply curtailment, transmission and storage. (Order No. 3621033, Columbia University). ProQuest Dissertations and Theses, 246 pages.

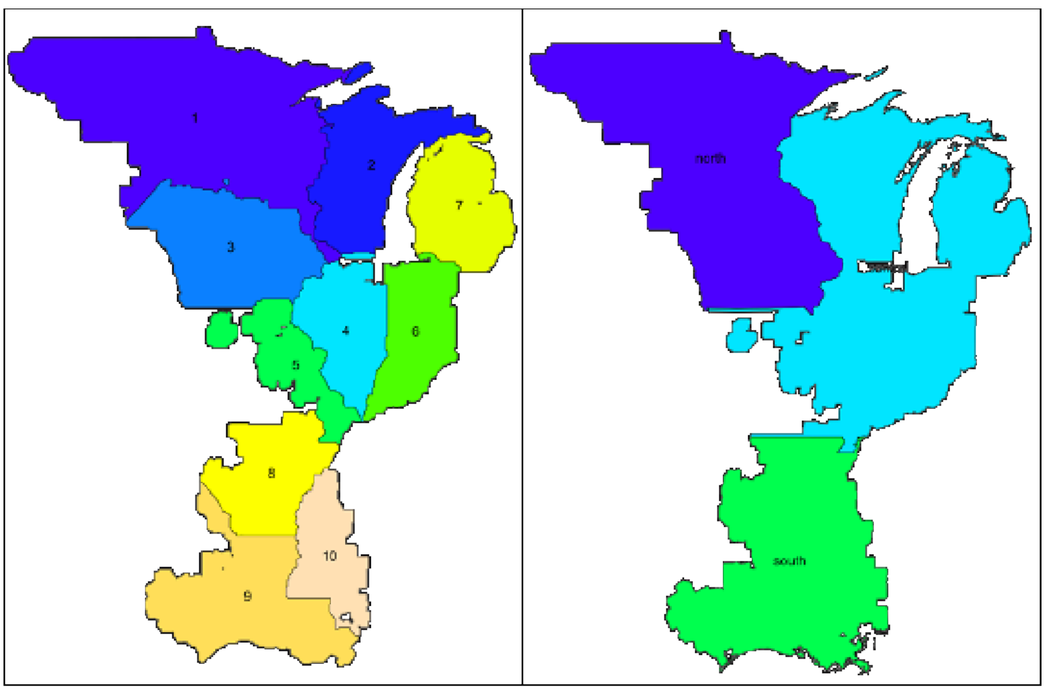
LCOE calculation. As with the MN SPA, it bears highlighting that discount rate has a moderate effect on generation costs but a minimal effect on the optimal resource blend.

Table 1: Costs for Wind, PV, Storage and Gas broken down by scenario (2050 high/low, 2025 high/low)

		Utility PV		Wind		Storage				Gas			
		CapEx $/kW	Opex $/kW-yr	CapEx $/kW	Opex $/kW-yr	CapEx $/kWh - pack	CapEx $/kW - BoS	Opex % total CapEx / yr	RT eff	CapEx $/kW	Opex fixed $/kW-yr	Opex variable $/MWh	Fuel cost $/MWh
2025	High	733	9	1,311	38	99	323	2.5%	85%	872	11	5	26
	Low	1,042	13	1,500	42	155	552	2.5%	85%	872	11	5	39
2050	High	356	4	813	24	41	133	2.5%	85%	800	11	5	29
	Low	899	11	1,294	38	112	471	2.5%	85%	800	11	5	65

Geographic Regions

The MISO as a whole and 13 divisions thereof comprise the 14 unique geographic regions investigated as islanded entities in this study. Pictured below in Figure 5 are these 13 distinct geographic subdivisions. The thesis behind understanding what optimal capacity expansion looks like in each of these regions individually (as islanded entities) is to understand what role geography has on the cost of meeting high-penetration renewables load targets. Each of the regions pictured come with their own renewable resource (wind + solar) and load characteristics; both magnitude and timing change. Changing regional scope influences the match between renewable supply and demand as well as the temporal variability of both the load and the resource through geographic smoothing.[14]



MISO Load Resource Zones MISO Market Sub-Regions

Figure 5: The MISO region with its 13 subdivisions as studied in this report.

[14] Perez, R., M. David, T. Hoff, M. Perez (2016) Spatial and Temporal Variability of Solar Energy. Foundations and Trends in Renewable Energy. Vol. 1, No., 1-44.

Renewable Resource Data

Hourly solar irradiance and production data were obtained from and simulated by SolarAnywhere®. SolarAnywhere is a commercial solar irradiance and weather dataset produced by Clean Power Research. Irradiance estimates are derived from satellite data and available from 1998 through present. Data was extracted and simulated so as to be temporally synchronous with both wind and load timeseries data. Spatial allocation of solar PV assets was considered to be homogeneous across each region of interest. This assumption likely overestimates the cost and underestimates the value of solar in each region as there is no spatial bias towards high-yield areas as there was in the MN SPA. Solar systems were uniformly assumed to be equator-facing and positioned at latitude tilt across the entirety of each spatial region.

