AUGUST 2022

ACHIEVING 100% CLEAN ENERGY IN WISCONSIN

EVOLVED ENERGY RESEARCH

Evolved Energy Research (EER) is a research and consulting firm focused on questions posed by transformation of the energy economy. Their consulting work and insight, supported by complex technical analyses of energy systems, are designed to support strategic decision-making for policymakers, stakeholders, utilities, investors, and technology companies. They have developed models to simulate and optimize economy-wide energy systems, bulk power systems operations, and utility distribution systems.

GridLab is an innovative non-profit that provides technical grid expertise to enhance policy decision-making and to ensure a rapid transition to a reliable, cost-effective, and low-carbon future.

RENEW Wisconsin is a nonprofit organization that promotes renewable energy in Wisconsin. We work on policies and programs that expand solar power, wind power, biogas, local hydropower, geothermal energy, and electric vehicles. Since 1991 we have been a champion for clean energy solutions in the Badger State.

For more than 50 years, Clean Wisconsin has been working to preserve and protect Wisconsin's clean water, clean air and natural heritage. With an active membership and advocacy base 20,000-strong, Clean Wisconsin's dedicated staff of experts conducts sound science, engages in public policy, takes legal action, and fosters strong partnerships with allies and stakeholders to help ensure a safe, healthy environment for everyone.

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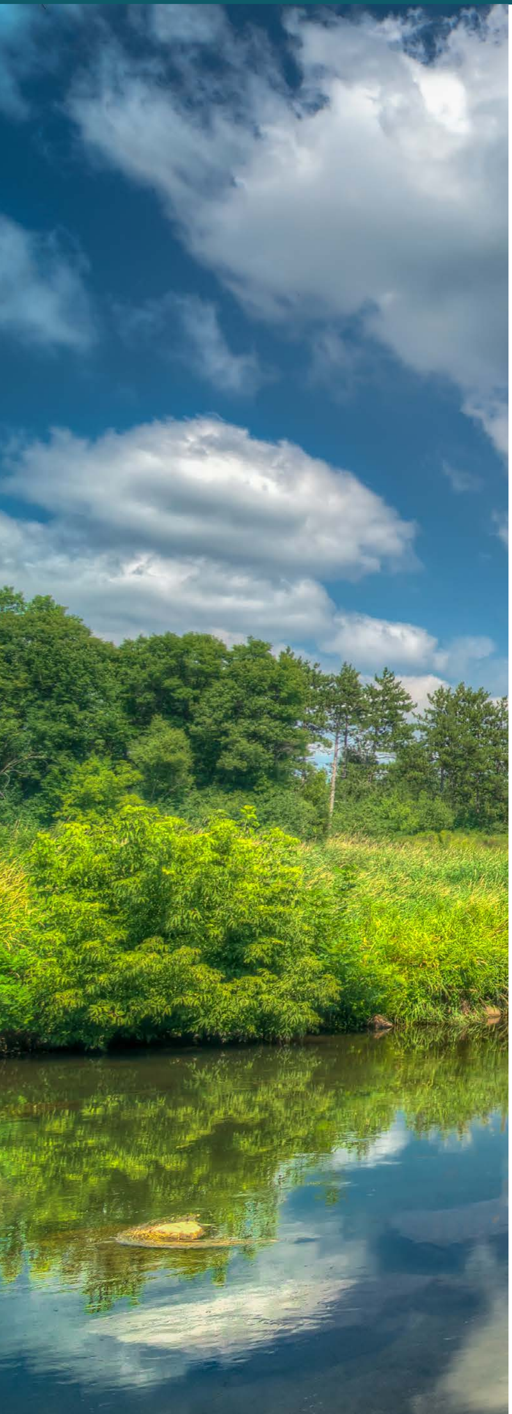


2 EXECUTIVE SUMMARY

This study is a collaboration between Evolved Energy Research, RENEW Wisconsin, Clean Wisconsin, and GridLab (the Project Team) identifying strategies to achieve 100% clean electricity in Wisconsin by 2050. The state's clean electricity target was established by Governor Evers' Executive Order 38; Wisconsin does not have a corresponding economy-wide[1] emissions target today. While this study's primary focus is electricity infrastructure investment, the electric sector is so closely integrated into the rest of the economy that any effort to study electricity decarbonization requires consideration of energy usage in other sectors. We therefore examined Wisconsin's clean electricity target in the context of key drivers of electricity supply and demand: demand-side technology adoption, economy-wide emissions policy, and interconnection with neighboring states.

Our modeling explored a **Baseline** "no policy" scenario and six clean electricity policy scenarios, each designed to evaluate a potential policy action or key uncertainty. Our results show that 100% clean electricity and economy-wide net zero emissions can be achieved relatively cost effectively in Wisconsin. However, implementing clean electricity policy alone,

1 Economy-wide refers to all sectors of the economy, including residential, commercial, agricultural, and transportation. Targeting net zero emissions would mean achieving net zero emissions across all economic sectors of Wisconsin's economy, and including non-CO_2 carbon equivalent emissions and incremental land sink emissions reductions

without demand side electrification and efficiency measures, achieves only a quarter of the emissions reductions of economy-wide decarbonization and costs nearly the same amount. The most cost-effective approach to reducing emissions in Wisconsin is to pursue comprehensive economy-wide decarbonization action, including but not limited to clean electricity policy.

Economy-wide decarbonization in our scenarios leads to a vastly different electricity sector relative to today's, with loads growing 166% by 2050 over 2022 levels — a sustained 3.5% annual growth rate from 2022 to 2050. Growth comes from increased consumption of electricity in transportation, buildings, and industry, including new flexible industrial loads. Population growth and economic growth are factors in driving an overall increase in the demand for energy services. New flexible industrial loads include electrolysis to produce hydrogen, and electric dual fuel boilers in industry. To meet increasing electricity demand, Wisconsin must make large electricity sector investments by 2050, including adding 31 GW of solar, 21 GW of wind, 7 GW of electricity storage[2], 2 GW of hydrogen electrolyzers, and 3 GW of dual fuel electric boilers. This degree of electric system expansion will require considerable advanced planning.

Taking early action to transition vehicles and buildings to electricity is important for cost containment on the path to net zero emissions. Electric vehicles and heat pumps provide significant energy savings over the technologies they replace, so their widespread adoption reduces total economy-wide energy demand. Furthermore, electric demand can be met with low-cost sources of clean energy, such as wind and solar. In a net zero scenario, end use electrification substantially drives down total energy costs by 2050 as compared to the alternative: retaining liquid and gaseous fuel use in vehicles and appliances.

Interconnection with the rest of MISO is an important part of Wisconsin's electricity future, with imports and exports providing system balancing and access to high-quality out of state clean energy resources. Expansion of transmission interties lowers the overall cost of regional decarbonization. We permitted up to an additional 6 GW of transmission capacity to be added to interties between Wisconsin and surrounding states. We found that Wisconsin can cost effectively add the full 6 GW per intertie of additional transmission permitted in the analysis. The alternative where Wisconsin was not permitted to expand transmission costs $1B/yr more by 2050. Importing clean energy reduces the reliance on in-state resources, avoiding potential challenges associated with in-state resource siting that could put clean energy targets at risk. Transmission expansion itself has been challenging historically; nonetheless, pursuing transmission expansion in Wisconsin increases optionality in achieving future clean electricity and net zero emissions goals. Early planning is required in the 2020s for long lead time transmission construction projects to come online when they are needed in the 2030s.

2 Storage referred to in this paper is lithium ion, based on currently forecasted pricing that is lower than competitors for other forms of commercially available short-term storage

Coal retirements are key to low-cost emissions reductions in the 2020s and early 2030s. Most of Wisconsin's coal fleet is scheduled to be retired by 2035 through voluntary commitments by the utilities. However, economically reducing emissions by 40% by 2030 drives coal generation almost completely out of the state's electricity mix by 2030. When our scenarios allow construction of a limited number of new gas power plants, gas takes over some of the electricity production from coal in the early years. Gas then transitions from a baseload resource to a low capacity factor reliability resource in the future. To maintain system reliability in 2050 while meeting the 100% clean electricity requirement, Wisconsin's gas fleet burns small amounts of biogas from agricultural waste, operating during a very limited number of hours. While the scenarios that allow new gas builds are lower cost than our **Limited Coal and Gas** scenario, those scenarios do not capture potential risks outside of the techno-economic analysis, such as fuel price changes, stranded asset risk, and environmental and environmental justice concerns.

Modeling least-cost pathways to clean electricity and net zero emissions by 2050 relies on 30-year forecasts of technology availability and pricing, service demand, and fuel prices. Moving forward in time, the uncertainty in these forecasts increases. Some of these uncertainties are explored in the scenarios we modeled, but much of our analysis relies on best available information at the time of modeling. Many factors can affect these assumptions including research and development and, as recent events demonstrate, geopolitics and world events that upend supply chains and impact commodity prices.

What needs to happen by 2030?

Economy-wide emissions policy to complement electricity policy

Four times the emissions reductions can be achieved with comprehensive economy-wide decarbonization action than with clean electricity policy alone by 2050, and for similar cost. The most cost-effective way to reduce Wisconsin's greenhouse gas emissions is to combine clean electricity generation with electrification and improved efficiency of the demand side. This includes electrification of transport, buildings, and industry, and production of clean fuels for parts of the economy that are difficult to electrify.

Action to transition the demand-side of the economy towards electrification and high efficiency equipment

Energy consuming technologies such as vehicles, space heaters, and boilers have long lives. It takes time to replace existing stocks with new technologies through natural retirement and replacement cycles. Most scenarios in this study assume aggressive electrification rates of vehicles, buildings, and industry, targeting 100% sales of electrified and/or high efficiency equipment by 2035. To achieve that target, Wisconsin should start early in supporting sales of electric and high efficiency technologies. We show that a slower demand-side transition will ultimately cost Wisconsin more on the path to net zero emissions.

Electricity sector planning for long-term future growth to ensure a successful transition

The pace and scale of the electricity sector expansion needed to meet load growth and incorporate clean energy sources will require early grid and land use planning and coordination. Long lead-time assets like transmission may take up to 10 years to construct. Our results indicate that when targeting net zero emissions, most coal plants are economically retired by 2030, another action which requires advance planning. Early feasibility studies will give Wisconsin a better picture of the challenges facing the electricity sector and ensure enough time to find solutions.

Distributed energy resources (DER), including rooftop solar and flexible loads are deployed in all our scenarios. Utility-scale generation developments, and the additional transmission investments needed for their integration, pose unique siting challenges that cannot be fully forecasted or captured in modeling. DERs can reduce the pace and scale of grid-scale resource investment, taking the pressure off potentially challenging rates of deployment and giving Wisconsin more options to achieve clean electricity and net zero emissions targets.

Summary of scenarios

To inform Wisconsin's 100% clean electricity policy, we developed a set of scenarios with the Project Team representing different potential policy actions and key uncertainties. These include:

- **Baseline:** No electricity or emissions policy. Energy consumption patterns continue to look much like they do today. While not realistic because Wisconsin is likely to take policy action towards clean electricity and emissions reductions over the next 30 years, this **Baseline** scenario serves as a useful point of comparison to the other scenarios to compare the impact of electricity and emissions policy interventions.
- **100% Clean Electricity:** Achieving 100% clean electricity looks very different with and without economy-wide emissions policy. This scenario examines what clean electricity looks like with no economy-wide emissions targets and therefore no large-scale electrification of the demand side, i.e. energy consumption patterns are the same as in the **Baseline** scenario.
- **Net Zero Economy-Wide:** This scenario models both 100% clean electricity and economy-wide net zero emissions by 2050. Since 100% clean electricity is a

means towards achieving emissions reductions, this scenario is coherent in uniting decarbonization action across the economy. It is also aligned with other state and international emissions targets. Comparing this scenario with **100% Clean Electricity** shows the relative costs and achieved emissions reductions of electricity policy alone versus comprehensive emissions policy.

- **No Transmission (Tx) Expansion:** In **Net Zero Economy-Wide** scenario, significant expansion of transmission paths to other states is part of the least-cost solution. This scenario looks at what happens when transmission expansion is either infeasible or too expensive. What resources does a more self-reliant Wisconsin invest in to achieve electricity and emissions goals while maintaining a reliable energy supply?
- **Accelerated Clean Electricity:** Policymakers have more direct control over decarbonization in the electricity sector compared to other sectors of the economy. Decarbonization costs may also be lower in electricity than in other sectors. This scenario evaluates accelerating action in electricity, reaching 100% clean electricity by 2040, including the impacts on electricity investments and the cost impact. This scenario also shows how accelerated clean electricity can displace emissions reductions in other sectors to achieve economy-wide net zero emissions.
- **Delayed Action:** In all other scenarios achieving net zero emissions, we model aggressive levels of electrification and efficiency improvements on the demand side to transition away from primary fuel use towards electricity, and to reduce overall energy use in the economy. This scenario looks at a potential future where consumer adoption of more efficient and electrified technologies on the demand side occurs more slowly, including, for example, slower sales of electric vehicles in the transportation sector and electric heat pumps in buildings, as well as lower overall adoption of distributed energy technologies.

- **Limited Coal and Gas:** Announced coal retirements in Wisconsin take almost all coal offline by 2035. In the other scenarios that model an economy-wide emissions target, coal is significantly curtailed by 2030 as one of the lowest-cost ways to achieve emissions reductions. Gas is used as a less polluting alternative to coal in those scenarios. This scenario includes two additional restrictions on thermal generators: 1) Coal retirements are accelerated to 2030; and 2) Lives of existing gas generators can be extended beyond their retirement dates but no new gas plants can be constructed. This scenario looks at what the infrastructure and operational cost premium is to avoid the environmental and environmental justice costs of new thermal power plant construction and operation.

Each of these scenarios is summarized in the following table:

TABLE 1.
Scenarios Investigated

	Scenario	Description	What are we investigating?
	Baseline	No electricity or emissions policy, the way we consume energy remains similar to today	Setting a useful point of comparison to other scenarios
	100% Clean Electricity	Reaching 100% clean electricity but no economy-wide emissions policy	What is the cost and impact on emissions of taking action only in electricity?
NET ZERO SCENARIOS	**Net Zero Economy-Wide**	100% clean electricity and economy-wide emissions policy. Aggressive electrification and efficiency of demand side energy consumption	With all resource options on the table, what is a least cost path to net zero in 2050 and what does the investment strategy look like?
NET ZERO SCENARIOS	**No Transmission Expansion**	Transmission paths to other states cannot be expanded to access more out of state energy	How impactful is transmission expansion on overall costs and in state investments?
NET ZERO SCENARIOS	**Accelerated Clean Electricity**	Economy-wide emissions target and pushing to 100% clean electricity by 2040	How much more would it cost to push to 100% clean electricity faster?
NET ZERO SCENARIOS	**Delayed Action**	Delayed demand-side transformation, 15 years slower than Net Zero Economy-Wide	How important is pushing demand-side transformation on overall costs?
NET ZERO SCENARIOS	**Limited Coal and Gas**	No new gas, and coal retired by 2030	If near-term policy retired coal and prevented new gas investments what would be the impact?

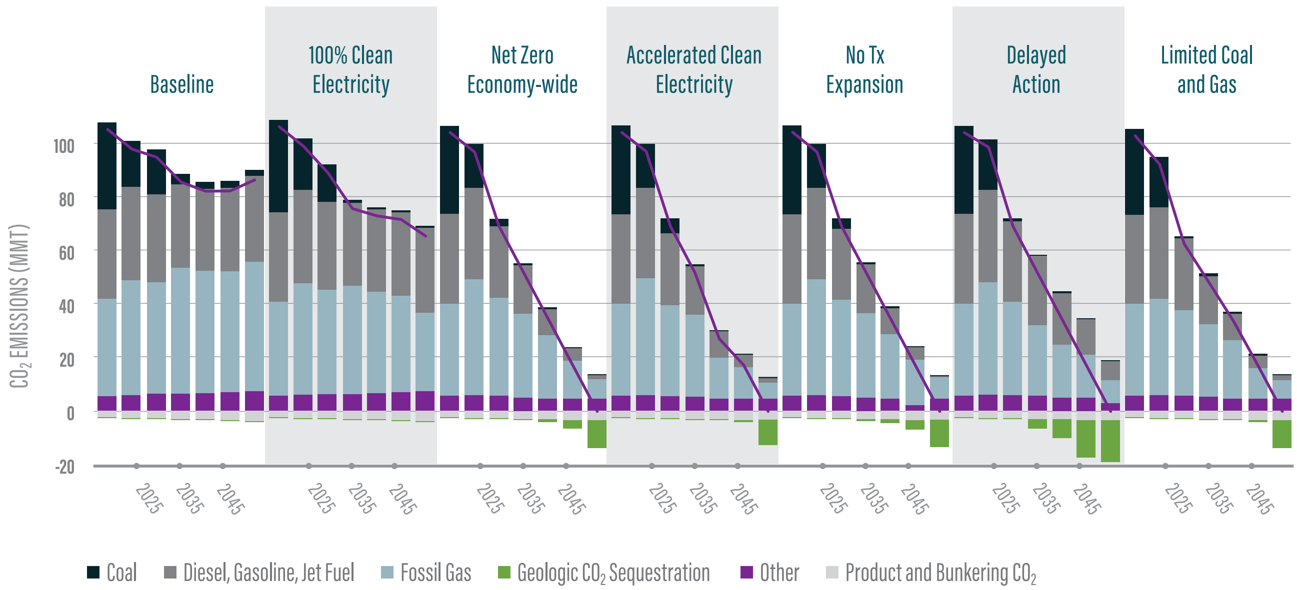
Emissions

Figure 1 shows the emissions by year for each of the scenarios. Coal retirements in all scenarios reduce emissions significantly. Coal accounted for 34% of Wisconsin's emissions in 2018; by 2035 emissions from coal electricity generation are zero in most scenarios and very low in the **Baseline** scenario. In the **100% Clean Electricity** scenario, total statewide emissions decrease relative to baseline as gas generation is removed from electricity. By 2050, total emissions in that scenario are 39% lower than 2022 levels and 24% lower than **Baseline** scenario emissions in 2050. In all other scenarios, which target net zero emissions, electrification of the demand side drives both liquid fuels and gas out of the economy, and clean electricity eliminates emissions from the electric sector. Some residual emissions come from pipeline gas and industry in 2050 and are offset by geologic carbon sequestration.[3]

3 Geologic carbon sequestration is the process of securing carbon dioxide in the ground rather than releasing it to the atmosphere (https://pubs.usgs.gov/fs/2010/3122/pdf/FS2010-3122.pdf). Product and bunkering CO_2 are emissions offset for CO_2 captured in products and not released to the atmosphere such as plastics, and the portion of emissions for air travel that is not allocated to Wisconsin's emissions budget

FIGURE 1.

Wisconsin Economy-Wide Emissions by Scenario and Year



Costs

Figure 2 shows the costs of each scenario compared to the costs of the **Baseline** scenario. The positive side of the axis shows categories where spending is higher than in the **Baseline** scenario and the negative side (savings side) of the axis shows categories where spending is lower. In scenarios that reach net zero, large increases in spending on demand side and electricity infrastructure are offset by savings in avoided liquid and gaseous fuel purchases.

Costs for achieving **100% Clean Electricity** are ~$1B/yr more by 2050 than the **Baseline**. In contrast, the **Net Zero Economy-Wide** scenario costs ~$2B/yr more than **Baseline** by 2050 but achieves four times the emissions reductions than **100% Clean Electricity** does by 2050. Figure 2 shows these costs and costs in years prior to 2050 in terms of Wisconsin GDP and broken out by investment category. By 2050 in the **Net Zero Economy-Wide** scenario, energy infrastructure costs rise to 2% of GDP above those in the **Baseline** scenario. However, these are offset by the savings in fuel purchases. Accounting for both increased energy infrastructure spending and savings in fuel purchases, energy spending rises by 0.25% of GDP by 2050. In years prior to 2050, energy costs and savings in **Net Zero Economy-Wide** approximately offset one another. Spending increases significantly in demand side equipment such as electric vehicles and electrified heat but decreases in fuel purchases, such as spending at the pump. While overall costs of the transition are low, large changes in the type of energy spending may impact particular customers or customer groups differently, and managing distributional impacts will be key to an equitable and cost effective transition.

FIGURE 2.

Net Infrastructure and Operating Energy Costs relative to Baseline by Scenario (% of GDP)

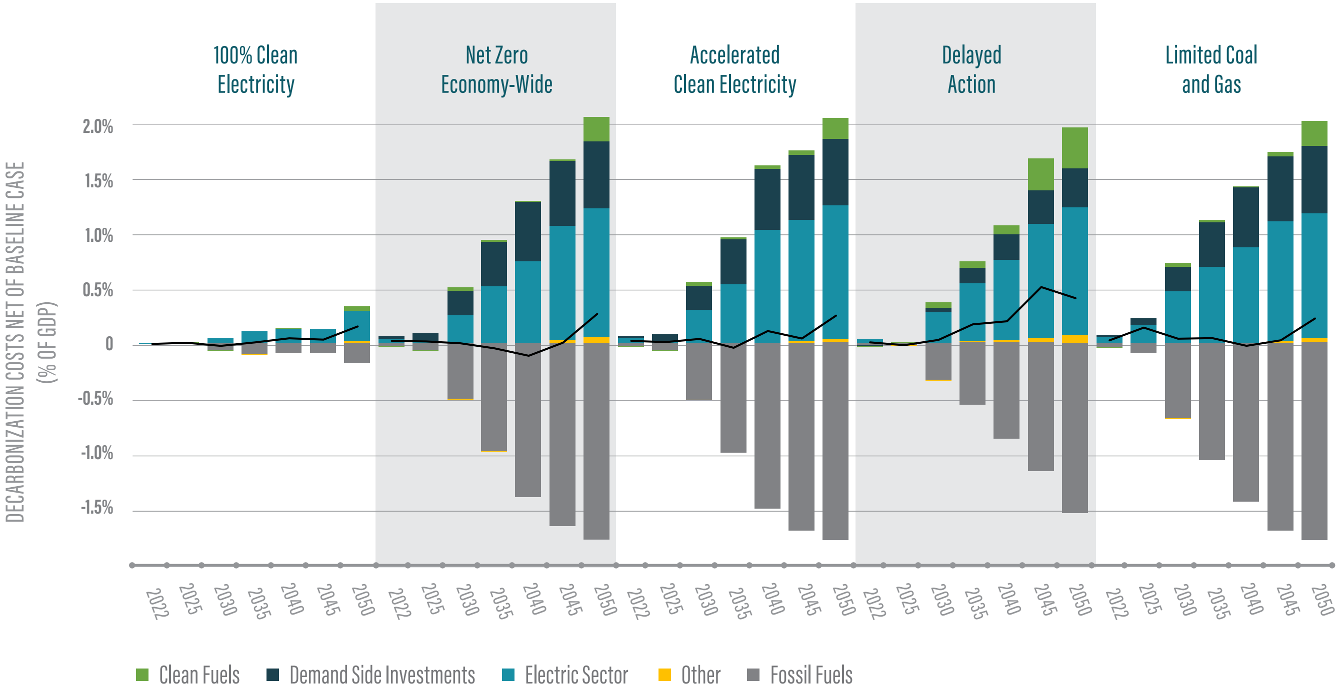
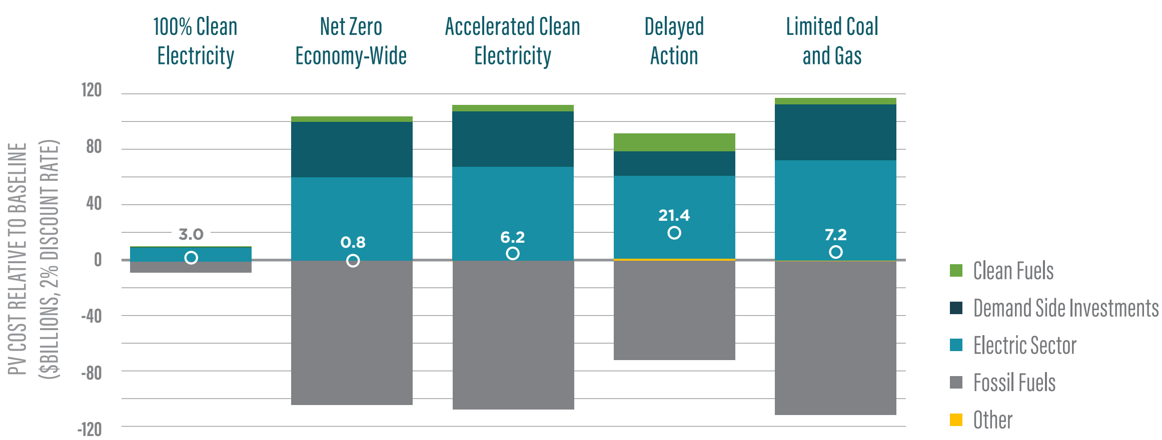


Figure 3 shows the same trend but in dollars, presented as present value of energy spending from 2022 to 2050. We have used a societal discount rate of 2% for the calculation. The low cost of **Net Zero Economy-Wide** relative to **100% Clean Electricity** shows that far deeper emissions reductions can be achieved for lower present value costs and only marginally higher costs in 2050 when targeting net zero emissions rather than clean electricity alone.

FIGURE 3.

Present Value of Energy Costs relative to Baseline by Scenario



The study also looked at the health benefits of decreasing emissions in Wisconsin using the EPA COBRA model to determine changes in fine particulate matter and impact on health outcomes in Wisconsin's population. Figure 4 shows energy costs and avoided costs alongside high and low estimates of the health impacts in 2050 relative to the **Baseline** scenario. While decarbonization costs in 2050 are slightly higher in 2050 than in the **Baseline** scenario, health benefits outweigh those additional costs, resulting in net benefits to the state. This trend is similar in prior years showing that targeting net zero emissions in the **Net Zero Economy-Wide** scenario is a net benefit to the state.

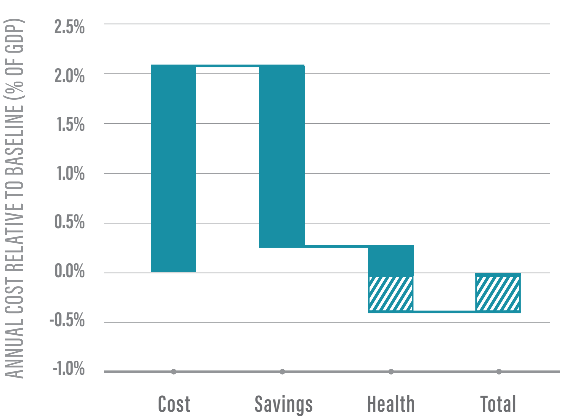


FIGURE 4.

System Costs and Heath Benefits in the Net Zero Economy-Wide Scenario in 2050

What is the impact of electricity policy?

Electricity policy is the main variable investigated across the scenarios in this study. The electricity policy options explored include: no new clean electricity policy; 100% clean electricity by 2050; 100% clean electricity by 2050 and net zero economy-wide emissions; accelerating 100% clean electricity to 2040; and preventing new gas generator build while retiring coal by 2030. Key findings from comparing these scenarios include:

Implementing 100% clean electricity policy alone achieves only 24% of the economy-wide emissions reductions of a net zero emissions policy relative to Baseline by 2050. Net costs for both are small through 2040, reaching 0.15%/yr of Wisconsin's forecast GDP by 2050 in **100% Clean Electricity** and 0.25%/yr of GDP in **Net Zero Economy-Wide**. 100% clean electricity policy in the absence of economy-wide emissions policy is not a cost-efficient means of achieving long-term emissions reductions

Economy-wide emissions policy drives a vastly different electricity system. Total Wisconsin electric load in 2050 is 127% higher in the **Net Zero Economy-Wide** scenario than in the **Baseline** scenario in 2050, driven by the electrification of end use loads such as vehicles and building heat, electrolysis, and electric boiler loads. By 2050, Transportation makes up 23% of all electricity demand in **Net Zero Economy-Wide** versus just 2% in the **Baseline** scenario. New industrial hydrogen production from electrolysis and electric boiler loads contribute to balancing the electricity system because of their inherent flexibility and make up 14% of electricity demand by 2050 in **Net Zero Economy-Wide**. Electrolysis stores energy from electricity in the form of hydrogen and hydrogen-derived liquid fuels; electric boilers enable fuel switching between pipeline gas and electricity. These flexible loads help avoid additional investment in electricity balancing resources such as storage and gas power plants.

Achieving 100% clean electricity and net zero emissions by 2050 is relatively cost effective. In the **Net Zero Economy-Wide** Scenario, total costs increase by 0.25%/yr of GDP in 2050 relative to the **Baseline** scenario. This cost is offset by additional health benefits of reduced fossil fuel combustion. In addition, if the rest of the world also follows a similar path to net zero, the collective benefits of mitigating climate change will benefit Wisconsin.

