Interpreting Global Energy Scenarios for Emissions Planning at the Utility Scale

Report Prepared for Madison Gas and Electric Company

Researched and written by

Tracey Holloway, Ph.D.
Clara Jackson

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Nelson Institute for Environmental Studies &
Department of Atmospheric and Oceanic Sciences
University of Wisconsin—Madison
Madison, WI 53726; taholloway@wisc.edu

Center for Sustainability
and the Global Environment
NELSON INSTITUTE
UNIVERSITY OF WISCONSIN–MADISON

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Executive Summary

Science has established that carbon emissions from fossil fuel burning, along with other factors, are changing the climate of the Earth. Here in Wisconsin, we are already seeing the consequences of climate change, with southern and western Wisconsin having 3-7 inches more precipitation per year by the early 2000s relative to 1950 and winter temperatures increasing about 2.5°F across the state. These changes will be more extreme in the future [*Wisconsin Initiative on Climate Change Impacts*, 2011].

An international effort called the Intergovernmental Panel on Climate Change (IPCC) recognized the need to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels to significantly reduce the risks and most adverse impacts of climate change. To date, the Earth has warmed about 1°C (1.8°F) on average. To achieve this recommendation, "bold and transformative steps .. are urgently needed," according to the United Nations [*Allen et al.*, 2018].

Multiple research groups around the world have developed computer models to assess what combination of energy and land-use changes are consistent with the 1.5°C analysis. Many organizations are using these science-based assessments as a component in decision-making, as these model results present multiple options for achieving a global environmental goal. Our group at the University of Wisconsin—Madison was asked by Madison Gas and Electric Company (MGE) to evaluate the IPCC scenarios relevant to its operation. Here we present the results of this analysis.

Major findings include:

The strength of the IPCC scenarios is in terms of qualitative guidance on the direction and magnitude of emissions changes.

Electricity production differs dramatically across the U.S. and around the world. In 2016, 48% of MGE's electricity generation was coal, and coal is the main source of electricity across the state. Even within the U.S., states vary in whether coal, natural gas, hydropower, or nuclear comprise the largest source of electricity generation. This heterogeneity is even greater across industrial nations. The IPCC scenarios do not account for these differences across countries and states. Rather, the industrial countries are grouped together and treated uniformly in the IPCC scenarios. As a result, it would be unwise to treat these model simulations as prescriptive for any individual sub-region, much less a single utility.

Rather, the pathways are useful to identify the general magnitude and timeline of emissions consistent with a 1.5°C outcome. All scenarios require electricity generation in industrialized countries to be at or near net-zero carbon by 2050, suggesting that a 2050 net-zero carbon target is consistent with the current scientific recommendations. Of these pathways, some "overshoot" the target (temporarily exceed the temperature goal but ultimately fall below the temperature threshold by 2100) and others include "negative emissions" (actively removing CO_2 from the air). For the purposes of informing a trajectory for a single utility over the coming decades, we limited the scenarios to omit those with "high overshoot" (i.e., temporarily exceeding the temperature goal by 0.1°C to 0.4°C—an exceedance of this magnitude can have detrimental effects even if temporary) and to omit “net-negative emissions” (i.e., not assuming that MGE would remove more CO_2 from the atmosphere than it emits).

Relative to these scenarios, **MGE’s goal is more aggressive than any of the modeled pathways for the electricity sector in industrialized countries**.

The analysis of the IPCC scenarios of a low-carbon future highlights that **electricity demand and carbon intensity of generation affect carbon emissions.**

In Madison, factors including increasing population, increasing average household income, and increasing electric vehicle (EV) adoption point toward a possible increase in electricity demand. Energy efficiency and/or conservation efforts can help modulate the projected increase in demand.

To decrease carbon emissions in an environment of increasing demand requires a lower-carbon intensity generation mix. MGE has been transitioning to lower-carbon sources since 2005, including discontinuing coal use at its Blount Generating Station and adding significant investment in renewable energy resources. To meet the net-zero carbon by 2050 goal, a continued switch away from fossil fuels and toward non-emitting energy sources will be required.

Consistent with the qualitative patterns expected for Madison, the IPCC scenarios show electricity consumption is going up, even as total carbon emissions go down. MGE will continue to evaluate how demand (including from EVs), energy efficiency measures, and the transitioning of the generation mix are best combined to support MGE’s goal of net-zero carbon by 2050.

By 2050, the carbon intensity of MGE electricity generation will need to decrease to net- zero. Although increasing electricity demand increases total carbon emissions, it is possible that an increase in demand can facilitate the transition to a low-carbon-intensity generation mix. Consistent with MGE’s stated goals of strategies for deep decarbonization, new facilities built to meet new demand should move MGE toward low-carbon-intensity generation.

The evolution of electricity generation and use in Madison depend on a wide range of factors specific to our community. Examining these opportunities and trade-offs would be a valuable direction for future research.

1. Introduction

In May 2019, MGE announced its goal of net-zero carbon electricity by the year 2050. Net-zero, or carbon neutral, may be achieved either by eliminating carbon emissions completely and/or by removing as much carbon from the atmosphere as is being added (e.g., by carbon offsets associated with planting trees, carbon capture and storage, or other technological or biological methods). **The net-zero carbon by 2050 goal was chosen by MGE in an effort to align with the current climate science from the IPCC.**

Here in Wisconsin, we are already seeing the consequences of climate change, with southern and western Wisconsin having 3-7 inches more precipitation per year by the early 2000s relative to 1950 and winter temperatures increasing about 2.5°F across the state. These changes will be more extreme in the future [*Wisconsin Initiative on Climate Change Impacts*, 2011]. (The IPCC has recognized the need to limit global-average warming to 1.5°C (2.7°F) to minimize the most adverse impacts of climate change.) To date, the Earth has warmed about 1°C (1.8°F) on average. To achieve this recommendation, "bold and transformative steps .. are urgently needed," according to the United Nations [*Allen et al.*, 2018]. MGE's 2050 goal stems from a 2018 report from the IPCC called the Special Report on Global Warming of 1.5°C (SR15). SR15 discusses the impacts and associated greenhouse gas (GHG) emission pathways of global warming of 1.5°C above pre-industrial temperatures.

To evaluate what combination of energy and land-use policies could support the 1.5°C goal, multiple research groups around the world have developed computer models. These models attempt to project the global temperature response to different assumptions about energy technology and other factors over the next 100 years. The results of these computer models were reported in the SR15 report of the IPCC and shared through an online database managed by the Integrated Assessment Modeling Consortium (IAMC). The IAMC database provides researchers, companies, and the general public with information to support planning for a low-carbon future.

The SR15 report of the IPCC was written to "strengthen the global response to climate change, sustainable development, and efforts to eradicate poverty." Nearly 100 authors from 39 countries contributed to the report (IPCC, 2018). In addition to the 1.5°C temperature threshold, the IPCC report considers a 2°C target, both of which emerged from the Paris Agreement of 2015. The Paris Agreement stated that countries should limit their GHG emissions in order to keep warming well below 2°C above pre-industrial levels with the pursuit of keeping warming below 1.5°C. These specific thresholds were chosen recognizing that keeping warming below these levels would help mitigate the most detrimental impacts of climate change.

