Reducing Greenhouse Gas Emissions for Climate Stabilization: Framing Regional Options

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The Intergovernmental Panel on Climate Change (IPCC) has stated that stabilizing atmospheric CO_2 concentrations will require reduction of global greenhouse gas (GHG) emissions by as much as 80% by 2050. Subnational efforts to cut emissions will inform policy development nationally and globally. We projected GHG mitigation strategies for Minnesota, which has adopted a strategic goal of 80% emissions reduction by 2050. A portfolio of conservation strategies, including electricity conservation, increased vehicle fleet fuel efficiency, and reduced vehicle miles traveled, is likely the most cost-effective option for Minnesota and could reduce emissions by 18% below 2005 levels. An 80% GHG reduction would require complete decarbonization of the electricity and transportation sectors, combined with carbon capture and sequestration at power plants, or deep cuts in other relatively more intransigent GHG-emitting sectors. In order to achieve ambitious GHG reduction goals, policymakers should promote aggressive conservation efforts, which would probably have negative net costs, while phasing in alternative fuels to replace coal and motor gasoline over the long-term.

Introduction

The call to cut global greenhouse gas (GHG) emissions by up to 80% below 2000 levels, which researchers have stated is necessary to avoid a global temperature increase of more than 2.5 °C (*1*), has prompted many actions at the subnational level to develop GHG reduction policies that are significantly more aggressive than the Kyoto protocol standards (*2*). However, there remains substantial disagreement around the effectiveness, cost, and unintended economic and ecological consequences of GHG reduction policies. In order to address these issues appropriately, policymakers must have accurate and objective information about the GHG reduction options available.

Many GHG reduction options will be implemented at the subnational level. In Minnesota, the governor and legislature have presented a strategic goal of reducing the state's greenhouse gas emissions by 80% below 2005 levels by 2050, presenting a challenge for development in Minnesota and requiring a significant shift in current policies and technologies governing energy generation and use. In 2003, per capita GHG emissions in Minnesota were 4 times the global average, and the rate of growth in total emissions between 1990 and 2003 was 56% higher in Minnesota compared with global emissions growth rates (*3*).

As subnational entities are often responsible for approving and siting electric generation facilities, developing transportation infrastructure, and making key building standard and land use decisions, understanding the potential policies used to achieve GHG reductions is key. Minnesota provides a useful case study as it is a region with high per capita emissions and fast-growing total emissions, and potential policies here would be instructive for a variety of other contexts. Minnesota is a cold-weather state with high heating requirements, moderate population densities, and significant land and biomass resources. In terms of these parameters, it is similar to many other regions of the northern United States, Canada, and northern Europe—regions that are emitting a disproportionate amount of the world's greenhouse gases. In the United States, national policies for controlling emissions have been proposed in both chambers of Congress, and their eventual adoption will undoubtedly draw from the examples in policy and practice set at the state level. Additionally, actual deployment of many of these policies depends—importantly—on state-level actions (*4*). Studying Minnesota, therefore, could allow us to draw conclusions applicable to other northern industrialized regions, the United States national scale, and other states.

A broad range of strategies and potential technologies might be imagined to meet a goal of 80% GHG reduction by 2050, but not all of these strategies are technically, economically, or politically feasible for Minnesota. The wedge framework developed by Pacala and Socolow (*5*) suggested that it is possible to stabilize atmospheric concentrations of greenhouse gases by use of a suite of currently available technologies and strategies. We found it helpful to use their GHG mitigation categories because progress toward a 2050 goal will have to begin with technologies that are available now or in the short term. However, our analysis of these strategies' contributions to GHG mitigation was significantly different from the Pacala and Socolow approach. They selected diverse strategies that could each contribute a set reduction of 1 Gt carbon emissions over 50 years, whereas we examined the *maximum* emissions reduction possible within Minnesota for the strategies considered and did not limit these wedges in terms of a contribution to a predetermined amount of emissions reduction. In our study, wedge refers to the size of the GHG reduction that a specific technology or strategy could contribute by 2050 compared to a trajectory of emissions representing currently implemented reduction actions and historically observed economic impacts on energy consumption (we call this trajectory "business as usual" or BAU).