While cost impacts of decarbonization are modest relative to Baseline energy spending, the changes in the economy to achieve clean electricity and emissions targets are significant. These changes include rapid demand-side transformation to electrified and more efficient technologies and the associated expansion of electricity distribution infrastructure, access to out of state resources through transmission expansion, rapid growth and high penetrations of renewables in Wisconsin, and build out of rooftop solar and other distributed energy resources.

Accelerating 100% clean electricity to 2040 increases costs by $1.2B/yr, or 0.2% of Wisconsin GDP, in 2040 relative to the Net Zero Economy-Wide scenario. Advancing the target for achieving 100% clean electricity drives earlier in-state investment in renewables, increasing solar investments by 36% and doubling wind investments by 2040. The **Accelerated Clean Electricity** scenario overshoots the 2040 emissions target in **Net Zero Economy-Wide** by 22%, driving emissions reductions faster than the economy-wide target does alone. This deeper 2040 emissions cut is achieved by reducing gas electric generation and transitioning to a fully clean gas supply in electricity. Though emissions are lower, **Accelerated Clean Electricity** is likely not as cost-effective as an economy-wide strategy targeting the same lower emissions level, because other potentially lower-cost options would be available outside of the electric sector.

Not permitting new gas development and retiring coal by 2030 increases costs by ~450M/yr between 2025 and 2040. This cost does not factor in environmental and evironmental justice benefits of reduced coal and gas combustion in that time period. Whether to allow new gas development is one of the biggest drivers of near-term investment decisions in our analysis. If new gas generation is permitted, 3 GW are added by 2025. If it is not permitted, those 3 GW of new gas are replaced by an additional 5 GW of wind, 2 GW of solar, and 4 GW of storage by 2030, as well as a 50% increase in imported energy.

Even without requiring early coal retirements, significantly reducing coal power generation by 2030 is economic in net zero scenarios. In the **Net Zero Economy-Wide** scenario, electricity generation from coal is reduced by 87% relative to the **Baseline** scenario in 2030. This large reduction indicates that accelerating coal retirements is a favored strategy for achieving 40% emissions reductions by 2030 (the reduction imposed in our net zero scenarios).

What investments are made in the electricity sector?

Growth and rapid decarbonization of the electric sector are key to economically reaching net zero emissions by 2050. Meeting the large increase in electric load driven by vehicle, building, and industrial electrification requires significant investment in Wisconsin's electricity infrastructure. In-state investments include 31 GW of solar (including 2.5 GW of rooftop), 21 GW of wind, 7 GW of electric storage, 2 GW of hydrogen electrolyzers, and 3 GW of dual fuel electric industrial boilers by 2050. Early planning is critical to overcome siting and permitting challenges of such a large and rapid expansion of grid-scale renewables and the new electric transmission required to access them.

Electric generation with fully decarbonized gas plays a crucial reliability role by 2050. Gas generation starts as a baseload resource in 2022, but by 2050 transitions into an infrequently used peaking and reliability resource (capacity factors of ~5%). 100% clean electricity policy in all but the **Baseline** scenario requires that these gas peakers operate entirely on non-fossil gas by 2050. Non-fossil gas is supplied predominantly by waste gases from anaerobic digestion.

Wisconsin accesses out-of-state clean energy resources through significant transmission expansion. Expanding transmission interties to surrounding states allows access to greater resource and load diversity, and high-quality renewables. By 2050, approximately a quarter of all electricity delivered to Wisconsin loads comes from out-of-state resources. Wisconsin adds an additional 6 GW of transmission capacity to Iowa, 6 GW to Illinois, and 6 GW to Minnesota by 2050—the maximum quantity of transmission expansion permitted in our analysis. Expansion of this magnitude raises questions of feasibility and will require early planning efforts.

What if demand side transformation happens more slowly?

Transitioning the demand side towards electrified and higher efficiency technologies is key to cost containment. When 100% sales targets of electrified and high efficiency equipment are delayed by 15 years and DER deployment is reduced by half in the **Delayed Action** scenario, total scenario costs increase by ~$3B/yr in 2045. Delaying the transition to electric equipment means the economy uses more energy overall, because the efficiency gains of electrification in transportation and heating applications are not realized.

Slower rates of electrification leave more fossil fuel use in vehicles, buildings, and industry. Higher sustained emissions in these sectors mean Wisconsin needs to reduce emissions in other sectors faster. Natural gas usage declines more rapidly in electricity in this scenario, reaching nearly 100% clean electricity by 2040 because greater quantities of natural gas and liquid fuel consumption remain in other sectors of the economy. The electricity sector gets cleaner faster to offset those increased emissions.

Carbon capture and sequestration is required earlier (by 2035) and in greater volumes to offset emissions from fossil fuel use. Our modeling shows that carbon sequestration is less costly than the alternative: displacing fossil fuels with large-scale clean fuels production. However, cost projections for both approaches are uncertain, and which of these is more cost effective in the future will depend on technological development.

What if transmission cannot be expanded?

Preventing transmission expansion drives significantly more investment in-state. In the absence of new interstate transmission capacity, Wisconsin's in-state wind, solar and electric storage capacity buildout is 36% larger. More in-state transmission investment is required to access those incremental resources. The total regional cost impact of not expanding Wisconsin's interties is $1B/yr by 2050.

Limiting transmission buildout reduces optionality in meeting policy targets, increasing risk on the path to 100% clean electricity or net zero emissions. All the policy scenarios we modeled require the Wisconsin's power sector to grow at a rate that will likely be challenging to implement. Without expanded intertie capacity, even more in-state resources must be sited and permitted, compounding that implementation difficulty and increasing the risk that 2050 policy targets are not met.

Early planning and coordination are needed to avoid the costs and risks associated with a failure to expand interstate electric transmission. Expanding the interties between Wisconsin and neighboring states carries feasibility challenges and long lead times, but given its potential to reduce total costs of achieving climate policy goals, it is an important avenue for the state to pursue. Wisconsin currently does not have an Integrated Resource Plan approach to utility planning, which makes this type of planning, and coordinated planning of the electricity sector in general, difficult.

3 STUDY DESIGN

This technical study of pathways to 100% clean electricity and net zero emissions in Wisconsin was commissioned by RENEW Wisconsin, Clean Wisconsin, and GridLab (the Project Team) to better understand the policy choices and tradeoffs in the state and inform near-term decision making. The project team designed and examined a set of scenarios encapsulating key policies and uncertainties in Wisconsin.

The scenarios in this analysis were defined using assumptions of how energy demand will evolve in Wisconsin and the surrounding region, and what supply resources will be available to meet that energy demand.

3.1 Scenarios

The scenarios studied are described in the Executive Summary. The following table reviews those definitions and shows the question each scenario was designed to answer.

TABLE 2.
Scenarios Investigated

	Scenario	Description	What are we investigating?
	Baseline	No electricity or emissions policy, the way we consume energy remains similar to today	Setting a useful point of comparison to other scenarios
	100% Clean Electricity	Reaching 100% clean electricity but no economy-wide emissions policy	What is the cost and impact on emissions of taking action only in electricity?
NET ZERO SCENARIOS	**Net Zero Economy-Wide**	100% clean electricity and economy-wide emissions policy. Aggressive electrification and efficiency of demand side energy consumption	With all resource options on the table, what is a least cost path to net zero in 2050 and what does the investment strategy look like?
NET ZERO SCENARIOS	**No Transmission Expansion**	Transmission paths to other states cannot be expanded to access more out of state energy	How impactful is transmission expansion on overall costs and in state investments?
NET ZERO SCENARIOS	**Accelerated Clean Electricity**	Economy-wide emissions target and pushing to 100% clean electricity by 2040	How much more would it cost to push to 100% clean electricity faster?
NET ZERO SCENARIOS	**Delayed Action**	Delayed demand-side transformation, 15 years slower than Net Zero Economy-Wide	How important is pushing demand-side transformation on overall costs?
NET ZERO SCENARIOS	**Limited Coal and Gas**	No new gas, and coal retired by 2030	If near-term policy retired coal and prevented new gas investments what would be the impact?

All scenarios share many of the same assumptions about how loads will evolve, how technology development will progress, and the availability of decarbonizing technologies. By changing only one or two assumptions between scenarios, we can attribute the resulting differences in costs and investment decisions to those specific changes.

All scenarios share the same resource potential and price evolution, except where limited in the **No Transmission Expansion** and **Limited Coal and Gas** scenarios. Renewable and thermal resource price forecasts come from the 2021 National Renewable Energy Lab (NREL) Annual Technology Baseline.

The study models 11 zones, as described in more detail in Section 3.2's discussion of modeling methods. In each of the scenarios where electricity and emissions policy are modeled, we assume that the rest of the US is subject to the same policy constraints. For example, in the **Baseline** scenario Wisconsin has no electricity or emissions policy and this is shared by the rest of the US. In the **Net Zero Economy-Wide** scenario, net zero emissions are targeted by 2050 in Wisconsin and in every other region modelled.

The following table describes the assumptions defining each of the scenarios.

TABLE 3.
Scenario Assumptions

Scenario Assumptions	1. Baseline	2. 100% Clean Electricity	3. Net Zero Economy-Wide	4. No Tx Expansion	5. Accelerated Clean Electricity	6. Delayed Action	7. Limited Coal and Gas
Clean Electricity Policy	None	**100% clean electricity by 2050**	Same as 2		**100% clean electricity by 2040**	Same as 2	
Economy-Wide GHG Policy	No emissions constraint		**40% below 2005 levels by 2030, net zero by 2050**				
Clean Resource Qualification	Constrained only by transmission limits						
Buildings: Electrification	AEO Reference Case		Fully electrified/hybrid appliance sales by 2035			**15-year delay**	Same as 3
Buildings: Energy Efficiency	AEO Reference Case		Sales of high efficiency tech: 100% in 2035			**15-year delay**	Same as 3
Transportation: Light-Duty Vehicles	AEO Reference Case		100% electric sales by 2035			**15-year delay**	Same as 3
Transportation: Freight Trucks	AEO Reference Case		HDV long-haul: 50% electric, 50% hydrogen sales by 2045. HDV short-haul: 100% electric sales by 2045. MDV: 100% electric sales by 2045			**15-year delay**	Same as 3
Industry	AEO Reference Case		Generic efficiency improvements over Reference of 1% a year; fuel switching measures; 80% decrease in refining and mining to reflect reduced demand			**0.5%/yr efficiency gains, fuel switching delayed 15 years**	Same as 3
Resource Availability	NREL resource potential; 6 GW of new transmission potential per path; REEDS Tx Costs; SMRs not permitted			**Reduce TX potential versus scenario 3**	Same as 3		**No new gas, existing gas can be extended. All coal retired by 2030**
Fuels	AEO Reference fuel prices; no sequestration potential; clean fuels have zero emissions associated with them, so sequestration credit is left in state of origin						
DER Schedule	2.5 GW of rooftop solar deployment by 2050, 10% of electric space and water heating and air conditioning and 75% of light-duty auto charging is assumed flexible by 2050					**1.25 GW of rooftop solar deployment**	Same as 1

3.1.1 BASELINE AND 100% CLEAN ELECTRICITY SCENARIOS

Both the **Baseline** and the **100% Clean Electricity** scenario assume that the demand side — consumption of energy in the form of electricity and fuels — changes little from today. This assumption comes from the 2021 EIA Annual Energy Outlook (AEO) Reference Case, which forecasts US energy consumption patterns over the next 30 years. Consumption patterns for all fuels and electricity in our model are relatively consistent in the AEO Reference Case. While the AEO Reference Case is likely unrealistic given increasing momentum around emissions reductions action in the US, using AEO's forecast in the **Baseline** and **100% Clean Electricity** scenarios provides useful counterpoints when determining what we need to do differently from today to reach lower emissions in the future.

The only difference between the **Baseline** and **100% Clean Electricity** scenarios is electricity policy: the **100% Clean Electricity** scenario must reach 100% clean electricity by 2050. The clean electricity constraint, which is aligned with Governor Evers' Executive Order 38, is the source of all differences in outputs between the two scenarios. Neither scenario includes emissions constraints.

3.1.2 NET ZERO ECONOMY-WIDE

The **Net Zero Economy-Wide** scenario includes both electricity and emissions policy. It is the core scenario of those that achieve net zero emissions in this study (i.e. all other net zero scenarios included here are variations on the **Net Zero Economy-Wide** scenario).

Net Zero Economy-Wide makes assumptions about demand side transformation towards electrified and higher-efficiency equipment that are aligned with least-cost decarbonization in other states, nationally, and internationally. These include electrification of transportation, electrification of heating loads in buildings, improvements in efficiency, and electrification and generic efficiency improvements in industry. More details on equipment sales assumptions are given in Table 3 and Section 4.3.1 on demand side infrastructure transition.

In most cases, electrified and high-efficiency equipment technologies achieve 100% sales penetrations by 2035. This assumption has been economically advantageous in other decarbonization studies because the lifetime of equipment is often 10 to 15 years. For example, if new light-duty internal combustion engine vehicles are still sold in 2035, those vehicles will remain in vehicle stocks when net zero emissions must be reached in 2050. To provide fuel for those remaining vehicles while meeting net zero requires either decarbonized liquid fuels or offsetting emissions from continued fossil fuel use, both strategies which are likely higher cost than conversion to electric vehicles.

In some cases, we assume 100% sales of electrified or high-efficiency equipment is reached later than 2035. We apply that assumption only for technologies where a more rapid transition may be more expensive or difficult to implement. Freight trucks are one example: we assume 100% sales of electric and hydrogen trucks are reached by 2045, to reflect that non-internal combustion engine (ICE) freight vehicles are less readily available today than other vehicle classes.

These scenario assumptions do not identify the least-cost demand side transition. They instead seek to balance cost effectiveness, feasibility, and acceptability given what we know today about pricing, pace, and scale. By comparing the **Net Zero Economy-Wide** scenario to the **Delayed Action** scenario, we show that the **Net Zero Economy-Wide** demand side sales assumptions are lower cost than transitioning more slowly. Ultimately, the achievable rate of demand side transformation will be driven by customer acceptance and economics (including incentives, utility rates, and tax policy).

Net Zero Economy-Wide includes both electricity policy, reaching 100% clean electricity by 2050, and emissions policy, reaching net zero emissions by 2050. Emissions must be 40% below 2005 levels by 2030.

This scenario has access to all supply resources permitted in the study, including renewable and thermal resources in-state and out-of-state, expansion of transmission interties to other states, new industrial loads including electrolysis and dual fuel electric boilers, and, on the fuels side, supply chains for clean alternative fuels derived from hydrogen and biomass.

3.1.3. NO TRANSMISSION (TX) EXPANSION

The demand side in the **No Transmission Expansion** scenario is the same as in **Net Zero Economy-Wide**.

On the supply side, in comparison to the **Net Zero Economy-Wide** scenario, the **No Transmission Expansion** scenario investigates the differences in investment and cost that result from not permitting transmission expansion between Wisconsin and surrounding states. Existing transmission can be used for imports and exports of electricity but no additional transmission can be built. As described in the Executive Summary, this scenario reflects two different but related potential risks: 1) expansion of transmission interties is infeasible for siting or execution reasons, and 2) the cost of expanding interties is greater than the assumed costs in **Net Zero Economy-Wide** such that expansion becomes uneconomic.

The costs and benefits of transmission expansion are shared across the region and will depend in the future on market design and cost allocation mechanisms. Costs are therefore presented differently for the **No Transmission Expansion** scenario. Instead of showing Wisconsin specific costs and benefits, we show the total regional cost impact of not permitting Wisconsin interties to expand. We have not tried to estimate what portion of these additional costs would be allocated to Wisconsin versus to other states in the region.

3.1.4. ACCELERATED CLEAN ELECTRICITY

The demand side is the same as **Net Zero Economy-Wide**.

On the supply side, **Accelerated Clean Electricity** investigates the impact of moving up the date to achieve 100% clean electricity from 2050 in the **Net Zero Economy-Wide** scenario to 2040.

3.1.5. DELAYED ACTION

Delayed Action investigates the impact of two potential future demand side outcomes: 1) policy designed to achieve electrification and high-efficiency equipment deployment is less aggressive than modeled in **Net Zero Economy-Wide**, or 2) deployment of demand side equipment is slower than expected for economic or customer acceptance reasons. Those outcomes are represented in the scenario as a 15-year delay in electrified and high-efficiency demand side equipment deployment relative to the **Net Zero Economy-Wide** scenario. For example, rather than achieve 100% sales of electric light-duty vehicles by 2035 (as in the **Net Zero Economy-Wide** scenario), 100% sales are achieved by 2050. This 15-year delay is applied across all sectors of the economy.

In addition, generic efficiency improvements in the industrial sector, assumed to be 1% per year in the **Net Zero Economy-Wide** scenario, are reduced to 0.5% per year. Rooftop solar deployment is also halved to 1.25 GW by 2050.

The supply side is the same as in the **Net Zero Economy-Wide** scenario.

3.1.6. LIMITED COAL AND GAS

The demand side is the same as the **Net Zero Economy-Wide** scenario.

On the supply side, **Limited Coal and Gas** explores the impact of not permitting new gas build and retiring coal by 2030. Extensions of existing gas generation are permitted and are assumed to retain the same operating characteristics as the existing plant, including emissions factors and heat rate. While coal is fully retired by 2035 in the **Net Zero Economy-Wide** scenario, coal is retired by 2030 in this scenario.

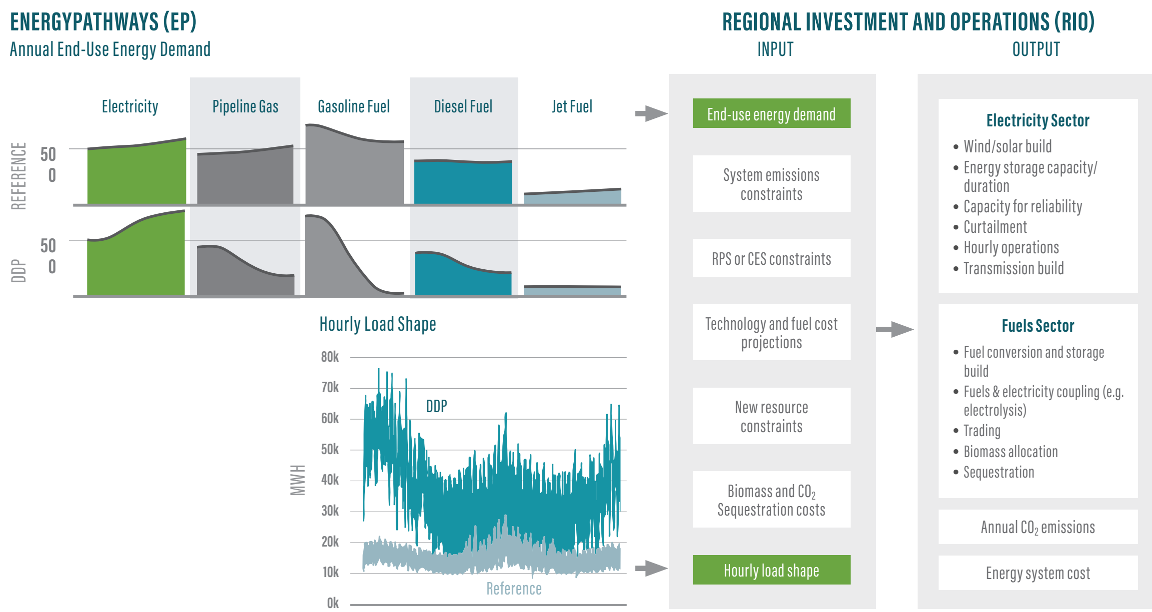
3.2. Modeling Methods

This section summarizes the modeling methods used in this analysis. Further detail on all modeling tools is available in sections S2, S5, and S6 of the supplementary material to Carbon-Neutral Pathways for the United States, published in AGU Advances[4]. Our modeling approach employed two models: EnergyPATHWAYS (EP) and the Regional Investment and Operations (RIO) model.

4 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284

FIGURE 5.

EnergyPATHWAYS and RIO modeling flowchart using illustrative data (study results are not pictured, illustrative purposes only).



3.2.1 ENERGYPATHWAYS

EnergyPATHWAYS (EP) is a bottom-up stock-rollover model of all energy-using technologies in the economy, employed to represent how energy is used today and in the future. It performs a full accounting of all energy, cost, and carbon flows in the economy and can be used to represent both current fossil-based energy systems and transformed, low-carbon energy systems. With over 380 demand-side technologies and 100 supply-side technologies, the model accounts for the costs and emissions associated with producing, transforming, delivering, and consuming energy in the economy.

Inputs to determining final energy demand include:

1. **Demand drivers** – the characteristics of the energy economy that determine how people consume energy and in what quantity over time. Examples include population, square footage of commercial building types, and vehicle miles traveled. Demand drivers are the basis for forecasting future demand for energy services.
2. **Service demand** – energy is not consumed for its own sake but to accomplish a service, such as heating homes, moving vehicles, and manufacturing goods.
3. **Technology efficiency** – how efficiently technologies convert fuel or electricity into energy services. For example, how fuel efficient a vehicle is in converting gallons of gasoline into miles traveled.

4. **Technology stock –** what quantity of each type of technology is present in the population and how that stock changes over time. For example, how many gasoline, diesel, and electric cars are on the road in each year.

The model has very high levels of regional granularity, with detailed representations of existing energy infrastructure (e.g., power plants, refineries, biorefineries, demand-side equipment stocks) and resource potential. Additionally, it is geographically flexible, with the ability to perform state-level to county-level analysis. For this report, the model was used to forecast energy demand of all types, including electricity and fuels, as the stocks of energy consuming technology in the economy change with assumptions about electrification and efficiency. The forecasted energy demands were then put into the Regional Investment and Operations (RIO) platform to solve for how to supply that energy over the next 30 years at least cost.

3.2.2. REGIONAL INVESTMENT AND OPERATIONS (RIO) PLATFORM

EnergyPATHWAYS, described in the previous section, focuses on detailed and explicit accounting of energy system decisions. These decisions are then used as the model inputs for developing scenarios. The Regional Investment and Operations (RIO) platform operates differently, finding the set of energy system decisions that are least cost. RIO is a highly temporally resolved capacity expansion model that is designed to faithfully represent energy systems from today to all imagined futures. It does so with an emphasis on flexibility of resource and technology configurations, an understanding that the principal economic challenges of future electricity systems are managing periods of renewable under-generation (while providing reliable service) and renewable overgeneration (while making productive use of otherwise-curtailed energy), and an ability to look for solutions economy-wide through its unique sector coupling framework. It incorporates final energy demand in future years, the future technology and fuel options available (including their efficiency, operating, and cost characteristics), and clean energy goals (such as RPS, CES, and carbon intensity).

The rationale for using two models in this study is that energy demand-side decisions (e.g. buying a car) are typically unsuited to least cost optimization because they are based on many socioeconomic factors that do not necessarily result from optimal decisions, and are better examined through scenario analysis. RIO's strength is in optimization of supply-side decisions where least cost economic frameworks for decision making are either applied already (e.g., utility planning) or are regarded as desirable in the future. Therefore, RIO is complementary to EnergyPATHWAYS. We use RIO to co-optimize fuel and supply-side infrastructure decisions within each scenario taking demand side inputs from EnergyPATHWAYS (Figure 5). RIO is the first model we are aware of to integrate fuels and electricity directly at a highly resolved temporal level, resulting in a co-optimization of infrastructure that is unique and critical for understanding the dynamics of low-carbon energy systems.

As noted above, the supplementary material to Carbon-Neutral Pathways for the United States, published in AGU Advances[5], describes the functionality of RIO in detail. The following sections, selected from that supplementary material, describe a few of the key elements of the model that were important to represent Wisconsin's future energy decisions realistically.

3.2.2.1. Zonal Representation

RIO represents discrete demand/supply regions flexibly based on model run configurations. This zonal representation becomes the basic unit of constraint enforcement in the model formulation in terms of energy balances and electricity reliability provision. These zones can have unique enforced policy regimes, resource availability, hourly load and resource shapes, existing generators, etc. They are linked to other zones with policy regimes, physical transmission ties that can be optimally constructed, and produced fuels (i.e. biofuels, hydrogen, etc.) and carbon.

Wisconsin is part of a larger electricity grid and larger markets for resources such as fuels derived from biomass and others. What happens to energy demands, electricity and emissions policy, transmission, electricity resource decisions, and markets for fossil and clean fuels outside of Wisconsin influences Wisconsin energy decisions and costs. Modeling the larger energy system is therefore necessary for realistic resource decisions, electricity system dispatch, and tradeoffs between resources of different potentials, costs, and characteristics. In electricity, for example, the larger region has greater load diversity and resource diversity, allowing optimization of resource selection for the system as a whole rather than just for Wisconsin.

We modeled state level geography for Wisconsin and the states surrounding Wisconsin to best represent local transmission and resource constraints. We modeled larger zones of aggregated states further from Wisconsin, as shown in Figure 6. Those states not shown are part of a large "Rest of US" zone that includes Western Electricity Coordinating Council states (the Western US) and Texas. Each zone contains: existing infrastructure; renewable resource potentials and costs; fuel and electricity demand (hourly); current transmission interconnection capacity and specified expansion potential and costs; biomass resource supply curves; and restrictions on construction of new nuclear facilities.

5 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284

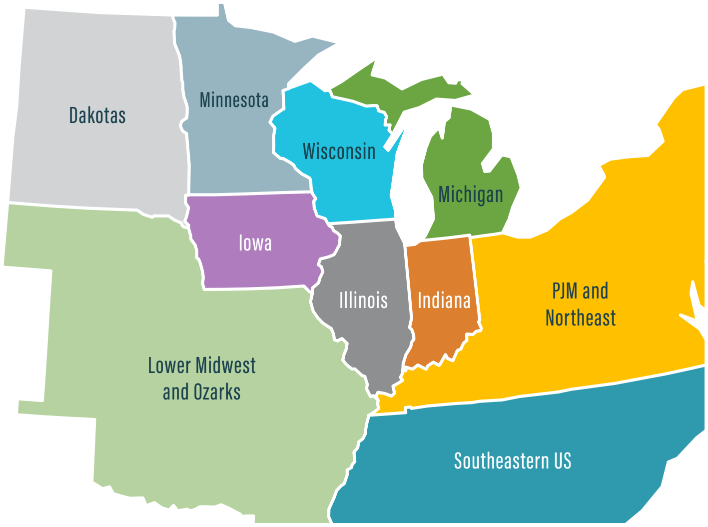


FIGURE 6.
Modeled Zones

3.2.2.2. Operations

Time sequential operations are an important component of determining the value of a portfolio of resources. All resources have a set of attributes they can contribute to the grid, including, for example, energy, capacity, ancillary services, and flexibility. They work in complementary fashion to serve the needs of the system. Whether a portfolio of resources is optimal or not depends on whether it can maintain system reliability, and whether it is cheaper than other portfolios.

Operations are split into short-term and long-term operations in RIO. This is a division between those resources that do not have any multiday constraints on their operations, i.e. they can operate in the same way regardless of system conditions, and those resources that will operate differently depending on system condition trends that last longer than a day. An example of the former is a gas generator that can produce the same output regardless of system conditions over time, and an example of the latter is a long-duration storage system whose state of charge is drawn down over time when there is not enough energy to charge it. The long-term category includes all long-term storage mediums.