Other organizations have incorporated the science of the IPCC SR15 as a component in decision-making, as these model results present multiple options for achieving a global environmental goal. A University of Denver study explicitly cites the IAMC scenarios as part of their rationale for utility-scale carbon-reduction goals [*Xcel Energy*, 2019].

Our group at the University of Wisconsin—Madison was asked by MGE to evaluate the IPCC scenarios relevant to its operation. Here we present the results of this analysis. This report presents an analysis of scenarios to limit global warming to 1.5°C. We focus on the application of the IAMC scenarios to MGE's planning to reduce carbon emissions. We focus on the following research questions:

1.) **Is MGE's goal of net-zero carbon emissions by 2050 in line with current climate science limiting global warming to 1.5°C?**
2.) **What can we learn from the IAMC scenarios to inform planning of a relatively small utility?**
3.) **What additional research on the transition to a low-carbon future would support planning by MGE and its community stakeholders?**

MGE has been transitioning to lower-carbon electricity sources, and since November 2015, the company has developed projects that will increase its owned renewable energy capacity by about 600%. In May 2019, MGE announced a goal of net-zero carbon electricity by 2050[1]. The goal for 2050 represents an aggressive continuation of the company's efforts over the last 15 years.

As an air pollutant, carbon dioxide (CO_2) is very different from other electricity emissions associated with air quality and public health, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), and mercury (Hg). These pollutants are regulated by the U.S. Environmental Protection Agency under the Clean Air Act. Because these pollutants are chemically reactive, technological controls are available to significantly reduce their emissions. Between 2005 and 2018, MGE has reduced SO_2 by 97% , NO_x by 69%, PM by 91%, and Hg by 92% [*MGE*, 2019]. Unlike these "traditional" air pollutants, there is no federal rule for carbon emissions from power plants, nor are there technologies to remove CO_2 from the waste stream.

In its goal of net-zero carbon emissions by 2050, **MGE is taking voluntary measures to reduce carbon emissions.** These measures broadly reflect a change in electricity generation sources, moving away from high-carbon fuel sources, especially coal, and increasing the role of zero-carbon electricity generation, such as solar and wind. (More detail on electricity generation options and carbon emissions are provided later in this report.) As a publicly held regulated utility, MGE is required to provide safe, reliable, affordable energy to its customers in Madison, Wisconsin. As such, the timing and structure of a plan to achieve net-zero carbon must be designed to balance environmental outcomes, cost, and reliability for the utility's customers and shareholders.

MGE has chosen to work toward the environmental outcome of a 1.5°C maximum global warming, as recommended by the IPCC. The IAMC scenarios provide the most up-to-date and advanced science to link electricity demand and production with the 1.5°C climate threshold. Still, there are important limitations to the interpretation of these data, which will be discussed throughout this report. The most significant limitation is the structure of the IAMC scenarios, which groups countries together in seven global regions – despite a high level of heterogeneity in the generation and utilization of electricity within each region. Results relevant to MGE in the IAMC draw from a coarse grouping of all industrialized nations.

Electricity production differs dramatically across the U.S. and around the world. Even within the U.S., states vary in whether coal, natural gas, hydropower, renewable energy, or nuclear comprise the largest source of electricity generation. This heterogeneity is even greater across industrial

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[1] https://www.mge.com/newsroom/news-releases/articles/mge-announces-goal-of-net-zero-carbon-electricity

nations. The IAMC scenarios do not account for these differences across countries and states. Rather, the industrial countries are grouped together and treated uniformly in the IAMC scenarios. As a result, it would be unwise to treat these model simulations as prescriptive for any individual sub-region, much less a single utility.

The challenge of applying the IAMC scenarios to utility-scale planning was discussed in a 2018 report from the Electric Power Research Institute [*EPRI*, 2018]. As shown in Figure 1, there are key steps in between the model calculation of global, long-term climate goals and the planning of a single company. The EPRI report emphasizes the importance of recognizing the uncertainty within the ranges of the scenarios and recommends flexibility given changing technology, economic development, energy markets, and policy design. Our report reflects on the utility sector of the IAMC scenarios for the specific planning needs of MGE.

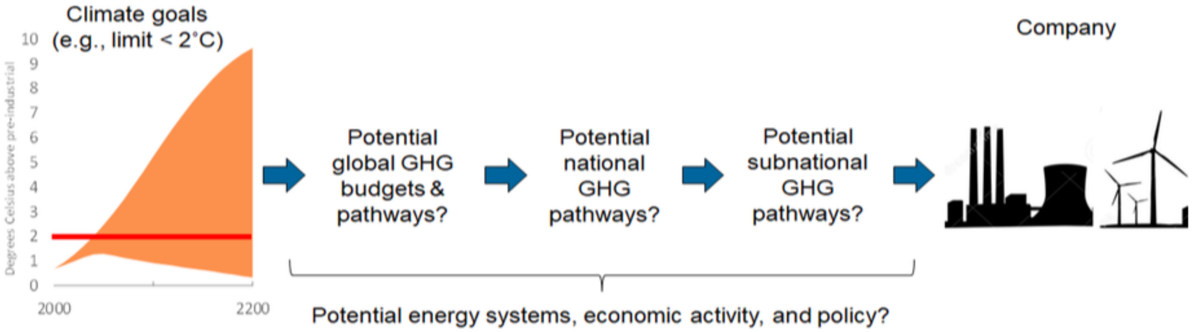


Figure 1. *Graphic showing the uncertainties present when relating a global climate goal to a single company [EPRI, 2018].*

2. Methodology

The IPCC database used in this study includes 414 scenarios of future energy use, developed by research groups around the world. The database is managed and hosted by the International Institute for Applied Systems Analysis (IIASA) and the IAMC.

The publication of this database, known as the 1.5ºC Scenario Explorer, is a concerted effort to increase the transparency and reproducibility of IPCC reports. The database provides researchers, companies, and the general public with a platform to create and view graphs, tables, and charts, comparing hundreds of different scenarios. The scenarios are considered representative concentration pathways (RCPs) or scenarios that demonstrate concentrations of GHGs over time, taking into account other factors such as land use. Although there are multiple GHGs affecting the climate, the main GHG affecting the climate, and main GHG from electricity generation, is CO_2.

Each scenario in the database represents one of many ways to achieve a specific temperature threshold [*Moss et al.*, 2010]. States and countries are not treated individually but rather grouped together in seven global regions. The 1.5ºC Scenario Explorer can be used to customize and view ensembles (sets of scenario results) to compare different pathways across energy sectors and global regions.

