Minnesota Decarbonization Scenarios

The Role of the Electric Sector

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Prepared for Xcel Energy

By Energy and Environmental Economics, Inc.

Tory Clark

Dan Aas

Sharad Bharadwaj

Amber Mahone

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1 Background

The Next Generation Energy Act (NGEA), signed in 2007, sets greenhouse gas (GHG) emission targets for Minnesota of 80% reductions by 2050 relative to 2005 levels with interim targets of 15% reductions by 2015 and 30% reductions by 2025.

Xcel Energy Northern States Power (NSP) hired E3 to develop a set of long-term economy-wide, deep decarbonization scenarios for the state of Minnesota. These scenarios provide an exploration of the cross-sectoral implications of meeting economy-wide carbon reduction goals, and highlight the role of Xcel Energy, and the electric sector as a whole, in meeting the state's economy-wide carbon goal.

This report describes background, modeling approach, and results of the Minnesota economy-wide decarbonization scenario analysis. An additional E3 analysis focusing on Xcel Energy NSP system portfolio and reliability, is discussed in a separate report. The geography of each analysis is shown in Figure 1.

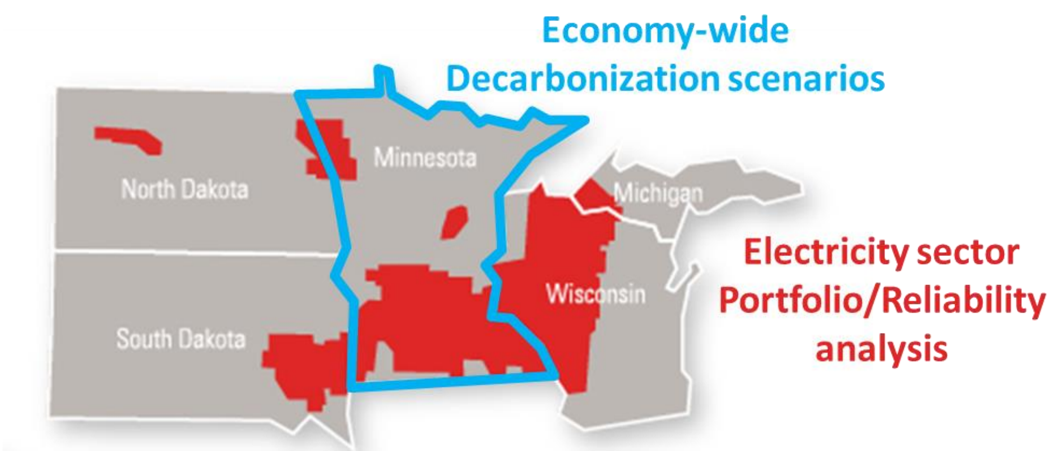

Figure 1. E3 Analysis Geographies for (1) Minnesota economy-wide decarbonization scenarios, and (2) Xcel Energy NSP portfolio and reliability analysis

Figure 2 shows all GHG emissions in the state of Minnesota by sector and subsector.[1] The largest sources of emissions in the state are electricity generation and transportation.[2] This analysis focused on the sectors that are most relevant to an electric utility: electricity generation, transportation, and buildings. Emissions from other sectors (agriculture, industry, and waste) were represented at a high level.

[1] Data pulled from MPCA 2014 GHG Inventory

[2] This work was based on the Minnesota Pollution Control Agency (MPCA) 2014 greenhouse gas inventory. At the time of this report, the MPCA has released updated inventory data through 2016 and transportation is now the largest emitter of GHGs in the state.

Figure 2. Minnesota GHG emissions by category in 2014

2 Approach

2.1 PATHWAYS Model Philosophy

This study used a PATHWAYS model to develop the reference case emission projection. The PATHWAYS model is an economy-wide representation of infrastructure, energy use, and emissions within a specific jurisdiction. The PATHWAYS model represents bottom-up and user-defined emissions accounting scenarios to test “what if” questions around future energy and climate policies. PATHWAYS modeling typically includes the following features:

- Detailed stock rollover in residential, commercial and transportation subsectors
- Interactive effects with electricity demand and electricity supply sectors
- Sustainable biomass feedstock supply curves
- Non-combustion and non-energy emissions

The inclusion of both supply and demand sectors captures interactions between sectors such as increased penetration of electric vehicles and a changing mix of technologies supplying electricity. The focus of the Pathways model is to compare user-defined policy and market adoption scenarios and to track physical accounting of energy flows within all sectors of the economy.

2.2 PATHWAYS in LEAP

E3 built a bottom-up PATHWAYS model of the Minnesota economy using the LEAP tool (Long-range Energy Alternatives Planning system)[3]. This model quantifies the energy and emissions associated with the projected trends in energy use and complementary policies targeting future mitigated emissions. We modeled the period of 2015-2050.

LEAP is an integrated, scenario-based modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector greenhouse gas (GHG) emission sources and sinks. LEAP is not a model of a specific energy system, but rather a modeling framework that can be adapted for different jurisdictions.

E3 built a model of Minnesota’s energy and non-energy emission sources, projecting them through 2050 using different scenarios to understand current trajectories and different pathways that can be reached through complementary policies within the state.

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[3] LEAP is developed by the Stockholm Environment Institute. More information on the LEAP software can be found at www.energycommunity.org

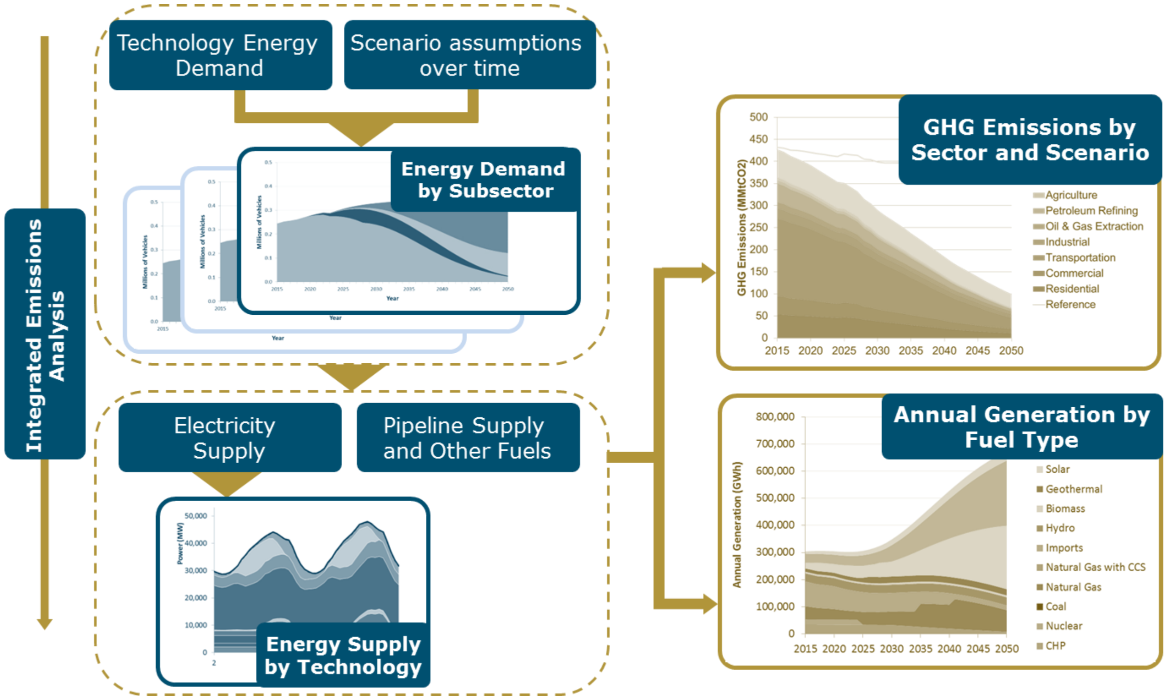

Figure 3. PATHWAYS Energy Modeling Framework

2.3 Scenarios

E3 modeled three scenarios to evaluate a range of emissions reductions from complementary policies.

- **Reference Scenario**: a current policy scenario, including utility-driven energy efficiency, expected adoption of zero emission vehicles, federal fuel economy standards for light-duty vehicles (LDVs)
- **High Electrification Scenario:** a mitigation scenario that includes increased adoption of electric and hydrogen vehicles in medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs) as well as electric space heating and water heating appliances in buildings.
- **High Biofuels Scenario:** a mitigation scenario that includes lower levels of electrification in favor of higher shares of low-carbon biofuels.

Table 1. Key Assumptions in all scenarios[4]

	Reference Scenario	High Electrification Scenario	High Biofuels Scenario
Carbon-free electricity generation	48% by 2025, held constant through 2050	48% by 2025, 90% by 2050	
Nuclear power	Retires at end of license	Relicensed or replaced with other carbon-free generation	
Building energy efficiency	50% of appliance sales are high-efficiency by 2030	100% of appliance sales are high-efficiency by 2030 100% adoption of efficient building shell/weatherization measures by 2030 15% reduction in non-stock energy below Reference Scenario by 2030, 30% by 2050 5% reduction in key demands due to smart appliances and conservation by 2030	
Sales of electric heat pump equipment	None	50% by 2030, 100% by 2050, replacing electric, natural gas and LPG	20-30% sales by 2030, replacing only electric and LPG equipment
Zero-emission vehicles	10% of sales by 2030 (Xcel "likely" sales forecast) for LDVs	LDVs: 50% by 2030, 100% by 2050 MDVs: 50% by 2030, 100% by 2050 HDVs: 40% by 2030, 100% by 2050	LDVs: 50% by 2030, 100% by 2050 MDVs: 50% by 2030, 80% by 2050 HDVs: 20% by 2030, 50% by 2050
Vehicle fuel economy	Federal CAFE standards for LDVs by 2026		
Conventional biofuels	20% biodiesel blend in diesel by 2018 (MN239.77); 30% ethanol blend in gasoline by 2025 (MN239.7911)	Transition to advanced biofuels by 2050	
Advanced Biofuels	None	Advanced biofuels without purpose-grown biomass feedstocks	Advanced biofuels with purpose-grown biomass feedstocks
Other sectors (agriculture, waste, industry)	Energy consumption grows at AEO 2017 reference scenario rates by fuel; non-energy GHG emissions held constant at MPCA 2014 Inventory levels	Reduction of 64% below 2005 GHG Emissions by 2050	Reduction of 69% below 2005 GHG Emissions by 2050

[4] More detailed assumptions are included in the sections that follow

In addition to mitigation scenarios, we developed three sensitivities to test the impact on emissions of federal action and consumer adoption. The three sensitivities were defined as follows and are documented further in Section 3.2.4:

1. **Efficiency, Electrification, and Clean Electricity Only**: Evaluates the impact of only pursuing building efficiency, high adoption of electric vehicles and household devices, and clean electricity towards meeting GHG targets
2. **No CAFE Extension**: Evaluates the impact of EPA's proposal to freeze federal Corporate Average Fuel Economy (CAFE) standards at 2020 levels.
3. **Lower Electric Adoption**: Evaluates the combined impact of lower consumer adoption of electric vehicles and electric household devices.

2.4 Inputs

To populate the Minnesota PATHWAYS model, we focused on in-state data sources where possible, supplementing with national data sets to fill remaining data gaps. Specific inputs are listed below.

2.4.1 FIRST YEAR EMISSIONS BENCHMARKING

In 2014, Minnesota had a population of 5.45 Million people residing in 2.1 Million households.[5] In each sector of the economy, we create a representation of a base year (2014) of infrastructure and energy, and then identify key variables that drive activity change over the duration of each scenario (2015-2050). Table 2 shows emissions benchmarking from the MN PATHWAYS model created for this analysis and the Pollution Control Agency (PCA) 2014 GHG Inventory.

