PRINCETON UNIVERSITY

ZERO LAB

Zero-carbon Energy Systems Research and Optimization Laboratory

POLICY MEMO

Impacts and Feasibility of an Hourly-Matched Clean Electricity Standard in Minnesota

Wilson Ricks and Jesse D. Jenkins

Princeton University | April 14, 2025

Executive Summary

- **A proposed requirement to evaluate compliance with Minnesota's 100% carbon-free electricity law on an hourly basis is likely to be feasible.**
- **Tighter regional boundaries on qualifying clean power reduce emissions and increase costs.**
- **Hourly matching is made easier by long-duration energy storage and creates an early market for this technology.**

Introduction

In 2023, the state of Minnesota passed a law requiring all local electric utilities to provide 100% carbon-free electricity to Minnesota customers by 2040. As with many similar state-level clean electricity standard (CES) policies, Minnesota utilities will be required to demonstrate compliance by procuring and retiring "energy attribute certificates" (EACs) representing individual units of qualifying clean generation. However, many important details of the law's implementation have yet to be determined.

One key emerging question is whether utilities should be required to procure EACs from generation that is correlated in both time and space with their customers' electricity demand and that could by extension be reasonably understood to have physically met Minnesotans' electric power needs. Temporal and spatial matching requirements are an emerging gold standard for claims to consumption of clean electricity, and such requirements were recently adopted by the US federal government in a rulemaking governing the use of carbon-free electricity for subsidized clean hydrogen production.

In recent comments submitted to the Minnesota Public Utilities Commission, the Minnesota Department of Commerce recommended that the PUC require utilities to match the clean generation they procure on an hourly basis with their retail electric sales in order to demonstrate compliance with the 100% CES law. The DOC proposed the following escalating matching requirements:

- **By 2035**, an hourly matching requirement of 80% for public utilities and 60% for other utilities;
- **By 2040**, an hourly matching requirement of 90% for all utilities; and
- **By 2045**, an hourly matching requirement of 100% for all utilities.

In addition, the DOC proposed that all EACs used to meet this requirement must be sourced from within the Midwest grid region defined in federal clean hydrogen production regulations, equivalent to the northern half of the Midwest Independent System Operator's territory (see Figure 1). In this policy memo we examine both the feasibility and impacts of DOC's proposal, as well as the implications of potential variations on the proposed policy.

Princeton University's Zero-carbon Energy systems Research and Optimization Laboratory conducts research to improve decision-making and accelerate rapid, affordable, and effective transitions to net-zero carbon energy systems. The ZERO Lab improves and applies optimization-based modeling tools and methods to understand complex macro-scale energy systems and uses these tools to evaluate and optimize emerging low-carbon energy technologies and generate decision-relevant insights to guide national and sub-national jurisdictions in transitioning to net-zero emissions energy systems. Prof. Jesse D. Jenkins is the Principal Investigator. For more, see http://zero.lab.princeton.edu

Approach

We used the GenX electricity system optimization model to evaluate the emissions, resource procurement, and consumer cost impacts of an hourly matching requirement for Minnesota's electric utilities following the DOC's proposed schedule. GenX is an open-source system planning model that optimizes investments and operations (at hourly resolution) to minimize the cost of delivered power, subject to physical and policy constraints. In doing so it simulates the expected behaviors of both competitive markets and system planners, making it a useful tool for assessing the expected impacts of electricity sector policy interventions. GenX is capable of operating with high temporal resolution, and has been used in the past in multiple peer-reviewed studies examining the impacts of hourly-matched clean electricity procurement in the context of both federal clean hydrogen subsidy rules and corporate carbon accounting.