The University of Denver study, which used the IAMC database to determine whether Xcel Energy's CO_2 emissions reductions goals were in line with 2ºC and/or 1.5ºC of warming [*O'Neill and Hedden*, 2018], is most similar to that presented here. We chose 2005 as a baseline year to facilitate comparison with the University of Denver study.

In addition to considering total carbon emissions by year, we use the IAMC scenarios to compare changes in assumed electricity demand, carbon intensity of the generation mix, and transportation electrification. We consider these patterns as simulated by the IAMC models and consider their relevance to Madison, Wisconsin. Here we describe the structure and components of the 1.5ºC Scenario Explorer, taking a step-by-step approach toward compiling an appropriate ensemble for MGE.

The database consists of 416 scenarios, of which two serve as historical reference and are not relevant to future projections. All scenarios were produced from 25 models from 13 different modeling teams, with each scenario being assessed and validated for completeness, plausibility, and consistency. Model results include CO_2 emissions, energy consumption, price of carbon over time, and other variables, but not every model includes every variable. Each model simulation reflects a consistent set of assumptions, such that modeled electricity sector carbon emissions take into account increased electricity demand, including by the transportation sector.

The seven regions included in the database are aggregations of countries, including Latin America and the Caribbean, Asia, Middle East and Africa, Reforming Economies of Eastern Europe and the Former Soviet Union, the Organization for Economic Cooperation and Development countries plus the European Union (OECD90+EU), and a category that encompasses the rest of the world. The OECD90+EU region includes the United States and other industrialized countries.

Among the 414 modeled future scenarios, there are 177 different assumptions of energy futures. In many instances, the same energy scenario may have been evaluated by different models. Not all models include the same energy sectors (e.g., electricity); not all model results have been correctly uploaded to the database for evaluation. Of these 414 future scenarios, three are categorized as “no climate assessment” meaning they are not categorized by warming impact.

Pathway Group	**Pathway Class**	**Pathway Selection Criteria and Description**	**Number of Scenarios**	**Number of Scenarios**
1.5°C or 1.5°C-consistent	Below 1.5°C	Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50%-66% likelihood*	9	90
	1.5°C with low overshoot	Pathways limiting median warming to below 1.5°C in 2100 and with a 50%-67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways	44	
	1.5°C with high overshoot	Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1-0.4°C higher peak warming than Below-1.5°C pathways	37	
2°C or 2°C-consistent	Lower 2°C	Pathways limiting peak warming to below 2°C warming during the entire 21st century with greater than 66% likelihood	74	132
	Higher 2°C	Pathways assessed to keep warming below 2°C during entire 21st century with 50%-66% likelihood	58	
Above 2°C				189
Total				411

*No pathways were available that achieve a greater than 66% probability of limiting warming below 1.5°C during the entire 21st century based on the MAGICC model projections.

Table 1: *Overview of scenarios and assumptions. Adapted from SR15 (Section 2.1.3) outlining likelihoods of temperature pathways within the database (Rogelj et al., 2018). Shaded scenarios are those included to meet the more climate-protective no- or low-overshoot criteria requested by MGE.*

The 411 scenarios with warming impact characterized may be split into six categories based on temperature outcome. These are: below 1.5°C, 1.5°C with low overshoot, 1.5°C with high overshoot, lower 2°C, higher 2°C, and above 2°C as shown in Table 1 [*Rogelj et al.*, 2018]. In this context, “overshoot” refers to temporarily exceeding a specific level of global warming but ultimately returning to the goal temperature. Low overshoot scenarios allow an exceedance of 0.1°C (i.e., scenarios that stay below 1.6°C and return to below 1.5°C by the end of the century). High overshoot scenarios allow an exceedance of 0.1°C to 0.4°C (i.e., scenarios that may reach

1.9ºC and return to below 1.5ºC by the end of the century). Each of these temperature thresholds are expressed as probabilities calculated by the Model for the Assessment of Greenhouse Gas-Induced Climate Change (MAGICC). MAGICC6, the newest version of the model, is a reduced-complexity carbon cycle, atmospheric composition, and climate model [*Meinshausen et al.*, 2011]. Another model, the Finite Amplitude Impulse Response (FAIR) is also used; however, it is primarily used in the context of adjusting carbon budgets based on non-CO_2 forcing contributions rather than classifying scenarios based on temperature outcomes, though results from both models are used to classify uncertainty [*Smith et al.*, 2018].

The MAGICC-calculated likelihoods associated with each temperature outcome can be summarized in Table 1. The pathway group labeled "1.5ºC or 1.5ºC-consistent" refers to pathways with a 50%-66% likelihood of no overshoot, with a 50%-67% likelihood of limited (low) overshoot, and with a greater than 66% likelihood of high overshoot of 1.5ºC. Similarly, 2ºC or 2ºC-consistent refers to pathways with either a greater than 66% likelihood (lower 2ºC) or between 50% and 66% likelihood (higher 2ºC) of keeping warming below 2ºC during the entire 21st century. It is worth noting that there were no solutions that limited warming to below 1.5ºC with a likelihood greater than 66%. This speaks to the considerable uncertainty associated with all scenarios and models included in the database and the relatively few scenarios meeting this goal in the published literature. Higher likelihoods are representative of more aggressive pathways and thus affect the scenarios available that meet a certain temperature goal.

To align with IPCC recommendations, MGE asked us to focus on the "no overshoot" or "low overshoot" scenarios. Recall that in this context, "overshoot" refers to temporarily exceeding a specific level of global warming but ultimately returning to the goal temperature. By limiting the choice of scenarios to no/low overshoot, MGE chose a more climate-protective threshold to constrain our analysis. There are 53 scenarios that meet these criteria.

These stronger climate assumptions are sub-sets of less protective scenario ensembles, including weaker climate assumptions (e.g., 2ºC and/or high overshoot). As shown in Table 1, more aggressive temperature thresholds generally result in fewer solutions from the database.

Different scenarios reflect different assumptions about the levels of consumption, generation mix, and other factors. We focus on CO_2 emissions from the electricity sector, using scenarios from the 1.5ºC Scenario Explorer for "CO_2 emissions from electricity and CHP (combined heat and power) production and distribution (Mt CO_2/yr)." (These were selected through the database scenario selection process: Emissions → CO_2 → Energy → Supply → Electricity). In summary, we consider three major criteria:

1. ***Temperature threshold:*** below 1.5ºC or 1.5ºC with low overshoot
2. ***Region:*** industrialized countries
3. ***Data:*** CO_2 emissions from electricity sector

With these constraints, the database returned 35 out of 53 possible scenarios, a screenshot of which is shown in Figure 2. Although 53 scenarios are noted as meeting our constraints, data are only available for 2/3 of these results (35 lines on Figure 2). This difference is due to a high number of model results missing from the database.