[5] Source: Minnesota State Demographic Center

Table 2. Emissions Benchmarking in Minnesota PATHWAYS model to Minnesota PCA GHG inventory in 2014. MST = million short tons.

Sector	MPCA 2014 [MST CO2e]	PATHWAYS 2014 [MST CO2e]	Difference [MST CO2e]	Difference [%]
Buildings	19.0	19.0	0.0	0%
Transportation	39.1	39.2	0.1	0%
Electricity Generation	46.7	46.6	0.0	0%
Other	53.4	53.4	0.0	0%
Total	**158.2**	**158.2**	**0.0**	**0%**

2.4.2 KEY DRIVERS AND DEMOGRAPHICS

Each sector includes assumptions about key drivers of activity within that sector. Table 3 identifies the key drivers behind each sector's energy consumption in the reference scenario. Additional detail is available in the sections that follow.

Table 3. Key Drivers by PATHWAYS Sector in the Reference Scenario

Sector	**Key Driver**	**Compound annual growth rate [%]**	**Data Source**
Buildings	Population	0.44%	MN State Demography Center
Industry	Energy growth	Varies by fuel	EIA AEO 2018 growth rates (2018-2050)
On Road Transportation	Vehicle-miles traveled (VMT)	0.5% LDV 1.3% MDV 1.2% HDV	EIA AEO 2018
Off Road Transportation	Energy growth	Varies by fuel	EIA AEO 2018 growth rates (2018-2050)
Electricity Generation	Electric load growth	-0.1% average 2015-2030 (0.2% 2015-2050)	Built up from Pathways demands in Buildings, Industry, Transportation

The sections that follow will detail scenario assumptions for each key sector in the Minnesota PATHWAYS model.

2.4.3 BUILDINGS SECTOR

2.4.3.1 Base Year

The Minnesota LEAP model includes a stock-rollover representation of 17 residential and 10 commercial building subsectors, including space heating, water heating, and lighting. Sectoral energy demand is benchmarked to energy consumption by fuel from the Minnesota GHG inventory for 2014 and is disaggregated by subsector based on the EIA National Energy Modeling System (NEMS) technology characterization. All residential and commercial subsectors are listed in Table 4.

Table 4. Representation of 2014 Building Energy Consumption by Subsector in Minnesota

Sector	Subsector	Modeling Approach	Energy Use in 2014 [Tbtu]	Percent of 2014 Energy Use [%]
Residential	Central Air Conditioning	Stock Rollover	3.2	1%
	Room Air Conditioning	Stock Rollover	0.2	0%
	Building Shell	Stock Rollover	-	0%
	Clothes drying	Stock Rollover	4.7	1%
	Clothes washing	Stock Rollover	0.7	0%
	Cooking	Stock Rollover	5.7	1%
	Dishwashing	Stock Rollover	1.9	0%
	Freezing	Stock Rollover	1.7	0%
	Reflector Lighting	Stock Rollover	0.8	0%
	General Service Lighting	Stock Rollover	3.7	1%
	Exterior Lighting	Stock Rollover	0.6	0%
	Linear fluorescent lighting	Stock Rollover	0.6	0%
	Single Family Space Heating	Stock Rollover	103.6	23%
	Multi Family Space Heating	Stock Rollover	16.3	4%
	Refrigeration	Stock Rollover	7.7	2%
	Water heating	Stock Rollover	43.2	10%
	Residential Other*	Total Energy by Fuel	59.2	13%
Commercial	Air conditioning	Stock Rollover	1.9	0%
	Cooking	Stock Rollover	15.9	4%
	General service lighting	Stock Rollover	7.0	2%
	High intensity discharge lighting	Stock Rollover	7.5	2%
	Linear fluorescent lighting	Stock Rollover	7.6	2%
	Refrigeration	Stock Rollover	3.5	1%
	Space heating	Stock Rollover	66.5	15%
	Ventilation	Stock Rollover	9.5	2%
	Water Heating	Stock Rollover	7.5	2%
	Commercial Other*	Total Energy by Fuel	64.2	14%
All Building Sectors			**444.7**	**100%**

*Residential Other includes furnace fans, plug loads (e.g. computers, phones, speakers, printers), secondary heating, fireplaces, and outdoor grills. Commercial Other includes plug loads, office equipment, fireplaces, and outdoor grills.

2.4.3.2 Reference Scenario

The primary reference measure represented in buildings is the achievement of electric energy efficiency. Energy efficiency in buildings is implemented in the PATHWAYS model in one of three ways:

1. As new appliance or lighting end use technology used in the residential and commercial sectors (e.g., a greater share of high efficiency appliances is assumed to be purchased). New equipment is typically assumed to replace existing equipment “on burn-out”, e.g., at the end of the useful lifetime of existing equipment.

2. As a reduction in energy services demand, due to smart devices (e.g. programmable thermostats), conservation, or behavior change.

3. For the sectors that are not modeled using specific technology stocks (Residential Other and Commercial Other), energy efficiency is modeled as a reduction in total energy demand.

Table 5. Reference Scenario Assumptions for Building Energy Efficiency

Category of Building Measures	Reference Scenario Assumption
Building retrofits for high efficiency building shells	None
New appliance sales	50% of new sales of all appliances are assumed to be efficient (e.g. EnergyStar) by 2030. See Figure 4.
Building electrification	None
Behavioral conservation and smart devices	None
Other non-stock sectors	None

Since the model is based on a bottom-up forecast of technology stock changes in the residential and commercial sectors, the model does not use a single load forecast or energy efficiency savings forecast as a model input. It is important to note that the modeling assumptions used in this analysis may not reflect specific future energy efficiency programs or activities.

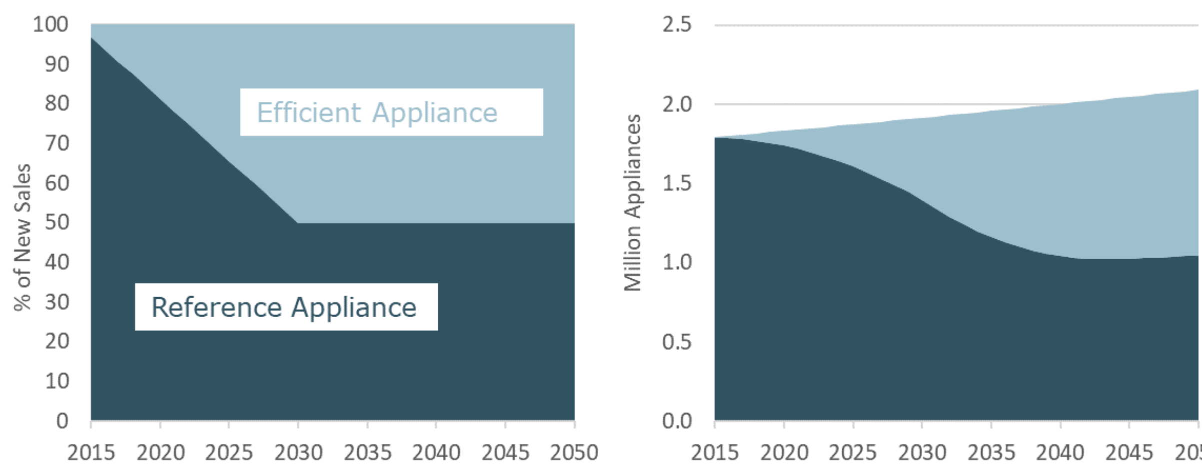

Figure 4. Assumed New Sales for Building Appliances (left) and Resulting Appliance Stocks (right), Reference Scenario

2.4.3.3 Mitigation Scenarios

Each Mitigation Scenario includes more aggressive energy efficiency and electrification in buildings. The High Electrification Scenario assumes more ambitious adoption of electric heat pumps for space heating and water heating, while the High Biofuels Scenario assumes electric heat pumps displace only existing electric and LPG equipment. See Table 6 for a full list of assumptions.

Table 6. Mitigation Scenario Assumptions for Building Energy Efficiency

Category of Building Measures	High Electrification Scenario	High Biofuels Scenario
Building retrofits for high efficiency building shells	100% adoption of efficient building shell and weatherization measures by 2030	
New appliance sales	100% of new sales of all appliances are assumed to be efficient (e.g. EnergyStar) by 2030.	
Building electrification	50% sales of electric heat pumps by 2030, 95% by 2050, replacing electric, natural gas and LPG systems	20-30% sales of electric heat pumps by 2030, replacing only electric and LPG equipment
Behavioral conservation and smart devices	10% reduction in energy services demand below Reference Scenario in residential lighting, space heating, and water heating	
Other non-stock sectors	30% reduction in energy consumption below Reference Scenario by 2050	

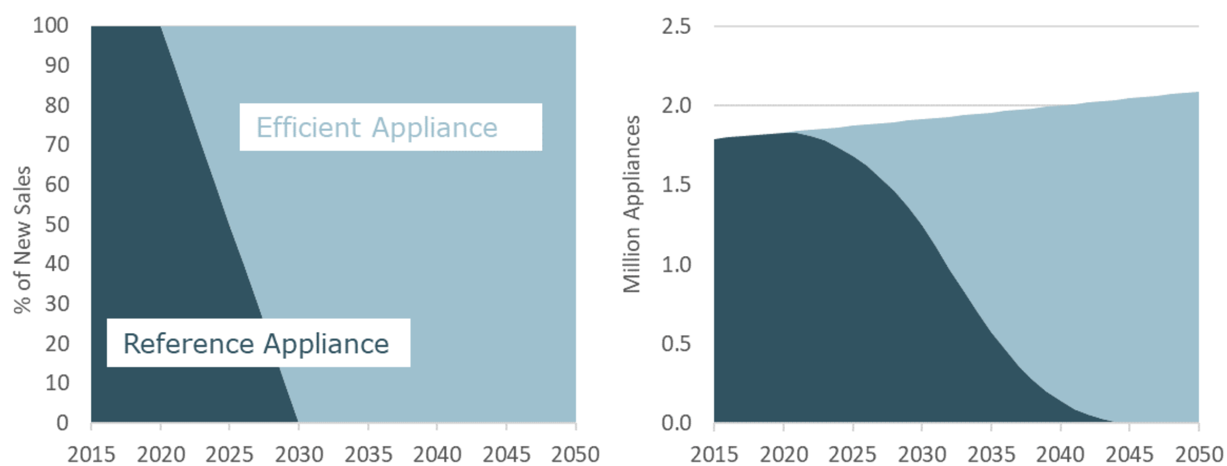

Figure 5. Assumed New Sales for Building Appliances (left) and Resulting Appliance Stocks (right), High Electrification Scenario

A key assumption across our scenarios is the adoption of high efficiency electric heat pumps for space heating and water heating. Currently in Minnesota electric heat pumps make up less than one percent of space heaters and water heaters.

In the High Biofuels Scenario we assume a shift to heat pump space heaters (20-30% of new sales by 2030), displacing sales of existing electric and LPG equipment. In the High Electrification Scenario, we assume significant adoption of heat pumps for both space heating and water heating, reducing sales of natural gas, existing electric, and LPG systems. The total number of electric heat pump space heaters in Minnesota residences is reported in Figure 6.