Hourly wind production data, temporally synchronous with both the irradiance data used to simulate PV output and the load, was obtained from MISO. The spatial distribution of wind power capacity factors presented in Jacobson and Delucchi's seminal work[15] was used to scale this timeseries to reflect the wind capacity factor for each location. Spatial allocation of wind assets was equally assumed to be homogeneous across each of the regions under consideration.

Because of the homogeneous approach to distribution of wind and PV across the territory, shorter-timescale aggregate resource variability is minimized more than it would be if assets were more centrally located.

In Figure 6 below is an image showing the aggregate annual AC capacity factor in percent for wind and PV at latitude tilt across the MISO region: the resources evidently express a strong degree of spatial anti-correlation: the sun shines more strongly in the south and the wind blows more strongly in the north.

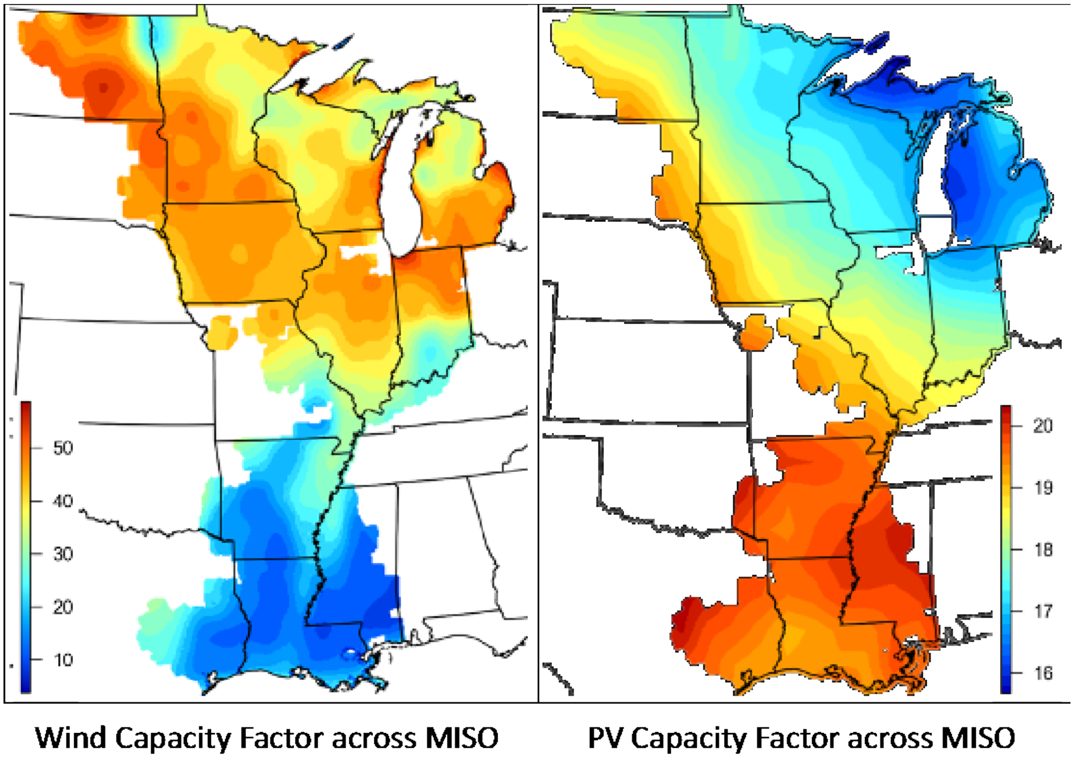


Figure 6: Average wind and PV capacity factors across the MISO region.

[15] Jacobson, M. et al. (2015) 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. Energy & Environmental Science 2015, 8, 2093

Load Data

Hourly-interval load data temporally synchronous with renewable resource data was obtained from MISO for the MISO as a whole and the three macro-regions.

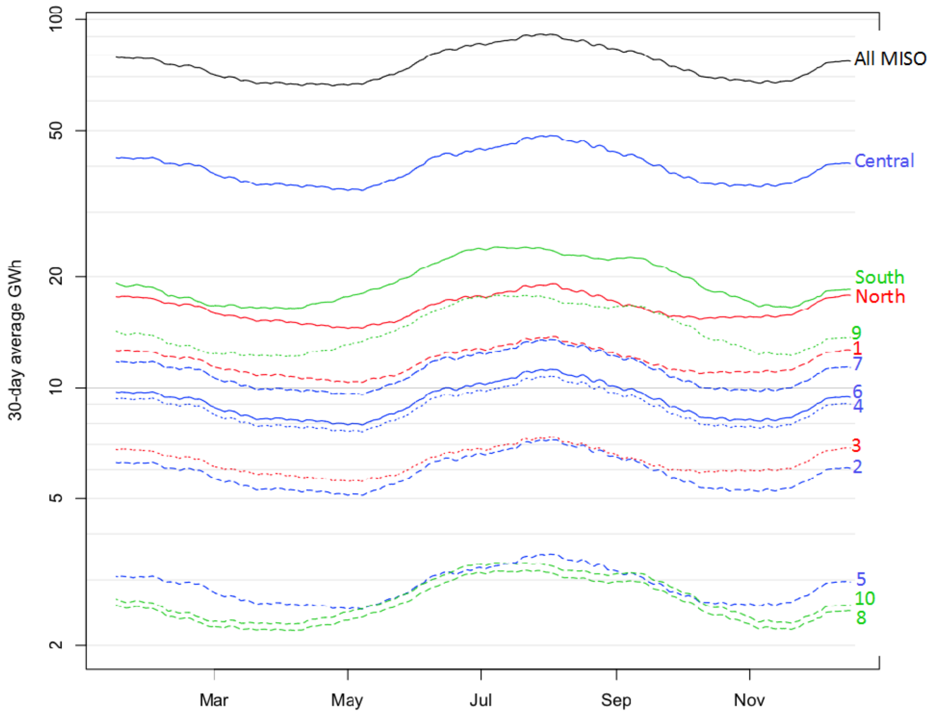


Figure 7: 30-day moving average of hourly load across each of the 14 regions under study across a single year plotted with a log-scale on the y-axis (units in GWh).