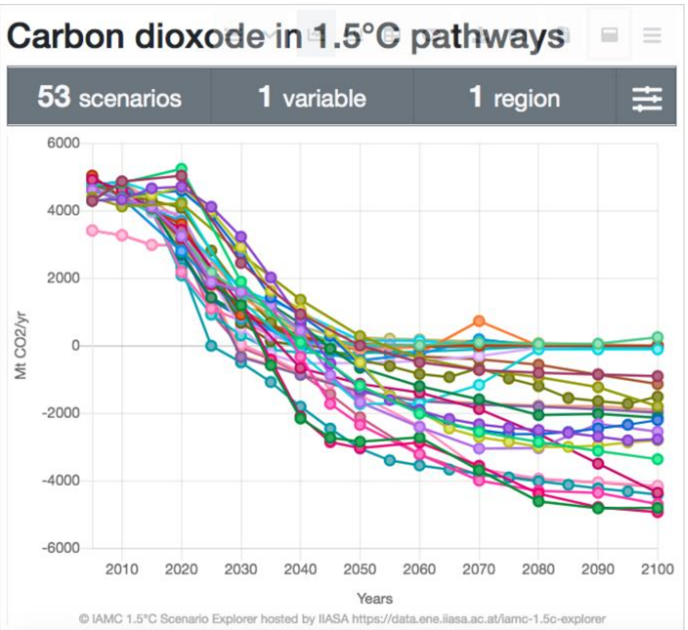


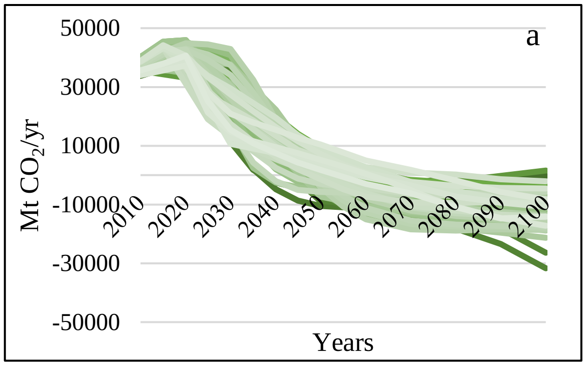
Figure 2: *Screenshot from the 1.5°C Scenario Explorer depicting the 35 scenarios that match our initial query.*

Next, we filtered the scenarios by taking into account the inclusion of "net-negative emissions." In general, negative emissions are a result of carbon dioxide removal (CDR) techniques in which carbon is actively removed from the atmosphere and stored in the earth. Negative emission technologies include afforestation, bioenergy with carbon capture and storage (BECCS), and direct CO_2 air capture. While these methods make sense at the multinational scale included in the models, they bear less relevance to a single utility. While a utility could utilize one or more of these negative emissions approaches to achieve the net-zero carbon emission goal, for this analysis we do not consider a single utility transitioning from a source of CO_2 (through the process of generating electricity) to a sink of CO_2 by 2050. Thus, all scenarios that include net-negative emissions through the year 2100 were excluded. After this exclusion, we were left with three scenarios. This ensemble was supplemented by the inclusion of two non-public scenarios to arrive at five final scenarios.

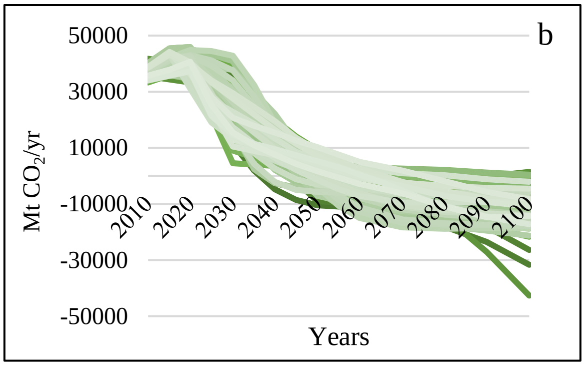
Figure 3 shows our process to get from scenarios with default selections to a final group of five scenarios discussed in this report. Figure 3a shows the 78 scenarios generated by the default assumptions of the IAMC data browser. One of these default assumptions is compliance with the requirements of the Kyoto Protocol. We removed this requirement, increasing the number of scenarios from 78 to 90 (change from Figure 3a to 3b). Then, we filtered out the scenarios that project "high overshoot" of the 1.5°C goal. These scenarios were omitted to set a more climate-protective goal, as the higher warming levels could have detrimental effects even if the climate eventually returns to 1.5°C. With this more climate-protective filter, the number of scenarios decreases from 90 to 53 (change from Figure 3b to 3c). By restricting scenarios to those which simulate the electricity sector only, the number of scenarios further decreased from 53 to 45 (change from Figure 3c to 3d; note this is not a direct subset, as not all models simulate the same group of emission sectors). By restricting scenarios to those which simulate the industrialized countries only, the number of scenarios further decreased from 45 to 35 (change from Figure 3d to 3e; note this is not a direct subset, as not all models simulate the same group of global regions). The last filter we applied was to remove assumptions about net-negative emissions. This removed scenarios that assume a net removal of CO_2 from the atmosphere, cutting the set of scenarios 35 to just 3 (change from Figure 3e to 3f; note that this does not preclude the remaining scenarios from employing one or more negative emissions technologies).

The final step of our scenario selection sought to address model simulations that were referenced in the IAMC results but not uploaded to the public database. To address this, we emailed every modeling research group whose data appeared to be absent from the IAMC database. These emails requested detailed scenario information directly from the researchers named in IAMC documentation. The only group to respond to this email request was the POLES modeling team at the Joint Research Centre in Seville, Spain, who suggested that a data transfer error may have resulted in ten scenarios missing from the database. The POLES team sent us ten scenarios, of which two met the search criteria described above. These were added to the three public scenarios, resulting in a total of five scenarios from three different models (Figure 3g). These five scenarios appear to match the ensemble in the Xcel Energy analysis by the University of Denver.

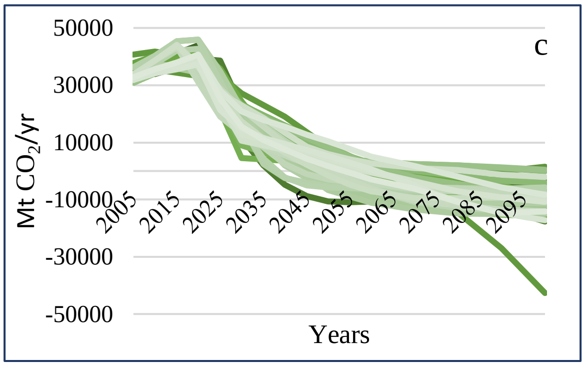
Results presented through the rest of this report draw from this final ensemble and the electricity demand and transportation sector electricity demand scenarios associated with these models.