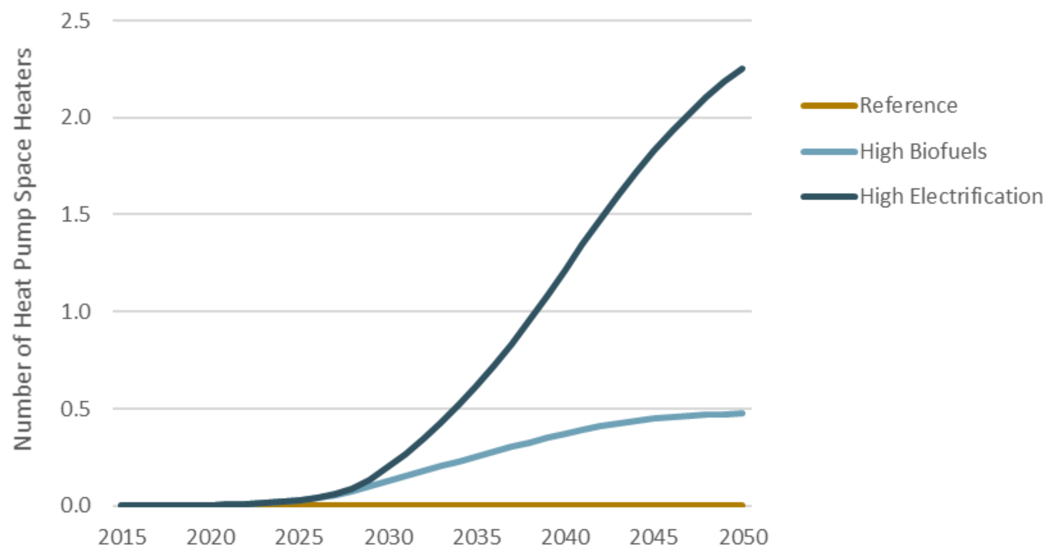

Figure 6. Total number of residential electric heat pump space heaters in all scenarios.

2.4.4 TRANSPORTATION SECTOR

2.4.4.1 Base Year

The Minnesota LEAP model includes a stock-rollover representation of four transportation sectors and an energy representation of six subsectors. Sectoral energy demand is benchmarked to energy consumption by fuel from the Minnesota GHG inventory for 2014 and is disaggregated by subsector based on the EIA National Energy Modeling System (NEMS) technology characterization and additional data from PCA. All subsectors represented in the transportation sector are listed in Table 7.

Table 7. Transportation 2014 Subsector Energy Consumption in Minnesota

Sector	Subsector	Modeling Approach	Estimated Energy Use in 2014 [TBtu]	Estimated % of 2014 Energy Use [%]
Light Duty Vehicles	Light Duty Autos	Stock Rollover	128	26%
	Light Duty Trucks	Stock Rollover	148	30%
Medium Duty Vehicles	Medium Duty Trucks	Stock Rollover	71	14%
Heavy Duty Vehicles	Heavy Duty Trucks	Stock Rollover	74	15%
Transportation Other	Aviation	Total Energy by Fuel	46	9%
	Rail	Total Energy by Fuel	15	3%
	Motorcycles	Total Energy by Fuel	3	1%
	Bus	Total Energy by Fuel	4	1%
	Military and Off-Highway	Total Energy by Fuel	7	1%
	Marine	Total Energy by Fuel	4	1%
All Transportation Sectors			**501**	**100%**

2.4.4.2 Reference Scenario

Two key measures were represented in the Minnesota PATHWAYS Reference Scenario: (1) Federal Light Duty Vehicle (LDV) Corporate Average Fuel Economy (CAFE) Standards, and (2) expected sales of zero-emission vehicles (ZEVs) in Minnesota. LDV CAFE Standards are represented in the marginal fuel economy of new gasoline vehicles sold in addition to an increased share of ZEVs sold. Increasing marginal fuel economy assumed is shown in Figure 7 for light-duty automobiles (LDA) and light-duty trucks (LDT).

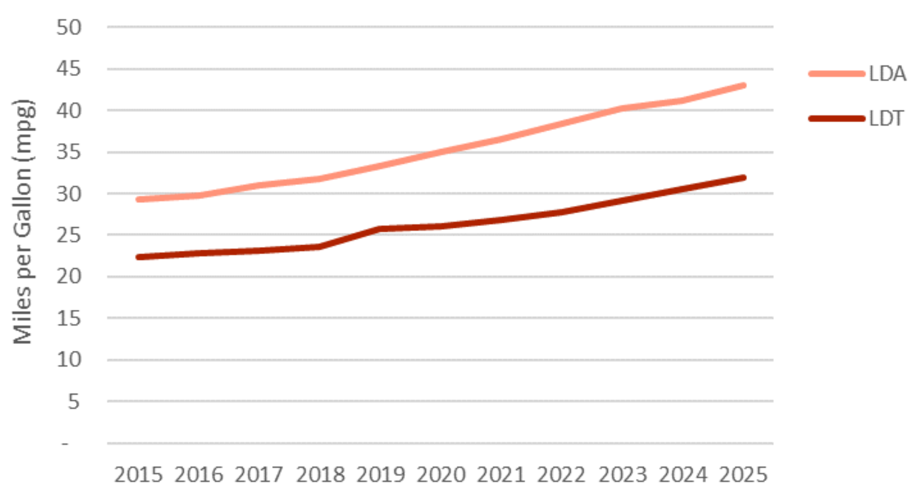

Figure 7. Marginal Fuel Economy for Gasoline LDVs in Minnesota

The second key measure, expected ZEVs in Minnesota, is represented through increasing sales of plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs) over time. We used Xcel Energy's "likely" sales of BEVs for their service territory and assumed that for the state of Minnesota. We assume that new sales increase linearly to be 20% ZEV sales by 2020. In our stock rollover methodology, this means that of all the cars that are purchased in 2020 (either due to retirement or new growth), 15% will be battery electric vehicles and 5% will be plug-in hybrid electric vehicles. This assumption is shown for light duty autos (LDAs) and light duty trucks (LDTs) in Figure 8. No changes were assumed in the heavy-duty fleet.

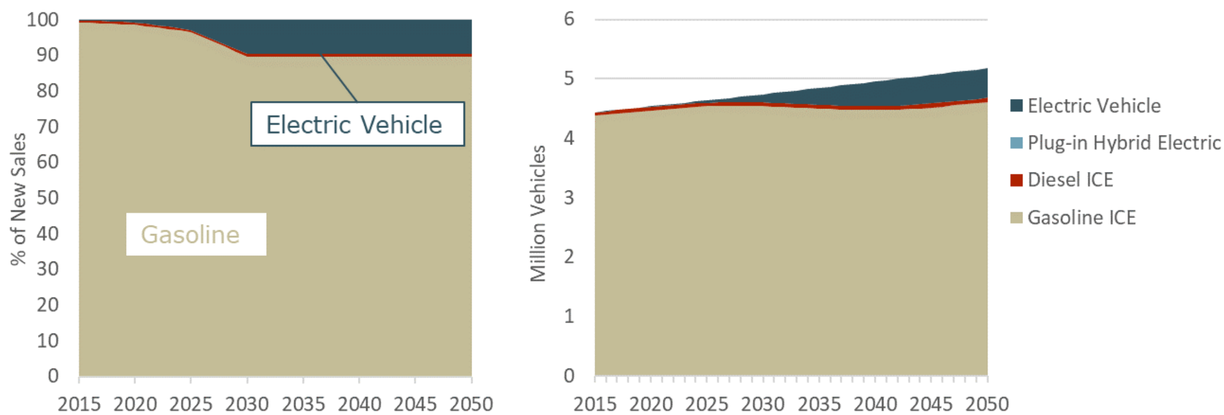

Figure 8. Assumed new light duty vehicle sales (left) and resulting stocks (right), Reference Scenario

In other subsectors of transportation, total energy consumption in Table 7 was assumed to grow at EIA AEO 2018 growth rates by fuel.

2.4.4.3 Mitigation Scenarios

Both Mitigation Scenarios assume significant reductions in light-duty vehicle-miles traveled (VMT), which could be achieved through urban design, transportation demand management, or mode shifting. Both scenarios assume aggressive electrification in light duty vehicles, up to 100% of new sales in 2050, representing no internal combustion vehicles being sold after that year. The High Electrification Scenario includes more aggressive zero-emission vehicle sales in medium- and heavy-duty vehicles, reaching 100% of new sales by 2050. The High Biofuels Scenario includes lower adoption of ZEVs in medium- and heavy-duty vehicles, where biofuels are assumed to be blended into transportation fuels.

Table 8. Mitigation Scenario Assumptions for Transportation

Category of Transportation Measures	High Electrification Scenario	High Biofuels Scenario
Vehicle Miles Traveled (VMT) reductions in light duty vehicles	Annual VMT is reduced by 15% below Reference by 2050	
Zero-emission Light Duty Vehicle (LDV) sales	50% sales by 2030, 100% by 2050	
Zero-emission Medium Duty Vehicle (MDV) sales	50% by 2030, 100% by 2050	50% by 2030, 80% by 2050
Zero-emission Heavy Duty Vehicle (HDV) sales	50% by 2030, 100% by 2050	20% by 2030, 50% by 2050
Aviation efficiency	Reduction in energy use of 40% below Reference Scenario by 2050	
Transportation Other	AEO 2018 reference scenario growth rates by fuel	

Assumptions for total new sales of light-duty vehicles and resulting total stocks is shown in Figure 9.

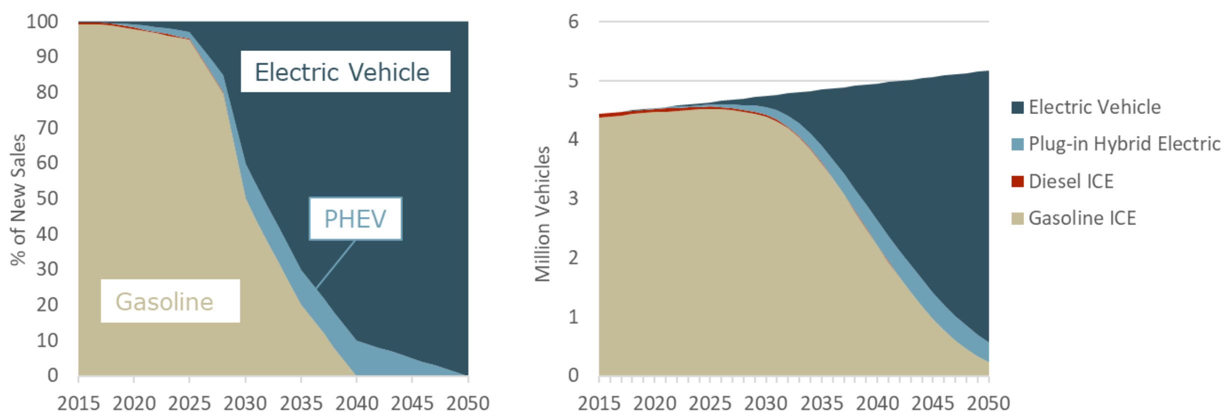

Figure 9. Assumed new light duty vehicle sales (left) and resulting stocks (right), High Electrification and High Biofuels Scenario

2.4.5 ELECTRICITY SECTOR

The Minnesota PATHWAYS model contains a dedicated branch for modeling electricity generation. Operations in the electricity sector are modeled on an annual basis, based on projected changes in electric capacity, generation, and changes in load. More detailed analysis of capacity expansion and operations for Xcel Energy Northern States Power were modeled in a parallel project with E3's RESOLVE and RECAP models.

2.4.5.1 Base Year

In-state generation capacity for Minnesota resources is based on EIA. Assumed generation by resource is shown in Table 9.

Table 9. Minnesota Electricity Generation in 2014[6]

Resource	**Generation [TWh]**	**Share of 2014 Generation [%]**
Nuclear	12.7	17%
Coal	28.0	38%
Natural Gas	3.9	5%
Oil	0.1	0%
Hydro	0.5	1%
Biomass	2.2	3%
Onshore Wind	9.7	13%
Utility Solar	0.0	0%
Net Imports	15.7	22%
Total	**72.7**	**100%**

2.4.5.2 Reference Scenario

In the Minnesota PATHWAYS model, total electricity demand is calculated from independent assumptions in each demand sector (buildings, transportation, industry, and agriculture). This approach ensures that we take into account linkages between sectors so that our generation and emissions from the electric sector are aligned with electrification loads in our mitigation scenarios. The Minnesota PATHWAYS model simulates dispatch of in-state generators and imported power from the Midcontinent Independent System Operator (MISO) to meet electricity demands in each year based on assumed percent shares of generation coming from generator types. All scenarios include an assumption of 6% transmission and distribution losses.