Notice in Figure 7 how the load across each region differs in both magnitude and seasonality: in the case of the loads representing each individual LRZ (1-10), these magnitudes are scalars that reflect the ratio between their annual load and that of the surrounding macro-region. In the figure, the lines representing each region (Central / South / North) are unique colors, the lines representing the loads for each LRZ are colored according to which region they fall in. Likely due to temperature-driven loads, the South region and its constituents see the bulk of their demand in the summer while the opposite is true of the North region.

Landcover

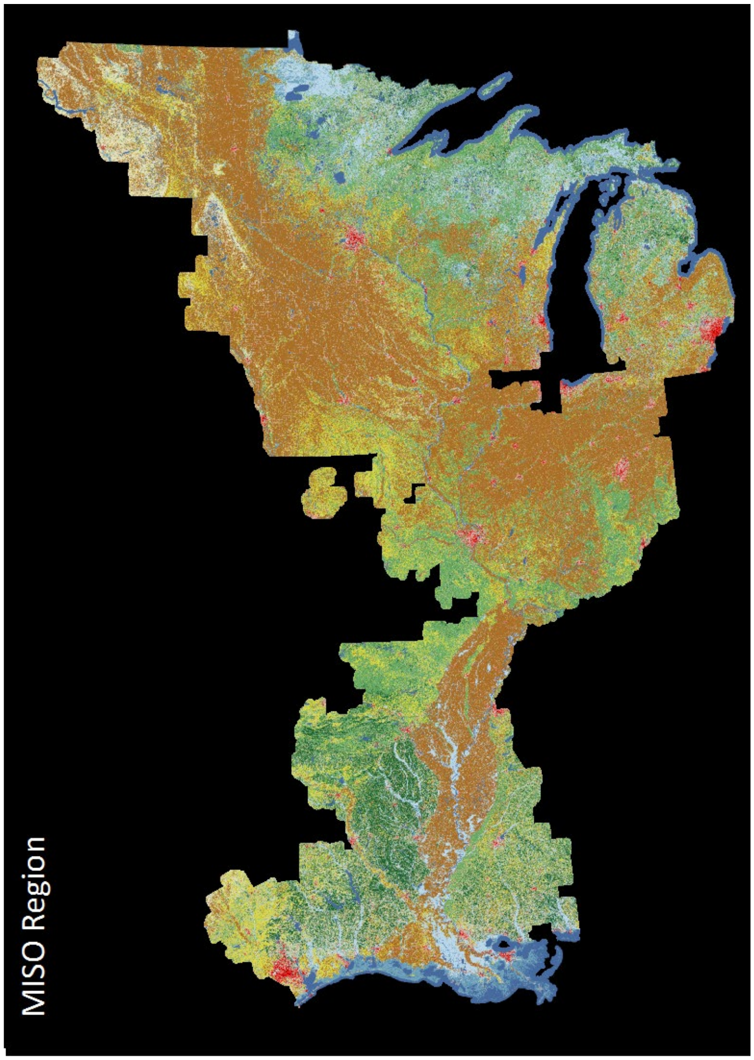


Figure 8: NLCD extract for the MISO region. Colors reflect different landcover types and are listed in Figure 9 below

The National Landcover Database (NLCD)[16] was used to extract existing landcover statistics across each of the 14 regions under investigation. Unlike the MN SPA, this landcover was not used—in conjunction with existing transmission right-of-ways and substation information—to spatially allocate renewables across each territory but to contrast land use for each of the different scenarios with existing land use. Above is a map showing the land-cover across MISO and below is a corresponding column-plot (which also serves as a legend to the map) showing the surface area covered by each landcover category. From a landcover perspective, meeting 100% of MISO's current 670 TWh/yr electrical load would require roughly 4 km^2 of PV, inclusive of a doubling of capacity to serve as implicit storage.