In this study we use GenX to model the evolution of the electricity sector from the present day through 2045 across four five-year planning periods. In each planning period we model the operations of the system at hourly resolution across 30 representative weeks, which are selected from seven weather years of demand and generation data. The model is capable of tracking energy held in storage across this entire seven-year period, a key feature permitting accurate modeling of multi-day energy storage resources. We use 30 model zones to represent the US Eastern Interconnection – the larger synchronous grid of which Minnesota is a part – including four zones representing the state of Minnesota itself (see Figure 1).

To model the DOC's proposed hourly matching requirement, we implement a constraint requiring that enough qualifying carbon-free energy be sourced from within a specified spatial boundary to match the required portion of Minnesota electricity demand across the required number of hours. Qualifying carbon-free resources are assumed to include biomass, hydropower, in-state nuclear, wind, solar, and any qualifying energy stored and then discharged from batteries. Technologies eligible for new deployment in our central scenarios include wind, solar, batteries, gas, and nuclear, and costs are adopted from the National Renewable Energy Laboratory's Annual Technology Baseline 2024.

We model three hypothetical sets of spatial boundaries on qualifying EACs to assess the influence of this potential policy lever on outcomes of interest. These three boundaries are shown in Figure 1, and are here referred to as:

- **Midwest**, equivalent to the region of the same name defined in the US DOE's Transmission Needs Study and federal clean hydrogen regulations, and consisting of the MISO North and MISO Central grid regions;
- **MISO North**, a tighter geographic boundary based on the MISO region of the same name, and roughly covering the states of North Dakota, Minnesota, and Iowa; and
- **In-State Only**, a case where all demand must be matched with generation in Minnesota.

Figure 1: Illustration of three potential sets of spatial boundaries for qualifying EACs used for hourly matching of clean electricity in Minnesota, outlined in bold and overlaid on a map of the 30-zone model of the US Eastern Interconnection used in this study.

We also recognize that intermediate fractional hourly matching requirements like those included in the DOC proposal (e.g. 90%) can have multiple possible interpretations. One such interpretation is that a 90% matching target requires matching 90% of demand in every hour of the year. A second interpretation is that a 90% matching target simply requires matching 90% of all demand in a year without any restrictions on which particular hours are or are not matched. We refer to these interpretations as **"firm"** matching and **"flexible"** matching, respectively (see Figure 2 for illustrations), and model both in this study.

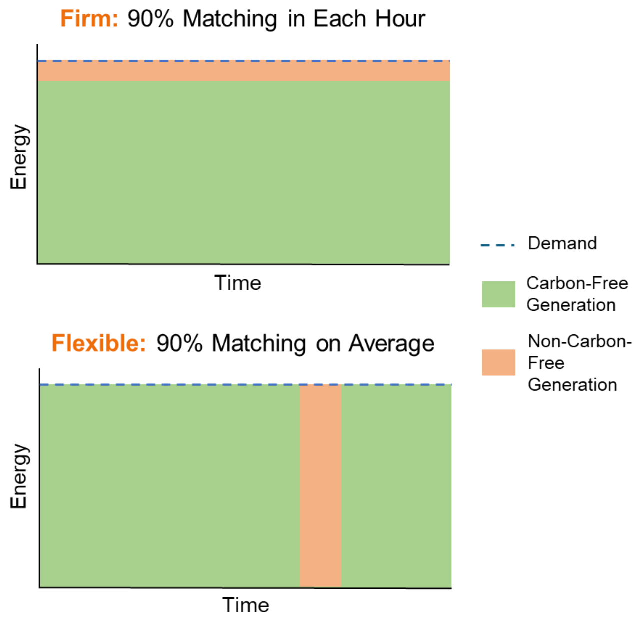

Figure 2: Stylized illustration of two potential implementations of a fractional hourly matching requirement (in this case 90%). In the flexible case, it is possible for demand in some hours to be entirely unmatched as long as 90% is matched on average over the year.