In this study we examine the potential for policies and technologies to effect GHG reductions. We consider this to be the first step toward operationalizing deep emissions cuts that require significant institutional, political, and societal shifts. We build projections of GHG emissions in Minnesota

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to (i) determine how Minnesota's GHG emissions are likely to grow in the future, (ii) examine potential strategies for reducing GHG emissions, and (iii) evaluate the maximum reductions these strategies might accomplish. We also discuss briefly how these strategies might compare in terms of economic cost.

Experimental Procedures

We created scenarios to evaluate potential GHG reductions from technologies determined to be feasible and available in Minnesota within 10−20 years, primarily in the transportation and electricity production sectors (see Supporting Information) (*6*). Population growth and energy consumption per capita have frequently been used as drivers to model energy consumption (*7*). We included these variables in univariate and multiple regression equations along with other independent variables that might affect the efficiency of energy use, such as price. We did not assume linear variable relations but tested logarithmic and polynomial regressions for each equation. In almost every case, Minnesota-specific data from 1970 through 2006 were used to build the historical relationships and project future energy consumption values. Equations with the best fit for each energy consumption sector were used to predict GHG emissions up to the year 2050 (see Supporting Information). Some variables—such as the proportion of Minnesota's electricity demand produced in-state or the number of feedlot cattle produced in the state—demonstrated no clear or consistent pattern over time; we took an average value from the most recent 10 years for these variables and assumed a constant value up to 2050.

Sensitivity analyses were performed on the emissions projections by varying energy consumption behavior. We conducted a projection by assuming a stabilization of electricity demand at 2005 levels, a reduction in electricity demand to 1999 levels by 2050, a stabilization of vehicle miles traveled at 2005 levels, and a reduction in vehicle miles traveled to 1999 levels by 2050. This analysis was intended to uncover the effects of consumption choices on Minnesota's GHG trajectory.

We decided not to include conservation tillage or no-till farming as GHG reduction strategies, because of a general consensus in the literature that soil types and climatic conditions in Minnesota preclude meaningful carbon storage in agricultural soils (*8, 9*).

The database of historical GHG emissions was assembled by the Minnesota Pollution Control Agency (MPCA) from a variety of in-state reporting agencies. The values in the database have been cross-checked and validated extensively, and they have been used to make predictions of future emissions in other reports (*10*). However, GHG flux from agriculture and forest lands have not been monitored as thoroughly or consistently as the emissions from fossil fuel-driven sectors, so we consider the outcomes from this portion of the analysis to be less certain.

We decided to focus on the sectors that together contribute three-quarters of Minnesota's GHG emissions and are targeted in the Pacala and Socolow wedge analysis: electricity production, fuels for personal vehicles, agriculture, and energy used in residential and commercial buildings. These GHG-emitting activities or sectors were projected individually, while all other sectors were projected together as a remainder. GHG flux from forest land was also projected separately. See Supporting Information for a complete list of equations used to project future emissions.

In general, the changes in technology or practice associated with each wedge were projected as a gradual transition, reaching 50% adoption statewide by 2030 and 100% adoption by 2050.

Electricity Generation. GHG emissions from out-of-state electricity production consumed in Minnesota were included in the analysis (in the past 10 years, out-of-state production has contributed between 15% and 23% of Minnesota's electricity demand). Other studies have included these numbers in GHG inventories for the state (*10*). In addition, current Minnesota policy addresses emissions from all electricity consumed in-state. Minnesota has been a net electricity importer since 1979, and out-of-state production is generally more GHG-intense than in-state production, due to the portion of Minnesota's in-state generation filled by nuclear (25% of net generation) and wind power (3.5%).

Emissions from electricity generation for each fuel type were projected as

$$\begin{gathered}[(\text{megawatt}\cdot\text{hours of electricitydemand filled in-state})\\ (\text{in-state percentage ofelectricity demand}\\ \text{filled by fuel type})(\text{GHG intensity of fuel type})\\ (\text{fuel type efficiency})][(\text{percentage of electricity}\\ \text{demandfilledout-of-state})(\text{megawatt}\cdot\text{hours ofout-of-state}\\ \text{electricity demand filled by fuel type})\\ (\text{GHG intensityof fuel type})(\text{fuel type efficiency})]\end{gathered}$$

Transmission and distribution losses are embedded in the calculation of fuel type needed to fill a given megawatt·hour of consumer demand. GHG intensities of each fuel type were assumed to be constant and were calculated from Minnesota-specific data, except for natural gas (for which Energy Information Administration data were used).