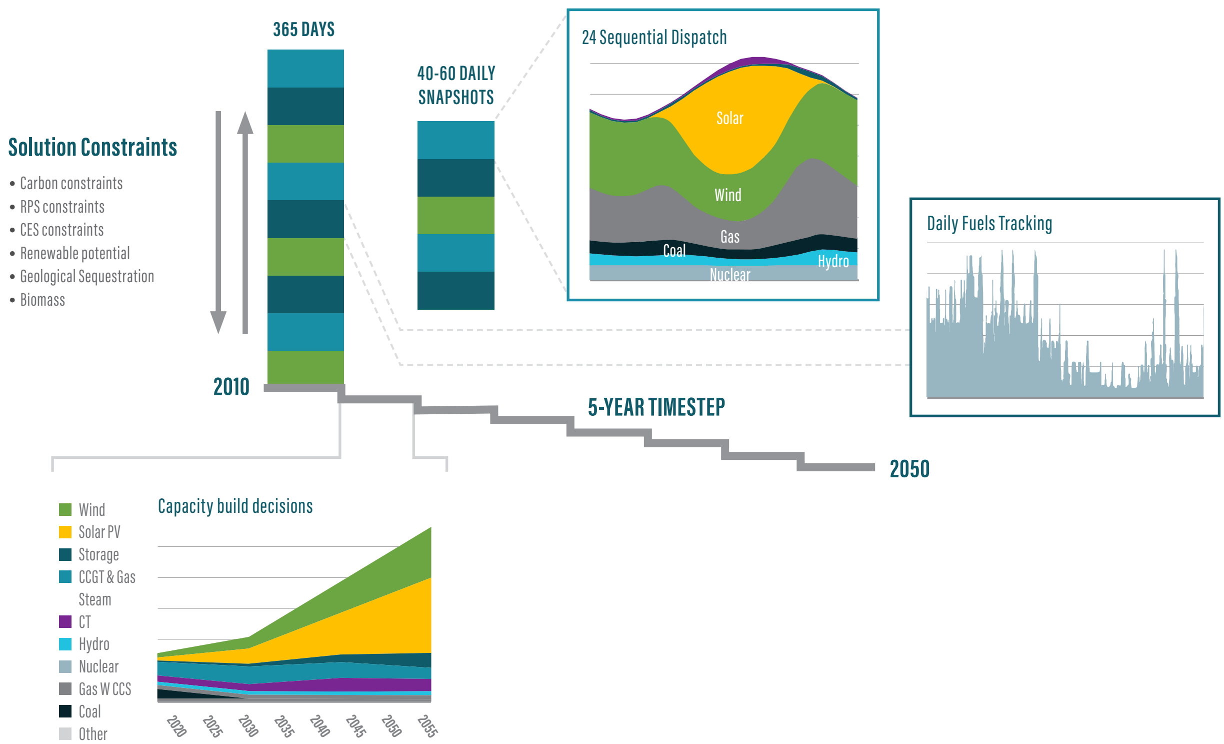
Operational decisions determine the value of one investment over another, so it is important to capture the detailed contributions and interactions of the many different types of resource that RIO can build. The overall RIO operational framework is shown in Figure 7.

RIO operations involve modeling hourly dispatch over a series of sampled daily snapshots (the 40-60 daily snapshots shown in the figure below). These are selected as representative of the distribution of daily load and supply conditions the system may experience in the future. Hourly dispatch incorporates the operating and cost characteristics of each resource option.

The challenge of day sampling in any modeling platform is faithfully representing both extreme conditions, which drive investment for system reliability, while also accurately representing annual averages for things like renewable resource capacity factors. A clustering process is designed to identify days that represent a diverse set of potential system conditions, including different fixed generation profiles and load shapes.

These daily snapshots are mapped back to a 2011 historical weather year in Wisconsin by finding the snapshot that most closely matches the conditions the Wisconsin system experienced on each day in 2011. This enables modeling of long-term operations by tracking state of charge of different storage mediums, including electrical storage as well as fuels production and fuels storage.

FIGURE 7.
RIO Operations Framework



3.2.2.3. Flexible Load

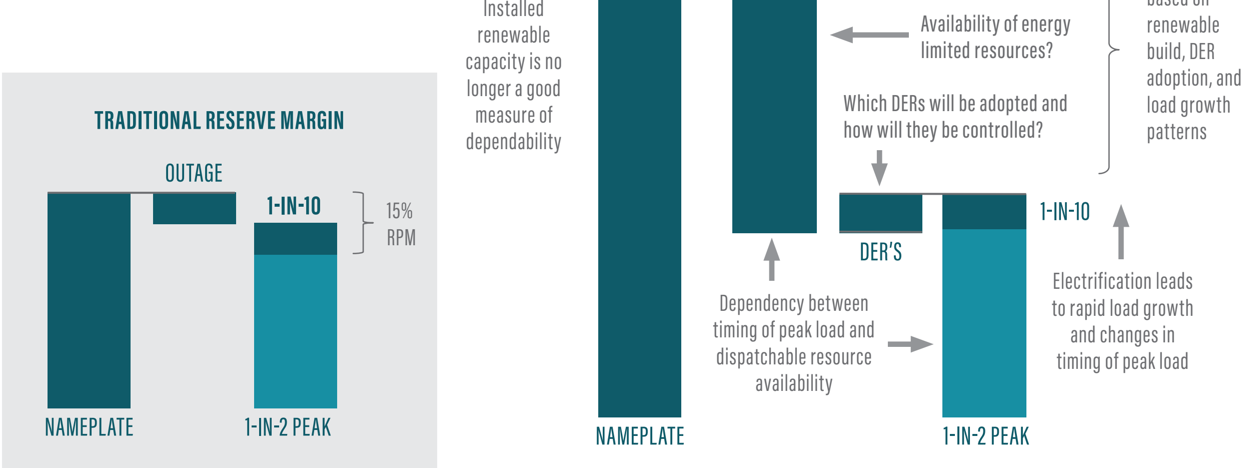
Flexible loads are end-use loads (electric vehicles, space heating, water heating, etc.) where there can be a delay in the delivery of electricity to a customer without incurring significant costs in terms of customer utility. This is referred to as "latent flexibility", though there may be necessary investments needed to unlock this flexibility (i.e. controls, smart meters, etc.). RIO models these flexible loads using flexibility envelopes parameterized with the share of end-use energy that is deemed flexible (analogous to customer participation rates) along with the number of hours this energy can be advanced (moved ahead in time from when demand would otherwise occur) or delayed (moved back in time). We parameterize end-use loads differently based on the inherent characteristics of the shape of the native service demand. EVs, for example, have a service demand shape based on a statistical assessment of the arrival time of uncharged batteries to chargers (i.e. the shape peaks when vehicles are likely to be arriving home with less than fully charged batteries). Given this definition, charging can't be advanced from the native shape (i.e. moved ahead to a time before vehicles arrive home) but it can be delayed. For thermal end-uses, there can be advances or delays, reflecting the ability to pre-heat or pre-cool as well as the ability to delay demand for electricity by taking advantage of lags in temperature changes.

3.2.2.4. Reliability

The conditions that will stress electricity systems in the future and define reliability needs will shift in nature compared to today, shown in Figure 8. Capacity is the principal need for reliable system operations when the dominant sources of energy are thermal. Peak load conditions set the requirement for capacity because generation can be controlled to meet the load and fuel supplies are not constrained. As the system transitions to high renewable output, the defining metric of reliability need is not just peak load but net load (load net of renewables). Periods with the lowest renewable output may drive the most need for other types of reliable energy even if they do not align with peak gross load periods. In addition to that, resources will become increasingly energy constrained. Storage can only inject the energy it has in charge into the system. Reliability is therefore increasingly driven by energy need as well as capacity need.

In the future, the defining reliability periods may be when renewables have unusually low output, and when that low output is sustained for unusually long periods. To model a reliable system in the future, both capacity and energy needs driven by the impact of weather events and seasonal changes on renewable output and load need to be captured.

FIGURE 8.
Reliability framework in high renewable systems



To ensure we capture the impacts of these changing conditions on reliability, we enforce a planning reserve requirement on load in every modeled hour. This "planning demand" is found by scaling load up to account for the possibility that demand in each hour could be greater than expected. At the same time, we determine a dependable contribution of each resource to meeting the planning demand. Dependability is defined as the output of each resource that can be relied upon during reliability events. The planning demand must be met or exceeded by the summed dependable contributions of available resources in each hour.

3.2.2.5. Dependability

The dependable contribution from thermal resources is derated nameplate, reflecting forced outage rates. Renewable dependable contribution is the derated hourly output, reflecting that renewable output could be even lower than expected. For energy constrained resources such as hydro and storage, dependable contribution is derated hourly output. By using derated hourly output we can capture both the risk that it is not available because of forced outage, and the risk that it is not available because it has exhausted its stored energy supply. Dependability factors are shown in Table 4.

TABLE 4.

Dependability Factors when Enforcing RIO Reliability Constraints

Resource	Dependability
Existing Thermal Resources	93% applied to nameplate
New Thermal Resources	93% applied to nameplate
Transmission	70% applied to hourly flows
Energy storage	95% applied to hourly charge/discharge
Variable generation (wind & solar)	80% applied to hourly output
Electricity load	106% applied to hourly load

Cross-Sectoral Integration

In addition to electricity investment and operating decisions, RIO optimizes the fuel blend that fuel consuming end uses in the economy are eligible to receive, while also allowing fuels produced by electricity or from biomass to contribute to fuel stocks. For example, natural gas power plants can be fueled by 100% fossil gas, a blend of fossil gas and clean gases such as agricultural waste gases and hydrogen, or 100% clean gases. Injections of hydrogen into the natural gas pipeline are limited to 7% by energy, however we allow up to 100% agricultural waste gases to flow to gas generation.

Likewise, fuel blends consumed in other sectors of the economy such as diesel, gasoline, fuel oil, pipeline gas, hydrogen etc., can come from conventional sources such as fossil oil and gas products, or from unconventional sources including biomass and synthetic fuels produced from hydrogen. This functionality is what allows RIO to extend beyond the electricity sector and optimize the entire energy supply side. These unconventional sources of fuel involve conversion of one type of energy to another and require infrastructure, transportation, and storage investments. The capital investments in the technologies along these supply chains and their operating costs are represented in RIO as least cost investment options to meet Wisconsin's energy needs. These provide opportunities for decarbonization and more efficient utilization of electricity resources, lowering the costs of meeting future emissions targets. Rather than curtailing electricity when generation exceeds load, flexible industrial loads such as hydrogen production can be dispatched to make use of that energy. Including these electricity balancing and economy-wide decarbonization opportunities leads to more efficient and more realistic solutions than optimizing each sector of the economy in isolation. Figure 9 shows a simplified version of the supply chain for clean hydrogen from electrolysis. This shows hydrogen going to methanation, Fischer-Tropsch[6], and direct injection into the gas pipeline. In Wisconsin, we assume growth of hydrogen demand in trucking that is also supplied by the hydrogen blend.

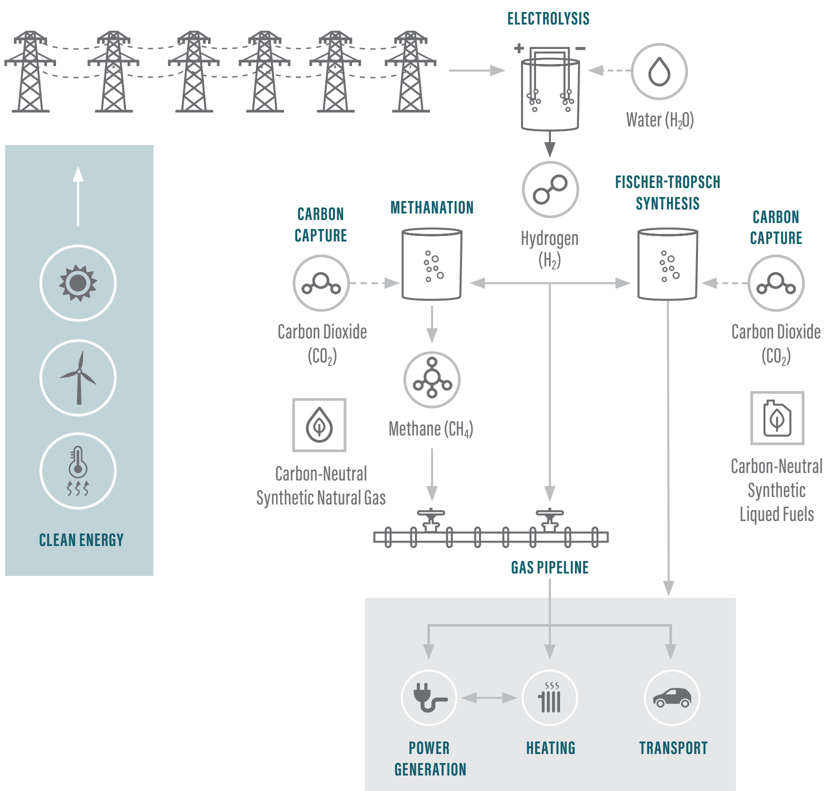


FIGURE 9.
Simplified Representation of Clean Hydrogen Supply Chain[7]

6 Fischer Tropsch is a chemical process of combining hydrogen and carbon monoxide to create a range of different hydrocarbons. It has been used to create hydrocarbons from coal gasification, but hydrogen and carbon can come from electrolysis and carbon capture, respectively, to create clean drop-in hydrocarbon fuels for end uses. https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/ftsynthesis

3.3. Study Assumptions

This study used Evolved Energy Research's United States database to represent US energy supply and demand. Comprehensive details of sources used to populate the database are given in the supplementary material to Carbon-Neutral Pathways for the United States, published in AGU Advances[8]. Relative to the sources described in that paper, data collected from the EIA Annual Energy Outlook[9] and NREL's Annual Technology **Baseline** (ATB)[10] was updated in the database to reflect the 2021 release of those studies.

The database was also updated with assumptions specific to this study to best capture Wisconsin's energy constraints and opportunities. These Wisconsin-specific assumptions are detailed in the following subsections.

3.3.1. 100% CLEAN ELECTRICITY

Clean electricity policy modeled in each of the scenarios other than the **Baseline** was in line with Executive Order 38, achieving 100% clean electricity by 2050. We also assumed interim targets achieving 40% clean electricity by 2030 and 70% clean electricity by 2040. The Project Team made several assumptions to define **100% Clean Electricity** and the set of resources eligible to provide clean electricity under that definition. These include:

- Wisconsin can draw upon clean resources located outside of the state to provide clean electricity. However, all electricity must be delivered over transmission to loads in Wisconsin and balanced on an hourly basis. This means that the Clean Electricity requirement specified for each year in Wisconsin must be achieved in every hour, rather than on an average basis over a long period of time (a year, for example). Enough transmission must be in place to deliver the clean electricity counted towards the requirement from out of state sources. This is a more stringent requirement than balancing clean electricity credits over a year, for example. The implementation of clean electricity policy in Wisconsin will depend on future policymaking.
- All electricity losses are included in the load that must be met under the **100% Clean Electricity** standard. Often clean electricity policy is defined at retail sales level, i.e. 100% of retail sales must be clean electricity, leaving room for fossil generation in the system to provide the losses between point of generation and point of delivery. In this analysis, we assume that those losses fall under the clean electricity requirements as well.

7 Clean Energy Transition Institute, Northwest Deep Decarbonization Pathways Project, 2019. https://raw.githubusercontent.com/cleanenergytransition/mtc-report-graphic-p2x/gh-pages/Illustration of Power-to-X.pdf

8 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284

9 https://www.eia.gov/outlooks/archive/aeo21/

10 https://atb.nrel.gov/electricity/2021/data

- Wind, solar, hydropower, biomass, clean gas from waste gases or green hydrogen and its derivatives, and nuclear, all qualify to meet **100% Clean Electricity**. Fossil generation with carbon capture, including from natural gas and coal, is assumed not to qualify under **100% Clean Electricity**.

3.3.2. ECONOMY-WIDE EMISSIONS TARGETS

Wisconsin currently has no economy-wide emissions policy. However, whether economy-wide emissions policy is present or not has a profound impact on the electricity sector, particularly if emissions policy drives demand side electrification. In this study, electricity demand in the scenarios with emissions policy is 127% higher than in the **Baseline** scenario in 2050. Modeling emissions policy is important to make near-term planning decisions in electricity in the context of potential future state or federal policy action to reduce emissions economy-wide.

To model emissions policy, we drew upon other state examples, targeting 40% emissions reduction by 2030 and net zero emissions by 2050. These were relative to Wisconsin's emissions in 2005, provided in the 2020 Wisconsin Greenhouse Gas Emissions Inventory Report.[11]

Evolved's models include emissions from energy and industry sources. We make an assumption outside of the model about what will happen in non-energy and non-CO_2 emissions in the economy to determine the overall emissions target for energy and industry in the model. For example, if net emissions in non-energy and non-CO_2 categories were forecasted not to reach net zero by 2050, energy and industry emissions would have to drop below net zero to reach net zero emissions economy-wide.

For simplicity in this study, we assume that non-energy and non-CO_2 emissions reach net zero by 2050 so that the target for energy and industry emissions is also net zero. Examples of non-energy and non-CO_2 emissions include agricultural emissions from animals and farming practices and leakage from pipelines (such as methane). Examples of measures to reduce and offset those emissions include pipeline maintenance and land-based measures to increase land sink (such as forestation). In practice, reducing many of categories of non-CO_2 emissions may be challenging and expensive, and studies are needed to identify solutions to achieve these reductions in Wisconsin. The potential for increasing the land sink is another unknown. Depending on the true cost and feasibility of non-energy and non-CO_2 emissions reductions, it may be more cost effective for Wisconsin to target net negative emissions in the energy and industry sectors. This would be achieved through net negative emissions technologies, such as bio-energy with carbon capture and direct air capture. However, in this study we target net zero emissions in energy.

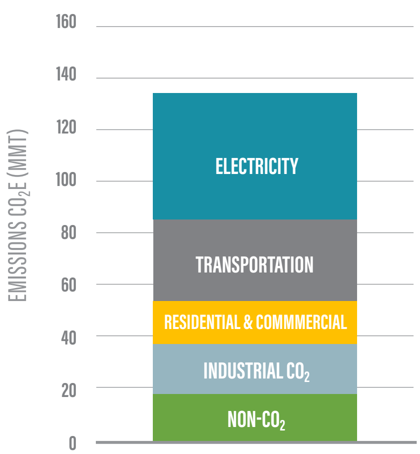


FIGURE 10.
Wisconsin Economy-Wide 2005 Emissions Inventory

11 Wisconsin Department of Natural Resources, "Wisconsin Greenhouse Gas Emissions Inventory Report", August 2020, Publication Number: AM-580-2020

Figure 10 shows the 2005 Emissions Inventory developed by Wisconsin Department of Natural Resources. Electricity is the largest contributor to emissions, followed by transportation, industry, non-CO_2, and the residential and commercial sectors. Our targets for emissions reductions are set at a 40% reduction from this total by 2030 and achieving net zero by 2050. Based on our assumption that both energy/industry and non-CO_2 target the same percentage emissions reductions, we apply the economy-wide target to energy and industry in our modeling.

Figure 11 shows the target emissions trajectory from present day through to 2050. Also shown is the 2017 Wisconsin emissions inventory produced by Wisconsin Department of Natural Resources. Relative to 2005, some emissions reductions have already been achieved.

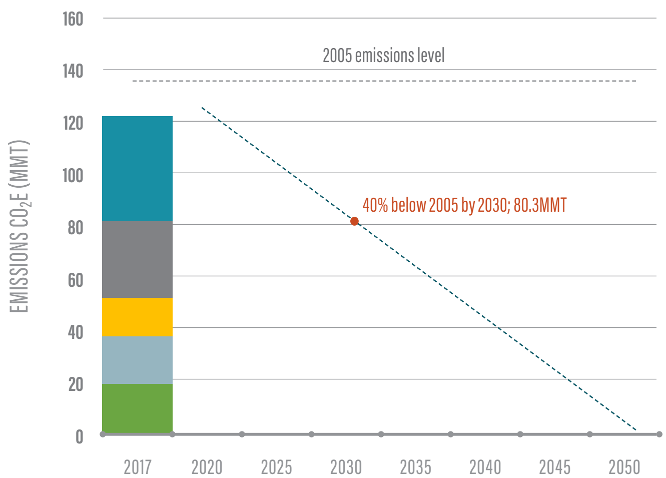


FIGURE 11.
Wisconsin Economy-Wide Emissions Reduction Trajectory

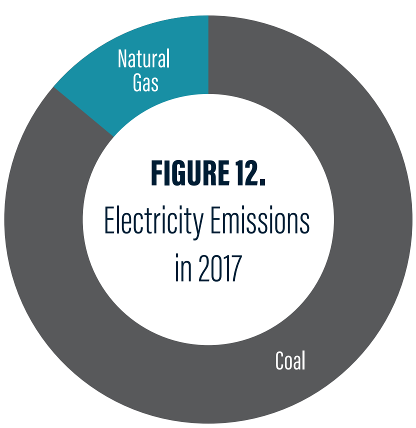


FIGURE 12.
Electricity Emissions in 2017

Electricity remains the largest emitting sector of the economy in 2017, within which coal constitutes most of the emissions (taken from EIA Wisconsin power sector emissions reporting for 2017[12]). Emissions reductions from coal are therefore a significant opportunity in Wisconsin. Removing coal emissions from the power sector would take Wisconsin much of the way towards achieving the 2030 40% emissions reductions target without requiring any other action.

12 https://www.eia.gov/environment/emissions/state/

3.3.3. COAL RETIREMENTS

Almost all coal in Wisconsin is set to retire by 2035 or before. Announced retirement dates by generator at the time the study was completed are given below in Table 5. Since that time, some of these dates have been updated but without material impact on the conclusions of the study[13]. The only plant that does not have a planned retirement is John P Madgett 1.

TABLE 5.
Wisconsin Coal Plant Capacity and Announced Retirement Dates

Plant	Capacity (MW)	Retirement
South Oak Creek_5	241	2023
South Oak Creek_6	245	2023
South Oak Creek_7	303.3	2024
South Oak Creek_8	309.4	2024
Edgewater_5	415.7	2022
Weston_3	327.4	2035
Weston_4	550.1	2035
Genoa_ST3	307.5	2021
John P Madgett_1	389.8	Not Specified
Columbia (WI)_1	575	2023
Columbia (WI)_2	570	2024
Elm Road Generating Station_1	633	2035
Elm Road Generating Station_2	633.4	2035

Modeled Coal Retirement Assumptions

We assume the above retirement dates in the **Baseline** scenario. The aggregate remaining megawatts of coal in years through 2050 are shown in Figure 13. In scenarios assuming 100% clean electricity by 2050, we assume all coal is retired by 2035 as a supporting policy coherent with achieving clean electricity. In the **Limited Coal and Gas** scenario, we assume all coal is retired by 2030. These two alternative retirement schedules are shown below.

Note that this represents the maximum number of megawatts of coal that can remain in future years. The model can economically retire coal earlier than scheduled as well. As

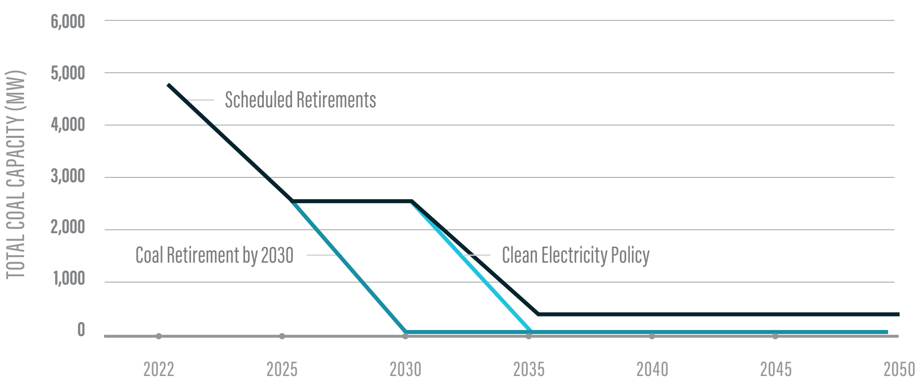
13 Since conducting the study, these announced retirement dates have changed as follows: Edgewater is now scheduled for retirement in 2025; Oak Creek 5&6 are scheduled for 2024; Oak Creek 7&8 are scheduled for 2025; and Columbia is scheduled for 2026. The impact of this would be to increase coal generation in the 2025 modeled year but does not affect later years. These updated dates are therefore not impactful on the conclusions of the study.

the next section describing the model results shows, in cases with emissions policy, coal generation is minimal by 2030 because reducing coal generation is an economic way to achieve the 2030 emissions target.

FIGURE 13.

Aggregate MWs of Coal in Wisconsin by Year

COAL RETIREMENT SCHEDULE



3.3.4. TRANSMISSION COSTS AND POTENTIALS

Transmission interties between Wisconsin and surrounding states, as well as between other modeled regions, are represented using transfer capacities from the EPA Platform v6 database[14]. Table 6 gives these capacities. Currently there is no capacity between Wisconsin and Iowa, however Cardinal – Hickory Creek 345 kW between Wisconsin and Iowa is a MISO Multi-Value Project (MVP) scheduled to supply 800 MW of capacity between the two states.

TABLE 6.

Intertie Capacity between Wisconsin and Surrounding States

From	To	MWs in 2022
Wisconsin	Minnesota	2400
Wisconsin	Iowa	0
Wisconsin	Illinois	2200
Wisconsin	Michigan (LMI)	100

14 https://www.epa.gov/system/files/documents/2021-09/table-3-28-annual-transmission-capabilities-of-us-model-regions-in-epa-platform-v6.xlsx

Modeled Transmission Assumptions

Our model starts with the existing transmission capacity described above. It then has the option to build up to 6 GW of new transmission capacity per state-to-state intertie. This is true in all scenarios except for **No Transmission Expansion**. The cost of expanding the interties comes from the EPA Platform v6 cost inputs. These are sourced from the NREL JEDI model that factors in determination of likely voltage rating, estimation of representative line lengths, and assessment of terrain into producing a cost estimate.

For comparison, the 102-mile 345 kilovolt Cardinal-Hickory Creek[15] between Wisconsin and Iowa has an estimated cost of $492M to $543M[16] or $615/kW to $679/kW. The generic cost for a Wisconsin-Iowa intertie in the EPA database is $646/kW, a close match to the real-world cost estimate.

These cost estimates may be significantly different from real future project costs expanding transmission capacity between states. The **No Transmission Expansion** scenario acts as a bookend to that uncertainty by assuming that transmission expansion is either infeasible, too expensive to build, or not desirable for other reasons.

3.3.5. ROOFTOP SOLAR

Rooftop solar adoption is an input assumption to the model (rather than an economic optimization) because several factors that influence its adoption are not represented in our model: 1) customer economics based on rate designs, financing, and incentives, 2) customer preferences, and 3) other benefits such as promoting jobs creation or supporting local labor. We therefore rely on rooftop PV forecasting performed by Cadmus in Wisconsin that considers economic potential of rooftop PV from a customer perspective[17]. Cadmus simulates market adoption potential through 2034 in Wisconsin. We extrapolate the rates of rooftop solar adoption in each of their scenarios through 2050. When doing so, most scenarios in their analysis converge around 2.5 GW of rooftop solar deployment by 2050. We use that value as our default rooftop solar deployment in the model.

We permit the model to economically deploy rooftop solar beyond the 2.5 GW input assumption. However, because grid scale solar is less expensive on a per kW basis, and our model does not capture the avoided costs of DER, our model (which does not account for the non-cost factors motivating rooftop PV adoption) selects grid scale over rooftop PV. As a result, total rooftop solar adoption is 2.5 GW in each of our scenarios, except the **Delayed Action** scenario which halves the total rooftop solar installed by 2050 to 1.25 GW.

15 This line has received necessary approvals and certificate of authority, but is under further legal review at the time of drafting this report

16 PSC of Wisconsin Docket ID: 5-CE-146, https://psc.wi.gov/Pages/MajorCases/CardinalHickoryCreek.aspx

17 Cadmus 2021 Rofftop Solar Potential Study Report, https://focusonenergy.com/sites/default/files/inline-files/Potential_Study_Report-FoE_Rooftop_Solar_2021.pdf

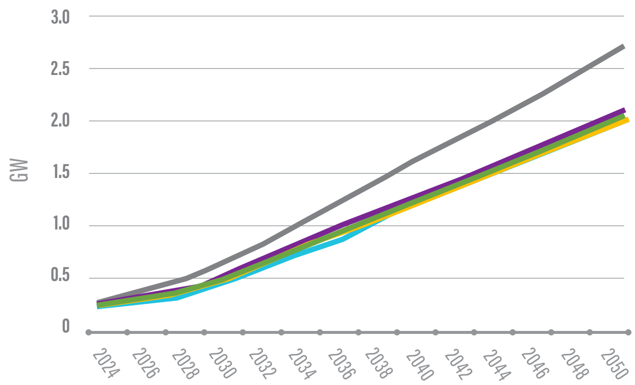


FIGURE 14.
Cadmus Rooftop PV Economic Potential by 2050

3.3.6. FUELS NETWORK ASSUMPTIONS

Electricity transmission is only one means of importing energy into the state of Wisconsin. Others include liquid and gaseous fuels, both fossil fuels and decarbonized alternatives. Our analysis uses fossil fuels price forecasts (both commodity prices and delivery costs) from the EIA Annual Energy Outlook 2021. Our analysis allows clean fuels to be sourced from outside Wisconsin, drawing upon future national markets for hydrogen, biomass, and carbon. We determine biomass potential and prices from the supply curves in the DOE Billion Ton study[18]. We assume clean liquid fuels, derived either from biomass or hydrogen, use the existing delivery network currently used to transport fossil fuels.

This analysis assumes that the same economy-wide emissions policy is applied to all parts of the US and not just the Eastern Interconnection. Though Wisconsin is not electrically connected to states in the WECC and Texas, it belongs to the same market for fuels. Ensuring that the rest of the US economy decarbonizes in parallel with Wisconsin is a conservative assumption when forecasting clean fuel supply and cost, as Wisconsin must compete with the rest of the country for limited biomass and high-quality renewable resources.