We assess the impacts and feasibility of different potential implementations of an hourly matching requirement in Minnesota by comparing model outcomes in 2035, 2040, and 2045 to a baseline scenario where Minnesota's carbon-free electricity standard is implemented similarly to other state CES policies, i.e. via annual matching of EACs. We focus on two primary metrics of interest: **impacts on emissions** and **impacts on consumer electricity costs** in Minnesota. We calculate emissions impacts by comparing total emissions in the entire Eastern Interconnection model to those observed in the baseline case, recognizing that there may be knock-on emissions impacts that extend beyond the borders of the matching region due to the interconnected nature of electricity grids and markets. We calculate weighted average electricity costs for Minnesota consumers by extracting energy prices, capacity prices, annual EAC prices for conventional CES and RPS programs, and hourly EAC prices for hourly programs from the model. Because the GenX only optimizes generation and transmission expansion, it is assumed that costs for distribution and existing transmission are identical across cases.

Findings

Compliance with the DOC's proposed escalating hourly matching requirement and regional boundaries is feasible at no excess cost under baseline assumptions. Due to the large spatial extent of the Midwest regional boundary and the relatively large amount of qualifying clean energy development projected within this boundary, even a 100% hourly matching requirement is technically feasible under our baseline assumptions at no excess cost. Figure 3 shows a comparison between Minnesota's hourly electricity demand and the hourly stacked generation from qualifying clean energy technologies within the Midwest region in 2045 without any hourly matching requirement (i.e., those deployed based on economic viability alone), illustrating sufficient availability of qualifying power in all hours. A 100% hourly matching requirement could thus be met at no excess cost in this scenario if Minnesota utilities are able to effectively acquire the necessary EACs through markets and would therefore also bring no additional benefits beyond the baseline (see Table 1). Larger impacts may be possible if real-world renewable deployment is less than the modeled baseline, in which case Minnesota's policy could drive deployments that would not have occurred otherwise.

Using MISO North as the boundary for qualifying clean power increases both the impact and cost of an hourly matching requirement. In scenarios where MISO North is used as the regional boundary on qualifying clean electricity, the emissions impact of an hourly matching requirement becomes significant. A 100% matching requirement with MISO North boundaries mitigates up to 5 MMT CO_2/yr systemwide in 2045 (see Table 1), equivalent to roughly a quarter of Minnesota's total emissions from in-state generation today. This impact requires greater investment in a clean portfolio that provides the reliability necessary to displace fossil emissions, leading to cost premiums of up to $10/MWh for consumers in 2045 (or roughly 8% of the current average Minnesota retail rate).