The following GHG reduction wedges were projected out to the year 2050:

- business as usual scenario
- electricity used in the residential/commercial sector reduced to parameters determined by the Architecture 2030 challenge
- efficiency of all coal-powered plants increased to 60%
- all coal replaced with natural gas
- carbon capture and sequestration (CCS) technology employed at all coal plants
- all coal electricity generation replaced with wind
- all fossil fuel electricity generation replaced with biomass (poplar).
- all fossil fuel electricity generation replaced with biomass, with CCS

The renewable fuel scenarios and the CCS scenarios incorporated all life cycle emissions from the production of technologies and transport and conversion of fuel feedstocks, as well as the emissions involved in constructing the plants. The numbers for this analysis were taken from Rhodes and Keith (*11*) and Mann and Spath (*12*) for biomass production, from Jungbluth et al. (*13*) for wind production, and from the IPCC report (*14*) for CCS.

Replacement of fossil fuel electricity by wind would require backup systems to provide power on windless days. The amount of energy required for the backup system would be dependent on daily minimum wind speeds for wind-producing regions of Minnesota (*15*), and these data are not currently available. For this analysis, we assumed a backup system using natural gas and diesel fuel similar to the backup system currently used for Minnesota's coal-produced electricity.

GHG emissions attributed to residential and commercial sector electricity demand were projected by use of the equations above, with the assumption that the grid mix for these sectors was the same as for overall state electricity use. The Architecture 2030 challenge used as a parameter for the building efficiency wedge was developed by Edward Mazria et al. (http://www.architecture2030.org/). The challenge suggests a 60% GHG reduction from existing levels for new buildings built between 2010 and 2015; a 70% reduction for buildings built between 2015 and 2020; 80% for buildings built between 2020 and 2025; 90% for buildings built between 2025 and 2030; and carbon-neutral buildings beginning in

2030. This is combined with a 50% reduction in GHG emissions from existing building stock. We assumed this reduction would apply to residential/commercial sector GHG emissions attributed to electricity as well as emissions from heating and other building uses.

Personal Vehicle Fuels. For this analysis, greenhouse gas emissions from motor gasoline and ethanol used to fuel private vehicles in Minnesota were considered separately from other transportation emissions (diesel trucks, airplanes, and boats). These other transportation sources were combined in the emissions remainder category. GHG emissions from personal vehicle fuels were projected as

(vehicle miles driven)(fleet fuel efficiency)
(percentage of fuel demand filled by gasoline/ethanol)
(GHG intensity of fuel)

The GHG intensity of motor gasoline was taken from EPA statistics; the life cycle emissions values for GHG intensity of ethanol fuels were taken from Wang et al. (*16*) and Groode and Heywood (*17*). In calculating emissions from plug-in hybrid electric vehicles (PHEVs), we assumed that 50% of the vehicle miles traveled would be powered with electricity, and 50% with motor gasoline (*18*). We also assumed that PHEVs would operate off of the current electrical generation fuel mix, although hybrid vehicles could obviously be combined with any of the renewable electricity generation scenarios.

Transportation wedges include

- business as usual, with current ethanol blending mandates
- complete transition to corn-based ethanol for personal vehicles
- complete transition to switchgrass-based ethanol
- vehicle miles driven cut to 50% of 2005 levels by 2050, with ethanol blending mandates
- fleet vehicle efficiency increased to 55 miles per gallon (mpg) average by 2030, with current ethanol blending mandates.
- complete fleet transition to PHEVs