18 DOE Billion-Ton Report, https://www.energy.gov/eere/bioenergy/2016-billion-ton-report

4 RESULTS

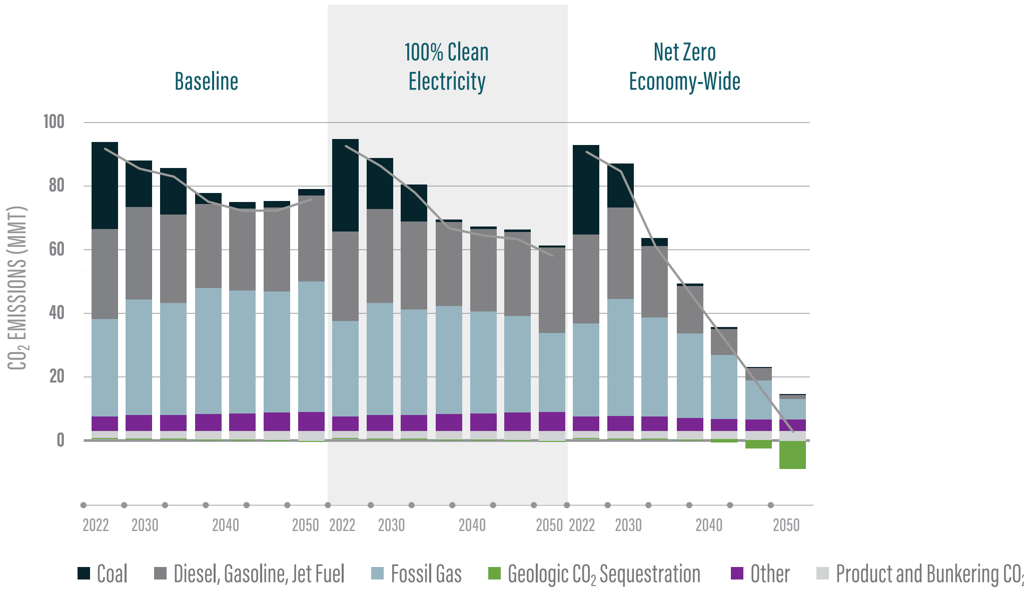
4.1. Emissions

4.1.1. EMISSIONS BY CLEAN ENERGY POLICY

The largest emissions differences between scenarios are driven by electricity and emissions policy. The **Baseline** scenario includes neither, the **100% Clean Electricity** scenario reaches zero emissions from electricity by 2050, and the **Net Zero Economy-Wide** scenario (as well as all other net zero policy scenarios) achieve net zero emissions by 2050. For ease of comparison, we show emissions for these 3 scenarios in Figure 15.

FIGURE 15.

Wisconsin Energy and Industry Emissions by Clean Energy Policy Scenario



4.1.1.1. Baseline

In our **Baseline** scenario, emissions in Wisconsin decline 18% by 2050 compared with 2022 levels, driven by changing economics in the power sector. Much of the decline in emissions is driven by coal retirements: by 2035, announced retirements in the state will remove most coal plants from operation, which were the source of 34% of total emissions in 2018. Though natural gas emissions increase in the **Baseline** scenario as gas generation expands to replace coal and meet new loads from population growth, on net, Wisconsin sees a decline in emissions through 2035. In addition to the transition from coal to gas, economic adoption of solar energy also increases by 2040 as the result of projected declines in solar costs, further reducing **Baseline** emissions.

4.1.1.2. 100% Clean Electricity

In the **100% Clean Electricity** scenario, emissions reductions accelerate over the **Baseline** scenario, dropping 6% in 2030, 12% by 2035, and 24% by 2050. These reductions are driven by increased renewable generation between 2030 and 2050, reduced gas generation as renewables displace it, and increased clean energy imports between 2035 and 2050. Gas remains in use outside the electric sector, including various heating applications, so natural gas emissions still make up 45% of total emissions by 2050. Vehicles remain predominantly internal combustion powered, representing 49% of emissions. The remaining 6% of emissions come from the industrial sector. The total reduction in 2050 emissions in this scenario is 38% over 2022 levels.

4.1.1.3. Net Zero Economy-Wide

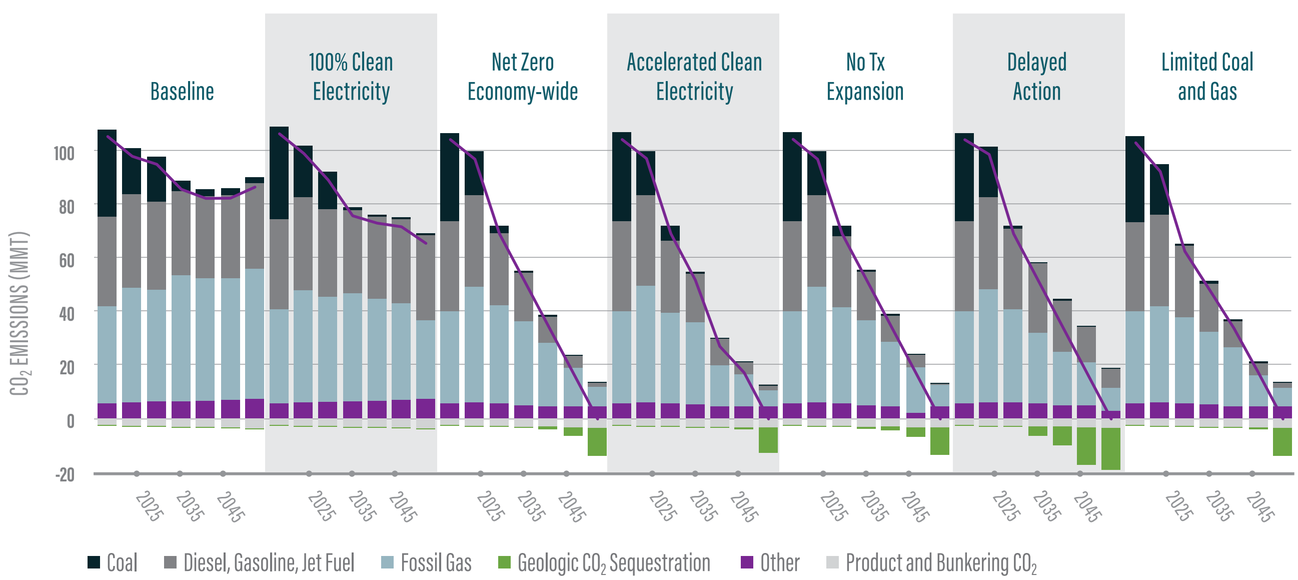
The **Net Zero Economy-Wide** scenario incorporates net zero emissions policy and the accompanying demand side transition to electric and high efficiency equipment. Emissions reductions in 2025 are similar to the first two scenarios, as turnover of demand side equipment stocks is too small to significantly drive down energy demand in that period. However, by 2030, emissions are significantly lower. Emissions from coal generation in electricity are 86% lower than in the **Baseline** scenario in 2030 as renewables replace coal. Demand for liquid fuel and end use natural gas also decline as heat pumps and electric vehicles start to gain a more meaningful share of total equipment stocks. Beyond 2030, emissions decline steeply as the demand side continues its transformation and gas generation in electricity is displaced by renewables. Some residual emissions in 2050, from end use natural gas demand (including hybrid heat pumps) and industrial activity, are offset by geologic sequestration of carbon.

4.1.2. EMISSIONS ACROSS NET ZERO SCENARIOS

While emissions contrast less significantly across scenarios that achieve net zero by 2050, there are still important differences to highlight. Figure 16 details total emissions across all scenarios.

FIGURE 16.

Wisconsin Economy-Wide Emissions by Scenario and Year



4.1.2.1. Accelerated Clean Electricity

The **Accelerated Clean Electricity** scenario reduces gas emissions faster than **Net Zero Economy-Wide**. In **Accelerated Clean Electricity**, natural gas must be eliminated from electric generation by 2040, as opposed to 2050 in other scenarios; as a result, it is not economic to build as much new gas generation capacity in the interim years. As a result, coal generation is slightly higher in 2030 in the **Accelerated Clean Electricity** scenario, taking advantage of existing capacity while remaining under the 2030 emissions cap. This scenario also reduces economy wide emissions faster than required under the emissions target by 2040 because fossil gas generation in electricity must retire earlier. This scenario therefore has less cumulative emissions than the others through 2050.

Though the **Accelerated Clean Electricity** scenario does result in more rapid emissions reductions relative to the Net Zero Economy Wide case, our analysis does not imply that accelerating clean electricity policy is a least-cost mechanism for achieving faster reductions. A modeled scenario with a more stringent economy wide emissions target would be needed to evaluate the least-cost path to accelerated emissions reductions.

4.1.2.3. No Transmission Expansion

No Transmission Expansion follows a similar trend to **Net Zero Economy-Wide**. While different resource investment decisions are made to accommodate lost access to resources outside of Wisconsin, these changes are not reflected in the scenario's emissions profile.

4.1.2.2. Delayed Action

Delayed Action retains fuel use in end uses for a longer period, reflected in the remaining liquid fuels emissions beyond 2040. While natural gas is also retained in end uses, overall natural gas emissions are lower than in **Net Zero Economy-Wide** until 2050 because gas in electricity is forced out of the portfolio earlier to make room for higher liquid fuels emissions. For the same reason, coal is fully retired in electricity by 2030. Geologic sequestration of carbon begins sooner and reaches greater quantities by 2050 to offset remaining end use emissions.

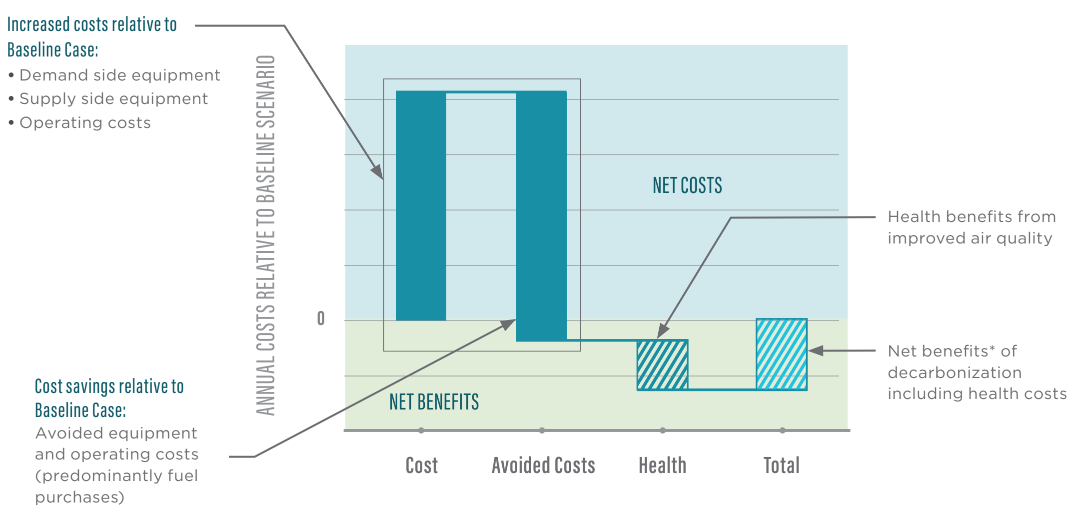
4.1.2.3. Limited Coal and Gas

Limited Coal and Gas shows slightly steeper emissions declines in 2030 because coal is fully retired and gas generation is prohibited from replacing it. Instead, additional renewables and batteries are built to fill the capacity and energy need. Beyond 2030, emissions are similar to the **Net Zero Economy-Wide** scenario.

4.2. System Costs

Cost assessment of the scenarios is critical to understanding the potential economic and societal impacts of achieving clean electricity and net zero emissions targets. We present all costs as net relative to the **Baseline** scenario. Some cost categories are consistently higher in the clean electricity and net zero emissions scenarios than in the **Baseline**: for example, the cost of electrifying appliances and vehicles, or investment in electric sector generation, transmission and distribution capacity to meet demand increases. There are also categories of spending that are highest in the **Baseline** scenario, primarily fossil fuel purchases which persist in the **Baseline** but are phased out in other scenarios. These net costs and avoided costs are shown conceptually in Figure 17. All costs and avoided costs in our results are shown on a societal cost basis; costs reported here do not include any distributional impacts (i.e. they do not tell us who pays for what in the transition). Societal cost is a useful cost perspective for long-term planning because it indicates the total size of the pie that we must pay for in the future. How we pay for the pie is subject to market designs, rate structures, tax policy, and incentives – all levers available to equitably achieve electricity and emissions targets. However, minimizing the overall size of what we must pay across the economy is a necessary first step prior to developing implementation strategy to achieve it.

FIGURE 17.
Conceptual Overview of Costs



Beyond the direct costs calculated in our decarbonization modeling, there are additional benefits that are not included in the net benefits presented in this section. One major benefit is the health impact of reducing emissions. These health benefits are calculated separately using the EPA COBRA model and are covered in Section 4.5. There are also impacts of decarbonization to economic activity and employment, which are covered in a separate analysis performed by Cambridge Econometrics. Finally, there are benefits from mitigating climate change by reducing CO_2 emissions. However, those mitigation benefits rely on the rest of the world taking action to reduce emissions and cannot be attributed to Wisconsin's decarbonization actions alone. Therefore, we have not included them in the analysis of costs and benefits.

Figure 18 shows the net costs of each scenario relative to the **Baseline** scenario. These costs reflect annualized capital costs plus operating costs, akin to an economy-wide revenue requirement for energy infrastructure and fuels. These costs include demand side equipment, supple side equipment, and energy system operating costs. Examples of demand side equipment include electric vehicles and heat pumps. Additional spending in this category is due to assumed adoption of electrified and efficient technologies by customers and businesses. Examples of supply side equipment include power plants such as wind turbines, solar panels, and gas generators, transmission and distribution infrastructure such as new power lines and substations, clean fuels production facilities, fuels transportation infrastructure, and carbon sequestration infrastructure. Further detail on all cost categories, subsectors, and cost data sources is available in sections S2, S5, and S6 of the supplementary material to Carbon-Neutral Pathways for the United States, published in AGU Advances[19].

We see similarities across all scenarios in the main categories of spending. In all net zero emissions scenarios, significant investment appears in renewable power plants, the electricity grid, and demand side equipment, making up the majority of additional costs over the **Baseline** scenario. Signficant savings from decarbonization come from avoiding purchases of fossil oil and gas products. Comparing costs across scenarios indicates which pathways present lower societal cost options to Wisconsin.

19 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284

FIGURE 18.

Net Costs relative to the Baseline Scenario ($/yr)

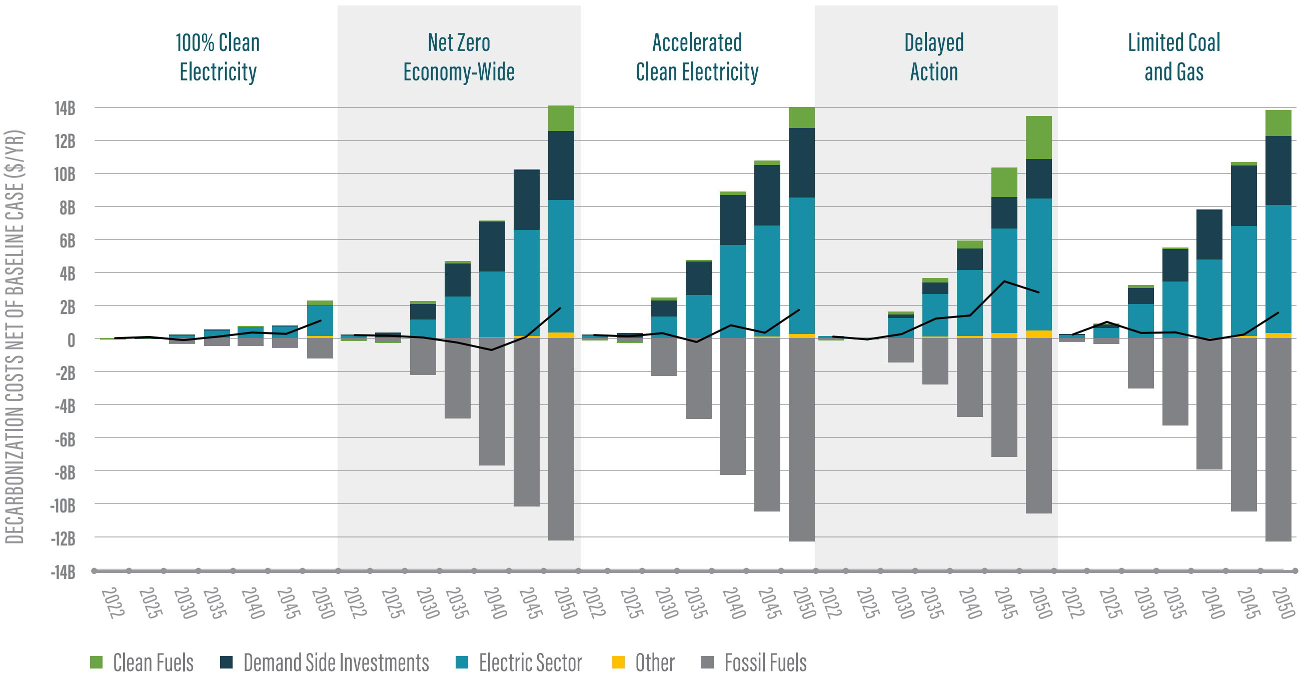


Figure 19 translates this net energy spending into a percentage of GDP. In the **Net Zero Economy-Wide** scenario, additional spending on energy reaches approximately 2% of GDP per year by 2050, however this is offset, as described above, by savings on fuel purchases. Net energy spending by 2050 is 0.25% of GDP per year.

FIGURE 19.

Net Costs relative to the Baseline Scenarios (%GDP/yr)

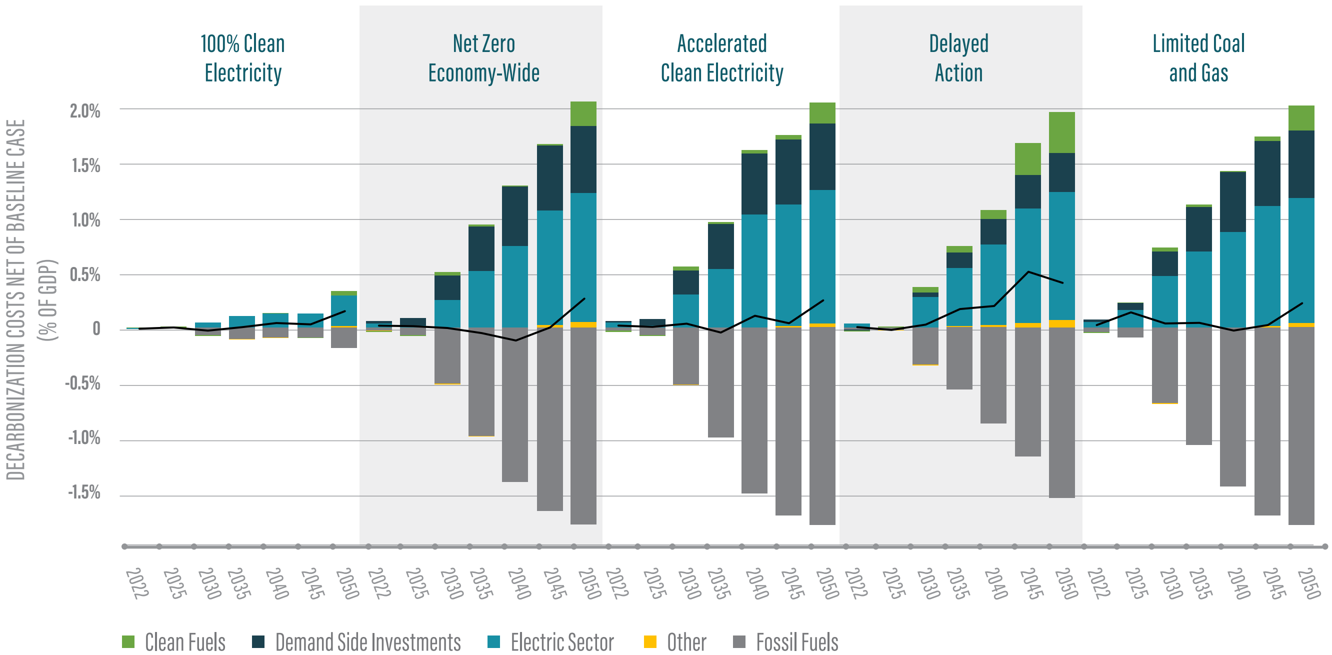
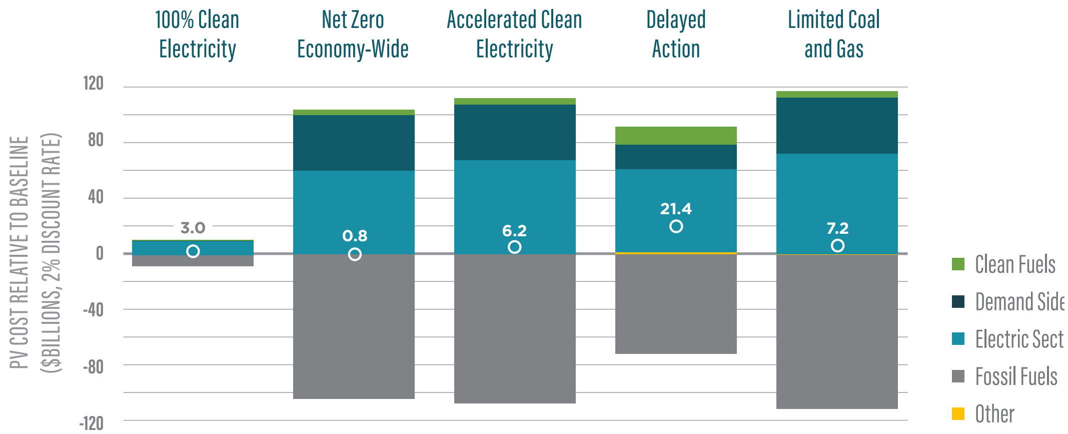


Figure 20 compares costs on a present value basis. We have used a societal discount rate of 2% to determine present value of energy spending in each category. This supports the conclusion that net zero policy and not just clean energy policy alone is competitive on cost and achieves far greater emissions reductions. The comparison of **Delayed Action** to **Net Zero Economy-Wide** highlights the importance of taking early action to transition the demand side to electrified and high efficiency equipment. Present value costs are ~$20B more when demand side transformation is delayed. **Limited Coal and Gas** costs are increased due to higher near-term spending that has a larger proportional impact on present value. This comes from increased renewable investment by 2030 to replace energy generated by gas in the other scenarios.

FIGURE 20.

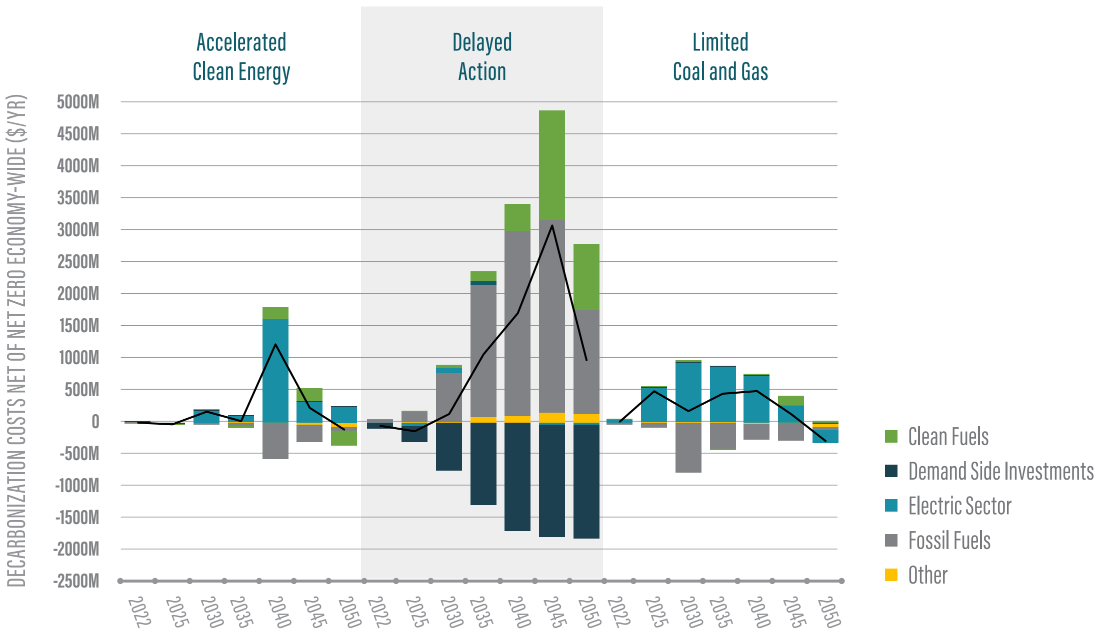
Present Value of Costs relative to Baseline Scenario (2% Discount Rate)



Highlighting the categories of spending that change between decarbonization scenarios, Figure 21 presents the net costs relative to the **Net Zero Economy-Wide** scenario. **Accelerated Clean Electricity** increases electric sector investments by 2040 to achieve 100% clean electricity by 2040. **Delayed Action** retains fossil fuels for longer, increasing the cost of fuel purchases, while also increasing the need for clean fuels to meet the emissions target. At the same time, demand side investments are decreased as fewer electric vehicles and high efficiency appliances are adopted. Limited coal and gas replaces fossil generation and fuel spending with increases in clean electricity sector investments.

FIGURE 21.

Net Costs relative to Net Zero Economy-Wide ($/yr)



The impact of the **No Transmission Expansion** scenario is not shown on the charts above because it impacts the broader Midwest region rather than only the state of Wisconsin. Prohibiting expansion of the transmission interties between Wisconsin and surrounding regions increases costs for the region by $1B/yr by 2050 compared to the **Net Zero Economy-Wide** scenario. Who pays for transmission expansion, and how benefits accrue, depends on cost allocation decisions and electricity market design. Given the costs of transmission expansion assumed in our analysis, building out Wisconsin's interties reduces the cost of reducing emissions for the Midwest region as a whole.

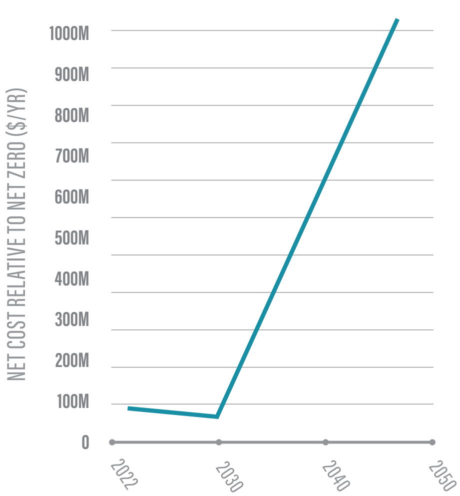


FIGURE 22.

No Tx Expansion Net Cost relative to Net Zero ($/yr)

4.2.1. COSTS INCLUDING HEALTH BENEFITS

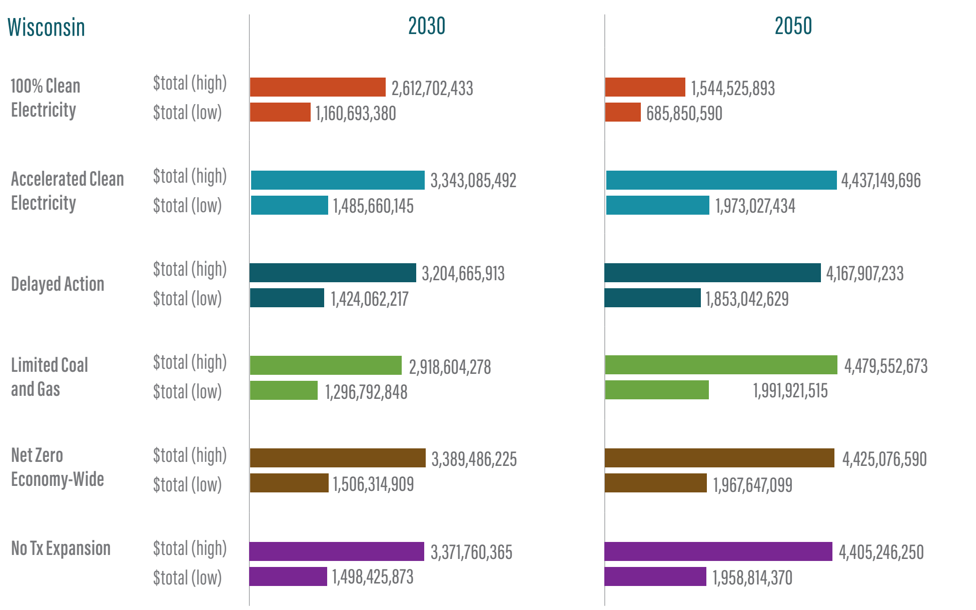
In addition to the system costs, we used the EPA COBRA model to calculate the benefits from reduced fine particulate matter. More details of this modeling are provided in Section 4.5. The benefits in dollar terms are shown by scenario in Figure 23 relative to the **Baseline** Scenario. COBRA provides low and high estimates of the benefits.