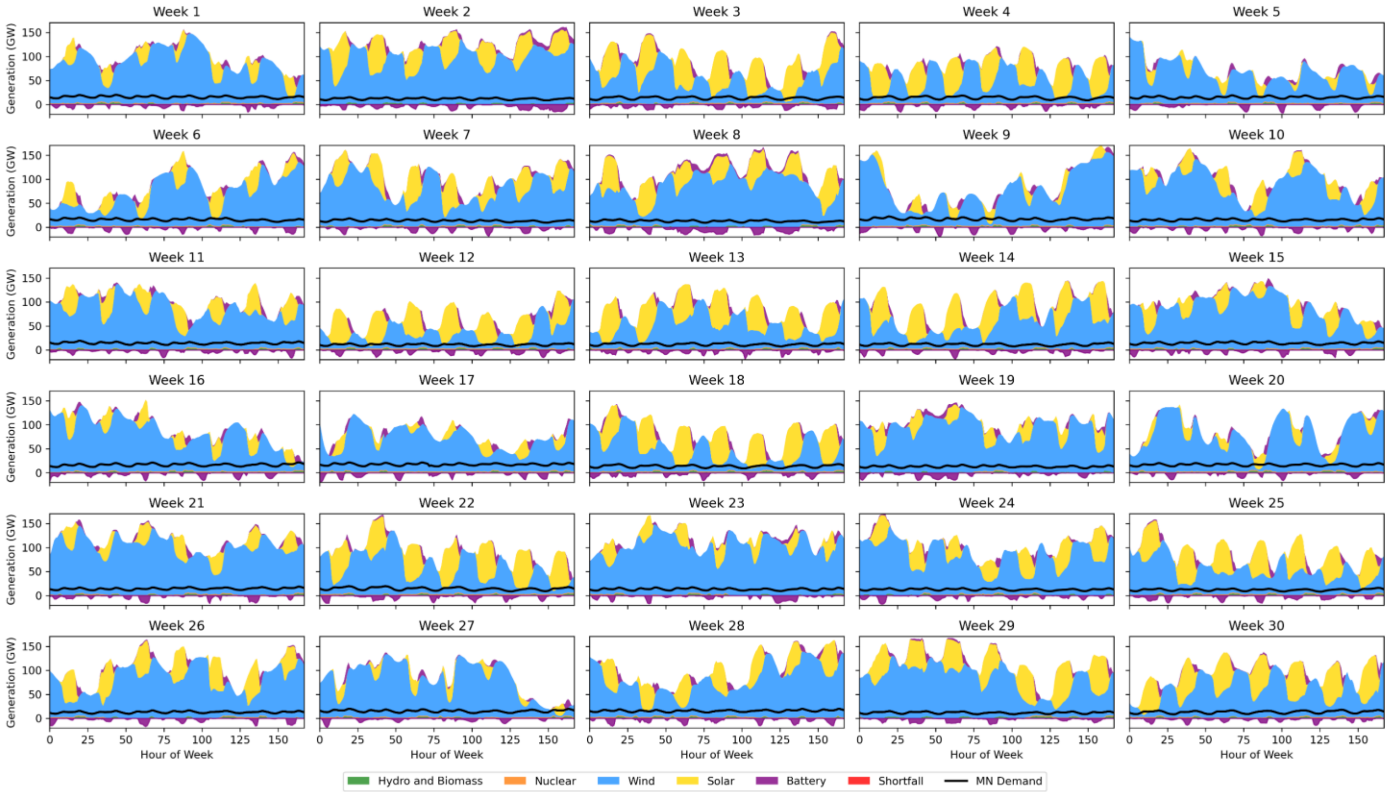

Figure 3: Stack plot showing Minnesota's hourly electricity demand alongside qualifying clean generation and storage charging within the Midwest regional boundary across 30 representative weeks in the baseline modeled scenario in 2045. If Minnesota utilities are able to trade for the necessary hourly EACs, compliance with a 100% hourly matching requirement becomes trivial.

Policy Scenario						
Matching Interpretation	**"Firm" Hourly Requirement**			**"Flexible" Hourly Requirement**		
Regional Boundary	**Midwest Region**	**MISO North**	**In-State Only**	**Midwest Region**	**MISO North**	**In-State Only**
Impact on Consumer Cost Compared to Baseline ($/MWh)						
2035	**+0**	**+2**	**+12**	**+0**	**+0**	**+0**
2040	**+0**	**+3**	**+18**	**+0**	**+0**	**+0**
2045	**+0**	**+10**	**+33**	**+0**	**+11**	**+39**
Impact on Grid Emissions Compared to Baseline (MMT CO_2/yr)						
2035	**-0**	**-6**	**-23**	**-0**	**-0**	**-0**
2040	**-0**	**-5**	**-28**	**-0**	**-0**	**-0**
2045	**-0**	**-5**	**-24**	**-0**	**-3**	**-18.5**

Table 1: Consumer cost and emissions impacts of different potential implementations of an hourly matching requirement in Minnesota. Both metrics are reported as changes relative to a baseline case where no hourly matching requirement exists. Bulk electricity costs for Minnesota consumers in the baseline case (non-inclusive of distribution costs and existing transmission costs, which are not modeled) are $30/MWh in 2035, $28/MWh in 2040, and $34/MWh in 2045.