[16] Jin, S., Homer, C.G., Yang, L., Danielson, P., Dewitz, J., Li, C., Zhu, Z., Xian, G., and Howard, D. 2019, Overall methodology design for the United States National Land Cover Database 2016 products. Remote Sensing, 11(24); https://doi.org/10.3390/rs11242971

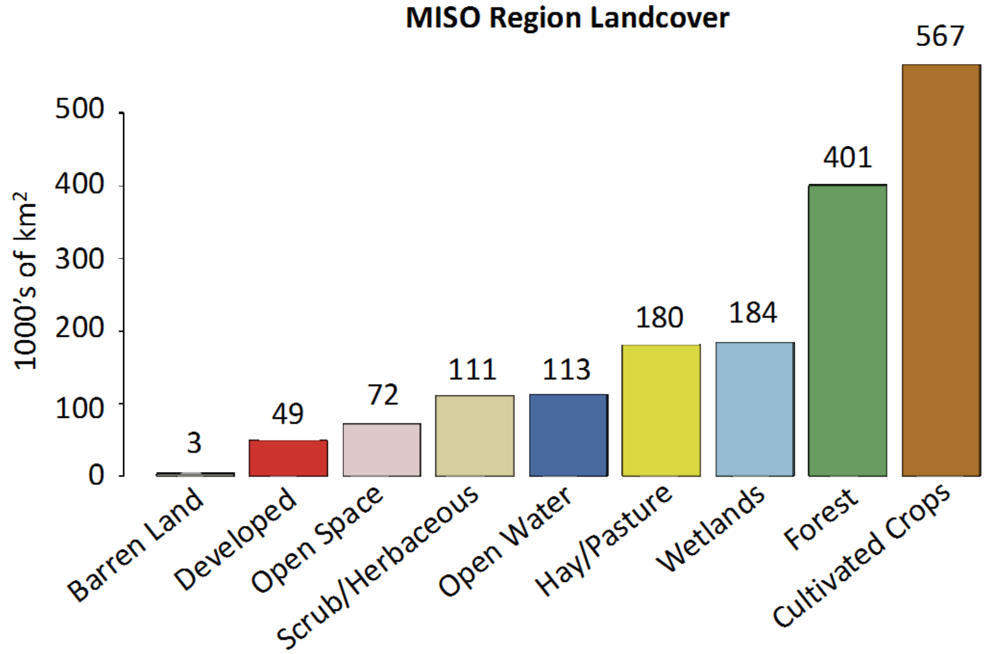


Figure 9: Colum plot of the extant (2016) landcover types across the MISO territory, units in 1000's of km^2.

MISO SPA Results

The MISO SPA work produced an extensive set of results. 69,152 year-long hourly-interval dispatch simulations were performed in seeking the optimal capacity expansion and dispatch while varying geographic scope, (wind/PV/gas) generation resource blend and technological cost. In this section, we present: (1) A guide to the dynamic web-app which permits the user to dive into all of each of these results, (2) An analysis as to the impact of geographic scope with respect to the optimized wind/solar blend and resulting costs (3) A more in-depth discussion of results for the following scenarios:

- 100% Renewables, 2025, MISO Load Resource Zone 7
- 100% Renewables, 2050, MISO Central Region
- 0-2.5% Gas (95-100% Renewables), 2050, MISO System

ShinyApps User Interface

A dynamic web dashboard containing all of the MISO SPA results was created using the *R* programming language and the Shiny package for interactive web design. Upon arriving at the site, the user is presented with a split screen shown below in Figure 10. The left portion of this screen contains the input assumptions that the user can select from using a series of drop-downs, as well as check-boxes, date-selectors and a button to both view and download key results. The right portion of the screen presents selected scenario outputs across a series of tabs.