It is important to note that future projections of the ethanol scenarios incorporate life-cycle estimates of GHG emissions from production, processing, and transport of biofuels, taken from Wang et al. (*16*) to be 81% of motor gasoline emissions for corn ethanol and 40% of motor gasoline emissions for switchgrass ethanol (*17*). It is assumed that, in the future, production of these fuels will occur entirely within Minnesota. In contrast, the historical numbers have been adjusted only for emissions from corn land used for ethanol production (this land was removed from projected agriculture sector emissions to avoid double-counting). Processing and transportation emissions associated with current and historical ethanol production are embedded in various sectoral emissions from the historical database and would be difficult to analyze separately. Because these other sectors are projected to grow as a function of the driving forces identified in the stepwise regression, future GHG emissions for the ethanol scenarios may be overestimated. However, ethanol production is currently a small fraction of Minnesota's overall GHG budget, so this overestimation is likely small.

Residential and Commercial Sector Emissions. By definition, all GHG emissions from the residential sector are tied to buildings. In Minnesota, most residential energy use (other than electricity) is for space and water heating—primarily from natural gas (75%). We divided total residential emissions by the number of occupied households to get the greenhouse gas intensity of Minnesota households, which is declining. GHG emissions from residential buildings were calculated as

(GHG intensity of household)(number of occupied households)

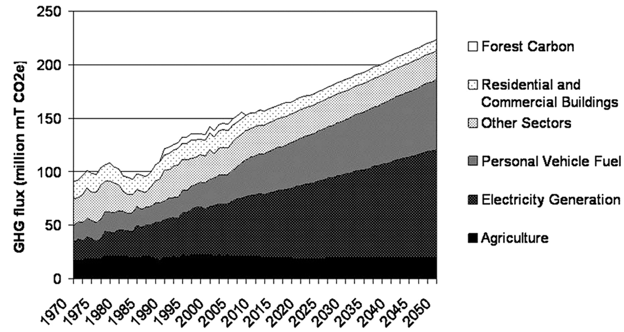

FIGURE 1. Historical and projected GHG flux by sector, 1970−2050, under the business as usual scenario. See Supporting Information for methodology behind GHG projections.

Commercial building emissions were calculated by subtracting out the GHG emissions from motor gasoline in the commercial sector, with the assumption that all other emissions were related to the commercial building stock. There are no (known) databases containing numbers of commercial buildings in Minnesota, so we used total GHG emissions, rather than GHG intensity, in the regression equation (see Supporting Information).

Agriculture. In forecasting agricultural emissions, we assumed that total land area in agriculture would be 'frozen' at current acreage. The biofuel production scenarios assume that land for corn (or switchgrass) ethanol is taken first from land already planted in corn, then from land planted in other crops (mostly soybeans), then from shrub or grassland.

Agricultural emissions were calculated to be

(off-road vehicle emissions) +
(other emissions from combustion) +
(livestock emissions) + (legume emissions) +
(manure application emissions) +
(methane emissions from wild rice) +
(all other GHG flux from agricultural fields)

The "other GHG flux" category includes CO_2 emissions attributed to erosion, cultivation of histosols, field liming, and urea applications and N_2O emissions attributed to crop residue decomposition, cultivation of histosols, nitrogen deposition, fertilizer application, and runoff. For equations, see Supporting Information.

Forest Carbon. Acreage in forest under the business as usual scenario was assumed to be constant. Forest land in Minnesota actually decreased between 1992 and 2002, resulting in a net carbon release as calculated by the U.S. Forest Service Carbon Calculation Tool (*19*). Forest carbon flux was also evaluated under a maximum forest scenario, in which forest land in Minnesota was increased by 1.25 million hectares (5.5%) between 2005 and 2050.

GHG Remainder. All remaining GHG emissions were projected as one response (see Supporting Information). These included emissions from the industrial sector, transportation fuels for commercial vehicles, emissions from the waste sector (mainly landfills), and nonbuilding related commercial emissions.

Results and Discussion

Under the business as usual (BAU) scenario, GHG emissions in Minnesota would rise to approximately 223 million metric tons of CO_2 equivalent by 2050 (Figure 1). This represents an increase of 49% over 2005 emissions levels. Minnesota's population is expected to grow by 30% during this time period, and real gross state product by 253%.