The benefits from reducing coal generation are significant and are present in all scenarios. **100% Clean Electricity** sees significant benefits even without demand side transformation and tailpipe emissions reductions in the vehicle fleet because of coal retirements. Benefits from **100% Clean Electricity** decrease by 2050 because the **Baseline** scenario retires coal by then. However, Wisconsin air quality is affected by emissions in surrounding states that continue to burn coal in the **Baseline** scenario in 2050.

Additional benefits over **100% Clean Electricity** in the net zero cases come from removing emissions on the demand side, particularly in the vehicle fleet. Benefits therefore continue to increase relative to the **Baseline** scenario through 2050, even as the **Baseline** scenario retires the Wisconsin coal fleet.

FIGURE 23.

Total Benefits attributed to Emissions Reduction in 2030 and 2050



Figures 24 and 25 show system costs and health benefits side by side for the **Net Zero Economy-Wide** scenario in 2030 and 2050. The solid and shaded areas show the difference between the low and high health benefit estimates. The benefits in 2030 from coal retirements and early transition of the vehicle fleet are significant in scale compared with the costs of decarbonization. While direct decarbonization costs and avoided costs approximately breakeven, health benefits drive significant savings for the state overall. In 2050, health benefits increase in dollar terms, but are smaller in GDP terms as the projected economy grows. Net system costs are higher in 2050 but health benefits make decarbonization a net benefit to Wisconsin.

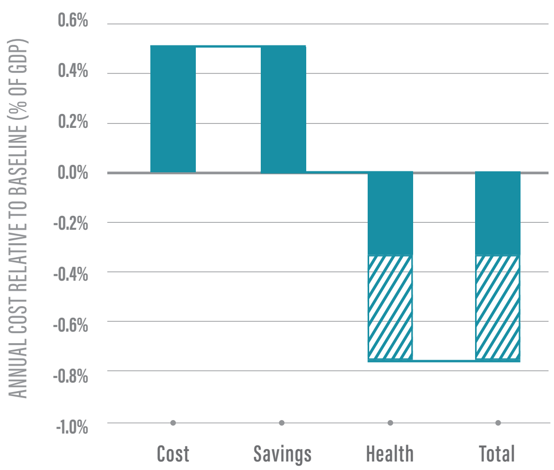


FIGURE 24.

System Costs and Health Benefits in the Net Zero Economy-Wide Scenario in 2030

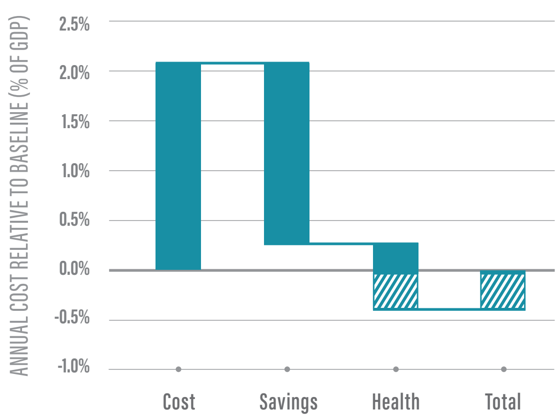


FIGURE 25.

System Costs and Heath Benefits in the Net Zero Economy-Wide Scenario in 2050

4.3. Infrastructure Transition

This section describes the infrastructure changes necessary to move from present day to a 100% clean electricity and net zero emissions future. On the demand side, the transformation happens in the types of technologies used to consume energy in the residential, commercial, transportation, and productive sectors. An example of the demand side transition is the gradual replacement of today's fleet of light-duty internal combustion engine vehicles with electric vehicles. On the supply side, the transformation happens in the replacement of existing energy supply resources, the addition of new technologies to meet changes in energy demand, and changes in volumes of fuels supplied.

4.3.1. DEMAND SIDE TRANSFORMATION

On the demand side, we assume that service demands remain the same regardless of scenario. In the **Baseline** and all clean energy policy scenarios, consumers use the same amount of heat and light and drive the same number of miles, and the productive sector generates the same output. Energy service demands come from the EIA Annual Energy Outlook 2021. What differs across scenarios is the type of equipment and appliances consumers and businesses select to provide those services.

There may be changes in service demand that are driven by policy, pricing, and consumer choice in a net zero emissions future, such as greater utilization of public transportation, service demand reductions through greater awareness, better urban planning, etc. However, we exercised conservatism in assuming service demands were the same across all scenarios. The cost effectiveness of policy that reduces service demands relative to alternative measures of decarbonizing the economy can be evaluated using the framework presented in this report, however we have not looked at any service demand reduction scenarios in this analysis.

We modeled three unique demand side scenarios used across the study scenarios. These include Baseline, Net Zero, and Net Zero Delay, shown in Table 7.

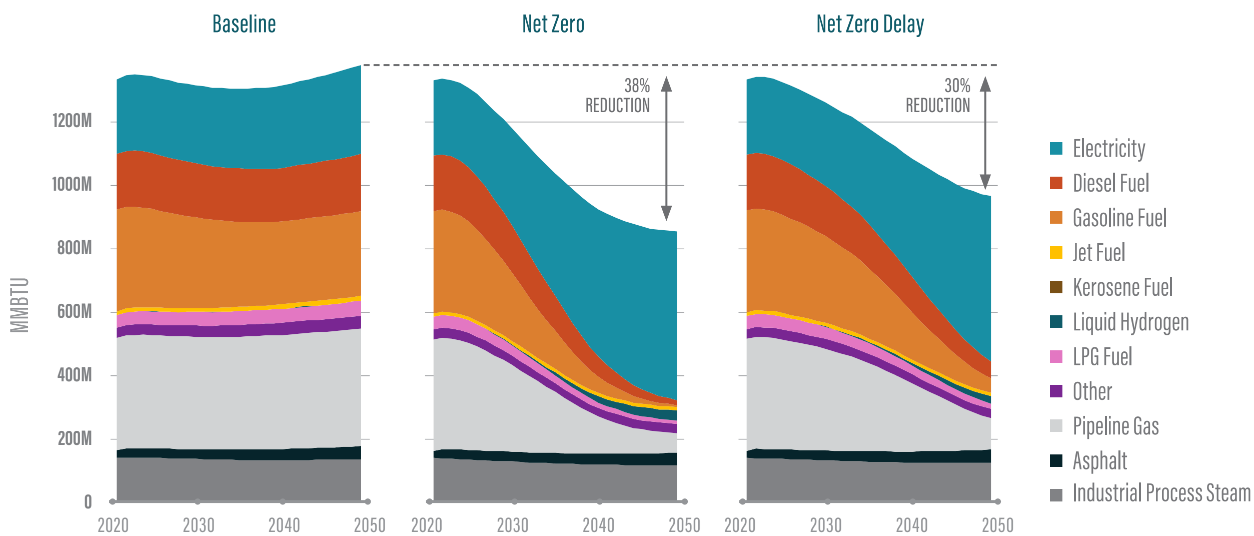
TABLE 7.
Demand Scenario by Study Scenario

Scenario	Demand Scenario
Baseline	Baseline
100% Clean Electricity	Baseline
Net Zero Economy-Wide	Net Zero
No Tx Expansion	Net Zero
Accelerated Clean Electricity	Net Zero
Delayed Action	Net Zero Delay
Limit Gas and Coal	Net Zero

In the **Baseline** scenario, the types of technologies providing energy services look much as they do today for the next 30 years. There is minimal electrification of appliances or vehicles. Efficiency improves as new more efficient vintages of technologies replace aging ones. For example, newer internal combustion engine vehicles have greater fuel economy than older vehicles. However, customers generally replace vehicles and appliances like-for-like. Figure 26 shows the impact of this **Baseline** demand scenario on final energy consumption by fuel. Initially there is some growth in energy consumption as the economy recovers from the Covid-19 pandemic. This growth period is followed by a slight overall decline as higher efficiency vehicles and appliances become more prevalent. Finally, energy consumption picks up again as the effect of population and productivity growth outpaces efficiency gains. However, these effects are relatively minor in the **Baseline** scenario, and energy consumption by fuel in 2050 is similar to today.

FIGURE 26.

Final Energy by Fuel and Demand Scenario



The **Net Zero** demand scenario incorporates the building, transportation and industrial sector assumptions described in Table 3. In light-duty vehicles and buildings, sales shares of electrified and high efficiency equipment reach 100% by 2035, alongside a slower transition in heavy-duty vehicles, and efficiency improvements and electrification in the productive sector. These measures drive down fuels consumption in final energy and increase electricity. Figure 26 shows that electricity makes up the majority of energy consumed by 2050 in final end uses, with diesel fuel and gasoline demand dropping to minimal amounts. Overall energy consumption is significantly reduced relative to the baseline, resulting from the transition from internal combustion to electric motors and boilers and furnaces to heat pumps, as well as the generic efficiency gains assumed in the productive sector. Total Wisconsin energy consumption in **Net Zero** is 38% lower in 2050 than in the **Baseline** scenario.

The **Net Zero Delay** demand scenario describes the demand side assumptions used in the **Delayed Action** pathway. Relative to the **Net Zero** scenario, electrification and efficiency measures are delayed by 15 years. As a result of this delay, sales targets of 100% by 2035 become 100% by 2050. Generic efficiency gains in the productive sector are also cut in half in this scenario. The overall impact of these variations is that liquid and gaseous fuel consumption remains higher and electricity demand grows more slowly. Overall energy consumption is higher than in the **Net Zero** scenario because a) fuel-consuming technology stocks are inherently less efficient than their electric counterparts, and b) the productive sector sees fewer efficiency gains.

Figure 27 shows energy consumption by sector. The transportation sector is most impacted by fuel switching and efficiency measures: transportation energy demand is half of the **Baseline** amount by 2050 in **Net Zero**. Residential and commercial appliances gain in efficiency as heat pumps and heat pump hybrid systems displace gas boilers and appliances become more efficient in general. Productive sector energy consumption also declines due to generic energy efficiency measures of 1% a year and fuel switching to electricity.

FIGURE 27.

Final Energy Consumption by Sector

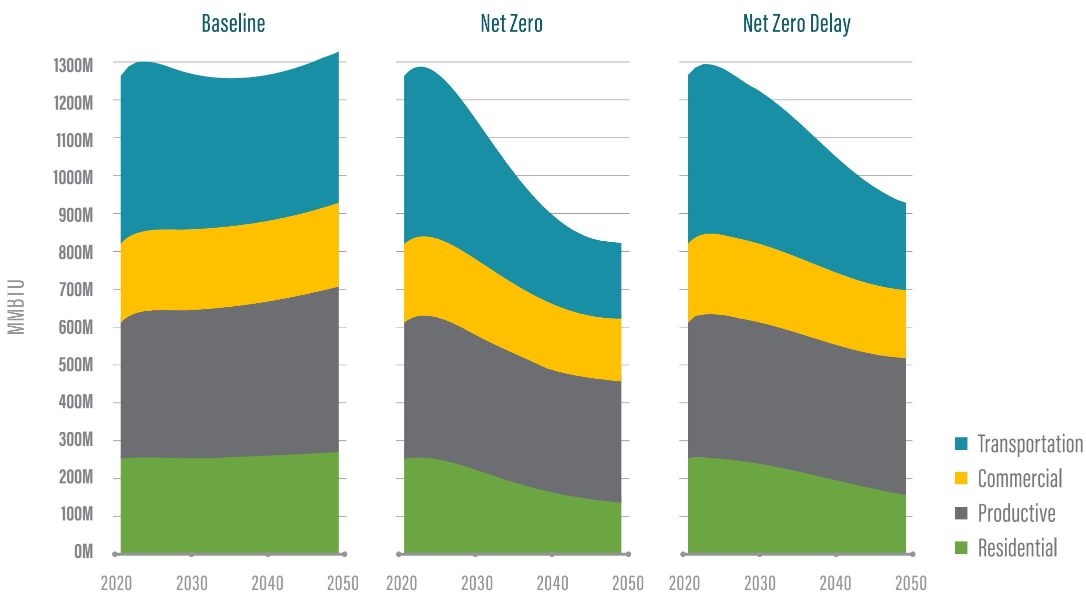
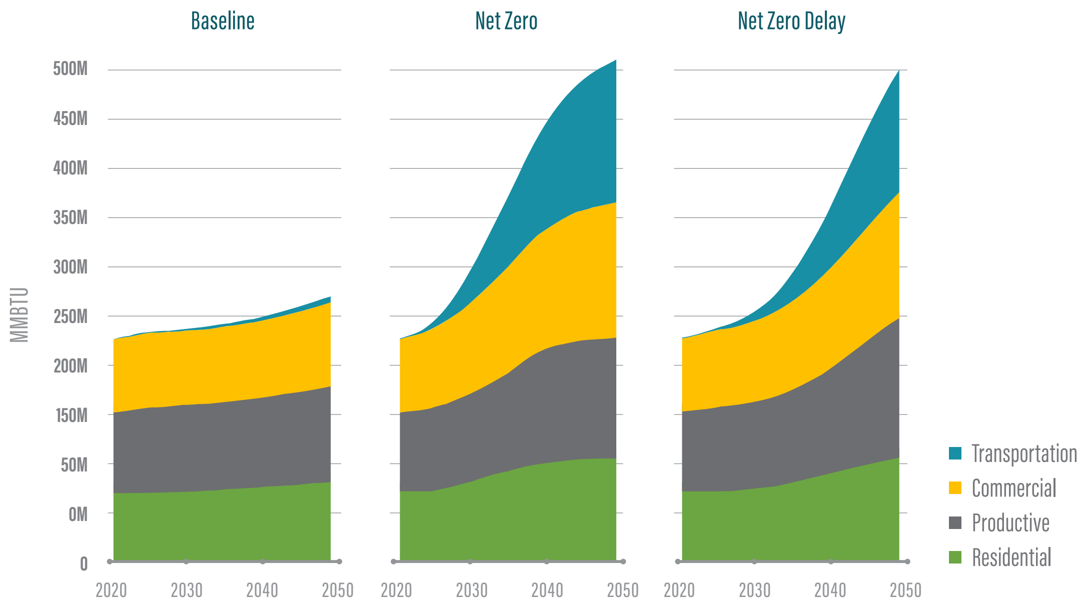


Figure 28 shows the impact of fuel switching on electricity demand. In the **Net Zero** scenario, loads, not including electrolysis and electric boilers, grow by 125% over 2022 levels, and 89% over the **Baseline** scenario in 2050. Electricity demand grows across all sectors of the economy. New transportation loads drive just over half of all growth from 2022 to 2050, with electrification in buildings and industry responsible for the rest. The **Net Zero Delay** and **Net Zero** demand scenarios reach similar levels of electricity demand by 2050, but demand is significantly lower from 2030 to 2040 in the delayed scenario because fuel use persists through that time period.

We determined electric loads for new flexible industrial electrolysis and electric boiler loads as part of a least cost supply side investment strategy for each of the full scenarios modeled in this report. Total electric load by scenario is shown in Figure 32 later in the report.

FIGURE 28.

Electricity Demand by Sector (excluding electrolysis and dual fuel electric boilers)



4.3.1.1. Varying Demand Side Assumptions — Subsector Examples

EnergyPATHWAYS tracks stock rollover based on assumptions about sales shares across 70 subsectors of the economy. Below are some examples of the transition in each of the demand scenarios.

Internal combustion vehicles continue to dominate light-duty vehicle sales in the **Baseline**, with sales of electric vehicles reaching 14% by 2050. In contrast, we assume sales are 100% electric by 2035 in the **Net Zero** scenario and 100% electric by 2050 in the **Net Zero Delay** scenario. The top row of charts in Figure 29 shows electric vehicle sales percentages. In any single year, only a fraction of the total vehicle stock will be old enough that it needs replacing. We assume the lifetime of a light-duty vehicle is 15 years, so it takes time for electric vehicles to filter into stocks, even after they make up all new sales. As shown in the second row of the figure, the light-duty vehicle fleet reaches nearly 100% electric in 2050. Energy consumption (in the final row of the figure) decreases overall through 2050, but electricity consumption increases, reflecting the transition to electric vehicles.

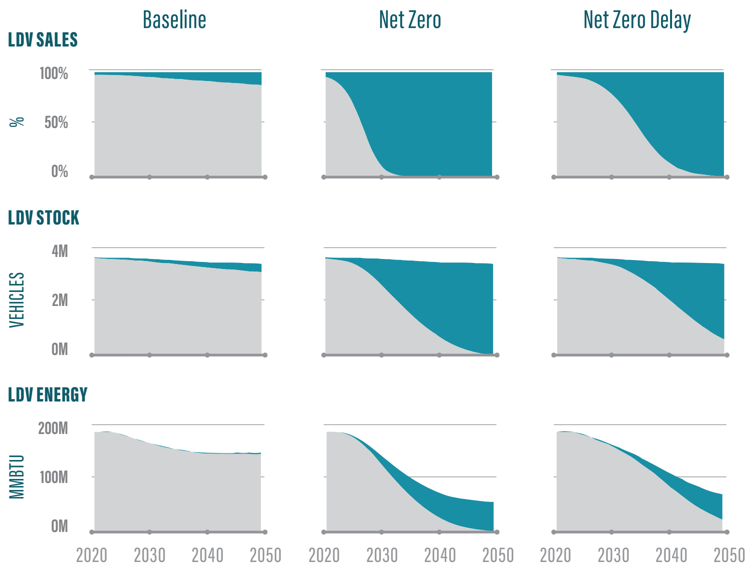


FIGURE 29.
Light-duty Vehicle
Sales, Stocks, and Energy

A similar trend is present in heavy-duty vehicles, depicted in Figure 30, which shows sales, stocks, and energy for both short-haul and long-haul heavy-duty vehicles. We assume that 50% of all new long-haul vehicle sales are hydrogen fuel cell vehicles by 2045. Electric and hydrogen vehicles make up 100% of all long haul and short haul vehicle sales by 2045 in the **Net Zero** scenario. In **Net Zero Delay**, internal combustion vehicles are still sold by 2050. As described in the case of light-duty vehicles, hydrogen and electric vehicle sales gradually impact vehicle stocks and energy consumption.

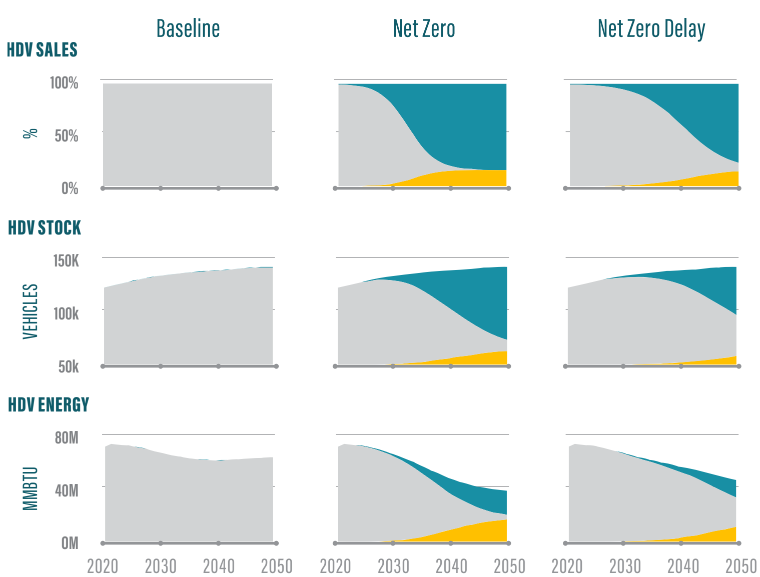


FIGURE 30.
Heavy-duty Vehicle
Sales, Stocks, and Energy

Residential space heating is shown in Figure 31. In the **Baseline** scenario, fuel dominates, as gas boilers and furnaces make up the same share of space heating stock from the present through 2050. By contrast, the **Net Zero** scenario transitions to a mix of air source heat pumps (ASHP), ground source heat pumps (Geothermal), and air source heat pump hybrid systems (ASHP Hybrid). We assume hybrid systems are installed in some of the Wisconsin building stock because of the cold temperatures experienced in the winter. These systems hybridize heat pump and gas technology. The heat pump is used for most of the year, but when temperatures reach very low levels, the gas side of the system is used to meet heating demand. Hybrid systems reduce peak electricity demand in the winter. This avoids creating a large winter electricity peak and better balances summer and winter loads for higher electricity infrastructure utilization.

As with electric vehicle adoption, the shift to electric and electric hybrid heating systems increases energy efficiency, significantly reducing the total energy demand for space heating. In the **Net Zero** scenario, total energy demand for residential space heating is reduced by 63% versus **Baseline** in 2050 and 50% in the **Net Zero Delay** scenario.

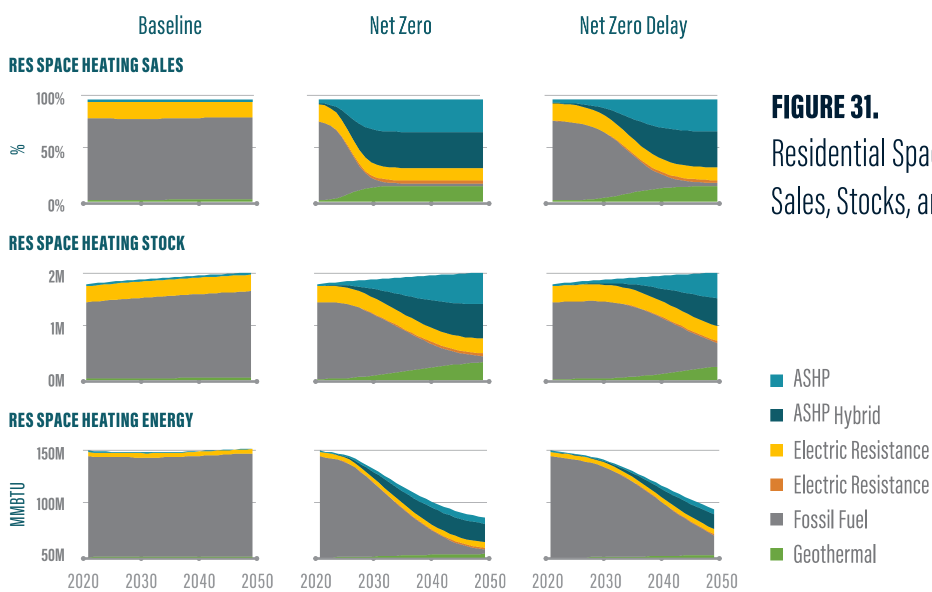


FIGURE 31.
Residential Space Heating Sales, Stocks, and Energy

4.3.1.2. Demand Side Discussion

The strategy for how to plan electricity sector investments for the future is heavily dependent on how the rest of the economy decarbonizes. If all sectors electrify much of their load, electric loads will increase dramatically. In the Net Zero demand scenario, end use electric loads, not including new electrolysis and electric boiler loads, are 89% higher than in the **Baseline** scenario in 2050.

Electrification of transportation, buildings, and industry is a key strategy to meeting potential future net zero targets and should be considered in long-term electricity planning. While the primary focus of this report is decarbonizing electricity, it must be considered in the context of action taken across the economy to decarbonize. As shown in the next section, moving more slowly on demand side electrification in the **Delayed Action** scenario is more expensive than the more aggressive action taken on the demand side in the **Net Zero Economy-Wide** scenario. Planning for a much larger electricity sector is therefore imperative in a world heading towards net zero emissions.

One reason why the more aggressive path is lower cost is that overall energy demand is reduced because of greater vehicle and appliance efficiencies. Electricity demand increases significantly, but is more than offset by the reductions in energy demand for other types of fuel, reaching 38% lower energy demand in the **Net Zero Economy-Wide** scenario than **Baseline** by 2050.

Achieving the benefits of electrification requires significant changes to the way customers consume energy. For the average household, electricity consumption and their monthly electricity bills will increase significantly at the same time as spending decreases on other fuels, such as gasoline. This relationship is discussed in more detail in Section 4.2. This transition will come with challenges, including, for example, customer acceptance, customer economics and ratemaking, and equity between customer groups. Rapid electrification will require early planning and policy support if aggressive sales targets are to be met.

There are risks to electrification in both directions. Electrify too slowly and the costs of decarbonization increase as other more expensive measures of achieving emissions reductions must be used. Electrify too quickly and risk customer backlash. Our modeling indicates that achieving 100% sales of electric and high efficiency equipment by 2035 in Wisconsin is a reasonable balance between these two outcomes for most technologies. However, further work is required at a sectoral level to identify the opportunities, challenges, and implementation strategy right for Wisconsin.

4.3.2. SUPPLY SIDE TRANSFORMATION

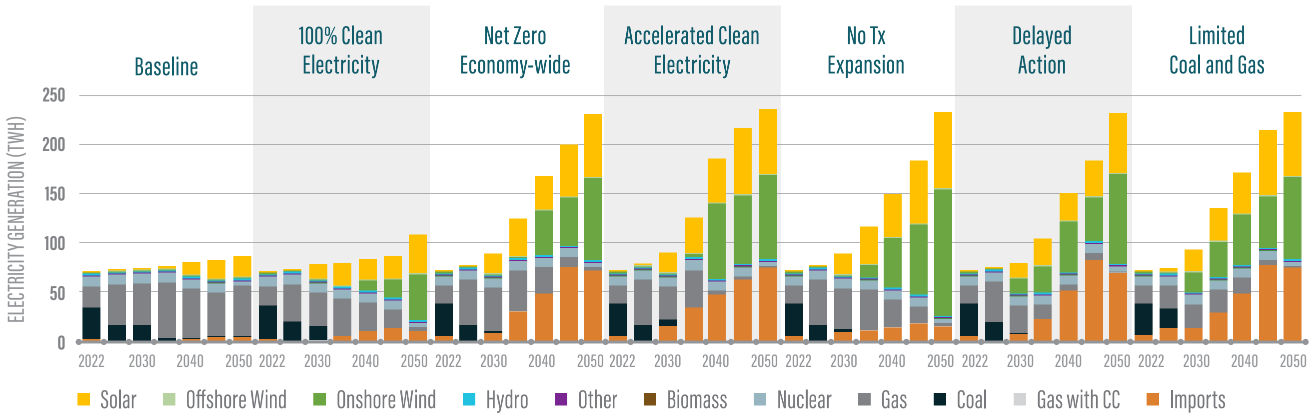
The previous section described the energy demands from end uses that must be met with energy supply in every year through 2050. Significant investment in electricity infrastructure is necessary to meet these demands reliably while demand for other fuels decreases. This section describes how these energy demands can be met with supply side investments and operations.

4.3.2.1. Electricity Investments and Operations

Figure 32 shows electricity generation and demand for each of the scenarios, Figure 33 shows electricity capacity, Figure 34 shows pipeline gas capacity and capacity factor, and Figure 35 shows new wind and solar additions. These sets of outputs are referred to in the discussion of electricity sector investments and operations by scenario below.

FIGURE 32.

Electricity Generation and Demand



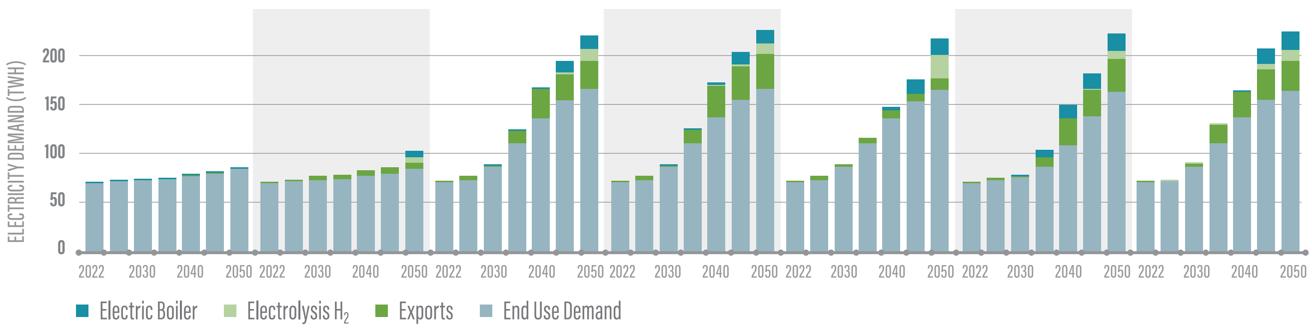


FIGURE 33.