In the Reference Scenario, we assume that in-state nuclear facilities retire at the end of their license and are replaced with imported power. We assume moderate reductions in coal generation to reflect planned utility retirements. Table 10 shows the assumed share of electricity generation by resource.

Table 10. Assumed share of electricity generation by resource type, Reference Scenario

	2020	2030	2040	2050
Carbon-Free Generation*	43.6%	49.8%	33.7%	33.7%
Natural Gas	7.1%	10.0%	10.0%	10.0%
Oil	0.1%	0.1%	0.1%	0.1%
Coal	33.9%	30.0%	30.0%	30.0%

[6] US Energy Information Administration, Minnesota Electricity Profile, Table 5, full data available online: https://www.eia.gov/electricity/state/minnesota/index.php

Net Imports	15.3%	10.1%	26.2%	26.2%
Total	100.0%	100.0%	100.0%	100.0%

*Carbon-Free Generation includes utility-scale solar, onshore wind, biomass, hydro-electric, and nuclear generators

2.4.5.3 Mitigation Scenarios

Each Mitigation Scenario assumes significant ramp up of carbon-free generation over the next 30 years. Both Mitigation Scenarios are designed to meet the same share of carbon-free electricity by 2050, as shown in Table 11.

Table 11. Assumed share of electricity generation by resource type, Mitigation Scenarios

	2020	2030	2040	2050
Carbon-Free Generation*	42.5%	56.2%	73.6%	90.0%
Natural Gas	5.3%	5.3%	5.3%	5.3%
Oil	0.1%	0.0%	0.0%	0.0%
Coal	31.5%	20.0%	10.0%	0.0%
Net Imports	20.6%	18.4%	11.1%	4.7%
Total	100.0%	100.0%	100.0%	100.0%

*Carbon-Free Generation includes utility-scale solar, onshore wind, biomass, hydro-electric, and nuclear generators

Even though both scenarios have the same share of generation being met by carbon-free electricity, total generation is very different due to assumptions about electrification, as shown in Figure 10.

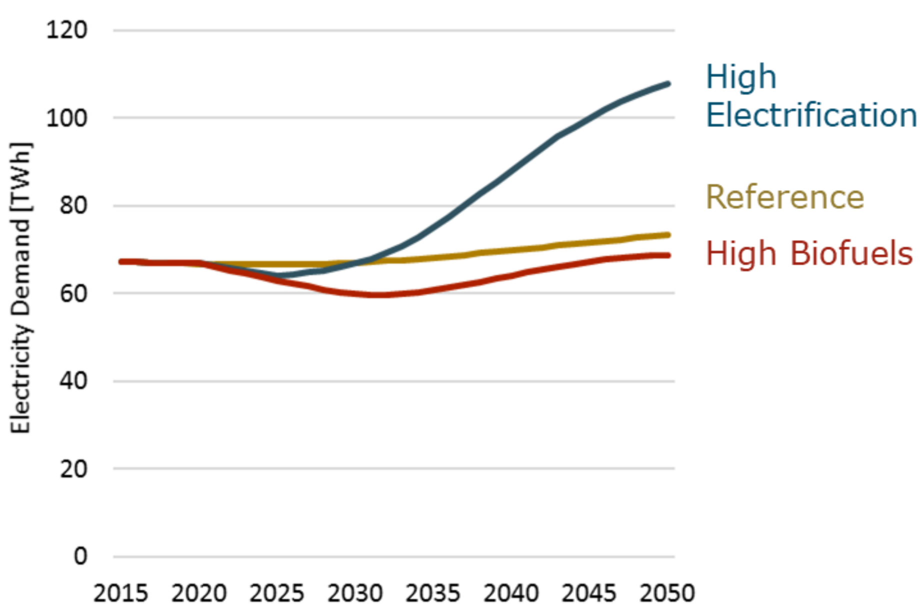

Figure 10. Electricity demand by scenario

2.4.6 BIOFUEL SUPPLY

The decarbonization transition will require strategic use of limited biomass and careful screening of sustainable feedstocks to ensure that bioenergy produces zero carbon emissions and is sustainably grown without producing adverse land-use impacts. Examples of biomass products that are used to produce biofuels include corn, soybeans, sugar cane, forest products, manure, switch grass and other agricultural waste products, such as corn stover.

Minnesota has a robust conventional biofuels industry that produces ethanol (from corn) and biodiesel (from soy and other waste oils). Our Reference Scenario assumes continued growth of the conventional biofuels industry, while our Mitigation Scenarios assume a transition after 2030 to an advanced biofuels industry. Note that both conventional biofuels and advanced biofuels are treated as having zero carbon emissions at the point of combustion from the Minnesota PCA Inventory accounting.

New sustainable biomass feedstock assessments are taken from the 2016 DOE Billion Ton Study (BTS) Update[7], which estimates sustainable yield of a variety of raw biomass sources, including agricultural (including dedicated energy crops), forestry (including new forests and residues), and waste streams (including municipal waste and forest residues).

2.4.6.1 Reference Scenario

The Reference Scenario assumes compliance with current targets for conventional ethanol and biodiesel. For ethanol, we assume a 30% blend of ethanol in motor gasoline by 2025.[8] For biodiesel we include the seasonal Minnesota B20 mandate, modeled as a 10% blend of biodiesel for the whole year.[9]

2.4.6.2 Mitigation Scenarios

In our Mitigation Scenarios, we assume a transition from conventional biofuel blends in the next 10 years to advanced biofuel production by 2050.

To determine available sustainable biomass supply through our study period, we assumed that Minnesota would have access to its population-weighted share of the total national feedstock supply, which is about 2% of the total supply. This approach assumes that all US states begin to transition to developing advanced biofuels with these resources. Minnesota has more biomass feedstocks within the state than its population-weighted share, which indicates that Minnesota would be able to sell excess biofuel products into a national market.

Figure 11 shows the national estimated biomass feedstock supply. The High Biofuel Scenario assumes that both residues and energy crops are available, while the High Electrification Scenario assumes only residue categories are available. The “Residues” category includes agricultural residues, food waste, forest residues, municipal solid waste, and manure. Residue feedstocks have fewer concerns about land-use constraints and competition with food crops.

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[7] DOE, 2016 Billion-Ton Report. Available online: https://www.energy.gov/eere/bioenergy/2016-billion-ton-report

[8] 239.7911 Petroleum Replacement Promotion: https://www.revisor.mn.gov/statutes/cite/239.7911

[9] 239.77 Biodiesel Content Mandate: https://www.revisor.mn.gov/statutes/cite/239.77

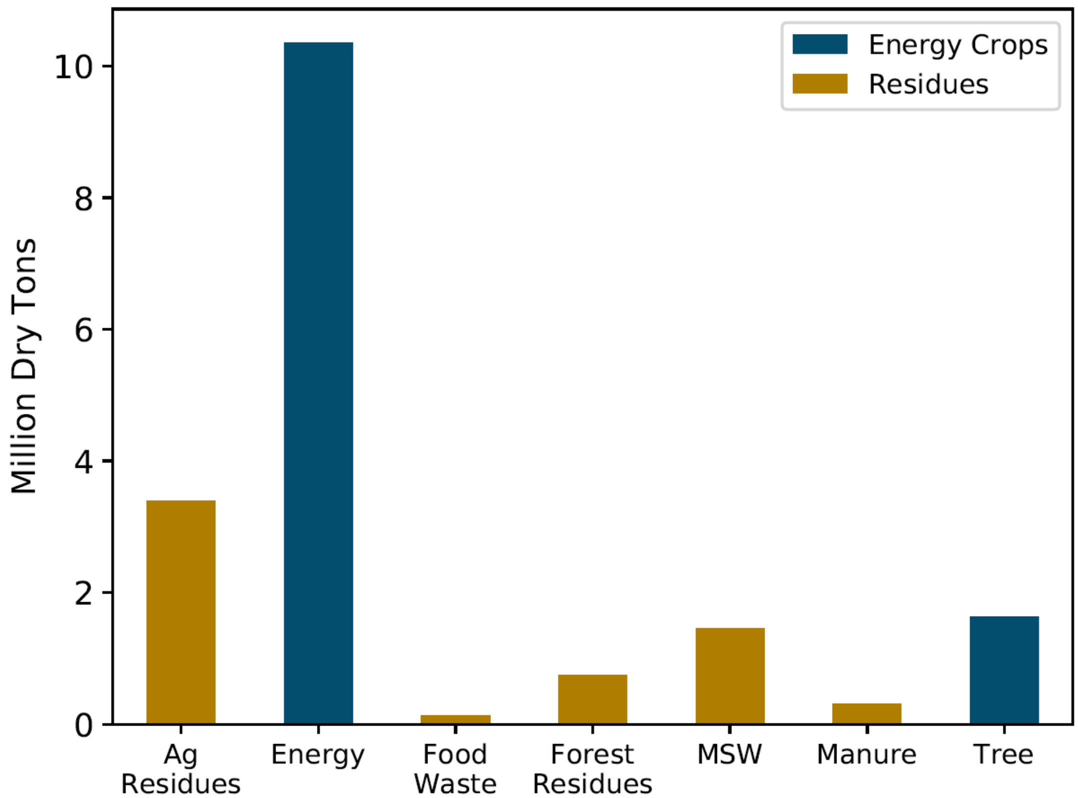

Figure 11. Minnesota Biomass Feedstock Supply by 2040 by Resource Category

To calculate the optimal portfolio of biofuels, E3 has developed a model which generates biofuel supply curves that determine the availability and cost of renewable liquid and gaseous fuels. The model optimizes the selection of combinations of feedstocks and conversion pathways. The model adds preparation, process, transportation, and delivery costs to BTS feedstock cost curves to achieve supply curves by feedstock and conversion pathway. To obtain biofuel demand, we apply the percentage biofuel penetration targets to aggregate calculated final energy demand.

Figure 12 shows the total resulting advanced biofuel consumption by fuel for each scenario. Because the High Biofuels Scenario includes feedstocks from energy crops and dedicated forests, that scenario is able to use more than two times the total quantity of biofuels than the High Electrification Scenario, which is limited to wastes and residues.

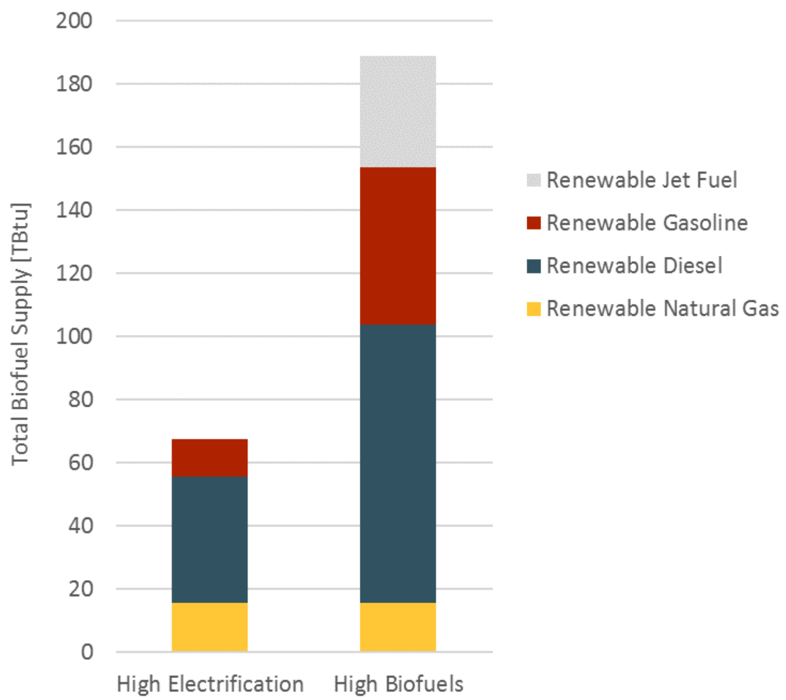

Figure 12. Total Advanced Biofuel Production by Biofuel in 2050, Mitigation Scenarios

Figure 12 highlights a different view of the same result, showing total consumption of gasoline, diesel, and natural gas by the share that is blended biofuel (and therefore zero-carbon) and the remaining share that is fossil.