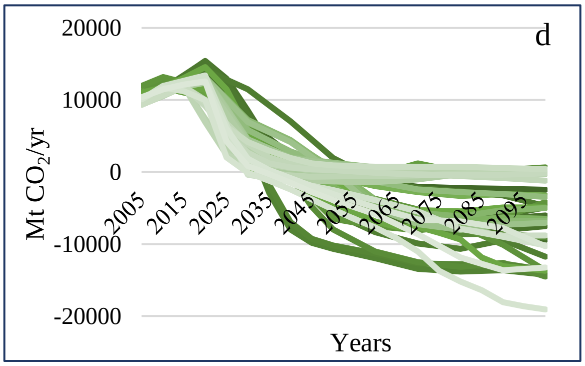
Default settings: 78 scenarios →



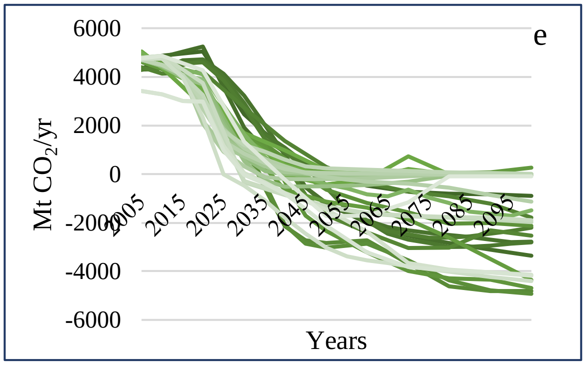
Remove Kyoto filter: 90 →



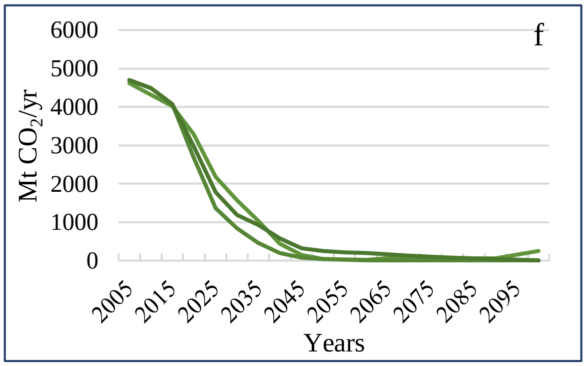
Below 1.5ºC & 1.5ºC + low OS: 53 →



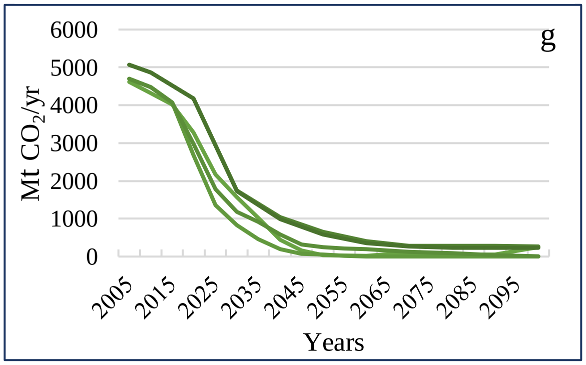
Elec. sector CO$_2$ emissions: 45 →



Industrialized countries: 35 →



No net-negative emissions: 3 →



Inclusion of POLES non-public data: 5

Figure 3: *Graphic depicting the scenario selection process.*

3. Results and Discussion

I. Carbon Emissions

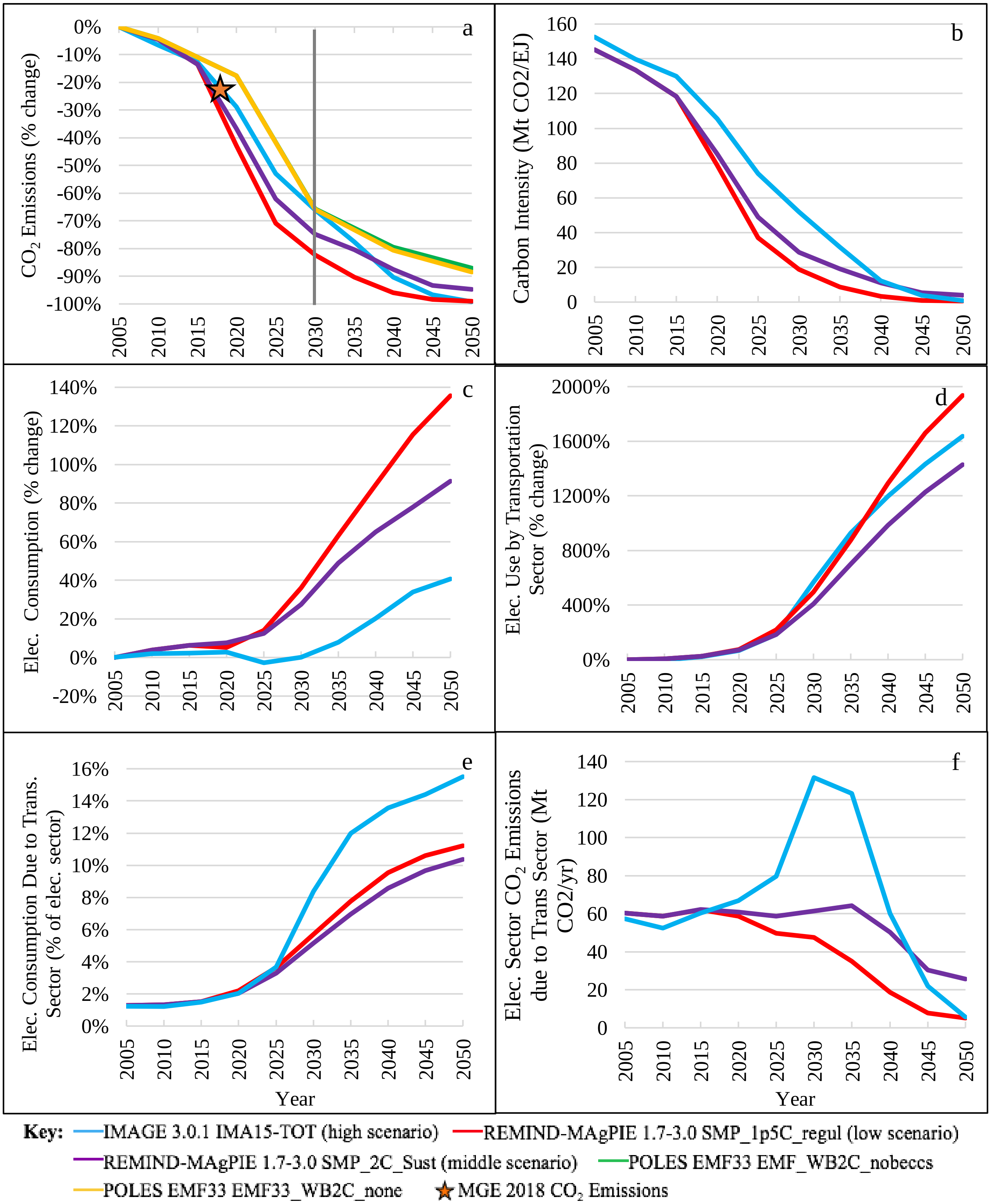
The five final scenarios meeting the MGE inclusion criteria are shown in Figure 4. The range of this ensemble is fairly narrow, and all pathways follow a similar trajectory for CO_2 emissions (Figure 4a). The percent CO_2 emissions reductions for the five scenarios through 2050 is shown in Table 2.