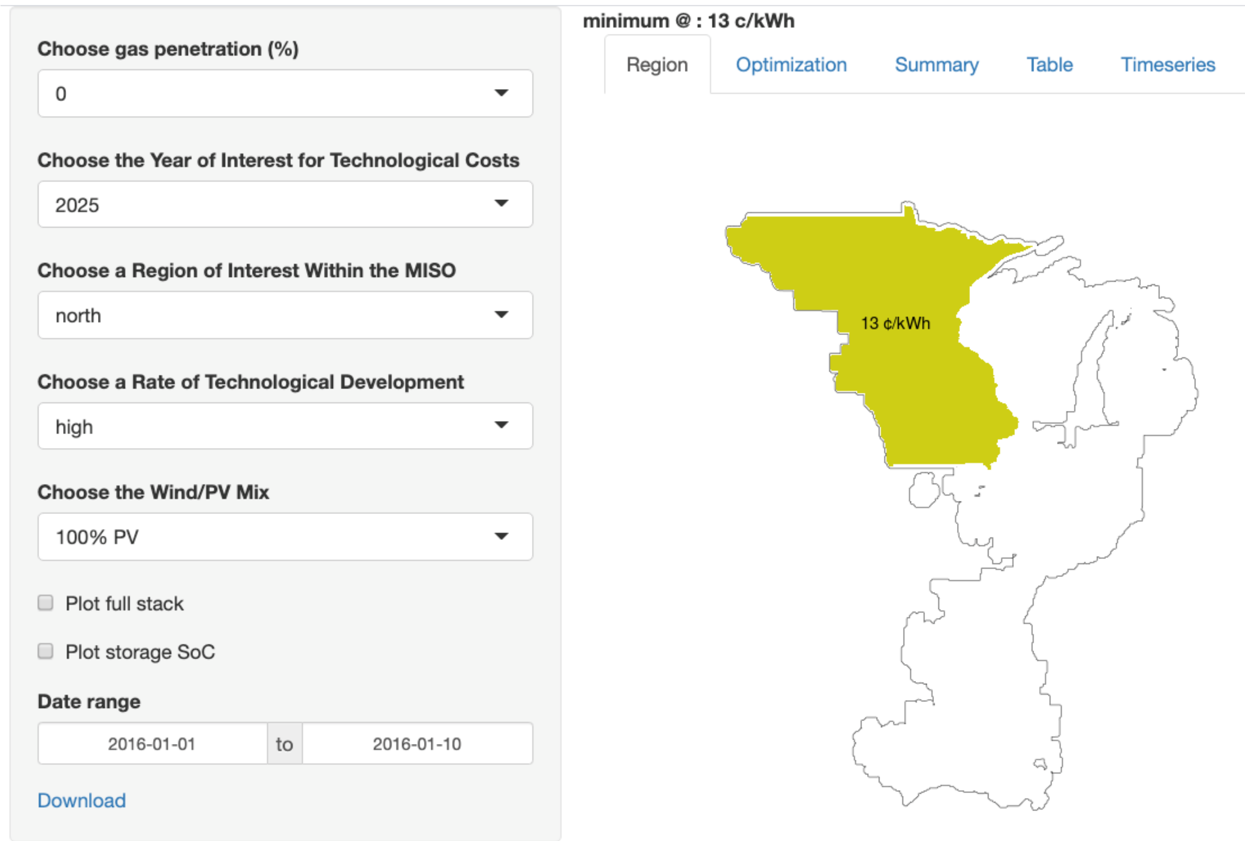


Figure 10: User-Interface for the interactive web-tool built to investigate results in a more in-depth fashion.

Scenario-Related Inputs

Among the drop-down menus, one can select from the following options that affect the region of interest—in turn affecting the wind and solar resource profiles and load profiles—the costs and the specified resource blend.

(1) The fixed percentage of gas in the final energy mix
⇥ Options are 0, 2.5% and 5 %
(2) The year of interest to query technological costs for storage, wind and PV
⇥ Options are 2025 and 2050
(3) The region of interest within the MISO
⇥ Options are north, south, central, (LRZ) 1 – 10 and MISO.
⇥ Each of these regions becomes highlighted in the map of the MISO region at right upon selection.
(4) The rate of technological development, which also influences technological cost
⇥ Options are high and low
⇥ High technological development yields lower projected costs and vice-versa
(5) The wind/PV mix : Influences the relative energy contribution of wind and solar towards meeting load in the selected zone.
⇥ Options are 100% PV, 100% Wind and "optimal" which presents results reflecting the cost-optimal wind/pv blend

Timeseries-Related Inputs

The final options (two radio buttons, a date-range selector and a download link) are linked to the timeseries tab.

- Plot Full Stack – allows the user to see what happens to renewable energy when it exceeds load: is it curtailed or is it put into storage?
- Plot storage SoC – allows the user to see the state of charge of energy storage associated with the given scenario on a second y-axis to the right of the plot on the timeseries tab.
- Date range – A date range selector allows the user to see how dispatch is taking place at different times of year.

A download button allows the user to download a csv containing key dispatch timeseries for a given scenario.

Outputs

The following outputs corresponding to the chosen parameters are viewable in the series of tabs at right initialized with the map tab.

(1) *Region tab*
⇥ Visualizes the region of interest superimposed upon the greater encompassing MISO region. The region color indicates the percentage of wind (blue) versus solar (yellow) and the optimized LCOE is printed in the center of the region of interest.

(2) *Optimization Tab*
⇥ Visualizes the optimization of implicit storage (overbuilding + curtailment use) via a stacked area plot. The Y-axis is LCOE for firmly guaranteeing load and the components contributing to this LCOE are highlighted by different colors.

(3) *Summary Tab*
⇥ Summarizes the system characteristics underpinning the scenario in question.

(4) *Table Tab*
⇥ The same data as presented in the optimization tab but in tabular format.

(5) *Timeseries Tab*
⇥ Visualizes dispatch for a date range selected by the user. Storage state of charge is also available as a viewable option.

100% Renewables, 2025, MISO Load Resource Zone 7

Table 2 below presents results for the 2025 time-frame for MISO LRZ 7. Two levels of technological development (High & Low) and three blends of renewables (100% PV, 100% Wind and Optimal Blend) were studied. Key results include: generation cost ($/MWh), solar capacity (GW), wind capacity (GW), storage power (GW), and energy storage capacity (GWh). In addition, we present the optimal percent of curtailment and the overbuild factor: i.e. how many kW of renewable capacity at the optimized level relative to how many kW of renewable capacity required to meet load in LRZ 7 on an energy basis. As a reminder, the reported generation cost is a levelized cost of energy (LCOE) calculated based upon the total 30-year CapEx + OpEx for PV, Wind and or Storage in the numerator and the 30-year energy delivered for the region in question in the denominator, all discounted by 4% per year. These LCOEs are reflective of *firmly* guaranteeing delivery of 100% of the specified load, in this case, the hourly load across MISO LRZ 7.