2.4.7 OTHER SECTORS

This analysis focused in detail on the electricity generation, transportation, and buildings sectors. Additional sectors not modeled in significant detail are the agriculture, industry, and waste sectors.

2.4.7.1 Base Year

All energy consumption in industry, agriculture, and waste is represented as total annual energy consumption by fuel, as shown in Table 12.

Table 12. Energy Consumption in Industry, Agriculture, and Waste sectors by fuel in Minnesota, 2014

Sector	Fuel	Modeling Approach	Estimated Energy Use in 2014 [Tbtu]	Estimated % of 2014 Energy Use [%]
Industry (All Subsectors)	Electricity	Total Energy by Fuel	78.7	21%
	Gasoline	Total Energy by Fuel	2.7	1%
	Residual Fuel Oil	Total Energy by Fuel	0.1	0%
	Coal	Total Energy by Fuel	19.0	5%
	Petroleum Coke	Total Energy by Fuel	1.6	0%
	Refinery Feedstocks	Total Energy by Fuel	18.7	5%
	Wood	Total Energy by Fuel	27.2	7%
	Natural Gas	Total Energy by Fuel	154.1	41%
	LPG	Total Energy by Fuel	0.0	0%
	Diesel	Total Energy by Fuel	39.0	10%
	Renewable Diesel	Total Energy by Fuel	1.7	0%
	Coal Coke	Total Energy by Fuel	0.6	0%
Agriculture (All Subsectors)	Electricity	Total Energy by Fuel	-	0%
	Gasoline	Total Energy by Fuel	3.3	1%
	Natural Gas	Total Energy by Fuel	-	0%
	LPG	Total Energy by Fuel	10.5	3%
	Diesel	Total Energy by Fuel	16.4	4%
	Renewable Diesel	Total Energy by Fuel	0.7	0%
Waste (All Subsectors)	Natural Gas	Total Energy by Fuel	0.3	0%
	Diesel	Total Energy by Fuel	0.4	0%
	Renewable Diesel	Total Energy by Fuel	0.0	0%
All Sectors			**374.8**	**100%**

Additional non-energy emissions in industry, agriculture, and waste sectors were represented as total annual emissions, as shown in Table 13.

Table 13. Non-Energy Emissions in Industry, Agriculture, and Waste sectors in Minnesota, 2014

Sector	Fuel	Modeling Approach	Estimated Emissions 2014 [MST CO2e]	Estimated % of 2014 Non-Energy Emissions [%]
Agriculture	Animals	Total emissions	10.1	30%
	Crops	Total emissions	16.4	49%
	Other	Total emissions	0.0	0%
Industrial	Coal Storage	Total emissions	0.0	0%
	Industrial Process	Total emissions	0.6	2%
	Industrial Other	Total emissions	0.0	0%
	Oil Refining	Total emissions	0.0	0%
	Refinery Processes	Total emissions	1.7	5%
	Semiconductor Manufacture	Total emissions	0.3	1%
	Taconite Induration	Total emissions	2.1	6%
Waste	Industrial Landfills	Total emissions	0.1	0%
	Landfill gas combustion and flaring	Total emissions	0.0	0%
	MMSW Landfills	Total emissions	2.1	6%
	Medical	Total emissions	0.0	0%
	Rural Open Burning	Total emissions	0.0	0%
	Sludge	Total emissions	0.0	0%
	Waste Processing	Total emissions	0.2	1%
	Waste Solvent	Total emissions	0.0	0%
	Wastewater Treatment	Total emissions	0.4	1%
	Yard Waste Composting	Total emissions	0.0	0%
	Sequestration in landfills	Total emissions	-0.6	-2%
Total			33.7	100%

2.4.7.2 Reference Scenario

In the Reference Scenario, all energy consumption is assumed to grow at EIA AEO 2018 growth rates by fuel. All non-combustion emissions are held constant at 2014 levels.

2.4.7.3 Mitigation Scenarios

The overall approach for Mitigation Scenarios is to first calculate emission reductions from other sectors, and then to calculate the required reduction from remaining sectors in order to hit economy-wide NGEA goals by 2050. In both scenarios, we find that industry, agriculture, and waste sectors require a reduction that is lower than that in buildings, transportation, and electricity generation. This might be a fair assumption if it would be more expensive to decarbonize these sectors or if new technologies and measure would take longer to ramp up. The one specified assumption is that in the High Electrification Scenario, we assumed half of agricultural equipment could be electrified by 2050. Mitigation Scenario assumptions for other sectors are documented in Table 15.

Table 14. Mitigation Scenario Assumptions for Industry, Agriculture, Waste, and Non-Combustion Emissions

Category of Other Measures	High Electrification Scenario	High Biofuels Scenario
Electrification	50% of agricultural equipment energy use was assumed to be electrified by 2050.	None
Emissions Reductions for All Sectors below 2005 Levels	64%	69%

3 Results

3.1 GHG Emissions

Based on the assumptions outlined in Section 2 above, GHG emissions are calculated for Minnesota as shown in Figure 13. In the Reference Scenario, emission reductions are achieved in the initial years due to energy efficiency in buildings and transportation, as well as cleaner electricity generation. Emissions begin to rise after current policies no longer have an incremental effect and increased population and economic activity continue to increase energy use. Mitigation Scenarios fall short of the 2025 goal but meet the 2050 NGEA target.

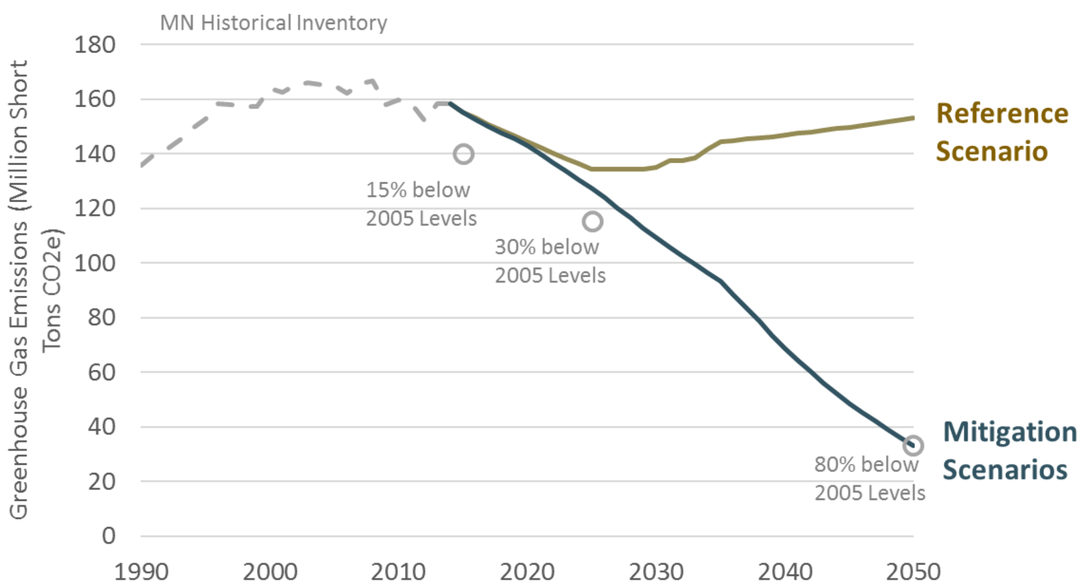

Figure 13. Minnesota GHG Emissions Results for Reference Scenario, 2015-2050

Emissions by Scenario are shown in Table 15 below.

Table 15. Total GHG Emissions by Scenario [Million Short Tons CO2e]

	2015	2020	2025	2030	2035	2040	2045	2050
Reference Scenario	155	144	134	135	144	147	150	153
High Electrification Scenario	155	143	127	109	93	69	48	33
High Biofuels Scenario	155	143	127	108	93	71	50	33
NGEA GHG Goals	140		115					33

Emissions for each modeled sector are shown over time in Figure 14 in the Reference Scenario. The largest direct reductions are in electricity generation, due to the retirement of in-state coal units and reduced demand due to efficiency, and transportation, due to federal CAFE standards and increased sales of ZEVs.

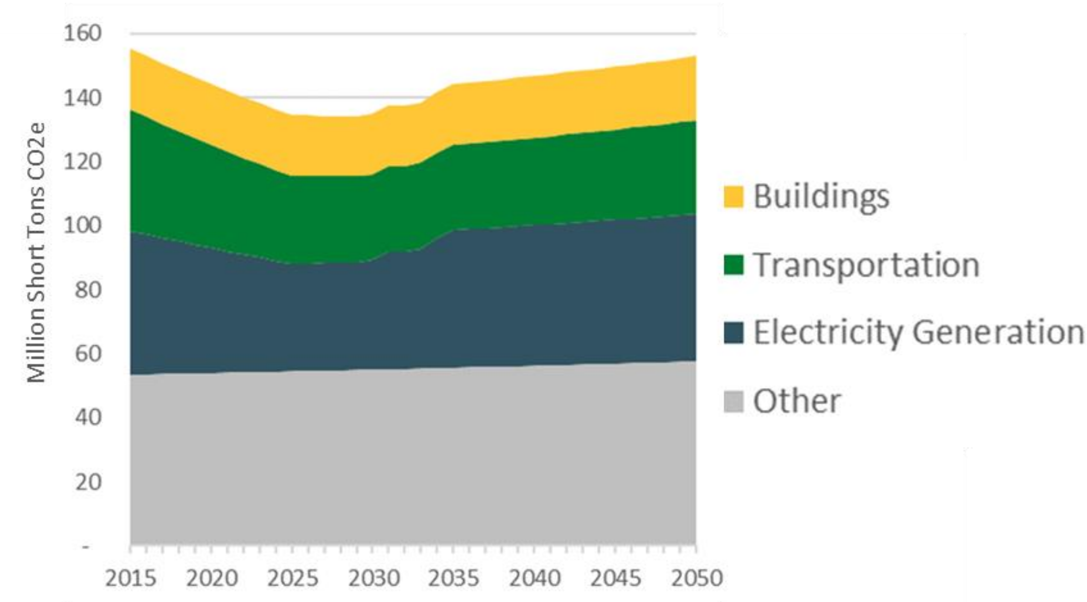

Figure 14. Minnesota GHG Emissions by Sector in the Reference Scenario, 2015-2050[10]

Emissions reductions by sector for each mitigation scenario is shown in Figure 15 and Increased electrification in the High Electrification scenario requires fewer reductions in “Other” sectors, but increases electricity generation demands, allowing for greater reductions in the High Biofuels Scenario.

Table 16. The High Electrification Scenario shows significant reductions in buildings and transportation due to adoption of electric appliances. The High Biofuels Scenario achieves fewer reductions in buildings and greater reductions in transportation due to allocating increased biofuels largely to on road vehicles.