By 2030, all scenarios report 66%-82% emissions reductions relative to 2005, and by 2050, all scenarios have a reduction of 87%-99%.

MGE's goal of 100% net-zero carbon emissions by 2050 is in line with these scenarios, and in fact, more aggressive than any of the five. As of 2018, MGE had reduced its emissions by more than 20% compared to 2005 levels, shown as the orange star in Figure 4a, within the range of model scenarios consistent with a path toward 1.5ºC warming.

Model	Scenario	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_regul	0%	-7%	-13%	-29%	-53%	-66%	-78%	-90%	-97%	-99%
REMIND-MAgPIE 1.7-3.0	SMP_2C_Sust	0%	-5%	-13%	-43%	-71%	-82%	-90%	-96%	-98%	-99%
IMAGE 3.0.1	IMA15-TOT	0%	-5%	-13%	-37%	-62%	-75%	-80%	-88%	-93%	-95%
POLES EMF33	EMF33_WB2C_nobeccs	0%	-4%	-11%	-18%	-42%	-66%	-72%	-79%	-83%	-87%
POLES EMF33	EMF33_WB2C_none	0%	-4%	-11%	-18%	-42%	-66%	-73%	-81%	-85%	-88%

Table 2: *Percent emissions reductions for five scenarios meeting criteria using 2005 as the baseline year.*



Figures 4: *a.) CO$_2$ % emissions reductions from 5 scenarios meeting criteria; orange star represents MGE's emissions reductions as of 2018*. b.) CO$_2$ intensity. c.) % change in consumption of elec. d.) % change in consumption of elec. by the transportation sector. e.) Elec. consumption due transportation sector. f.) Elec. sector CO$_2$ emissions due to transportation elec. consumption. *Note: We did not have non-public POLES data available for additional plots/calculations – only public data used for Figures 4b-f.*

II. Carbon Intensity

Examining the change in CO_2 emissions is the first step in understanding what each pathway assumes for electricity emissions. Two factors affect these emissions: electricity consumption/demand (discussed in the following section) and the carbon intensity of electricity generation (amount of carbon released for every unit of energy produced). The carbon intensity is determined by the fuel mix used to generate electricity. Note these calculations are available for the three public IAMC scenarios only, as we did not initially request POLES data for demand and other variables beyond CO_2 emissions.

Because the IAMC scenarios include both emissions and consumption, carbon intensity may be calculated:

$$\text{Carbon Intensity } \left(\frac{Mt\ CO2}{EJ}\right) = \frac{Carbon\ Emissions\ \left(\frac{Mt\ CO2}{yr}\right)}{Electricity\ Consumption\ \left(\frac{EJ}{yr}\right)}$$

Although all scenarios assume an increase in electricity demand (Figure 4c), the overall reduction in CO_2 emissions (Figure 4a) is due to the sharp decrease in carbon intensity (Figure 4b).

By 2030, carbon intensity for the three scenarios is expected to decrease by 66%-87%; by the year 2050, the CO_2 released per unit of energy produced is expected to be near zero. These transitions would be possible with a near complete transition to non-fossil fuel sources and/or the use of negative emissions technology to offset remaining fossil fuel emissions.

As shown in Figure 4b, the IMA15-TOT scenario ("high scenario") has higher carbon intensity (until 2040) and higher CO_2 emissions (4b) compared to the other IAMC scenarios but lower demand (4c). Scenario SMP_1p5C_regul ("low scenario") has the lowest CO_2 emissions (4a) as well as the lowest carbon intensity (4b), despite the largest increase in demand (4c). Scenario SMP_2C_Sust ("middle scenario") shows trends that fall in the middle of the other two.

As shown in Tables 3 and 4, energy sources differ widely in their carbon intensity. Note that Table 3 reports end-of-stack emissions; Table 4 reports life-cycle carbon emissions based on a review of the literature [*Moomaw et al.*, 2011], which includes the energy to refine and transport fossil fuels as well as manufacturing and disposal of solar panels, wind turbines, etc. In Table 4, CO_2-eq. refers to the CO_2 warming equivalent of other GHGs like methane and nitrous oxide, which may be significant as part of the life cycle. When considering natural gas, methane leakage can be an important determinant of overall emissions, given the higher warming potential of methane compared to CO_2. Despite system leakage, natural gas is still a much lower carbon option than coal, but leakage must be monitored and accounted for in considering natural gas as a bridge fuel to zero-emitting options [*Brandt et al.*, 2014].

Coal has the highest carbon intensity, and a transition from coal to natural gas would reduce emissions reductions ~ 50%. The amount of CO_2 released by the burning of fossil fuels is largely a function of the hydrogen to carbon (H/C) ratio of the fuel. The higher the H/C ratio, the more efficient the fuel and the lower the CO_2 emissions from its combustion. Natural gas is primarily methane (H/C of 4:1) while coal is primarily carbon (H/C of 0.2-1:1); thus, more CO_2 is released and less energy is generated per unit of coal burned than natural gas [*U.S. Energy Information Administration, 2019*]. MGE's transition from coal to natural gas at Blount Generating Station in 2011 contributed to their reduced company-wide CO_2 emissions more than 20% between 2005 and 2018.

Today petroleum oil accounts for only 0.01% of the 2018 Wisconsin-wide electricity generation mix, according to data from the U.S. Energy Information Agency.

Non-emitting energy sources include nuclear, wind, solar, hydropower, geothermal energy, and ocean (wave and tidal) energy, with 0 g of CO_2/kWh generation emissions, as shown in Table 3. Even when accounting for the full life cycle of these non-emitting sources and accounting for non-CO_2 GHGs, the net impact of these energy sources is less than 5% that of coal.

Life-cycle emissions are most essential when considering bioenergy as a source of fuel. Trees and plants grow by absorbing CO_2 out of the atmosphere. Thus, before they are harvested, plants have a net-negative impact on atmospheric CO_2 levels. When wood and other bioproducts are burned, this CO_2 is released back to the atmosphere as emissions. Thus, while emissions of CO_2 from wood and other biofuels may be comparable to coal when considering direct stack emissions only [*Sterman*, 2018], in fact the net impact of biofuels on carbon is much less, depending on the type of tree or plant used, where it was grown, soil management, and other factors.

In addition to the carbon intensity of a fuel, cost and reliability are additional factors that affect the trade-offs among potential sources of electricity generation.

Cost is determined by capital investments (including power plant construction, infrastructure updates and financing plans) and operational costs (fuel, labor, and other operational costs). An "apples to apples" comparison of generation costs would require a wide range of assumptions and analysis beyond the scope of this report [*U.S. Energy Information Administration*, 2019].

Reliability characterizes the capability of electricity generation to meet consumer demand. The availabilities of wind and solar, in particular, are currently determined by weather conditions: wind power is available when the wind is blowing; solar power is available when the sun is shining. This variability could potentially be balanced by large-scale energy storage solutions in coming years, offering the potential for larger-scale utilization of renewable energy generation [*Anderson*, 2019].