Electricity Capacity

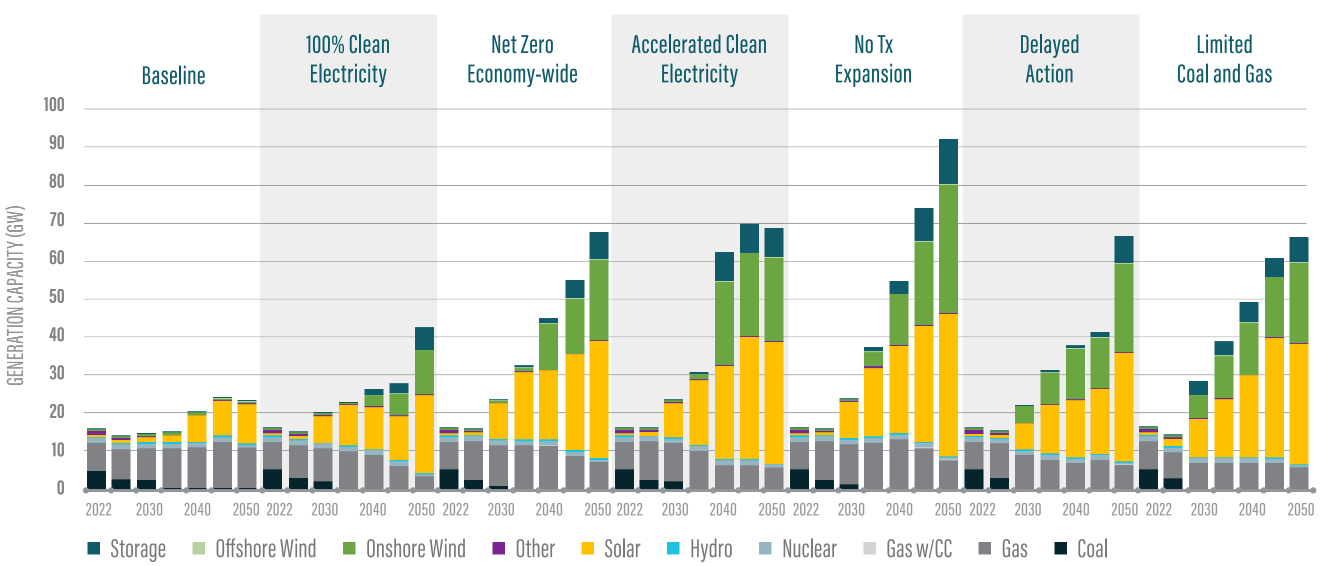


FIGURE 34.

Gas Capacity and Capacity Factor

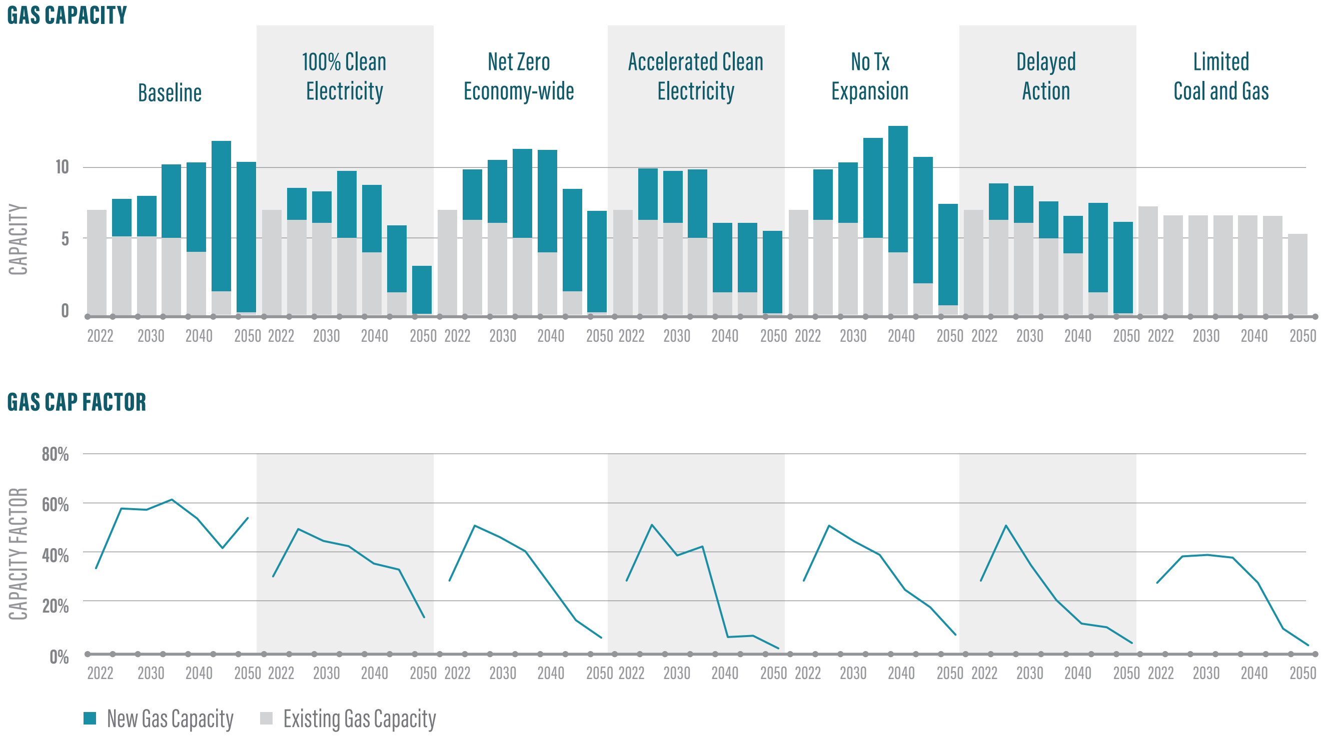
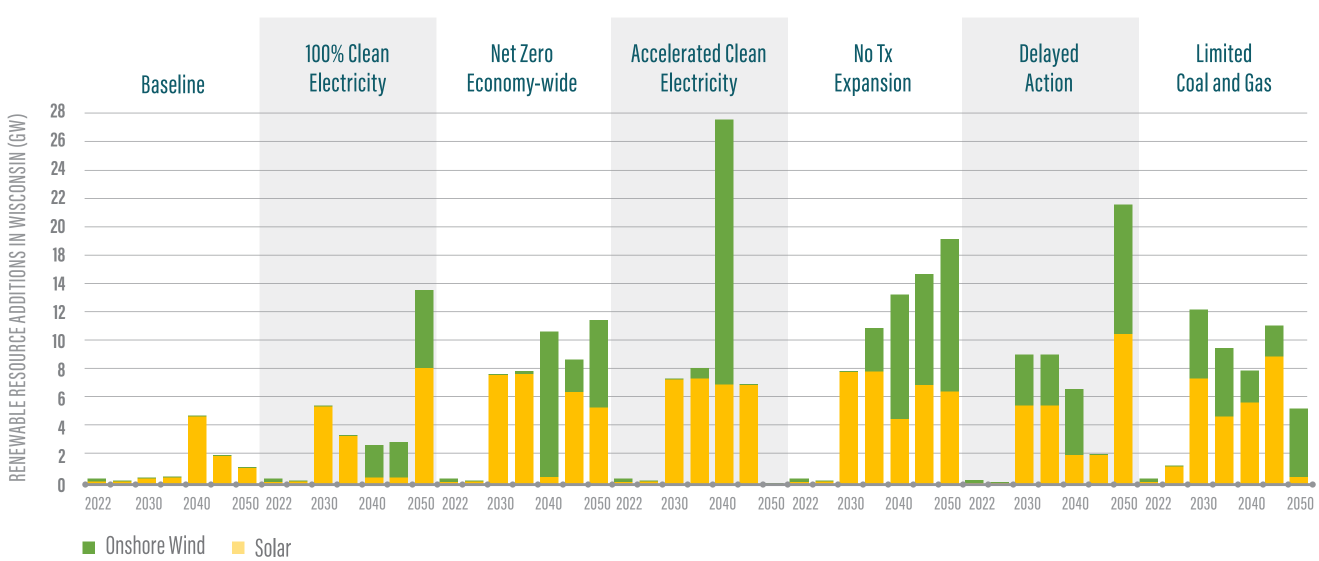


FIGURE 35.

Wind and Solar Additions in Wisconsin



Baseline

In the **Baseline** scenario, half of all electricity comes from coal in 2022, as is the case in all other scenarios. Following the announced coal retirement schedule in the state, coal generation drops off. By 2035 coal is a minimal part of the generation portfolio. Gas replaces the lost coal generation through 2035, with nuclear and existing renewables supplying consistent power over that time period. Even though there are no clean electricity or emissions constraints in the **Baseline**, investment in renewables becomes economic in 2035 and beyond with solar making up an increasing share of electricity generation through 2050. Gas remains the dominant source of electricity, however, with capacity factors increasing following the retirement of coal, remaining around 60% through 2035, decreasing as solar takes share away from gas, and then increasing again in 2050 as the last of the existing gas generation retires (leaving only new gas generators). By 2050 there are 11 GW of gas in service.

100% Clean Electricity

In the **100% Clean Electricity** scenario, renewable investments begin in 2030 to meet the clean energy requirements, and investments in in-state solar and wind continue through 2050 to reach 100% clean electricity. Coal generation is lower in 2030 than in the baseline to comply with the 40% clean electricity interim goal we modeled on the way to reaching 100% clean electricity by 2050. Imports increase over the same time frame, bringing in clean energy from out of state. By 2050, 10% of electricity delivered to Wisconsin loads comes from out of state clean resources. Investments in gas capacity are lower than in the net zero scenarios because of the smaller overall size of the electricity system in this scenario. However, gas generation operates at a higher capacity factor by 2050 in this scenario, using the full potential of waste gases under the definition of 100% clean electricity. Nuclear generation remains nearly constant throughout 2050 in all scenarios. The model chooses to relicense the Point Beach plant in the 2030s, and then retires one unit in 2050 based on economics, such that approximately 600 MW remain online at this time.

Net Zero Economy-Wide

The **Net Zero Economy-Wide** scenario includes the transition on the demand side to electrified appliances and vehicles, growing end use demand shown in light blue on the bottom row of Figure 32. Electricity supply must be scaled to meet that demand. Initially coal generation is replaced by gas in 2025 through 2035. However, gas is quickly curtailed in output after that, shifting from a baseload resource to a reliability resource by 2050. Renewable generation ramps up to meet emissions and clean energy requirements in 2030, both in in-state resource investments, and in imported clean energy from other states. By 2050, 23% of all energy delivered to Wisconsin loads is imported clean energy from elsewhere. Demand also increases beyond what is required for end uses, including new industrial electrolysis and electric boiler loads and exports to other states. Exports of energy generated in Wisconsin increase, reaching 20% of energy generated in Wisconsin from wind and solar in 2050. Imports and exports increase as transmission is built out and the electric system becomes more interconnected, taking advantage of load and renewable resource diversity to balance the grid.

By 2050, there are 31 GW of solar, 21 GW of wind, 7 GW of storage, and 7 GW of clean gas generation in Wisconsin. By 2050, gas capacity is operating at a 5% capacity factor and burning clean gases rather than fossil. Total gas generation from burning clean gases in 2050 is 1.2% of generation or 2.6 TWh.

Accelerated Clean Electricity

The **Accelerated Clean Electricity** scenario follows a similar pattern but removes gas from electricity generation earlier, replacing it with greater amounts of renewables. A small amount of coal remains in 2030 equal to 32% of coal generation in the **Baseline** scenario in 2030. In **Net Zero Economy-Wide**, coal is almost completely retired by 2030, dropping to 13% of **Baseline** coal generation in 2030. Greater residual coal generation in 2030 reflects that new gas investments are less economic in **Accelerated Clean Electricity** because they can operate only through 2040, when 100% clean electricity is required in this case.

Accelerated Clean Electricity adds 20 GW of new onshore wind over a 5 year time period (Figure 35). In the absence of constraints on the rate of construction of renewable generation, wind is procured rapidly late in the 2030s to take advantage of projected price declines right before 100% clean electricity must be met in 2040. This rapid rate of expansion may not be achievable. If targeting 100% clean electricity in 2040, earlier procurement of resources may be necessary to avoid encountering limits to the rate of resource adoption and the transmission infrastructure needed to support it.

No Transmission Expansion

Whereas other scenarios are heavily reliant on imported energy in later years, the **No Transmission Expansion** scenario relies much more on renewable investments within Wisconsin. By 2050, electricity generation is almost all from in-state wind and solar resources. Losing the opportunity for greater interconnection with surrounding states also means that grid balancing needs within state are increased. Therefore the amount of energy going to hydrogen electrolysis more than doubles in this case, bringing more synthetic fuel production into Wisconsin to better utilize intermittent renewable energy with flexible electrolysis loads.

Delayed Action

Delayed Action sees reduced electricity demand in interim years. However, we do not see a corresponding drop in renewables investment, because **Delayed Action** leaves greater amounts of fuel consumption in other sectors of the economy. It is most cost effective to reduce emissions not by decarbonizing those fuels but shifting the burden of emissions reductions into the electricity sector. As a result, electricity production is shifted from gas to renewables between 2030 and 2040 relative to the **Net Zero Economy-Wide** scenario, reducing emissions.

Limited Coal and Gas

Finally, **Limited Coal and Gas** retires coal fully by 2030, earlier than all other cases. However, because all scenarios have only small amounts of energy from coal remaining in 2030, earlier coal retirement has little impact on this case relative to the other scenarios. The prohibition on building new gas generation in this scenario is far more impactful, as coal cannot be replaced with gas generation in the first decade (as happens in the other scenarios). In the **Net Zero Economy-Wide** scenario, an additional 3 GW of gas are built in 2025. When that new gas build is not allowed, an additional 5 GW of wind, 2 GW of solar, 4 GW of storage, and a 50% increase in imported energy are needed by 2030 to meet electricity demands reliably.

4.3.2.2. Fuel Demand and Composition

Economy-wide fuel demand changes as demand technology stocks evolve and electricity becomes cleaner. Figure 36 shows the demand for liquid fuels, pipeline gas, and coal and coke blends, and whether these come from fossil or clean sources. Liquid fuels include gasoline, jet fuel, diesel, kerosine, oil, and liquified petroleum gas. Figure 37 shows just the portion of pipeline gas delivered to electricity generators and whether it comes from fossil gas or waste gases from anaerobic digestion.

FIGURE 36.

Major Fuel Blends used in the Economy and their Composition

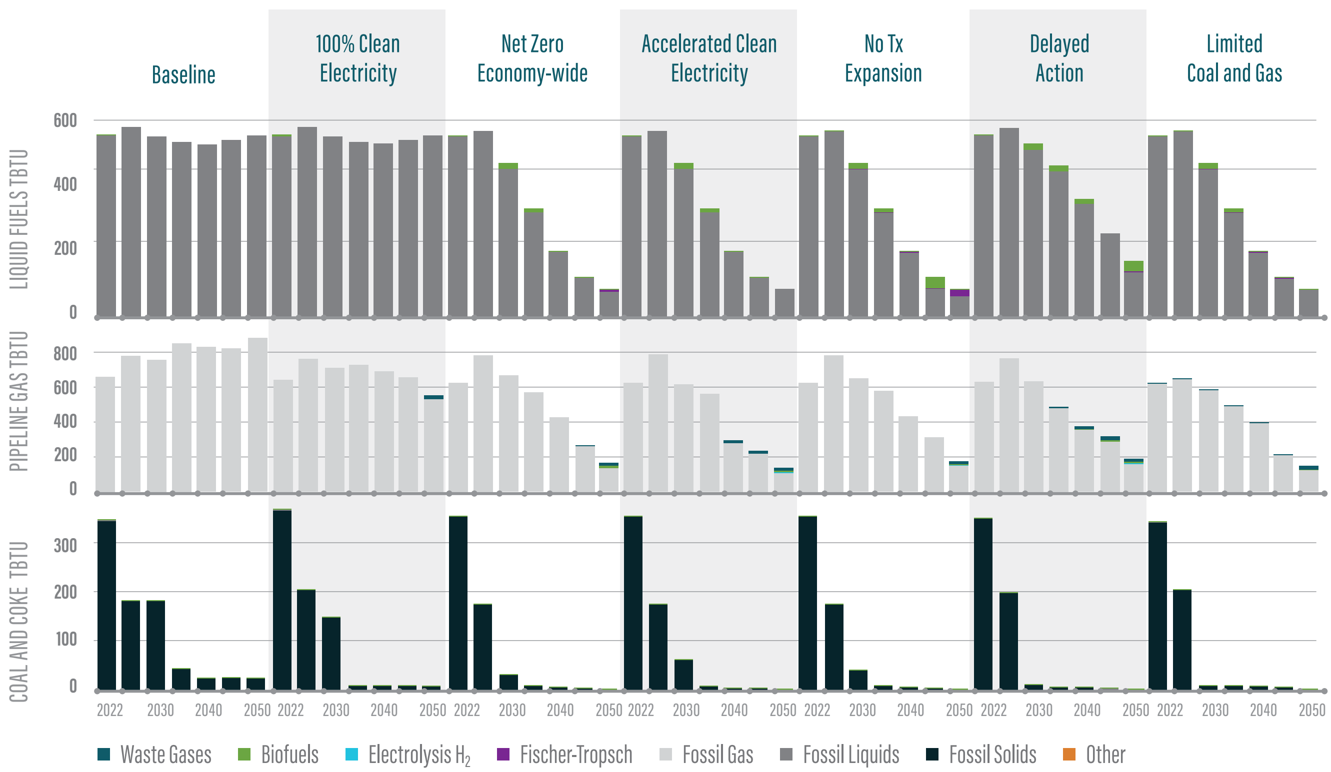
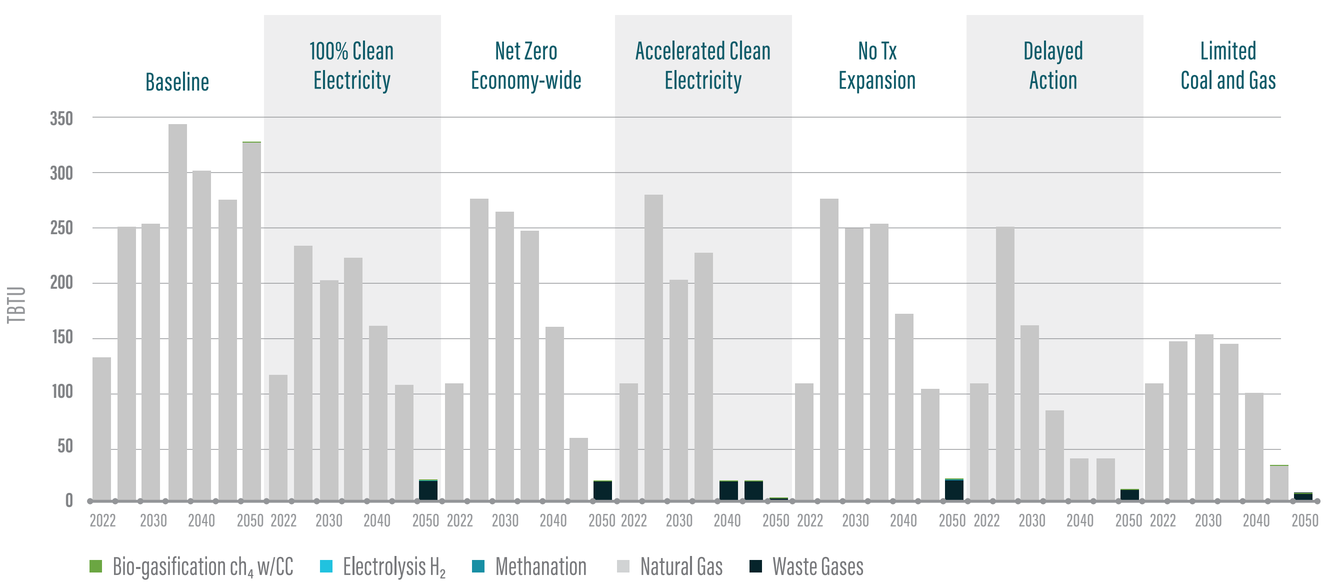


FIGURE 37.

Pipeline Gas used in Electricity and its Composition



Notable across all scenarios that target net zero is the decline in fuel use in every category. Coal and coke declines sharply to 2035 in all scenarios following the announced retirements in the state. In the **Baseline**, coal generation in electricity remains through 2050, supplying the one remaining coal generator not currently scheduled for retirement. Small quantities of coal remain in industrial applications through 2045 in the Net Zero scenarios.

Liquid fuel consumption declines with electrification of transportation. Small fractions of the remaining liquid fuels are decarbonized with biofuels and Fischer-Tropsch derived electric fuels. The composition of liquids fuels is relatively similar across the various net zero scenarios. In the **No Transmission Expansion** scenario, more gas use remains in electricity production in 2045 as an economic means of balancing the system when losing the balancing of additional interconnection present in the **Net Zero Economy-Wide** scenario. As a consequence, more emissions remain in electricity and emissions reductions must occur in other sectors to meet the emissions target. These reductions outside of electricity come from greater decarbonization of liquid fuels with biofuels in 2045 and Fischer Tropsch liquids in 2050, and from increased geologic sequestration of carbon. In the **Delayed Action** scenario, greater volumes of liquid fuels remain in the economy in 2050, producing greater emissions. Liquid fuel emissions are partially mitigated via biofuel use in 2050 as well as increased geologic sequestration of carbon.

Pipeline gas delivered directly to end uses is predominantly fossil gas. However, achieving 100% clean electricity requires electricity generated with gas to be decarbonized by 2050, or 2040 in the **Accelerated Clean Electricity** scenario. The composition of pipeline gas going to electricity is therefore fossil gas free by the 100% clean electricity target dates, with methane from anaerobic digestion of agricultural waste replacing fossil gas.

While displacing fossil fuels with clean alternatives derived from hydrogen and biomass is an economic solution adopted at large scale in other parts of the country by 2050 in our modeling, the quality of renewable resources available in Wisconsin make hydrogen production relatively more expensive compared to other regions. As a result, geologic sequestration is favored in our analysis as a means of reaching emissions reduction targets. However, costs for production of clean and electric fuels are uncertain and are not forecast to be part of Wisconsin's energy portfolio until the 2040s. Technological development in that time may change the balance between decarbonizing remaining fuels versus carbon sequestration. Both are potential pathways to reaching net zero in the future; whether one is favored over the other will depend on technological development in the intervening years.

4.3.2.3. Hydrogen and Carbon Markets

Hydrogen and carbon become commodities in a net zero future. Hydrogen is an energy carrier that can be used directly in end uses, for example heavy-duty trucking in this analysis. It is also a means of transporting energy via pipeline and a precursor to other types of fuel that can be dropped into fuel consuming end uses that are difficult to electrify. The typical example of this is in aviation, where energy densities and existing infrastructure makes conversion of aviation fleets away from jet fuel one of the more difficult and expensive means of reducing emissions. Carbon can be captured, utilized, transported, and sequestered in the ground. When utilized it can be combined with hydrogen to produce hydrocarbon fuels.

Figure 38 shows hydrogen supply and demand in Wisconsin. End use demand for hydrogen is primarily from hydrogen fuel cells in heavy-duty trucking, which varies by scenario based on assumptions about vehicle fleet transformation. In **100% Clean Electricity**, **Net Zero Economy-Wide**, and **No Transmission Expansion**, hydrogen is injected directly into the gas pipeline, shown in dark gray. We limit hydrogen blending in pipeline gas to 7% by energy as a conservative upper bound on hydrogen concentrations in the pipeline before upgrades to the pipeline may be required to accommodate it. Hydrogen is also combined with carbon in the **Net Zero Economy-Wide** scenario, and to a greater degree in the **No Transmission Expansion** scenario, to create synthetic hydrocarbon liquids to displace remaining demand for fossil liquid fuels in 2050 (via the Fischer Tropsch process).

The supply of hydrogen is split between electrolysis and gas reformation with carbon capture. In earlier years, gas reformation without carbon capture is used to supply hydrogen to heavy-duty vehicles because the emissions cap is not yet binding.

FIGURE 38.

Hydrogen Supply and Demand

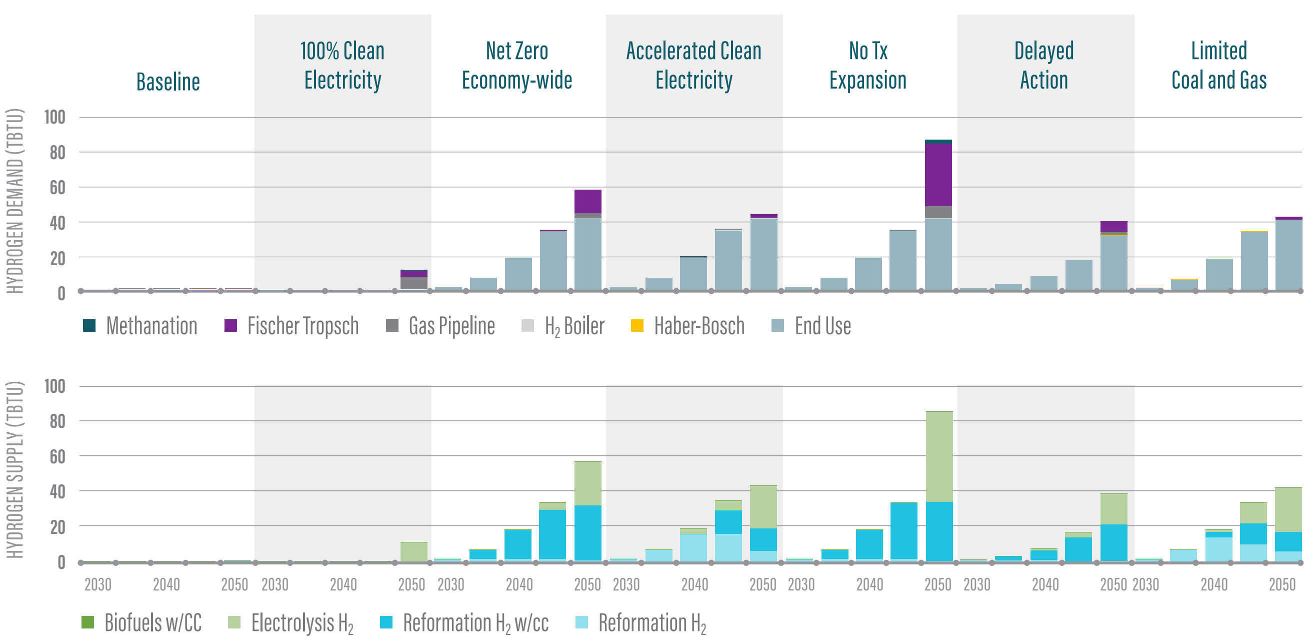
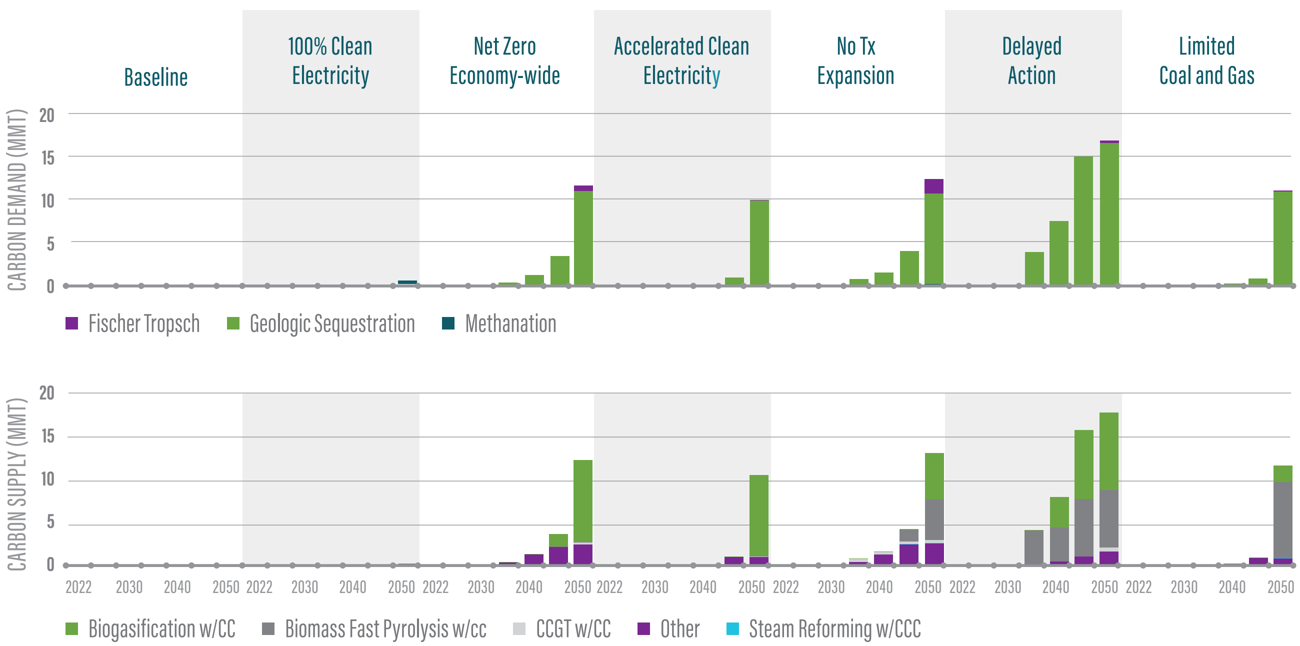


Figure 39 shows carbon supply and demand in Wisconsin. The majority of demand is for geologic sequestration, offsetting emissions of remaining fossil fuels in the economy. Wisconsin has no currently identified geologic sequestration formations, so carbon is exported via pipeline for sequestration out of state. Small amounts of carbon are used to create synthetic liquid fuels through the Fischer Tropsch process. Supply of carbon comes from biogasification and fast pyrolysis of biomass as well as the carbon captured during the reformation process to create hydrogen. Small quantities come from carbon capture on gas power generation.