[10] Other includes Agriculture, Industry, and Waste emissions

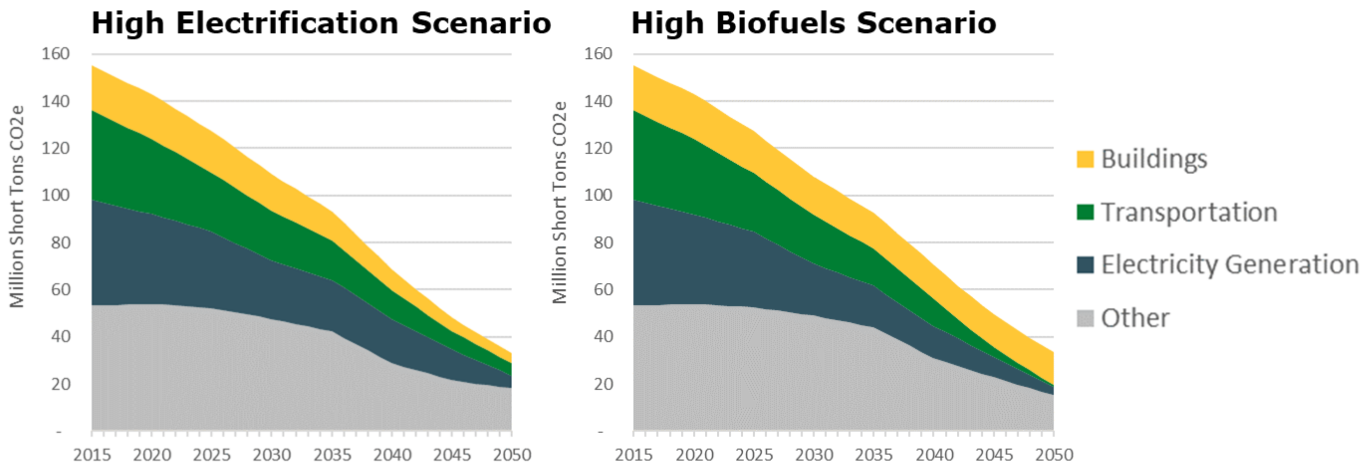

Figure 15. Minnesota GHG Emissions by Sector in Mitigation Scenarios, 2015-2050

Increased electrification in the High Electrification scenario requires fewer reductions in "Other" sectors, but increases electricity generation demands, allowing for greater reductions in the High Biofuels Scenario.

Table 16. GHG Reductions in Mitigation Scenarios in 2050 relative to 2005 emissions by sector

	High Electrification Scenario	High Biofuels Scenario
Buildings	-74%	-14%
Transportation	-87%	-98%
Electricity Generation	-91%	-94%
Other	-64%	-69%
Total	**-80%**	**-80%**

3.2 Sectoral Findings

3.2.1 BUILDINGS

The focus of measures in buildings is on energy efficiency and electrification. Increased sales of more efficient appliances and devices result in increased stock of those devices over time as old devices retire. Increased sales of efficient devices along with behavioral conservation and reductions in non-stock energy consumption results in significant reductions in total energy consumption as shown in Figure 16. Both scenarios achieve significant energy efficiency relative to the Reference Scenario, but the High Electrification Scenario achieves greater reductions in final energy consumption due to switching from natural gas appliances to more efficient electric heat pumps. Figure 16 also breaks out the impact of conventional efficiency and efficiency through electrification. The section between the black and grey lines highlights the reduction in building energy consumption from measures like improved device efficiency, improved building shell (e.g. insultation), and smart devices. The section below the grey line highlights the additional reduction in energy consumption from switching to high-efficiency electric heat pump technologies in space heating and water heating.[11]

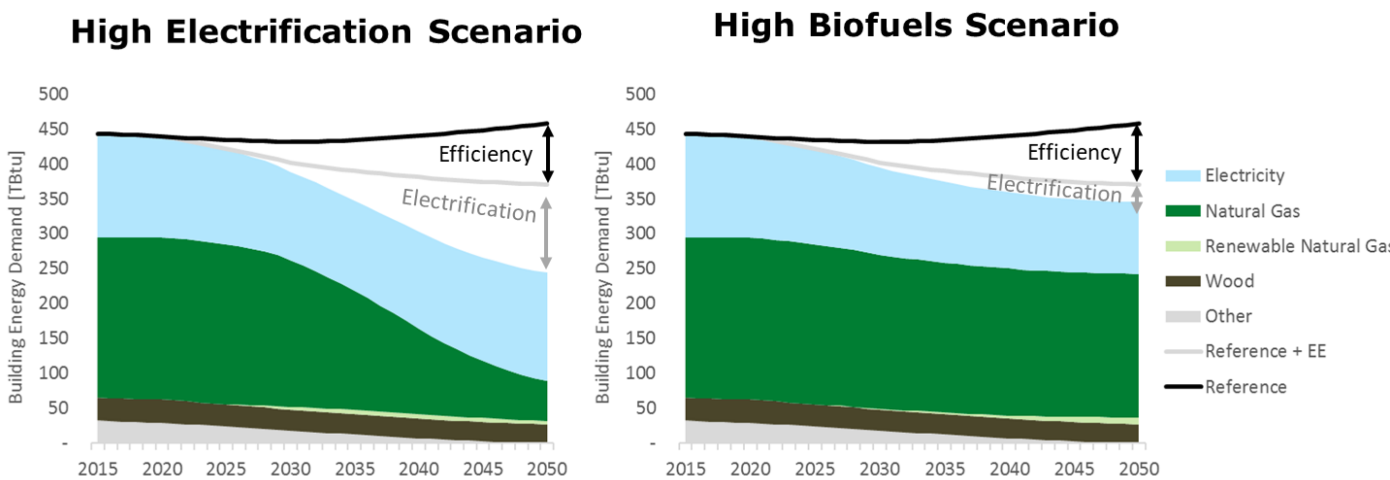

Figure 16. Total energy consumption by fuel and scenario in buildings

3.2.2 TRANSPORTATION

Reductions in emissions in the transportation sector are achieved through efficiency, electrification, and biofuels. Energy efficiency is included in two forms: (1) federal CAFE standards for new vehicle sales, and (2) VMT reductions due to transit and smart growth measures. New sales of vehicles with more efficient electric drive trains achieve significant efficiency and the potential to reduce emissions further by consuming cleaner electricity. Benefits of displacing fossil fuels with renewable diesel, renewable gasoline, and renewable jet fuel further reduces emissions within the transportation sector.

Figure 17 highlights the impacts of energy efficiency on total final energy demand in transportation. Both Mitigation Scenarios show significant reductions in total energy consumption relative to the Reference Scenario due to reductions in vehicle miles traveled and more efficient electric drive trains. In the High Electrification Scenario, hydrogen fuel cell heavy-duty trucks and electric medium-duty trucks are used. In the High Biofuels Scenario, advanced biofuels displace all remaining petroleum fuels by 2050.

[11] Note that these scenarios do not include a detailed analysis of electric heat pump performance in Minnesota.

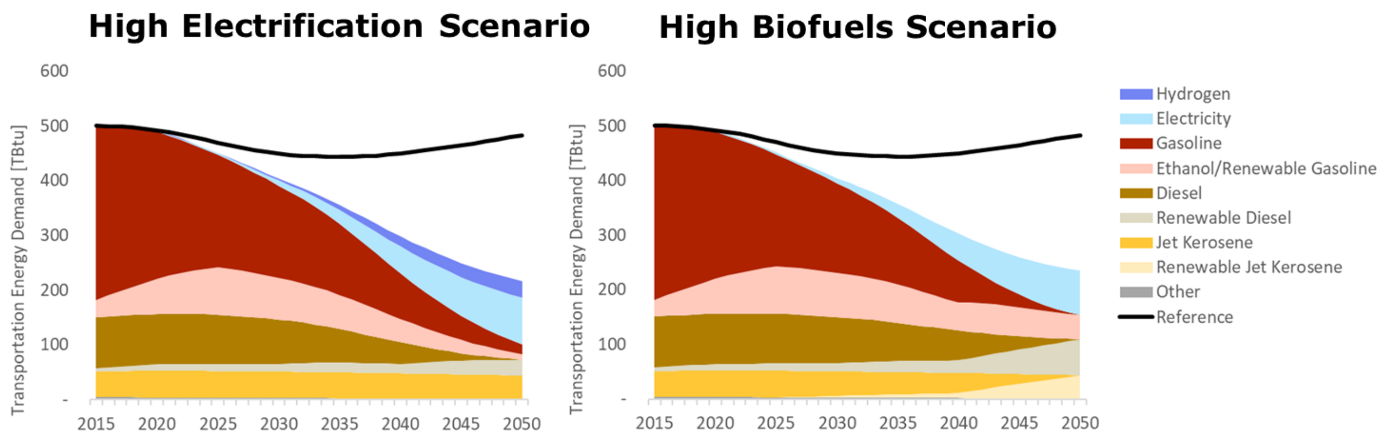

Figure 17. Total energy consumption by fuel and scenario in transportation

3.2.3 ELECTRICITY GENERATION

Each mitigation scenario has very different assumptions about adoption of electric technologies and therefore different projections of electricity demand, as shown in Figure 18. The High Electrification Scenario includes high adoption of electric household appliances, electric vehicles, and electrolysis to produce hydrogen for heavy-duty vehicles. The High Biofuels Scenario includes adoption of electric vehicles in light and medium duty vehicles, but lower electrification in other sectors. This leads to a load increase of 60% relative to 2015 in the High Electrification Scenario, and a much smaller load increase in the High Biofuels Scenario.

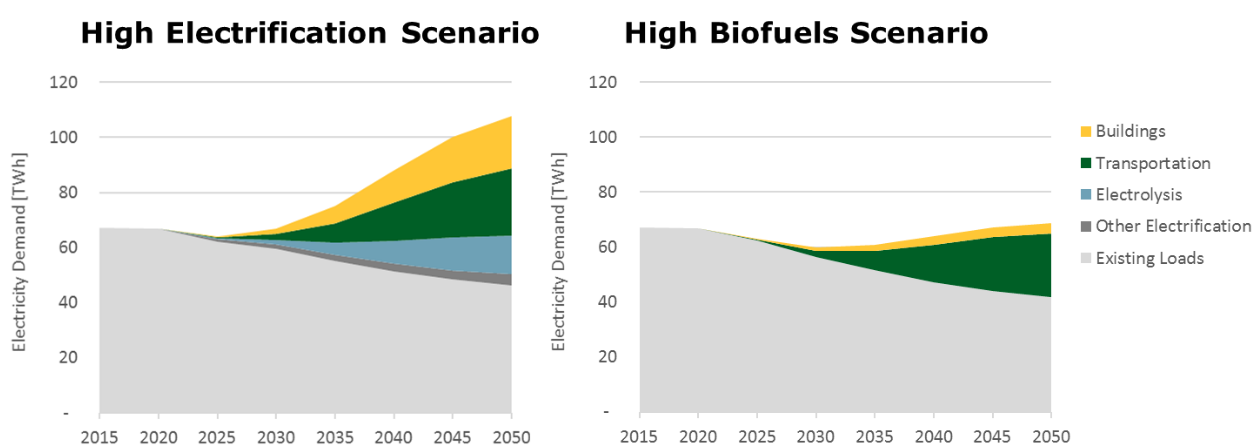

Figure 18. Electricity demand by sector and mitigation scenario

Demands for electricity determine required electricity generation. Each mitigation scenario achieves a 90% share of carbon-free electricity by 2050, but serves very different electricity demand, as shown in Figure 19.