Technology	**Direct CO_2 Emissions g CO_2 /kWh**
Coal	979
Natural Gas	431
Oil	783-1381
Nuclear Energy	0
Wind Energy	0
Solar Photovoltaic	0
Concentrated Solar Power	0
Bio-power	89-1000
Hydropower	0
Geothermal	0
Ocean Energy	0

Table 3: *"End of pipe" electricity generation-related CO_2 emissions from electricity generation by fuel. Fossil fuel emissions calculated for Wisconsin 2018 based on data and methods from the U.S. EIA (https://www.eia.gov/tools/faqs/faq.php?id=74&t=11); Oil represents ~0.1% of the 2018 Wisconsin generation mix – lower bound reflects 20% less CO_2 than coal on a per-kWh basis (see Figure 6 in Congressional Research Service report: https://fas.org/sgp/crs/misc/R45453.pdf); upper bound calculated from EIA data; Bio-power represents ~0.3% of the 2018 Wisconsin generation mix – lower bound reflects values calculated assuming Wisconsin 2018 U.S. EIA data for wood, wood-derived fuels, and other biomass used for electricity generation is responsible for all non-fossil CO_2 emissions from electricity generation in Wisconsin 2018 U.S. EIA data; upper bound based on comparison of direct wood vs. coal emissions in Sterman [2018].*

Technology	Median Lifetime GHG Emissions g CO_2 eq./kWh (min, max)
Coal	1001 (675, 1689)
Natural Gas	469 (290, 930)
Oil	840 (510, 1170)
Nuclear Energy	16 (1, 220)
Wind Energy	12 (2, 81)
Solar Photovoltaic	46 (5, 217)
Concentrated Solar Power	22 (7, 89)
Bio-power	18 (-633, 75)
Hydropower	4 (0, 43)
Geothermal	45 (6, 79)
Ocean Energy	8 (2, 23)

Table 4: *Aggregated results from literature review of Life Cycle Assessments (LCAs) of GHG emissions from electricity generation technologies [Moomaw et al., 2011].*

III. Electricity Demand

Although all IAMC scenarios show a decrease in carbon emissions (Figure 4a), all show an increase in electricity consumption (Figure 4c). However, this increase is offset by even greater reductions in carbon intensity to achieve a given CO_2 emissions goal.

The IAMC database variable representing production includes “final energy consumption of electricity (including on-site solar PV), excluding transmission/distribution losses (EJ/yr).” (Selected in the Scenario Explorer as Final Energy → Electricity.)

Electricity consumption tends to increase with increasing population, residential space, household income, and electrification of the transportation sector, while decreasing with increased energy efficiency and energy conservation. The connection between economic growth, electricity consumption, and CO_2 was evident from 2007 and 2009 during the recession, when U.S. CO_2 emissions declined by 9.9% [*Feng et al.*, 2015].

We expect many of these factors may impact MGE’s specific pathways for CO_2 emissions reductions. Between 2010 and 2018, the population of Madison increased 10.7% [*U.S. Census Bureau, 2018*], making it the fastest growing municipality in Wisconsin. The median household income in Madison increased from $50,508 to $64,101 between 2010 and 2018 [*American Community Survey, US Census Bureau, 2018]*, an increase of 26.9%. Higher household income is typically associated with larger home sizes and increased electricity use, although in Madison, population density has been increasing since 2009[2], suggesting a decrease in average home size. Whether home size is increasing or decreasing, energy-efficient appliances, windows, and building design can reduce residential electricity consumption, noting that the full impact of efficiency changes may be moderated by the “rebound effect” where more energy-efficient appliances and houses can increase usage [*Chitnis et al.*, 2013; *Yalcintas and Kaya*, 2017].

Factors Affecting Electricity Demand
Residential home size → expected to **increase** electricity demand
Population → expected to **increase** demand
Household income → Expected to **increase** demand (indirectly)
Efficiency of buildings, houses, appliances → Expected to **decrease** demand (*increase possible if rebound effect)*
Electrification → Expected to **increase** demand
Economic growth → Expected to **increase** demand

Table 5: *Factors that can affect electricity demand.*

Characterizing electricity consumption is complicated by trends to electrify transportation and home heating/cooking. Historically, electricity demand, transportation fuel use, and residential fuel use have been treated as separate sectors of the energy economy. However, there is a growing interest in the potential to increase the role of electricity in U.S. energy systems to leverage the wider range of generation sources available for electricity (especially wind, solar, and nuclear). We discuss the electrification of the transportation sector below and note that similar issues arise with the potential transition of residential fuel use for heating and cooking from natural gas to electricity.

Although increasing electricity consumption increases total carbon emissions, it is possible that an increase in demand can facilitate the transition to a low-carbon-intensity generation mix. New facilities built to meet new demand should move MGE toward low-carbon-intensity generation. In the three IAMC scenarios shown in Figure 4c, consumption increases range from 40% to 140%, where carbon emissions decrease 87% to 99% by 2050 due to large-scale reductions in carbon intensity. These results suggest that aggressive reductions in the carbon intensity of the total generation mix will be required, even over a fairly wide range of assumptions about future consumption.

IV. Electrification of the Transportation Sector

Electrification of the transportation sector is also expected to increase electricity demand. A 2016 study by the International Council on Clean Transportation found Madison, Wisconsin, to be one of the cities in the Midwest with the highest EV market shares. Although the Midwest’s uptake of EVs in general was 61% below the U.S. average [*Kwan et al.*, 2016], annual EV sales in Wisconsin

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[2] https://www.opendatanetwork.com/entity/1600000US5548000/Madison_WI/geographic.population.density?year=2018

have increased from 93 in 2011 to 1,956 in 2018, when taking into account both battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs) (run on either or both gas and electric fuel)[3]. BEVs alone increased from two sales in 2011 to 1,168 in 2018. This increase is qualitatively consistent with the increase in percent electricity consumption by the transportation sector seen in Figure 4d.

In the scenarios modeled by the IAMC, transportation electricity will increase by a factor of 15-20 by 2050 (Figure 4d). Projected electricity consumption of the transportation sector is defined as "final energy consumption by the transportation sector of electricity (including on-site solar PV), excluding transmission/distribution losses (EJ/yr)."

We compare this with total consumption (Figure 4c) to calculate how modeled scenarios project the contribution of vehicle electrification to total consumption. The percent electricity consumption due to the transportation sector (Figure 4e) may be calculated as:

$$\text{\% Elec. Consumption Due to Transportation Sector} = \frac{Elec.Consumption\ by\ Transportation\ Sector\ \left(\frac{EJ}{yr}\right)}{Overall\ Elec.Consumption\ \left(\frac{EJ}{yr}\right)}$$

These results suggest that transportation will account for 10%-16% of total consumption by 2050 (Figure 4e). While total electricity consumption is growing, the electricity consumption by the transportation sector is growing even faster. All IAMC models assume that, over time, EVs will constitute a larger part of consumption in the electricity sector.