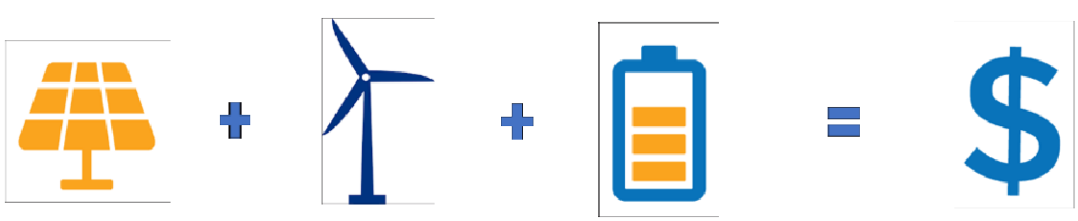
Table 2: Key results in the 2025 timeframe for the MISO LRZ 7

Tech Development	Resource Blend	Generation Cost	PV Capacity	Wind Capacity	Storage Capacity		Implicit Storage Statistics	
		$/MWh	GW	GW	GW	GWh	% Curtailment	Overbuild Factor
High	100% PV	162	174	0	69	719	62%	1.6
	100% Wind	99	0	75	18	192	65%	1.7
	Optimal	83	22	53	19	161	57%	1.6
Low	100% PV	247	174	0	69	719	62%	1.6
	100% Wind	118	0	75	18	192	65%	1.7
	Optimal	105	18	58	15	144	60%	1.6

We note the following takeaways from analysis of this set of results.

- A *High* degree of technological development yields lower LCOEs (16-34% reduction) than a *Low* degree of technological development, as expected.
- The optimal levels of implicit storage (curtailment + overbuilding) are not dramatically affected by the resource blend though optimizing the relative amount of Wind + PV yields lower curtailment. (65% optimal curtailment with wind alone, 62% optimal curtailment with PV alone, 58.5% average curtailment with optimal wind + PV)
- Optimal blending of Wind + PV yields lower LCOEs than PV or wind alone. (54% less expensive than PV alone, 13% cheaper than wind alone)
- LCOE for firmly meeting 100% of MISO LRZ 7 load, with in-zone optimally-blended wind + PV in 2025, are roughly $83/MWh.

100% Solar and Wind by 2025 in MISO LRZ 7



Solar Capacity	Wind Capacity	Storage Capacity	Generation Costs
18-22 GW	53-58 GW	15-19 GW (8-10h)	83 – 105 $/MWh

100% Renewables, 2050, MISO Central Region

Table 3 below presents results for the 2050 time-frame for MISO Central Region. Two levels of technological development (High & Low) and three blends of renewables (100% PV, 100% Wind and Optimal Blend) were studied. Key results include: generation cost ($/MWh), solar capacity (GW), wind capacity (GW), storage power (GW), and stored energy capacity (GWh). In addition, we present the optimal percent of curtailment and the overbuild factor: i.e. how many kW of renewable capacity at the optimized level relative to how many kW of renewable capacity required to meet load in MISO Central Region on an energy basis. These LCOEs are reflective of *firmly* guaranteeing delivery of 100% of the specified load, in this case, the hourly load across MISO Central Region.

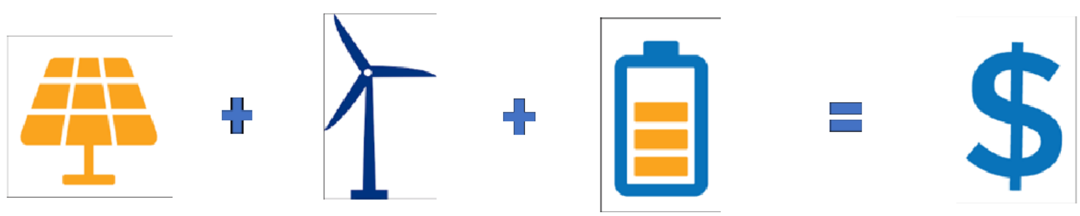
Table 3: Key results in the 2050 timeframe for the MISO Central region

Tech Development	Resource Blend	Generation Cost	PV Capacity	Wind Capacity	Storage Capacity		Implicit Storage Statistics	
		$/MWh	GW	GW	GW	GWh	% Curtailment	Overbuild Factor
High	100% PV	55	467	0	180	2097	52%	1.5
	100% Wind	70	0	262	80	2342	62%	1.6
	Optimal	42	251	37	114	1762	33%	1.3
Low	100% PV	152	467	0	180	2097	52%	1.5
	100% Wind	136	0	330	83	1267	69%	1.7
	Optimal	102	179	111	97	1211	47%	1.5

We note the following takeaways from analysis of this set of results.

- High degree of technological development once again yields lower LCOEs (48-64% reduction) than a low degree of technological development, as expected.
- The optimal levels of implicit storage (curtailment + overbuilding) are significantly lower than when considering a 100% wind or 100% PV future. (66% optimal curtailment with wind alone, 52% optimal curtailment with PV alone, 40% average curtailment with optimal wind + PV)
- Optimal blending of Wind + PV yields significantly lower LCOEs than PV or wind alone. (23% less expensive than PV alone, 38% cheaper than wind alone)
- LCOEs for firmly meeting 100% of MISO Central Region load, with in-region optimally-blended wind + PV in 2050, are roughly $42/MWh.

100% Solar and Wind by 2050 in MISO Central Region



Solar Capacity
179-251 GW

Wind Capacity
37 - 111 GW

Storage Capacity
97 - 114 GW (12-15h)

Generation Costs
42 – 102 $/MWh

95% renewables, 2050, MISO System

Table 4 below presents results for the 2050 time-frame for the entire MISO system with 0%, 2.5% or 5% new-build dispatchable gas capacity included in the costs when calculating LCOE. Capital, operating, and fuel costs for gas are added to the costs for storage, PV, and Wind, resources that together firmly supply 100% of MISO's hourly load. Gas is designed operationally to provide firming support to renewables such that its penetration does not exceed 0, 2.5 or 5% on an energy basis, the remainder being met by optimized renewables. Two levels of technological development (High & Low) and three flexible gas penetrations are analyzed (0%, 2.5%, and 5%) in combination with an optimized blend of renewables.