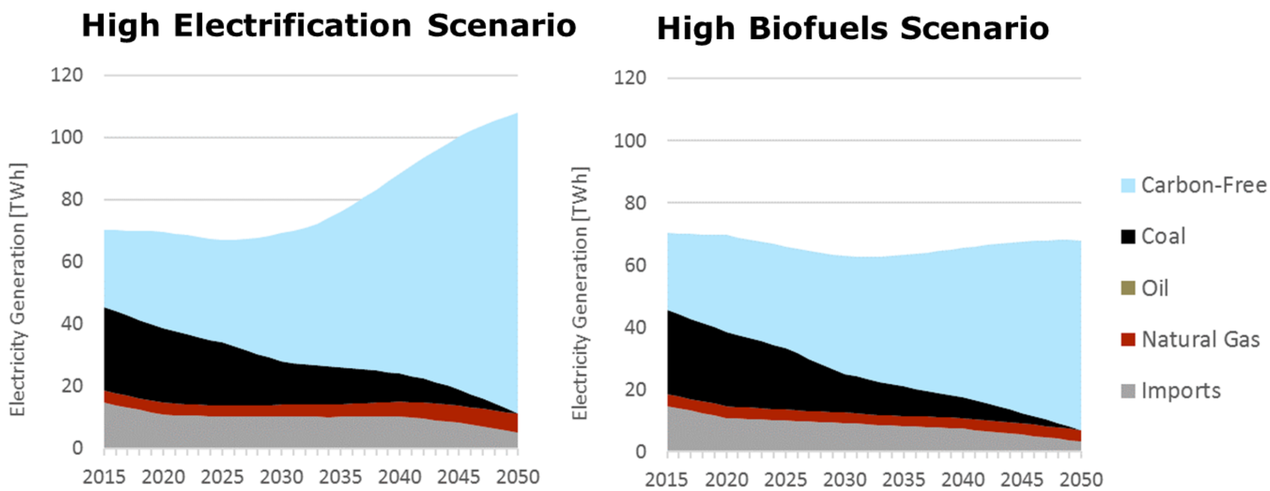

Figure 19. Total electricity generation by sources and mitigation scenario

Our accounting of GHG emissions aligns with the approach taken in the PCA's GHG Inventory, which accounts for all emissions from production of electricity in the electricity generation sector. In our scenarios, this shows a significant reduction in direct GHG reductions due to transitioning to carbon-free resources in our mitigation scenarios (see solid blue bars in Figure 20). In addition to those emission reductions, additional emissions are avoided in buildings and transportation, where electrification avoids emissions from direct combustion of natural gas, gasoline, and diesel fuels. Both Mitigation Scenarios reach 90% carbon-free electricity in 2050, but since the High Electrification scenario serves about 60% higher loads, total emissions in that scenario are 2 Million Short Tons higher, as shown in Table 17Table 18. Also shown are enabled emissions reductions in buildings and transportation in negative hatched bars, representing the petroleum and natural gas emissions avoided by switching to electric vehicles and appliances. Both Mitigation Scenarios see additional emission reductions due to electrification in buildings and transportation. The High Electrification scenario has increased direct electricity emissions of serving higher loads, but avoids an additional 20 MST CO2e elsewhere in the economy through electrification compared to the High Biofuels scenario

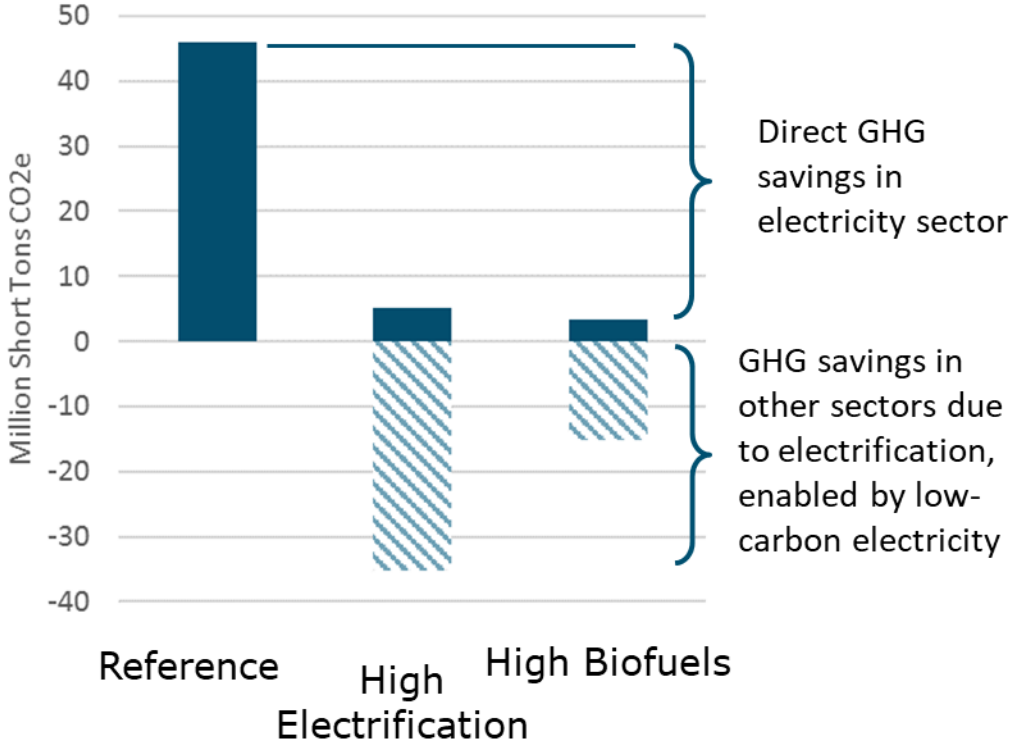

Figure 20. Electric sector GHG emissions by scenario in 2050

Table 17. Electric sector direct GHG emissions and indirect GHG reductions in 2050 [MST CO2e]

	Reference Scenario	High Electrification Scenario	High Biofuels Scenario
Total Direct Emissions from Electricity Generation	46	5	3
Total Emission Reductions from Other Sectors by Switching to Electric Devices		-35	-15

3.2.4 SENSITIVITY ANALYSIS

In addition to mitigation scenarios, we developed three sensitivities to test the impact on emissions of federal action and consumer adoption. The three sensitivities were defined as follows:

1. **Sensitivity #1: Efficiency, Electrification, and Clean Electricity Only**: Evaluates the impact of only pursuing building efficiency, high adoption of electric vehicles and household devices, and clean electricity towards meeting GHG targets
2. **Sensitivity #2: No CAFE Extension**: Evaluates the impact of freezing federal Corporate Average Fuel Economy (CAFE) standards from at 2020 levels.

3. **Sensitivity #3: Lower Electric Adoption**: Evaluates the combined impact of lower consumer adoption of electric vehicles and electric household devices.

3.2.4.1 Sensitivity #1: Efficiency, Electrification, and Clean Electricity

The first sensitivity we tested was a mitigation scenario that focused first on the emissions benefits of pursuing aggressive efficiency and electrification with higher shares of carbon-free electricity. This sensitivity is different from the High Electrification Scenario, which includes measures in other sectors such as industry, agriculture, and waste that allow the scenario to meet economy-wide goals

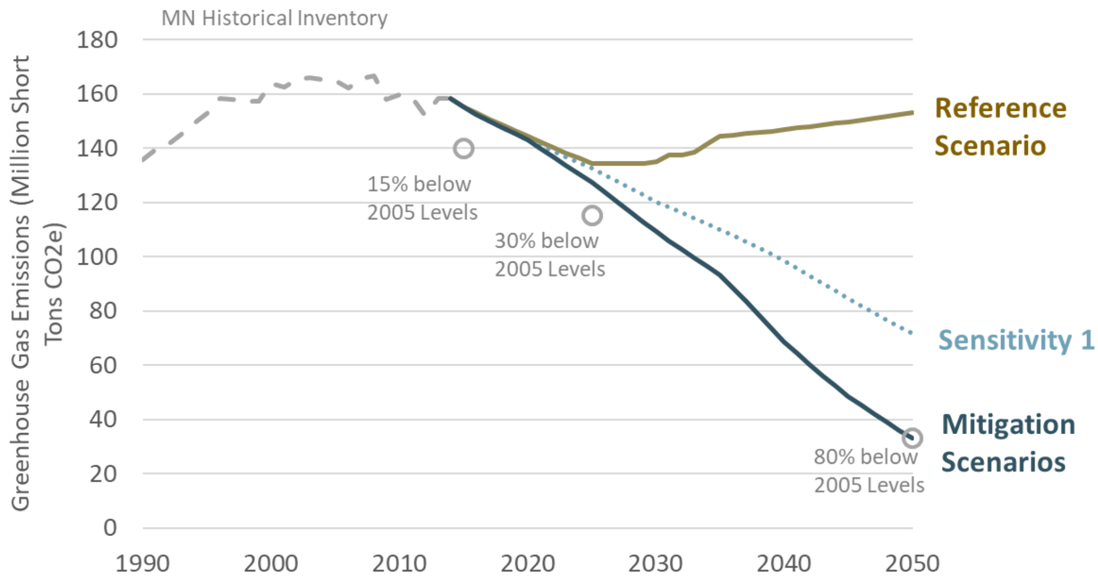

Figure 21. GHG Emissions from Sensitivity 1 relative to Reference and Mitigation Scenarios

This scenario highlights the need for additional measures and actions to meet the economy-wide GHG goal.

3.2.4.2 Sensitivity #2: No CAFE Extension

Federal Corporate Average Fuel Economy (CAFE) Standards impact the on-road efficiency of new light-duty vehicles sold in the US. The current federal administration has proposed freezing the standards at 2020 levels, removing the extension of the program from 2021 to 2026. We ran a sensitivity on our Reference Scenario and High Electrification Scenarios to quantify the impact of removing this federal program.

All scenarios benefit from CAFE improvements through 2020, but the sensitivity assumes no incremental improvement in new vehicles sold starting in 2021.

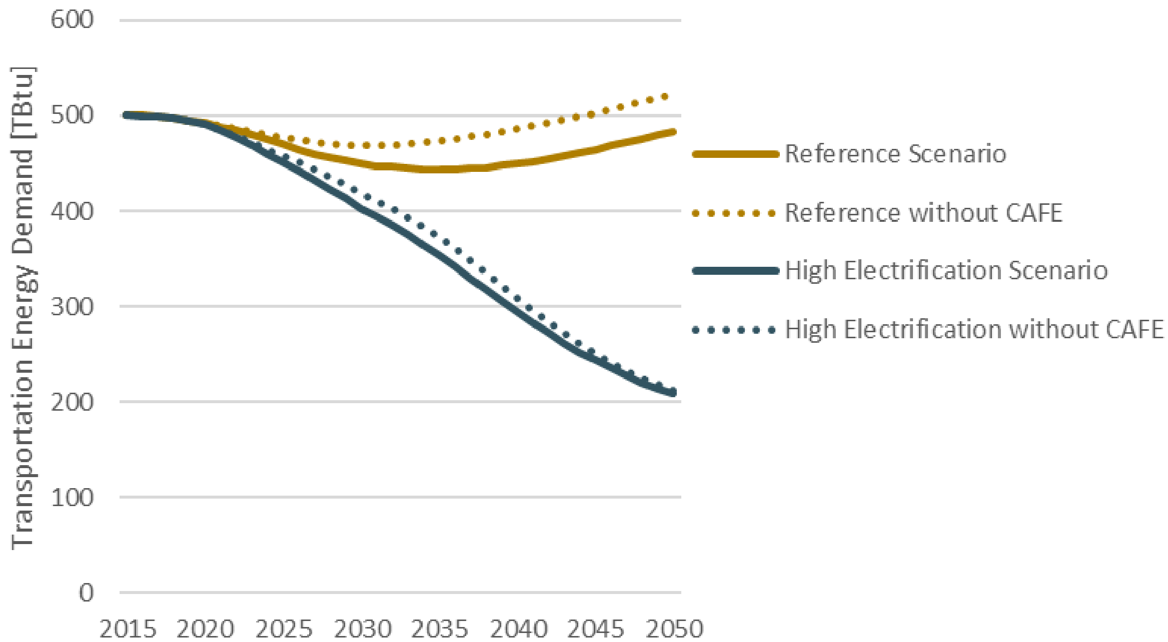

Figure 22. Total energy consumption in transportation by scenario and sensitivity

As shown in Figure 22, federal fuel economy standards have a larger impact on the Reference Scenario, which assumes more internal combustion engine vehicles are sold. Impacts are smaller in the High Electrification Scenario, especially by 2050, due to increasing share of electric vehicles on the road.