FIGURE 39.

Carbon Supply and Demand



4.3.2.4. Transmission

Figure 40 shows the transmission capacity of interties between Wisconsin and surrounding states from present day to 2050. The **Baseline** scenario includes very little transmission expansion.

The **100% Clean Electricity** scenario slightly increases transmission to Illinois in 2045 and 2050; however, expanding import capacity is not a major component of achieving 100% clean electricity without load growth from demand side electrification. In both the **Baseline** and **100% Clean Electricity**, the transmission capacity additions may be smaller than is realistic in a transmission planning context. In practice, transmission investments are lumpy, with large additions needed to justify the fixed cost components of putting in a new line or reconductoring an existing one. These results necessarily represent a simplification of the complex cost structures of building new transmission capacity.

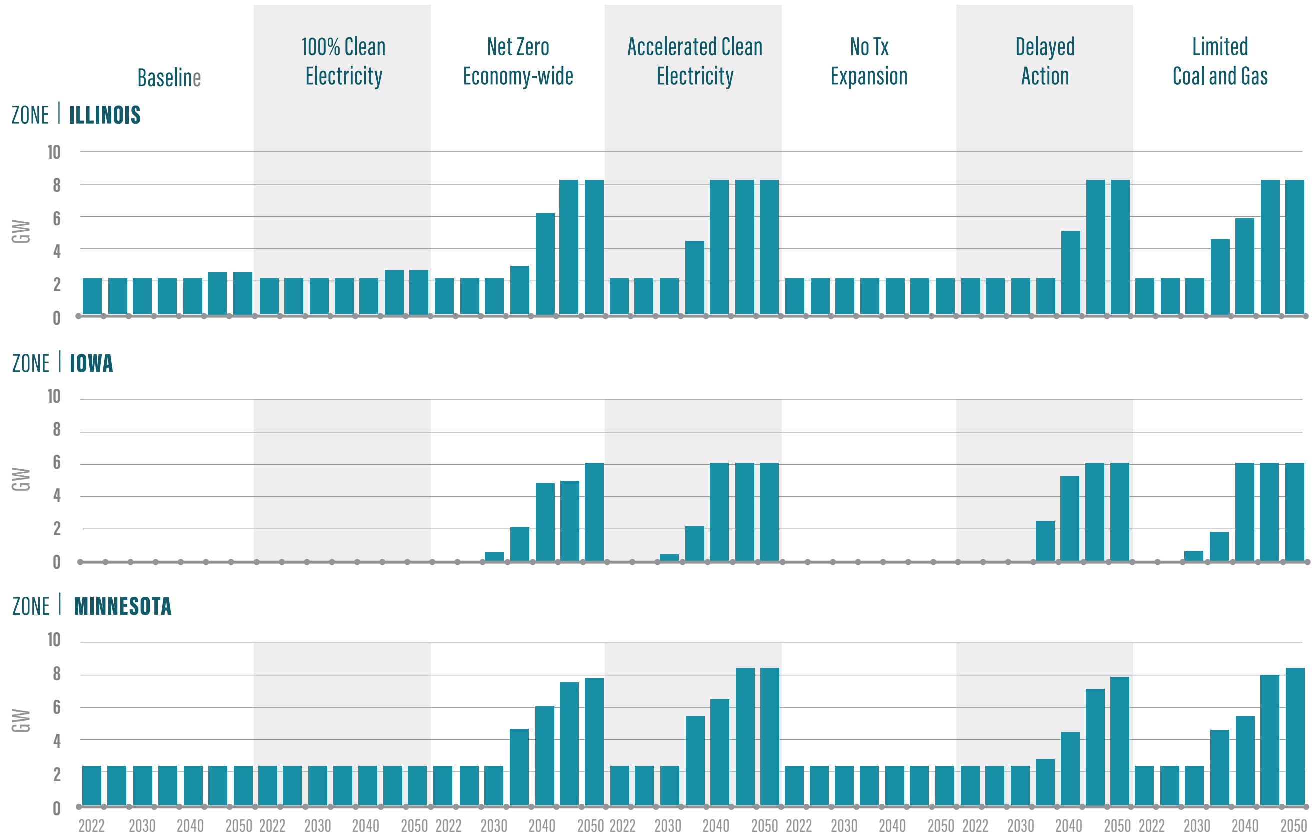
An additional 6 GW of transmission expansion is permitted on each intertie, priced at EPA Platform v6 database costs per kW of additional capacity. In the scenarios that target net zero emissions, the full 6 GW of additions is economically desirable on all interties. In the **Net Zero Economy-Wide** scenario, transmission expansion begins in 2035 with 2 GW added to Iowa[20] and Minnesota, and 1 GW added to Illinois. Renewable growth to meet new loads and achieve 100% clean electricity rapidly expands after 2035, as do imports into Wisconsin. Transmission expands quickly during the same period to facilitate greater imports and exports of clean energy, reaching the 6 GW cap on new capacity to Illinois in 2045 and Iowa and Minnesota in 2050.

Accelerated Clean Electricity reaches the maximum allowed transmission expansion by 2040 to Illinois and Iowa and 2045 to Minnesota. Earlier transmission expansion accesses out of state renewables for earlier compliance with 100% clean electricity. **Delayed Action** accelerates transmission expansion for similar reasons: emissions persist in other parts of the economy, so the electricity sector is decarbonized earlier, facilitated by access to out-of-state renewables. **Limited Coal and Gas** reduces the amount of gas in electricity and increases renewables, driving earlier adoption of transmission.

20 Cardinal-Hickory Creek is not scheduled for all scenarios but included in the additional 6 GW the model can invest in

FIGURE 40.

Transmission Interties to Surrounding States



4.3.2.5. Supply Side Discussion

Baseline

In the **Baseline** scenario, electric loads grow relatively slowly, rising 21% between 2022 and 2050. However, coal makes up 45% of generation in 2022, nearly all of which is retired by 2035 leaving an energy deficit that must be filled by new resource investments. Total gas capacity in the state expands between 2022 and 2050, with 4.8 GW of new gas generation additions. However, even without clean electricity or emissions policy, economics also drives the adoption of large amounts of renewables in the **Baseline** scenario. Additions of 10 GW of solar generating capacity are made between 2040 and 2050. Solar makes up 43% of all generating capacity in Wisconsin by 2050, driven by the economics of forecasted low renewable costs two decades from now. These partially displace fossil fuels.

Emissions decline in the **Baseline** scenario by 14% in 2050 relative to 2022, driven by scheduled coal retirements and economic adoption of renewables. Without clean electricity or emissions limiting policy, fossil gas remains a large component of electricity generation and emissions remain in other parts of the economy.

100% Clean Electricity

Adding **100% Clean Electricity** policy drives earlier and larger investments in renewables in Wisconsin compared to the **Baseline**. By 2030, 40% of energy serving Wisconsin loads must be clean. This requirement drives investment in 6 GW of new solar by 2030. The continuing tightening of the target to 100% clean electricity in 2050 drives an additional 3.7 GW of new solar between 2030 and 2035, and 9.6 GW of new solar and 11 GW of wind capacity between 2035 and 2050. The 2035 to 2050 period sees 6 GW of new storage investments as well to balance the electric system. Net imports increase over the same period to bring clean energy into Wisconsin from out-of-state renewable resources, reaching 5% of electricity delivered to Wisconsin loads by 2050. Total imports and exports increase as the electricity grid in Wisconsin and surrounding states becomes more renewable. Wisconsin imports 70% more energy than it exports by 2050. Gas electricity generation is fully decarbonized by 2050 using biogases from agricultural waste. This is used in low volumes, with gas generation operating as a reliability resource, generating 3.7% of all electricity in 2050 fueled by clean agricultural waste gases.

Targeting 100% clean electricity policy results in a 38% reduction in economy-wide emissions by 2050 compared to 2022, primarily from removing coal from the electricity portfolio. While falling significantly short of net zero, a CES standard achieves the most impactful single measure to reduce emissions: removing coal from electricity generation. Coal is replaced with new gas capacity, imported clean energy, and in-state renewables.

Net Zero Economy-Wide

Though Wisconsin is already on a schedule of rapid coal retirements through 2035, retiring coal earlier is the most cost-effective means of achieving emissions reductions by 2030. Coal generation in the **Net Zero Economy-Wide** scenario is 83% lower in 2030 than in the **Baseline** scenario. This indicates that accelerating coal retirements is a cost-effective strategy of achieving emissions reductions in the near-term.

At the same time, emissions reductions come from reduced liquid fuels consumption in transportation as electric vehicle penetrations increase, as well as reduced gas usage in building and industrial heating applications. Stock rollover of these energy consuming technologies is relatively low by 2030, given the time required for sales of new technologies to filter into stocks. However, following 2030 electric loads grow rapidly and end use fuel consumption falls in tandem as electrified and high efficiency technology alternatives reach 100% of equipment sales by 2035. Loads grow further with the addition of new industrial loads, including electrolysis and electric dual-fuel boilers, as part of a least-cost supply side investment strategy. These new industrial loads provide additional balancing capabilities to better utilize renewable generation and reduce investment in other technologies such as storage.

The **Net Zero Economy-Wide** scenario replaces coal with new gas generation and renewables, as well as increasing imported energy into the state. Wisconsin invests in 8.5 GW of new solar (Figure 35) and 3.5 GW (Figure 34) of new gas generation by 2030. To serve continuing load growth and reach clean electricity and emissions reduction goals, renewable investments continue at a rapid pace through 2050. Wisconsin invests in 8.6 GW of solar and wind between 2030 and 2035, followed by 11.6 GW in 2040, 9.4 GW in 2045, and 12.5 GW in 2050. Total in-state capacity approximately quadruples in the state from 2022 to 2050. This growth in in-state renewable capacity is paired with increasing imports of clean electricity into the state facilitated by transmission expansion. The study permitted 6 GW of transmission expansion per intertie to surrounding states, priced per MW of expansion based on EPA transmission assumptions. The model chose the expand all interties by the maximum 6 GW permitted by 2050, showing the value of transmission as part of a net zero strategy in Wisconsin.

Carbon sequestration is used by 2050 to offset emissions. These are transported via pipeline to out-of-state locations with geologic sequestration potential. The remaining emissions in 2050 come from fossil fuel use in industrial processes and gas in heating applications that use hybrid heat pump systems. CO_2 is predominantly captured from biofuels production with carbon capture.

No Transmission Expansion

Preventing transmission expansion increases overall in-state electricity generating capacity by 36% by 2050. These increases come from increased wind, solar, and storage investment to replace lost imports from the **Net Zero Economy-Wide** scenario. An increase in in-state transmission interconnections is needed to access the greater capacity of renewables.

Heavier reliance on in-state resources adds to an already challenging rate of power sector growth. A faster rate of renewable siting and permitting is needed, potentially increasing the chance of falling short of investment targets. Drawing upon a larger pool of high-quality resources through transmission expansion reduces the risk that roadblocks on any one pathway towards 100% clean electricity and net zero goals will result in failure to reach those targets. Early planning is needed to expand the interties between states given the past challenges to do so across the country and the long lead times for construction.

Accelerated Clean Electricity

Accelerating electricity policy to achieve 100% clean electricity in 2040 drives earlier renewable adoption than in **Net Zero Economy-Wide** scenario, including increased and accelerated in-state wind investment. The increased in-state renewable generation in 2040 relative to **Net Zero Economy-Wide** results in greater exports out of state.

Reductions in gas generation by 2040 overshoot the emissions target, driving reductions faster than the economy-wide emissions target does alone. In the **Net Zero Economy-Wide** scenario, gas generation remains in electricity because the state can still emit CO_2 in 2040 under the emissions constraint. By requiring clean electricity earlier, those gas emissions are removed from electricity, undershooting the emissions constraint and achieving greater overall emissions reductions. Gas generation remains in the power sector for reliability, but it is fully decarbonized by 2040. Gas generators are fueled predominantly with biogases from agriculture waste anaerobic digestion. Gas generation is close to zero in 2050 due to increased intertie storage and electrolysis over the **Net Zero Economy-Wide** scenario.

Delayed Action

The **Delayed Action** scenario retains end use fuels for longer, increasing the need for emissions reductions in other areas. These alternate reductions are achieved in part by reducing gas electricity generation earlier than in the **Net Zero Economy-Wide** scenario. Greater emissions offsets are required to continue fuels combustion at higher levels. Carbon sequestration begins 10 years earlier in 2035 and reaches greater volumes by 2050 than in the **Net Zero Economy-Wide** scenario. Some fossil fuels are displaced with clean drop-in fuels created using hydrogen from electrolysis and bio-energy.

In contrast to other regions of the country, in Wisconsin our analysis finds carbon sequestration to be more economic than producing synthetic drop-in fuels as a means of decarbonizing primary fuel use. However, which of these solutions is favored in the future will depend on technological development and the feasibility and cost of carbon exports.

The **Delayed Action** scenario has a smaller overall electricity sector through 2040 due to reduced end use electrification. Increased investment in wind by 2040 makes up for the reductions in gas generation needed to meet emissions targets.

Limited Coal and Gas

In the **Limited Coal and Gas** scenario, the gas generation fleet operates at lower capacity factors because of the lower efficiency (and corresponding higher operating costs) of the existing gas fleet versus new gas plants. However, existing gas generators operate at a higher capacity factor than they do in the other scenarios where new gas generators take over much of the electricity production from gas. This distinction has important air quality implications because older generators have higher emissions factors than new ones.

Gas generation contributes less energy and capacity than it does in other scenarios in all years through 2050. By 2030, the lack of investment in new gas drives renewable and storage investments to replace the lost energy. By 2030, Wisconsin invests in 9.3 GW of solar, 5.2 GW of wind, and 3.6 GW of storage. By 2050, greater investment in electrolysis and electric boilers is required to provide grid balancing that would have otherwise been supplied by gas generation. Lower gas generation in 2050 reduces the need for carbon capture and storage.

4.4. Residential Direct Energy Costs

Our analysis captures the direct energy costs for residential households, including the costs of electricity, fuels, and the incremental cost of electric and high-efficiency demand side equipment and appliances versus their inefficient counterparts. These costs are shown on a per household basis relative to household costs in the **Baseline** scenario in 2022 in Figure 41. The incremental cost for demand side equipment is levelized over the lifetime of the investment. These costs are the direct costs for energy production and delivery and incremental demand side investment for electrified and high efficiency demand side equipment and do not reflect customer payments through electricity rates, gas rates, or price of fuel at the pump.[21] Nevertheless, the cost of energy is the fundamental component behind the prices that customers pay, and the relative change in direct household energy costs shown in this section would be closely reflected by changes in total customer energy expenditures.

Comparing decarbonization scenarios to the **Baseline** scenario shows the significantly different direct energy costs of an average Wisconsin household in the future. A large portion of costs in the **Baseline** scenario in 2050 are variable costs, similar to customer energy costs today: fuel costs for transportation, primary gas use, and gas generation of electricity. In the Net Zero scenarios, almost all costs are capital costs and electricity is the dominant form of energy. Where customers procure their energy from is starkly different, shifting from a fuels-based economy to electricity from renewables as the dominant form, with implications for rates and energy markets. Making the switch to electricity and renewables reduces energy price volatility as exposure to international fuel markets is reduced.

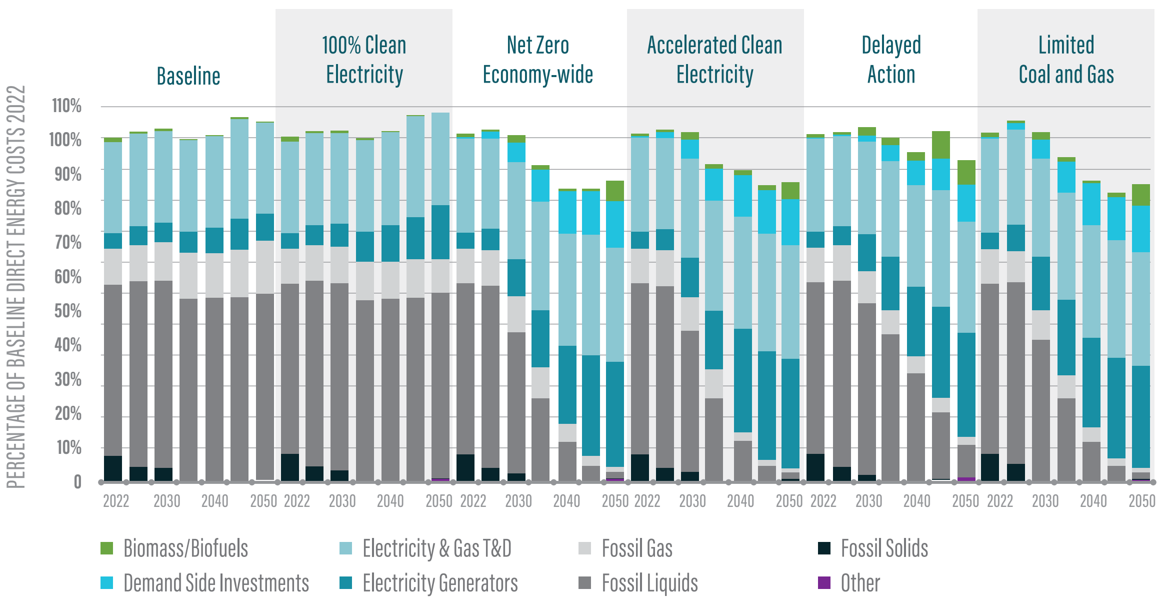
By 2050 costs in the **Baseline** scenario are 6% higher than in 2022 by 2050, and 9% higher in the **100% Clean Electricity** scenario. In contrast, they are 15% lower than **Baseline** 2022 costs in 2050 in the **Net Zero Economy-Wide** scenario. Costs across

21 Costs do not reflect: rates nor allocational/distributional impacts of current and future rates or market mechanisms; currently higher natural gas and oil prices or fuel taxes; market clearing prices and producer surplus in electricity markets nor transmission congestion pricing and wheeling charges; utility administration/program costs or revenue recovery for assets beyond their assumed book life; and additional decarbonization cost that customers will potentially pay through taxes and the cost of goods and services. T&D costs are high level estimates and one of the largest uncertainties in modeled costs.

all sectors of the economy are not 15% lower, as shown in Section 4.2, however costs to provide energy to the residential sector drop disproportionately to the rest of the economy because of the cost effectiveness of electric vehicles. Replacing gasoline purchases with the incremental cost of an electric vehicle and the cost of the electricity to charge it reduce the cost of energy to households. However, when this becomes cost effective depends on the year that a customer switches to an electric vehicle.

FIGURE 41.

Residential Direct Household Costs as a Percentage of Baseline 2022 Costs



To put this in the context of customer energy expenditures, we have scaled direct electricity costs in 2022 to match the average residential customer bill in Wisconsin[22] and added federal and state fuel taxes to gasoline[23]. The resulting estimated annual energy spending by household is shown in Figure 42. The underlying data is still subject to the caveat that it is direct household energy costs and not reflective of current or future tariff designs, but scaling the data to match current energy spending gives an idea of how spending will change in the future. Savings by 2050 in the **Net Zero Economy-Wide** scenario versus **Baseline** are $760 per year.

22 https://www.eia.gov/state/print.php?sid=WI

23 https://wisconsindot.gov/Documents/about-wisdot/who-we-are/dept-overview/comparison.pdf

FIGURE 42.

Estimated Annual Household Energy Expenditures

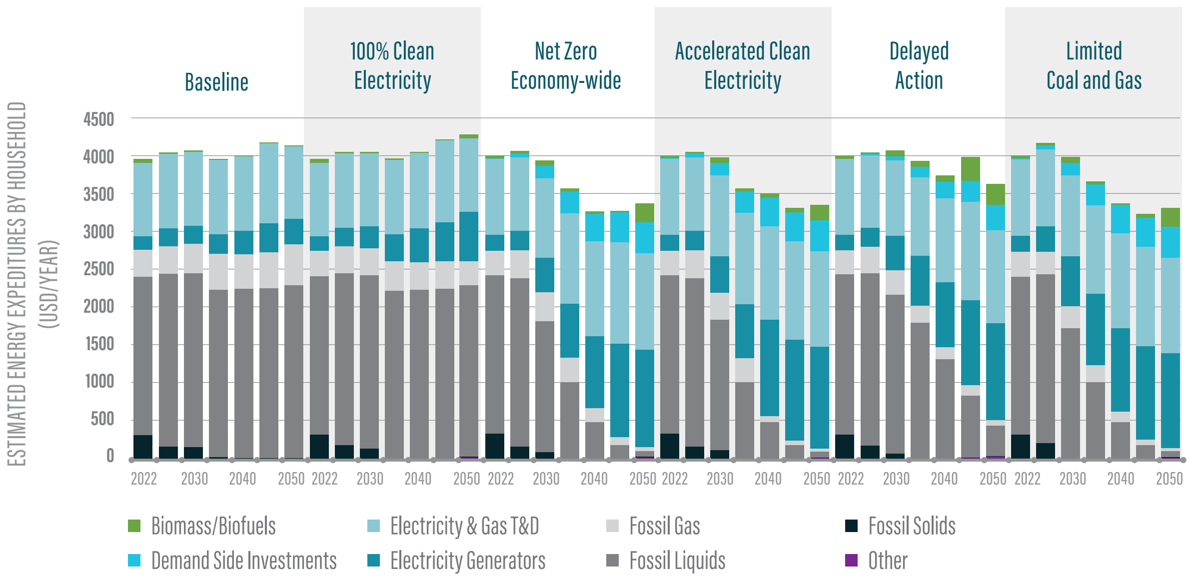
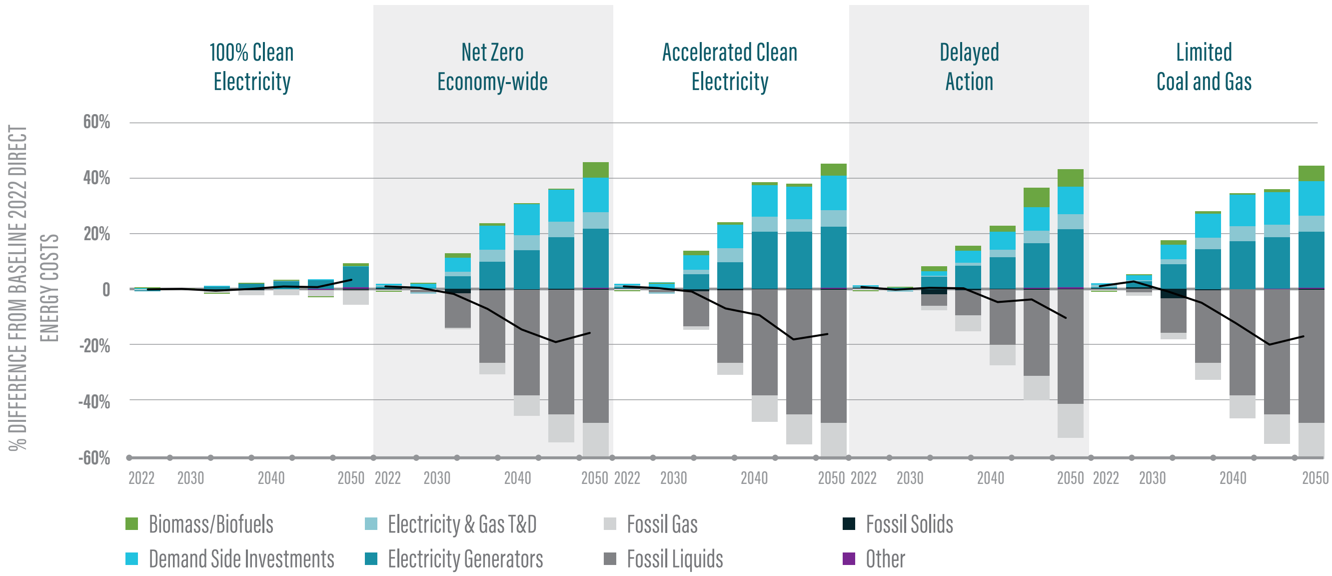


Figure 43 shows direct household energy costs net of **Baseline** 2022 costs. This shows the significantly increased cost of energy from electricity and increased spending on demand side equipment across the net zero scenarios. However, this is more than offset by the savings in gasoline and, to a lesser extent, natural gas. In the **Net Zero Economy-Wide** scenario, this shift in the type of energy delivered to customers results in costs that are approximately 20% lower in 2050.

FIGURE 43.

Net Direct Household Energy Costs as a percentage of Baseline 2022



Direct household energy costs by year of electric vehicle purchase shows how the year of electric vehicle purchase impacts households (Figure 44). Costs are provided for the average customer who purchases an electric vehicle in 2022, 2025, 2030, 2040, and 2050. These costs are presented relative to direct household costs without electric vehicle ownership in 2022. Energy costs for customers purchasing an electric vehicle in 2022 are 50 to 60% more between 2022 and 2035. This reflects the group of customers that are early adopters. One thing to note is that these costs are relative to an internal combustion engine vehicle of average cost. Adopters of an electric vehicle in 2022 are more likely to belong to a higher income bracket, and therefore choose between an electric vehicle or a luxury internal combustion engine vehicle. For those customers, the increase in direct household energy costs (of which the incremental cost above an internal combustion engine vehicle is a component) may be significantly less.

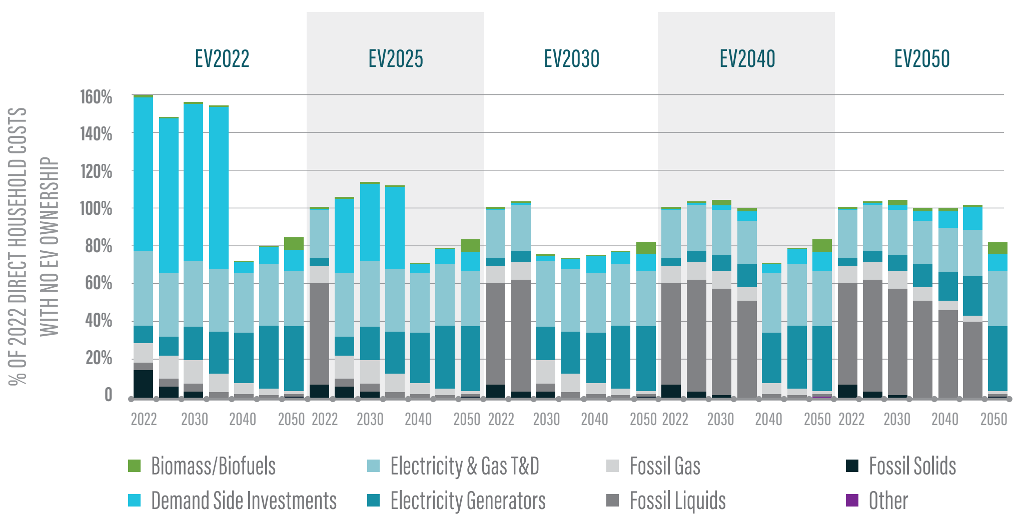
Adopting an electric vehicle in 2025 still incurs a price premium that drives up direct household energy costs through 2035. However, it is significantly reduced over a 2022 electric vehicle purchase due to projected electric vehicle price declines. Customers that adopt an electric vehicle in 2030 drop household energy costs to between 75%-80% of 2022 costs, significant savings over a customer that does not adopt an electric vehicle until 2050. Adoption both in 2040 and 2050 is more expensive than earlier adoption in 2030. While direct household energy costs do not translate directly to what a customer pays through rates, this indicates that customers that adopt an electric vehicle in 2030 will experience significant savings. Comparing EV2030 and EV2050 in the chart, direct household costs between 2030 and 2045 are consistently ~20% lower.