We also calculated how increased vehicle electrification will contribute to the electricity sector's total CO_2 emissions. Using carbon intensity and electricity consumption of the transportation sector, we calculate transportation CO_2 emissions as follows:

$$CO_2\text{ Emissions } \left(\frac{Mt\ CO2}{yr}\right) = Elec.\ Consumption\ by\ Transportation\ Sector\left(\frac{EJ}{yr}\right)\ x\ CI\ \left(\frac{Mt\ CO2}{EJ}\right)$$

As shown in Figure 4f, the trends for the electricity sector CO_2 emissions as a result of the transportation sector are somewhat varied. Despite the increase in transportation demand, two scenarios show a consistent decrease in transportation CO_2 emissions due to the assumed decline in carbon intensity. The high scenario shows a large spike in emissions from 2020 until 2030, with a steep decline occurring from 2030 until 2040, possibly due to the rate of electrification of the transportation sector compared to the rate of the electricity sector transition to non-emitting energy sources and other factors affecting carbon intensity.

We focus here on the role of transportation in electricity-sector emissions, but the net impact of vehicle electrification depends on displaced emissions from internal combustion engines. The evaluation of total change in CO_2 (and other emissions) depends on the emission characteristics of vehicles replaced by EVs.

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[3] https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/

4. Conclusion

Electricity production differs dramatically across the U.S. and around the world. The IAMC provides results for seven global regions in aggregate, where we focus on the region defined as the industrialized countries of the OECD grouped together with the EU which includes the U.S. These large-scale results offer qualitative insight on pathways consistent with a 1.5^{o}C warming goal, but care should be taken in mapping these paths onto a specific company or region.

Beyond the lack of geographic specificity in the IAMC results, the modeling framework is designed for national-scale decision-making rather than a single utility. For example, while 35 available scenarios offer information on industrial countries with a 1.5^{o}C goal, over 90% of these scenarios assume "net-negative emissions" at some point over the next 100 years. In other words, the scenarios consider the "what if" possibility that regions will take more carbon out of the air than they put into it. Today, there are a few – but limited – options for advancing negative emissions. Broadly, these include 1) planting trees (trees remove CO_2 from the atmosphere as they grow, at which point it becomes the wood, roots, etc.); 2) burning biomass for electricity and then capturing the carbon emissions and storing underground (plants remove CO_2 from the atmosphere as they grow, which would normally be released to the atmosphere when they burn; new technologies have been developed that could capture and bury the waste gas); and 3) emerging technology that could suck CO_2 out of the air, somewhat like a vacuum cleaner. Of these, CO_2 removal by trees is by far the most common and cost-effective, but the other technologies may become more viable in the future.

It is reasonable to consider nations designing policies to promote reforestation and afforestation, to promote investments in carbon sequestration, and/or to innovate on carbon removal technologies. For a single utility, however, such initiatives would require a massive change in the business model of electricity production. For this reason, we did not consider any scenarios with a net-negative carbon emission requirement (an assumption consistent with the IAMC analysis supporting Xcel Energy).

With these limitations, there were three publicly available IAMC scenarios to consider. Two additional scenarios were shared by a modeling team whose data were missing from the database. All five showed a steep decline in electricity CO_2 emissions by 2050, with reductions of 87%-99% relative to 2005. Relative to these scenarios, **MGE's goal is more aggressive than any of the modeled pathways for the electricity sector in industrialized countries**.

Our further analysis of the three IAMC scenarios shows that all assumed significant increases in overall electricity consumption as well as increases in vehicle electrification of 15-20 fold. **To reduce overall carbon emissions in the face of increasing demand requires steep reductions in the carbon intensity of the electricity generation mix**. Carbon intensity is determined by the fuel mix used by MGE to create electricity, with coal having the highest carbon intensity of any electricity source and nuclear and renewables having the lowest carbon intensity. Carbon intensity may be calculated on a life-cycle basis (considering production, distribution, etc.) or at the point of combustion (e.g., in the power plant). The former approach is most common in the climate research and policy community; the latter is consistent with the control of pollutants regulated under the Clean Air Act.

Because the IAMC scenarios aggregate multiple countries, we considered the degree to which model assumptions qualitatively align with trends in Madison, Wisconsin. In Madison, factors including increasing population, increasing average household income, and increasing EV adoption point toward an expected increase in electricity consumption. Consistent with the qualitative patterns expected for Madison, the IAMC scenarios show electricity consumption going up, even as total carbon emissions go down. MGE's ultimate pathway toward its goal will depend on many factors, including electricity demand (including from EVs), energy efficiency measures, and the transitioning of the generation mix.

By 2050, the carbon intensity of MGE electricity generation will need to decrease to near zero. Although increasing electricity demand increases total carbon emissions, it is possible that an increase in demand can facilitate the transition to a low-carbon-intensity generation mix. Consistent with MGE's net-zero carbon by 2050 goal, new facilities built to meet new demand should move MGE toward low-carbon-intensity generation.

Beyond the emission reductions planned by MGE, sectors beyond electricity will be critical to carbon reductions in Madison. Transportation has been estimated to contribute over 40% of CO_2 emissions in Madison[4], with additional emissions from agriculture and industry. To maximize the benefit of MGE's net-zero-carbon plan will require either complementary reductions in other sectors and/or the adoption of "beneficial electrification" efforts whereby direct fossil fuel combustion (e.g., cars and trucks) is replaced by electricity from non-emitting sources. Reducing carbon emissions in Madison depends on a wide range of factors specific to our community. Examining these factors would be a valuable direction for future research to support decision-making and link with developments in climate and energy science.

In particular, we highlight the potential value of research into the impact of low-carbon electricity, transportation electrification, and/or other fuel transitions to public health and environment beyond climate change. Because CO_2 has an atmospheric lifetime of over 100 years, climate benefits of carbon reductions at MGE would extend far beyond Wisconsin and far into the future.

However, many studies have shown that low-carbon energy transitions yield immediate, local impacts to public health and air quality [*Nemet et al.*, 2010]. Whether electricity, transportation, or other emission sector, nearly any energy transition that reduces carbon emissions also reduces emissions of NO_x and SO_2 and the formation of atmospheric ozone and particulates [e.g. *West et al.*, 2013; *Plachinski et al.*, 2014; *Thompson et al.*, 2014; *Abel et al.*, 2018]. Similarly, vehicle electrification and other transitions to reduce on-road fuel combustion have been shown to increase public health through reduced mortality, reduced asthma attacks, and other benefits [e.g., *Bickford et al.*, 2014; *Nichols et al.*, 2015; *Li et al.*, 2016]. Understanding the short-term, localized benefits of energy transitions to public health could inform decision-making and prioritization of energy investments.

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[4] https://energy.wisc.edu/news/uw-madison-students-help-city-cut-carbon-emissions

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