An In-State Only requirement for qualifying clean power leads to substantial emissions reductions, but at a more significant cost premium. As shown in Table 1, the cost premium of requiring 100% hourly matching with in-state clean resources only could exceed $30/MWh if only wind, solar, and lithium-ion batteries are available for deployment. However, this policy can also mitigate more than 20 MMT CO_2/yr of emissions under baseline assumptions. While a 100% in-state requirement may not be compatible with Minnesota statute, this is the scenario most likely to fully mitigate the state's reliance on fossil generation of any kind. The magnitude of the emissions abatement observed suggests that the requirement has a significant impact on out-of-state emissions as well.

An hourly matching requirement with tighter regional boundaries requires greater investment, in renewables and (especially) storage. As shown in Figure 4, compliance with "firm" matching targets and MISO North or In-State Only boundaries (top and middle, respectively) requires deployment of more renewables and storage than in the baseline scenario. Changes in renewable capacity vary, with the MISO North scenarios for example deploying less solar and more wind than the baseline. The most consistent change in outcomes is a much greater emphasis on battery storage, and especially battery *energy* capacity and duration.

Hourly matching with tight geographic boundaries creates a key early market for multi-day storage technologies, and the availability of these technologies reduces consumer costs. In a scenario where we model an In-State Only 100% hourly matching requirement and include a long-duration storage technology with relatively high power capacity costs ($2000/kW), low round-trip efficiency (42%), and very low energy capacity costs ($20/kWh) as a new-build option in the model, this technology is deployed to help meet the hourly matching requirement (Figure 4, bottom). The Minnesota policy thus creates an early market for this technology, which does not see uptake in the absence of the hourly matching requirement. Long-duration storage can be critical for cost-effectively eliminating fossil generation, and here cuts the cost premium of 100% in-state hourly matching in half from $33/MWh to $17/MWh (see Table 2 column 1).