These results show that lifecycle cost parity of electric vehicles with their internal combustion vehicle equivalents happens between 2025 and 2030, based on electric vehicle and fuel price assumptions used in the model. Incentivizing electric vehicle sales will become progressively easier when this happens. While early adopters will typically be in higher income brackets, electric vehicle price declines will increase access to lower income brackets. This will also be supported by a growing second-hand electric vehicle market. Lifecycle cost parity will be reached earlier than capital cost parity. Reaching 100% sales of electric vehicles by 2035 will require policy support to ensure that all customer groups can make the transition.

Electricity T&D costs increase as electric vehicles are adopted (shown below). This includes investments in the distribution system to support load growth as well as public and private vehicle charger infrastructure. Policy to ensure these investments are made early will be important to achieve electric vehicle adoption targets. Without adequate access to charging, reaching 100% sales of electric vehicles by 2035 will be impossible.

FIGURE 44.

Direct Household Energy Costs based on Year of EV Purchase



4.5. Fine Particulate Matter Health Impacts

Achieving 100% clean electricity and net zero emissions reduces carbon dioxide emissions but it also reduces pollutant emissions that have a direct effect on the health of Wisconsin's population. Improvements in air quality over the **Baseline** scenario come from reduced emissions of particulate matter, sulfur dioxide, nitrous oxides, ammonia, and volatile organic compounds from both point sources, such as electricity power plants, and tail pipe emissions from vehicles. The scenarios analyzed in this study assume that emissions are reduced not only in Wisconsin, but also in surrounding states where we have applied clean electricity and net zero emission target assumptions. This assumption increases the improvement in health outcomes among Wisconsin's population, as in-state concentrations of pollutants are impacted by air flows from outside of the state.

To assess health benefits for Wisconsin of reducing these pollutants, we used the EPA Co-Benefits Risk Assessment model (COBRA)[24]. COBRA determines the health impact of changes in fine particulate matter concentrations. This approach omits the health impact of ozone concentrations, which is much smaller than the impact of particulate matter. Figure 45 shows an overview of the COBRA modeling process. This starts with changes in emissions from demand technologies and supply technologies calculated in EnergyPATHWAYS and RIO. These are passed to COBRA that develops air quality scenarios and assesses health outcomes and economic benefits.

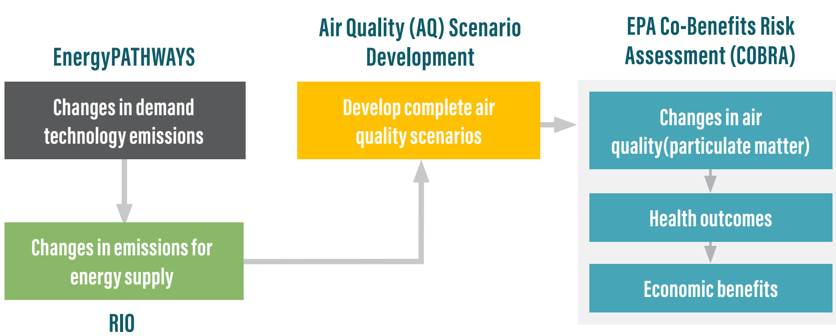


FIGURE 45. Overview of COBRA Modeling

COBRA uses data outputs from the EnergyPATHWAYS and RIO models on emissions from electricity, vehicles, and other sectors of the economy. The data used to determine emissions from all sectors of the economy, including the dominant power sector and tailpipe emission sources are shown in Figure 46. These include NO_x and SO_x that can form fine particulate matter in atmospheric reactions, and direct $PM_{2.5}$ emissions.

On the demand side, vehicle emissions were taken from the EPA Motor Vehicle Emission Simulator[25], OECD Non-exhaust Particulate Emissions from Road Transport[26], and EPA Emissions Inventories for point sources. The transition to electric vehicles over time reduces tail pipe emissions, which are calculated from the vehicle miles traveled of internal combustion powered vehicles in future years.

On the supply side, RIO incorporates the database of emissions factors for new and existing plants from the EPA Avoided Emissions and Generation Tool (AVERT) and

24 EPA COBRA: https://www.epa.gov/sites/default/files/2017-10/documents/cobra_training_eic_2017.pdf
25 https://www.epa.gov/moves
26 https://doi.org/10.1787/4a4dc6ca-en

eGRID 2019.[27] Based on dispatch of thermal generation in each year, we determine the total pollution from electricity generation.

FIGURE 46.

Data Development in EnergyPATHWAYS and RIO

RIO

Demand technology emission changes

- **Database of emissions factors for NO_x, $PM_{2.5}$ and SO_x from key technologies**
  - Vehicles emission factors taken from EPA Motor Vehicle Emission Simulator
  - Supplemental vehicle emission data from OECD (2020), Non-exhaust Particulate Emissions from Road Transport: An Ignored Environmental Policy Challenge, OECD Publishing, Paris, https://doi.org/10.1787/4a4dc6ca-en.
  - Building technologies adapted from EPA's Air Emissions Inventories for point sources
  - Can include additional criteria pollutant emission factors as data sources allow
- **Calculates emissions based on technology activity**

COBRA

Energy supply emission changes

- **Database of emissions factors for NO_x, $PM_{2.5}$, SO_x and Hg from existing and new power plants**
  - Existing plant emission factors taken from EPA Avoided Emissions and Generation Tool (AVERT) and eGRID 2019 data
  - Existing energy conversion technologies (e.g., boilers for steam) are adapted from EPA's Air Emissions Inventories for point sources
  - New power plant data is a combination of NREL ATB data and National Electric Energy Data System data
  - Can include additional criteria pollutant emission factors as data sources allow
- **RIO calculates emissions based on least cost dispatch**

The functions of COBRA can be grouped as shown in Figure 47 to determine changes in air quality across Wisconsin based on a reduced form air quality model called the Source-Receptor (S-R) Matrix. The S-R Matrix estimates the changes in ambient concentrations of particulate matter by county. The next step is to translate those changes into health outcomes through concentration response functions, which have been collected from numerous epidemiological studies looking at the spectrum of health impacts caused by particulate matter (specifically $PM_{2.5}$). The health impacts accounted for in COBRA are adult and infant mortality, non-fatal heart attacks, respiratory and cardiovascular hospital admissions, acute bronchitis and respiratory symptoms, asthma exacerbations and emergencies, and restricted activity and work loss days. Finally, these health metrics are translated into economic benefits using assumptions about economic costs of each type of health impact. Costs are sourced from the value of statistical life (VSL), cost of illness, hospital charges, willingness to pay to avoid illness, activity restriction, and lost workdays.

27 EPA AVERT: https://www.epa.gov/avert, EPA eGRID: https://www.epa.gov/egrid

FIGURE 47.

Flow Chart of COBRA Analysis

- Database of emissions factors by esisting plant and by new build generator
  - *Taken from EPA Avoided Emissions (AVERT) and eGRID 2019*
- RIO calculates emissions based on least cost dispatch

- Reduced form air quality model called the Source-Receptor (S-R) Matrix
  - *Estimates ambient concentrations of PM by county*
- Transfer coefficients of contribution from each plant to air quality of each county

- Concentration response functions
  - *Adult and infant mortality*
  - *Non-fatal heart attacks*
  - *Respiratory and Cardiovascular hospital admissions*
  - *Acute bronchitis and respiratory symptoms*
  - *Asthma exacerbations and emergencies*
  - *Restricted activity and work loss days*

- Economic costs of health impacts
  - *Value of statistical life (VSL)*
  - *Cost of illness*
  - *Hospital charges*
  - *Willingness to pay*
    - *Symptoms of illness*
    - *Restricted activity*
    - *Lost workdays*

Moving from the **Baseline** scenario to net zero emissions removes most pollutant emissions from electricity and vehicles, which are the main drivers of particulate matter concentrations in the economy. The resulting health impacts are significant. Figures 48 and 49 show the reduction in mortalities, lost days of work, and hospital admissions per million people in Wisconsin. Mortality estimates fall within a range. By 2030, mortalities are estimated to be 17 - 39 fewer than the **Baseline** scenario in **100% Clean Electricity**, showing the benefits of reductions in coal and gas generation. This is increased to 22 - 50 in **Net Zero Economy-Wide** as vehicle fleets have higher numbers of electric vehicles and coal is almost completely retired from electricity generation.

By 2050, the benefits of net zero emissions policy increase in contrast to the **Baseline** and to **100% Clean Electricity**. Clean Electricity results in 10 - 22 fewer mortalities. Coal electricity generation is fully retired in both **Baseline** and **100% Clean Electricity** and all older, more polluting gas plants have been retired in both scenarios, leading to reduced health benefits of **100% Clean Electricity** versus 2030. By contrast, **Net Zero Economy-Wide** avoids 28 - 63 mortalities by 2050, and significantly improves outcomes across all health metrics. The higher reduction in mortalities and the improvement in other health metrics in the net zero emission scenarios over **100% Clean Electricity** can be attributed to reduced emissions in transportation.

FIGURE 48.

Impact on Mortalities versus Baseline Scenario

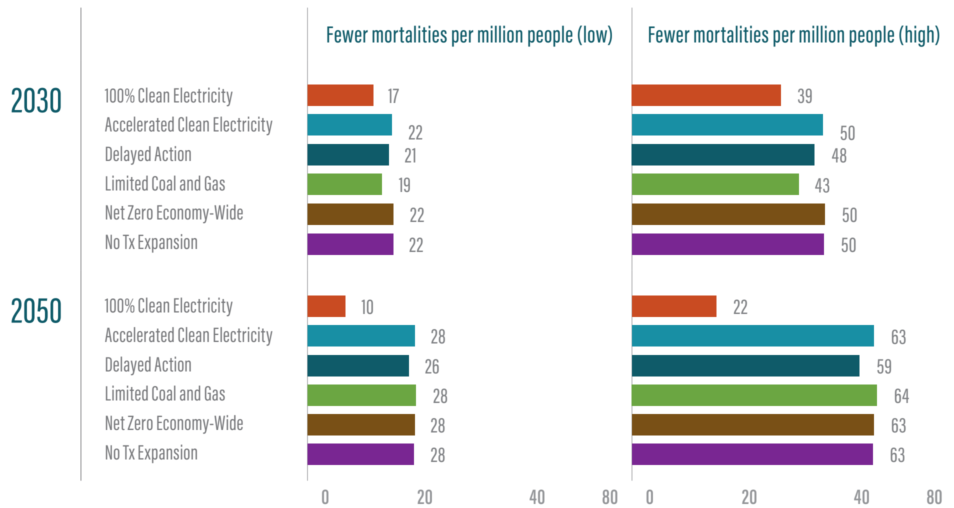
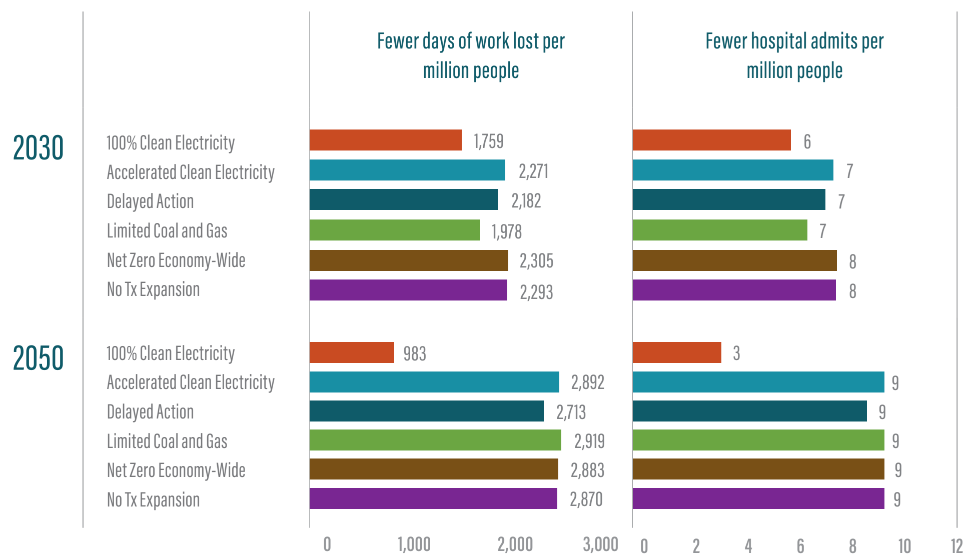


FIGURE 49.

Fewer Lost Workdays and Hospital Admissions versus Baseline Scenario



How this translates to monetized benefits per capita is shown in Figure 50, and total benefits to Wisconsin in Figure 51. Per capita health benefits range from $197 - $443 per capita in **100% Clean Electricity** and $255 - $575 per capita in **Net Zero Economy-Wide** by 2030. By 2050, these benefits increase in the net zero scenarios, moving the range in **Net Zero Economy-Wide** to $319 - $718 per capita. This translates to a range of $2.0B - $4.4B savings from reducing emissions in 2050 versus the **Baseline** scenario.

Even by 2030, the health benefits of reducing these emissions are significant and larger than the difference in direct energy costs between the **Baseline** and other scenarios. All policy scenarios investigated are of net benefit to the state when health outcomes are factored in.

FIGURE 50.

Total Monetized Benefits per Capita versus Baseline Scenario

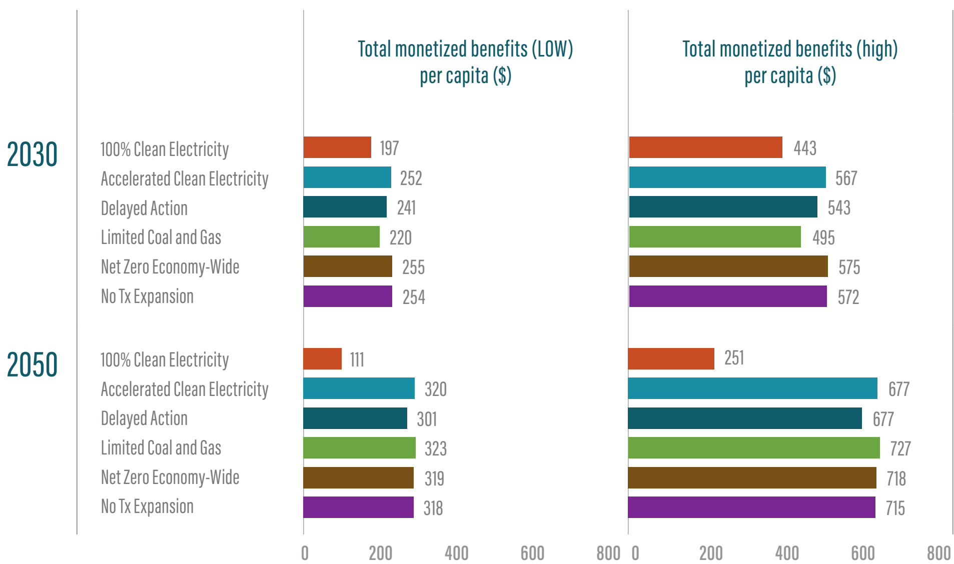
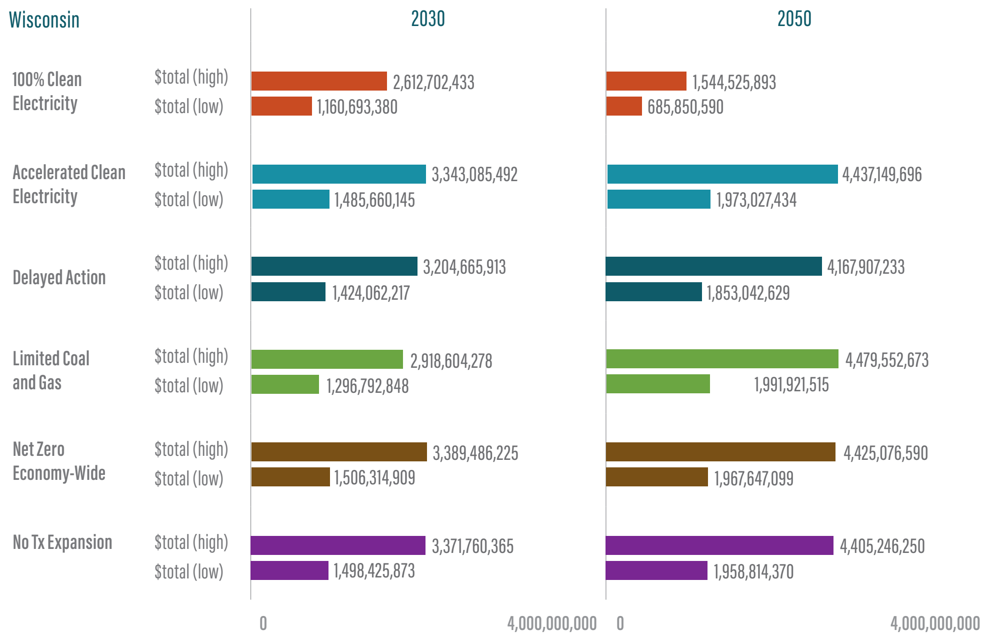


FIGURE 51.

Total Benefits attributed to Emissions Reductions in 2030 and 2050 versus Baseline Scenario



5 UNCERTAINTY

Modeling least-cost pathways to clean electricity and net zero emissions by 2050 relies on 30-year forecasts of technology availability and pricing, service demand, and fuel prices. Moving forward in time, the uncertainty in these forecasts increases. Some of these uncertainties are explored in the scenarios we modeled, but much of our analysis relies on best available information at the time of modeling. Some of the most impactful uncertainties are forecast fuel prices and electric vehicle costs.

This analysis was conducted prior to global oil and gas price increases resulting from the Russian attack on Ukraine. These price increases make energy more expensive in the near-term and demonstrate the impact of fuel price volatility on Wisconsin's energy sector. Switching to clean electricity and decarbonizing the economy protects against future oil and gas price increases and market volatility. If higher oil and/or gas prices were sustained in the future, perhaps from greater exposure to global LNG markets than the US has experienced in the past, decarbonization would become more favorable economically than this report presents.

As an example of an opposing economic uncertainty, lithium prices have recently increased significantly as the global mining industry works to develop new sources to meet increased demand. If electric vehicle pricing does not decrease as forecasted in the analysis due to sustained higher prices of lithium and precious metals required to manufacture vehicle batteries, transportation electrification may be less cost-effective than our findings suggest.

6 KEY ACTIONS BY DECADE

6.1. Key Actions in the 2020s

6.1.1. ECONOMY-WIDE EMISSIONS POLICY TO COMPLEMENT ELECTRICITY POLICY

Four times the emissions reductions can be achieved with comprehensive economy-wide decarbonization action than with clean electricity policy alone by 2050, and for similar cost. Clean electricity policy is a strategy to achieve emissions reductions, but requires complementary policy across the rest of the economy to achieve deeper improvements. It can be far more effective when combined with demand side electrification of transport, buildings, and industry, and production of clean fuels for parts of the economy that are difficult to electrify.

6.1.2. ACTION TO TRANSITION THE DEMAND-SIDE OF THE ECONOMY TOWARDS ELECTRIFICATION AND HIGH EFFICIENCY EQUIPMENT

Energy consuming technologies such as vehicles, space heaters, and boilers, have long lives and it takes time for stocks to rollover through natural retirement and replacement cycles. Getting started early in supporting sales of electrified and/or high efficiency technologies will ensure stocks are highly efficient when approaching net zero emissions targets in the future. This drives significant electric load growth.

The study assumes aggressive electrification rates of vehicles, buildings, and industry, targeting 100% sales of electrified and/or high efficiency equipment by 2035 in most of the scenarios that include emissions policy. We show that moving more slowly on making this transition will ultimately cost Wisconsin more when targeting net zero emissions.

6.1.3. ELECTRICITY SECTOR PLANNING FOR LONG-TERM FUTURE GROWTH TO ENSURE A SUCCESSFUL TRANSITION

The pace and scale of the electricity sector expansion to meet load growth and incorporate clean energy sources will require grid and land use planning and coordination early. Long lead-time assets like transmission may need lead times up to 10 years in advance to construct. Early feasibility studies will give Wisconsin a better picture of the challenges and give enough time to find solutions. When targeting net zero emissions, the study supports earlier retirement of coal plants, finding very little coal generation remaining as part of a least cost generation mix in 2030.

Distributed energy resources (DER), including rooftop solar and flexible loads are deployed in all scenarios. These can reduce the pace and scale of grid-scale resource investment, taking the pressure off potentially challenging rates of deployment and giving Wisconsin more options to achieve clean electricity and net zero emissions targets.

6.1.4. INVESTMENT IN RENEWABLE ENERGY

By 2030, solar investment in the state makes up 24% of all capacity in the **100% Clean Electricity** scenario and 40% in the **Net Zero Economy-Wide** scenario. That is 6.9 GW and 9.2 GW of solar, respectively. To reach this level of renewable investment by 2030, procurement, siting, construction, and interconnection must happen in the 2020s.

The pace of renewable investments needed in the 2020s is even higher when following a different future pathway to net zero. In the **Delayed Action** scenario, fewer emissions reductions come from reductions in fossil fuel use in vehicles and buildings. The electricity sector therefore takes on more of the emissions reduction burden. By 2030 there are 6.6 GW of solar and 4.5 GW of wind constructed. **Limited Coal and Gas** sees even greater investments over the same time frame. To replace coal and avoid new gas construction, 10 GW of solar, 5.9 GW of wind, and 3.6 GW of storage are constructed between 2020 and 2030 to provide energy and ensure reliability.

To reach this pace of renewable investment, planning will need to begin early this decade. At present, Wisconsin does not have an integrated resource plan, so establishing a planning process for the state will be necessary, including how demand side transformation may be achieved. In addition to the siting, permitting, and construction of the projects themselves, significant new transmission investment will be needed to interconnect these systems and deliver power to load. Tied to the previous action above, investments in transmission assets should be made in the context of future electricity system growth. In the 2030s, the rate of investment in new renewables is even greater and foresight of where new resources may be located in the future may offer opportunities for cost reductions in planning transmission to interconnect them.

6.2. Key Actions in the 2030s

6.2.1. FULL RETIREMENT OF COAL BY THE EARLY 2030S

Coal generation in the **Net Zero Economy-Wide** scenario is 90% less than in the **Baseline** in 2030 and fully retired by 2035. Coal plays a very small role in the power sector by 2030, indicating that earlier retirements of coal are an economic option if the state pushes towards net zero emissions policy. Coal generation reduces in the **100% Clean Electricity** scenario by 2030 as well, though only by 16%. This shows the need to reduce thermal generation to meet clean electricity policy, but with no emissions policy, coal generation is not constrained to the degree seen in **Net Zero Economy-Wide**.

6.2.2. ACCELERATED PACE OF RENEWABLE INVESTMENT

The pace of renewable investment made in the 2020s must accelerate to reach the investments needed during the 2030s to reach the clean electricity and net zero emissions targets. By 2040, a total of 11 GW of solar, 3 GW of wind, and 1.4 GW of storage are built in the **100% Clean Electricity** scenario. However, the expansion of electric load in the net zero scenarios due to electric vehicle and appliance adoption drives much larger rates of renewable growth. By 2040, clean electricity investments in the **Net Zero Economy-Wide** scenario total 18 GW of solar, 12 GW of wind, and 1.3 GW of storage. The rate of solar additions in Wisconsin equal 1.7 GW/year between 2025 and 2030, 0.9 GW/year between 2030 and 2040, and 1.3 GW/year between 2040 and 2050. Wind additions start later with a rate of 2.2 GW/year between 2035 and 2040, and 0.9 GW/year between 2040 and 2050. The model did not constrain the rate of additions. In periods where the rate of additions may be challenging to achieve, such as wind additions between 2035 and 2040, starting procurement earlier is an option to help ensure successful adoption.

In the **No Transmission Expansion** scenario, the significant imports of clean energy Wisconsin relies upon in the **Net Zero Economy-Wide** scenario are curtailed. In-state investments increase to meet those energy needs. By 2040 in **No Transmission Expansion**, 23 GW of solar, 13 GW of wind, and 3.0 GW of storage are needed. Increasing the rate of investment over the **Net Zero Economy-Wide** scenario puts further pressure on in-state resource siting and transmission interconnection.

6.2.3. TRANSMISSION EXPANSION

Transmission expansion is relatively low in the **Baseline** and **100% Clean Electricity** scenarios and doesn't happen until 2045. However, in the net zero scenarios, expanded transmission facilitates greater clean energy imports as early as 2035. In **Net Zero Economy-Wide**, transmission is expanded by 0.8 GW and 4.0 GW to Illinois, 2.1 GW and 4.7 GW to Iowa, and 2.3 and 3.6 GW to Minnesota, by 2035 and 2040, respectively. At the prices included in the model, transmission is clearly valuable to a net zero emissions strategy. It also gives Wisconsin optionality among different emissions reductions measures should there be challenges implementing one or more of them.

Expansion of transmission should happen in the context of transmission needs to achieve net zero by 2050. Transmission is further expanded in **Net Zero Economy-Wide** to reach the full 6 GW of expansion we permitted in the model by 2050 to Illinois and Iowa, and close to that in Minnesota. We modeled transmission allowing linear additions priced at a per MW of expansion cost. However, in reality these investments are lumpy. More detailed planning will be required to assess timing and cost of these investments that best fit with the long-term strategy if targeting net zero.

6.2.4. TRANSITIONING OF GAS IN THE POWER SECTOR

During this decade, gas transitions from a baseload resource, providing much of the energy to Wisconsin's loads, to a capacity resource used to maintain system reliability. Gas capacity factors drop close to 20% by 2040.

6.2.5. 100% ELECTRIFICATION AND HIGH EFFICIENCY EQUIPMENT SALES BY 2035

The net zero scenarios model reaching 100% sales of electric and high efficiency equipment in light-duty transport and building appliances by 2035. Comparison to the **Delayed Action** scenario shows this is a cost-effective strategy when targeting net zero emissions by 2050. While action on the demand side in the 2020s is key to begin making this transition, it is completed in the 2030s. Cost declines in electrified technologies are expected to make the customer choice to electrify an economic one, particularly in vehicles, potentially reducing the scale of policy intervention needed in this time period.

6.3. Key Actions in the 2040s

6.3.1. CONTINUED RAPID PACE OF RENEWABLE INVESTMENT

The pace of renewable development in **100% Clean Electricity** accelerates to achieve 100% clean electricity by 2050. In **Net Zero Economy-Wide**, the number of MWs of renewables installed remains similar to the previous decade as electrification continues and net zero is met by 2050.

6.3.2. INCREASED IMPORTS OF CLEAN ENERGY FROM OUT OF STATE

A quarter of Wisconsin's energy needs come from imported clean electricity by 2050 in the **Net Zero Economy-Wide** scenario. To facilitate this, transmissions expands on the interties to neighboring states by the maximum 6 GW permitted in the modeling constraints. Planning for this expansion must happen in prior decades, however the full 6 GW per intertie of new transmission is operating by this decade. As discussed for the previous decades, transmission investment is lumpy and studies will be required to identify the best transmission investment strategy.

6.3.3. COMPLETE TRANSITION OF GAS IN POWER SECTOR TO RELIABILITY RESOURCE

Prior to 2040, gas generation in power provides significant proportions of electricity delivered to Wisconsin loads. However, in the decade starting 2040, tighter emissions caps drive gas generation out of the energy mix. Gas remains by 2050 but in small quantities for maintaining system reliability. All gas burned by 2050 under the clean electricity policy comes from biogas produced from agricultural waste. By 2050, gas capacity is operating at a 5% capacity factor and burning clean gases rather than fossil. Total gas generation from burning clean gases in 2050 is 1.2% of generation or 2.6 TWh.

6.3.4. CARBON CAPTURE AND SEQUESTRATION

With the exception of the **Delayed Action** scenario where carbon capture and sequestration begins in the previous decade, all scenarios begin carbon capture and sequestration in this decade. This study used a database of identified geological formations suitable for carbon sequestration that did not contain potential for Wisconsin. We assume that carbon is sent out-of-state via pipeline for sequestration elsewhere. This will require planning and coordination with other states to develop carbon transportation networks unless local storage opportunities are identified.

6.3.5. INVESTMENTS IN ELECTROLYSIS

Electrolysis ramps up in this decade to support the heavy-duty vehicle fleet and provide balancing to the grid. The extent of the investment in electrolysis and carbon capture and sequestration will depend on research and development and subsequent technology costs not just of the electrolysis itself, but of the conversion processes to produce alternative fuels. Planning for electrolysis siting could consider hydrogen hub creation and potential co-siting opportunities with hydrogen demands such as drop-in fuels production or ammonia production for fuels or fertilizers.

6.3.6. CLOSE TO 100% PENETRATION OF ELECTRIFIED AND CLEAN END USES

On the demand side, electrified and clean end uses reach close to 100% penetration in many sectors of the economy this decade. Measures to drive sales of these technologies need to be strong in the previous decade to ensure the economy is on track for this transition. These may need to be continued through the 2040s though technology costs for electric vehicles, heat pumps, and other more efficient demand side equipment may be low enough that only light policy intervention is required.

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