Emissions impacts are small relative to economy-wide emissions (see Figure 23). Incremental emissions are 1.5 MST CO2e in 2050 in the Reference Scenario and 0.1 MST CO2e in the High Electrification Scenario.

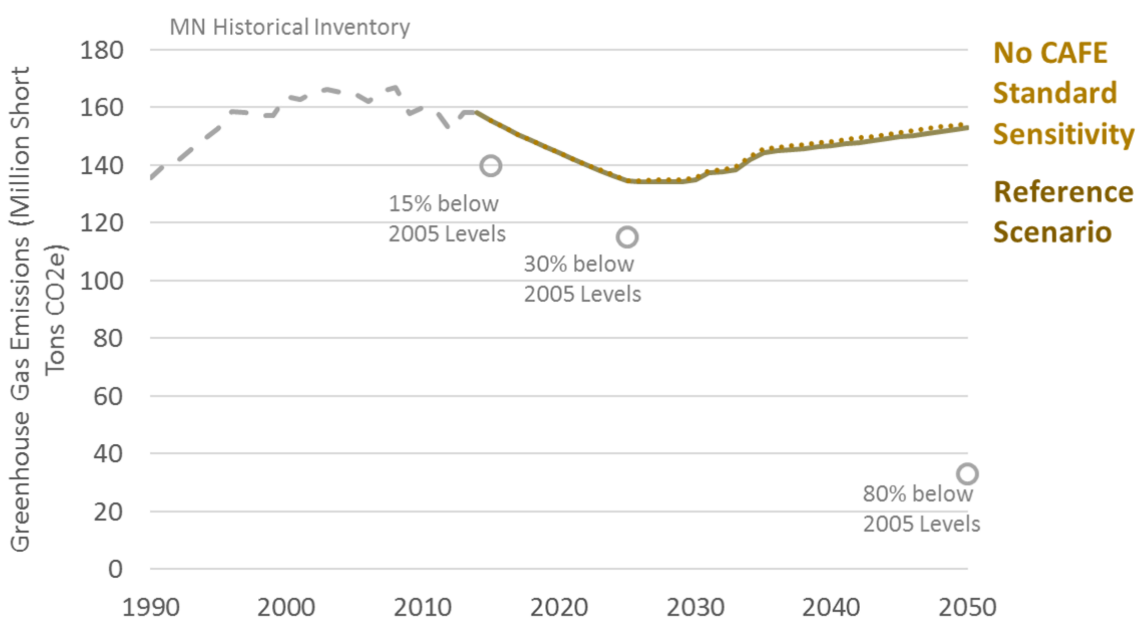

Figure 23. Total Minnesota GHG Emissions in the Reference Scenario and No CAFE Standard Extension Sensitivity

3.2.4.3 Sensitivity #3: Lower Electric Adoption

Rates of consumer adoption for new electric vehicles and electric appliances are uncertain. Our High Electrification Scenario assumes that no internal combustion engine vehicles or natural gas furnaces are sold by 2050. This sensitivity tests a lower level of adoption of key electric technologies, aligning with assumptions from NREL's Electrification Futures Study.[12] Full assumptions are shown in Table 18.

Table 18. New sales assumptions for key electric technologies in Mitigation Scenarios and Sensitivity #3 [% of new sales]

	High Electrification Scenario	**High Biofuels Scenario**	**Lower Electric Adoption Sensitivity**
Medium Duty ZEVs	100%	80%	60%
Heavy Duty ZEVs	100%	50%	40%
Heat Pumps in Residential Space Heating	100%	22%	80%
Heat Pumps in Residential Water Heating	100%	33%	30%
Heat Pumps in Commercial Space Heating	98%	2%	60%
Heat Pumps in Commercial Water Heating	100%	8%	30%

Impacts on energy consumption of the Lower Electric Adoption Sensitivity are shown by sector in Figure 24. The largest impacts are seen in buildings, representing the NREL assumption of lower adoption of heat pump water heaters and commercial space heaters than assumed in the High Electrification Scenario.

[12] Report available online: https://www.nrel.gov/docs/fy18osti/71500.pdf

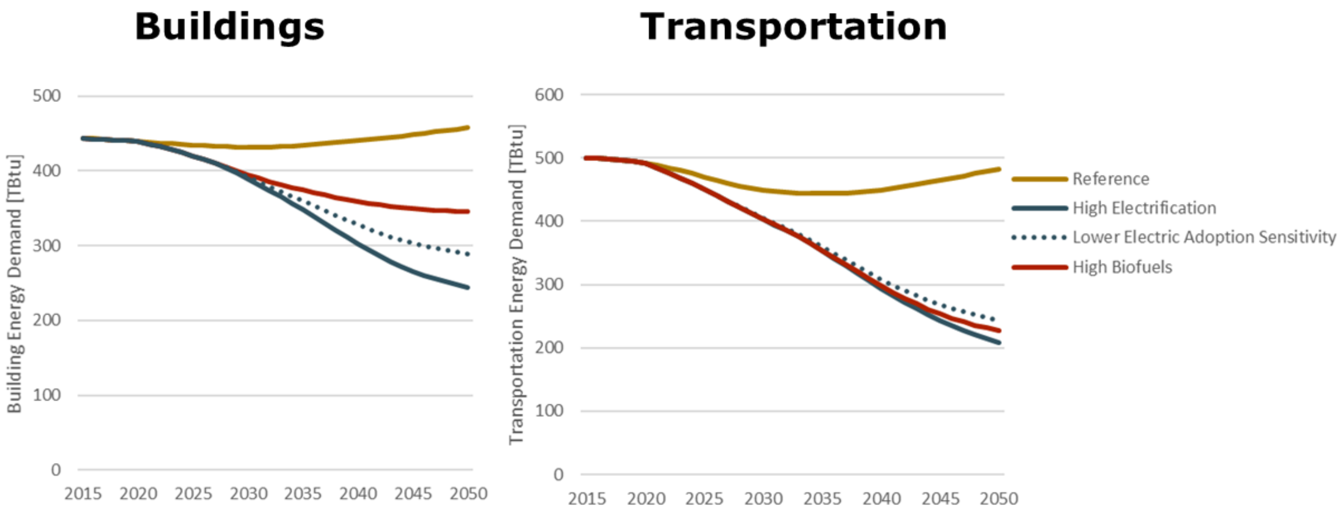

Figure 24. Total energy consumption in buildings and transportation by scenario and sensitivity

Figure 25 shows the emissions gap of 7.9 MST CO2e in 2050 created by lower levels of adoption relative to the High Electrification Scenario. If adoption is lower than expected in the High Electrification Scenario, emissions in Minnesota will fall short of the 2050 NGEA goal and additional measures would need to compensate.

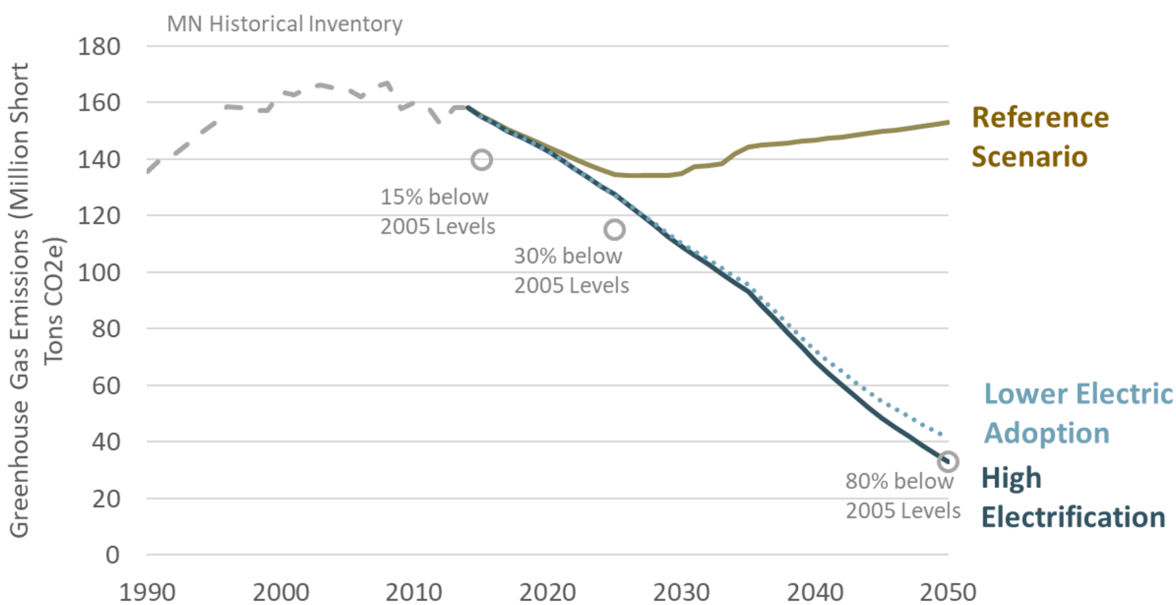

Figure 25. Total Minnesota GHG emissions in Lower Electric Adoption Sensitivity

3.3 Key Findings

The goal of this analysis was to develop a set of long-term economy-wide scenarios that reach the Next Generation Energy Act GHG emission targets for Minnesota of 80% reductions by 2050 relative to 2005 levels. These scenarios provide an exploration of the cross-sectoral implications of meeting economy-wide carbon reduction goals and highlight the role of the electric sector in meeting the state's economy-wide carbon goal. Based on the detailed analysis of Minnesota's statewide energy and emissions, we find the following:

Significant action is needed in every sector to decarbonize the state of Minnesota. This analysis highlights the need for aggressive action across all sectors of Minnesota's economy to meet a statewide goal of 80% reduction below 2005 levels. Reaching the NGEA goal of 80% GHG reductions by 2050 is challenging and will require significant effort beyond current policies within the state.

Buildings and transportation have significant potential to drive load growth, especially after 2025. The High Electrification Scenario highlights the significant potential for adoption of new electric appliances and vehicles, and the potential impact on total electricity requirements for Minnesota utilities. Transportation and building electrification drive electric load growth, especially after 2030, particularly in a future with less biofuels. Electrification of space heating has a particularly large impact on both total load (MWh) and peak demand (MW).

Reasonable electric rates and low costs for new electric devices are essential for electrification. The levels of electrification modeled in buildings and transportation are dependent on consumer adoption, which will benefit from reductions in capital costs and reasonable electric rates, even as the electric grid continues to decarbonize.

Electrification and zero-carbon electricity are necessary but not enough to reach statewide goals. Each Mitigation Scenario shows that increased reliance on low-carbon electricity enables emission reductions by avoiding direct combustion of fossil fuels in households, businesses, and vehicles. We also show that electrification and carbon-free electricity are necessary building blocks of a Mitigation Scenario but are not sufficient without additional measures and actions within the state.

This work highlights areas of future research. The scenarios modeled in this analysis represent an initial modeling assessment of required emission reductions in the state. This analysis has focused on emissions in electricity generation, buildings, and transportation, but further research is needed to explore building electrification impacts in Minnesota's climate and next steps for policy implementation within the state. In other sectors, further research is needed around opportunities in biofuels, agriculture, waste, and industrial sectors.