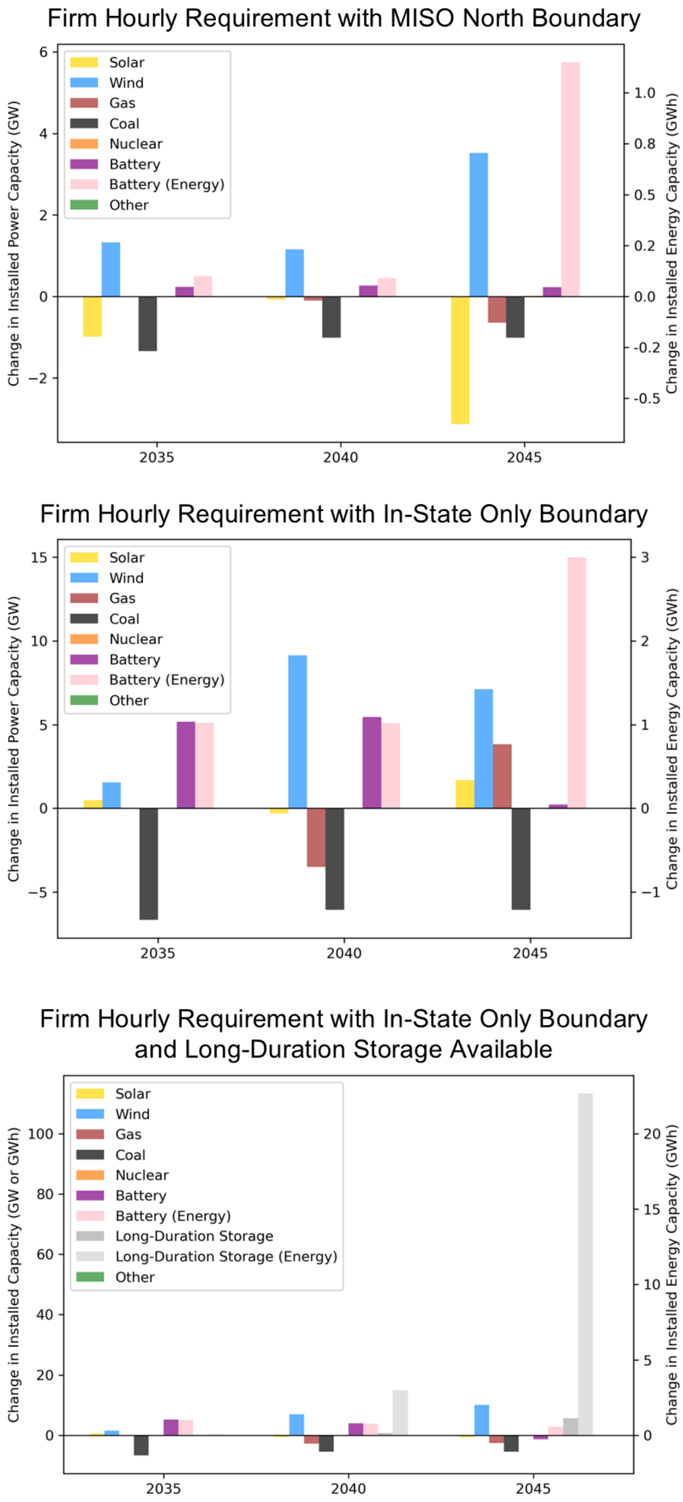

Figure 4: Changes in technology deployment compared to the baseline scenario, organized by year for three scenarios with "firm" hourly matching policies: one with a MISO North boundary and two with In-State Only boundaries, the latter of which includes a long-duration storage technology as a procurement option. Generating capacity changes are given in GW, and storage energy capacity changes are given in GWh.

"Firm" hourly matching requirements drive more and earlier impact than "flexible" ones. "Flexible" hourly matching requirements where utilities can pick and choose which hours they do or do not match lead to effectively no emissions impact until the matching requirement hits 100%, even with the tightest geographic boundaries (see Table 1). This is due to an abundance of qualifying clean power in the vast majority of hours. They also generally lead to greater consumer costs in 2045, as investments have been made in previous modeled periods that are not optimal for 100% hourly matching. These outcomes may be attributable in part to the structure of the model, which does not have foresight into future stages when planning for a given stage (e.g. it does not know that it will have to deliver 100% hourly matching in 2045 when designing a system that can achieve 90% in 2040). If utilities plan investments proactively and do not face policy uncertainty, the differences between the firm and flexible requirement cases may be reduced.

A circuit-breaker mechanism could constrain costs (and impact). In a scenario where we model the most restrictive version of an hourly matching policy (firm, with In-State Only boundaries) but allow utilities to avoid compliance at a cost of $300/MWh, the consumer cost impact in 2045 falls by more than $20/MWh on average to $13/MWh (see Table 2 column 2). The emissions impact of the policy is also reduced in this case, but not by as much as cost. When the breaker mechanism is utilized, the effective hourly matching rate in 2045 is still 98.5% and emissions fall by 16 MMT/yr.

A policy with wide spatial boundaries can still drive impact *if* neighboring states adopt similar policies. In a case where we model the Midwest regional boundary but assume that Illinois and Michigan also adopt hourly matching policies identical to Minnesota's, both the impact and cost of hourly matching using this boundary increase substantially due to competition for clean power in key hours (Table 2 column 3).

Outcomes can vary moderately depending on technology cost and fuel price assumptions. As shown in Table 2, columns 4 and 5, the impacts of an hourly matching requirement on consumer electricity prices and emissions can vary depending on assumed values for uncertain parameters like the cost of renewable energy resources and fossil fuels.