Key results include: generation cost ($/MWh), solar capacity (GW), wind capacity (GW), gas capacity (GW), storage power (GW), and stored energy capacity (GWh). We again present the optimal percent of curtailment and the overbuild factor: i.e. how many kW of renewable capacity at the optimized level relative to how many kW of renewable capacity required to meet load in the entire MISO system on an energy basis. These LCOEs are reflective of *firmly* guaranteeing delivery of 100% of the specified load, in this case, the hourly load across MISO system.

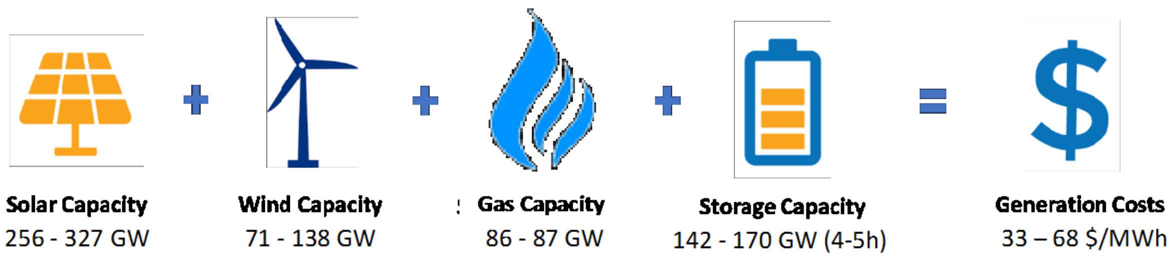
Table 4: Key results in the 2050 timeframe for the entire MISO system

Tech Development	Resource Blend	Generation Cost	PV Capacity	Wind Capacity	Gas Capacity	Storage Capacity		Implicit Storage Statistics	
		$/MWh	GW	GW	GW	GW	GWh	% Curtailment	Overbuild Factor
High	100% RE	39	510	58	0	221	2698	35%	1.3
	97.5% RE	34	408	52	86	195	1059	22%	1.2
	95% RE	33	327	71	86	170	837	18%	1.2
Low	100% RE	97	352	188	0	177	2183	45%	1.5
	97.5% RE	74	324	100	85	168	974	25%	1.2
	95% RE	68	256	138	87	142	579	28%	1.3

We note the following takeaways from analysis of this set of results.

- High degree of technological development once again yields lower LCOEs than a low degree of technological development, as expected. (51-60% reduction)
- The optimal levels of implicit storage (curtailment + overbuilding) generally decrease with the degree of gas penetration. This is because a dispatchable resource like gas does the work otherwise performed by either storage or implicit storage: ramping up when energy demand is greater than the energy supplied from intermittent renewables. (45% optimal curtailment for 100% renewables, 24% optimal curtailment for 97.5% renewables + 2.5% gas, 23% average curtailment for 95% renewables + 5% gas.)
- Costs decrease significantly with increased gas penetration, largely due to the avoided costs of displaced storage. This effect is less significant in the high development scenario than in the low development scenario due to the significantly decreased cost of storage. (29% reduction in *low* scenario, 6% reduction in *high* scenario.)
- LCOEs for firmly meeting 100% of MISO System load, with 95% met by optimally-blended wind + PV and the remaining 5% met by new-build gas in 2050, are roughly $33/MWh.

95% Solar and Wind by 2050 across the MISO System



Impact of Geographical Region on cost

Table 5 below presents results for the 2050 time-frame with a high degree of technological development for each of the 10 LRZs, all 3 MISO Regions and the entire MISO system with 5% new-build dispatchable gas capacity included in the costs when calculating LCOE. The intention behind slicing the results in this manner is to investigate the impact geographic region has on the optimal blend of wind vs PV and in turn on cost. Capital, operating and fuel costs for gas are added to the costs for storage, PV and Wind, resources that together firmly supply 100% of MISO's hourly load. Gas is designed operationally to provide firming support to renewables such that its penetration does not exceed 5% on an energy basis, the remaining 95% being met by optimized renewables.

Key results include: generation cost ($/MWh), solar capacity (GW), wind capacity (GW), gas capacity (GW), storage power (GW), and stored energy capacity (GWh). We again present the optimal percent of curtailment and the overbuild factor: i.e. how many kW of renewable capacity at the optimized level relative to how many kW of renewable capacity required to meet load in MISO Central Region on an energy basis. These LCOEs are reflective of *firmly* guaranteeing delivery of 100% of the specified load, in this case, the hourly load across the entire MISO system as well as its constituent regions. The rows each represent individual geographic regions, each with their own unique load and resource characteristics. Each row is colored along a spectrum from blue (95% wind) to yellow (95% PV) according to where the analysis landed in its wind/PV optimization.