Policy Scenario					
Description	**In-State Only with Long-Duration Storage**	**In-State Only with a Circuit-Breaker**	**Midwest Region with Illinois and Michigan**	**MISO North Region with High Wind, Solar and Storage Costs**	**MISO North Region with High Fossil Fuel Prices**
Impact on Consumer Cost Compared to Baseline ($/MWh)					
2035	+12	+3	+4	+6	+2
2040	+16	+9	+2	+0	+3
2045	+17	+13	+16	+6	+11
Impact on Grid Emissions Compared to Baseline (MMT CO_2/yr)					
2035	-23	-11	-24	+4	+1
2040	-24	-16	-19	+3	-8
2045	-25	-16	-35	-3	-9

Table 2: Consumer cost and emissions impacts of an hourly matching requirement in Minnesota under different variations of our central cases. All of the examples shown here assume a "firm" hourly matching requirement. Bulk electricity costs for Minnesota consumers in the baseline high renewable cost case are $34/MWh in 2035, $33/MWh in 2040, and $37/MWh in 2045. Electricity costs in the baseline high fuel price case are $30/MWh in 2035, $29/MWh in 2040, and $34/MWh in 2045.

For example, in a case where we use costs for wind, solar, and batteries taken from the National Renewable Energy Laboratory's "conservative" cost projections, we observe moderate increases in grid emissions in 2035 and 2040 followed by a moderate decrease in 2045. While hourly matching increases systemwide clean generation in these cases, we observe that in the early stages it reduces the buildout of *new* gas-fired power plants, which in turn displaces less coal power than in the baseline. This secondary gas-to-coal effect highlights the limitations of policies focused exclusively on increasing clean generation and could be mitigated by supplemental policies that seek to hasten the retirement of coal plants. In a scenario where we assume higher prices for all fossil fuels, hourly matching achieves larger emissions reductions in later stages than in our central cases.

Summary

There are several policy levers that could be used to adjust both the climate impact and manage the consumer cost premium of an hourly matching requirement for carbon-free power in Minnesota. Based on our modeling, **the most important of these levers is likely to be the geographic boundary** placed on qualifying carbon-free electricity. If the Minnesota DOC's proposed Midwest boundary is adopted, our analysis suggests that an hourly matching requirement will be quite easy to meet but will have little-to-no impact on emissions. It should be noted that if real-world renewable energy deployment lags behind the pace suggested by our modeled baseline scenario, Minnesota's policy as an important and impactful backstop even under these loosest requirements. Outcomes could also change if there is significant demand for hourly EACs in the Midwest region from other sources, including federally subsidized hydrogen producers, corporate voluntary action, or policies in neighboring states. In the absence of additional demand for hourly-matched clean power, **tighter regional boundaries on procurement can increase both the cost and emissions benefits of an hourly matching policy**. Both cost and impact are moderate when a MISO North boundary is used, and become more significant when only use of in-state clean resources is permitted. **The implementation of a circuit-breaker mechanism that establishes a maximum compliance price for utilities can help significantly constrain costs** in cases where they become excessive. **Availability of multi-day energy storage technologies (or other advanced clean firm resources like advanced nuclear or geothermal) can also reduce the cost of matching the most difficult hours**, and in turn an hourly matching policy in Minnesota could be an important demand driver for these technologies.

Our results also suggest that intermediate matching targets which drive toward the long-run goal of 100% matching are necessary to minimize costs and maximize impact. **A "Flexible" hourly matching requirement that allows utilities to pick and choose the hours they match is incredibly easy to comply with in a wind-rich state like Minnesota**, and can also create path dependencies where the resource investments made in the 2030s are not necessarily consistent with a long-run goal of 100% hourly matching. **By contrast, a "firm" hourly matching requirement aligns near-term investments better with long-run goals, drives impact even in early years, and creates an earlier demand-pull for advanced technologies like long-duration energy storage.** Additionally, because complete hourly matching with deliverable clean power will eventually be necessary to truly eliminate Minnesota's reliance on climate-warming sources of power, a policy that intentionally drives toward this goal from the start is likely the best way to deliver on the state's promise to use 100% carbon-free electricity.