Table 5: Key results in the 2050 timeframe for the MISO system and its constituent subregions: 95% renewables

Geographic Zone	Wind Energy Penetration (%)	PV Energy Penetration (%)	Generation Cost	PV Capacity	Wind Capacity	Gas Capacity	Storage Capacity		Implicit Storage Statistics		Region Centroid	Region Areas
			$/MWh	GW	GW	GW	GW	GWh	% Curtailment	Overbuild Factor	Lat, Long	1000 km^2
LRZ 1	52%	43%	31	36	18	12	22	88	21%	1.2	47, -95	506
LRZ 2	51%	44%	36	20	10	8	12	58	25%	1.3	45, -88	173
LRZ 3	71%	24%	31	12	14	7	7	25	29%	1.3	42, -94	224
LRZ 4	39%	56%	35	37	11	11	20	97	26%	1.3	40, -89	147
LRZ 5	25%	70%	37	14	3	4	8	42	25%	1.3	39, -91	110
LRZ 6	38%	57%	37	41	13	11	23	110	27%	1.3	40, -86	131
LRZ 7	58%	37%	35	34	21	13	21	97	27%	1.3	44, -85	135
LRZ 8	7%	88%	39	15	1	3	8	55	25%	1.3	35, -92	166
LRZ 9	3%	92%	36	89	3	16	45	238	24%	1.2	31, -93	294
LRZ 10	2%	93%	38	17	0	3	9	51	27%	1.3	32, -90	124
North Region	51%	44%	30	51	24	17	29	113	22%	1.2	45, -96	591
Center Region	33%	62%	35	176	42	48	90	494	21%	1.2	42, -88	686
South Region	0%	95%	35	122	0	23	62	328	23%	1.2	33, -92	504
MISO System	30%	65%	33	327	71	86	170	837	18%	1.2	40, -91	1986

We note the following takeaways from analysis of this set of results.

- Generation costs across each of the regions are all on roughly the same order of magnitude but do decrease with the size of the region (averaging $36.1/MWh for regions smaller than 500,000 km^2, and $32.7/MWh for regions larger than 500,000 km^2).
- The balance between percentage of load carried by PV relative to wind varies widely and reflects the differing resource characteristics and the degree to which they are able to match load in each given region (ranging from 95% PV | 0% Wind in the Southern region to 24% PV | 71% Wind in LRZ 3).
- The optimal levels of curtailment decrease with an increase in region size, in parallel to the decrease in generation costs. Both trends are due to geographic dispersion[17] (optimal curtailment averages 26% for regions smaller than 500,000 km^2, and 21% of regions larger than 500,000 km^2).
- If each individual LRZ islanded itself, the weighted average cost to supply the whole of MISO with 95% renewable penetration would be $34.9/MWh. If each macro region islanded itself, the weighted average cost decreases to $33.7/MWh. If the entire MISO region interconnects, the cost declines to at least $32.6/MWh. As is evident, larger regions = lower costs thanks to the better hybridization between the wind and solar resources and the effect of geographic smoothing. Generally, the MISO interconnect was seen to reduce costs on the order of 7-10% depending on the degree of dispatchable gas backup.

[17] Perez, R., M. David, T. Hoff, M. Perez (2016) Spatial and Temporal Variability of Solar Energy. Foundations and Trends in Renewable Energy. Vol. 1, No., 1-44.

Conclusions

The MN SPA afforded a unique opportunity for a broad set of energy stakeholders in the State of Minnesota to meet regularly over an 18-month period to develop a shared understanding of the opportunities and challenges associated with increasing levels of solar and wind generation across the state. The MISO SPA expanded the scope of this work to the surrounding region.

At the highest level the MISO SPA results indicate that solar, wind, and storage resources can firmly serve not only Minnesota's load, but the load of each of the surrounding regions at generation costs on par with current generation costs. Larger regions were seen to be capable of delivering lower costs than smaller ones, highlighting the value of regional power exchange. To be noted, there is also value in regional self-sufficiency linked to resiliency in the face of disaster. This value was not calculated as part of this study. Neither were the marginal costs linked to requisite T&D upgrades to support these build-outs.

The MISO SPA results can be used to as a resource to support the evaluation of solar, wind, and storage as part of not only Minnesota's but MISO's energy future – a process that many energy stakeholders in Minnesota and across the MISO region have already begun.

The MISO SPA results provide important insights into the solar, wind, and storage capacities that would achieve a future where solar and wind serve 95%-100% of MISO's annual load and that of its constituent regions. Under a 95% scenario, the MISO SPA results suggest that the MISO could expect to have hundreds of GW of solar and wind with roughly 5 hours of storage rated at just under 200 GWs of capacity; not 1000's of GWh of storage capacity. As we showed with the MN SPA, implicit storage effectively eliminates the need for seasonal storage. In this way, the MISO SPA results can be useful in combination with other studies, as decision-makers and stakeholders anticipate and plan for expanded solar, wind, and storage capacity.

These MISO SPA results also highlight the future need for discussion about solar and wind compensation policies that account for the 'additional' renewable capacity key to the implicit storage concept (and its associated energy curtailment). Note that the Pathways project is agnostic on the numerous potential solutions to achieving high penetrations of renewables, but rather raises this as a point for further discussion. Ongoing discourse with regulators, industry groups, policymakers and the public will prove valuable for any new compensation policies that would ultimately need to move through a regulatory process.