GHG emissions from electricity generation and passenger vehicles represent the largest share of total emissions and demonstrate the most rapid growth in the BAU scenario

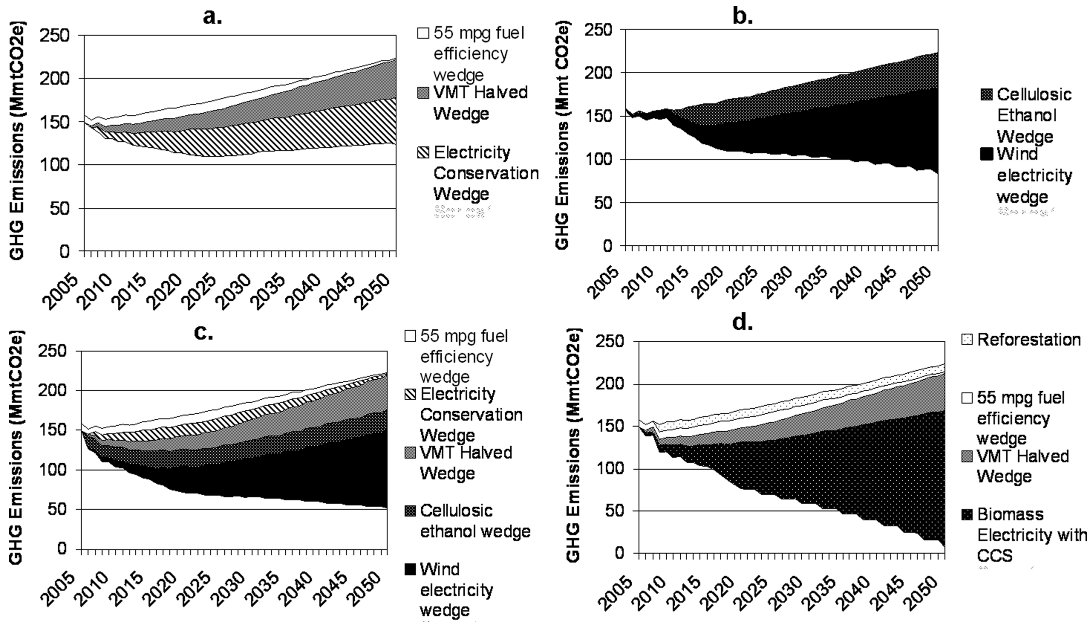

FIGURE 2. Projected GHG emissions in Minnesota with different reduction wedges and wedge portfolios, in million metric tons of CO_2 equivalent. The uppermost line in each graph represents emissions under the business as usual (BAU) scenario, while each patterned wedge depicts the reduction below BAU emission levels attributed to a given technology or practice. The portfolios are as follows: (a) Conservation portfolio, yielding 18% GHG reduction below 2005 levels: adoption of a 55 mpg fleet fuel efficiency standard, reduction of vehicle miles traveled by half, and reduction of residential and commercial electricity and heating demands consistent with Architecture 2030 standards. (b) Renewable portfolio, yielding 43% GHG reduction below 2005 levels: all coal electricity replaced by wind-generated electricity and all motor gasoline replaced with cellulosic ethanol. (c) Renewables plus conservation portfolio, yielding 65% GHG reduction below 2005 levels: all strategies listed under panels a and b. (d) Maximum reduction portfolio, yielding 95% GHG reduction below 2005 levels: biomass combustion for electricity generation with carbon capture and sequestration, reduction of vehicle miles traveled by half, adoption of a 55-mpg fuel efficiency standard, and reforestation of 5% of Minnesota's land area.

(Figure 1). Agricultural emissions are fairly stable throughout the time period—this agrees with prior estimates of GHG emissions in Minnesota (*10, 20*). Building emissions (other than from electricity) are projected to decrease as a response to policies and technologies already in place. Forest carbon flux is projected as zero with no increase or decrease of forest land area.

The wedge representing a complete conversion of fossil-fuel-generated electricity to biomass generation with carbon capture and sequestration (CCS) contains the largest GHG reduction potential (Figure 2). The size of this wedge is measured as the difference between the GHG trajectory with this technology implemented and the BAU trajectory, a potential reduction of 72% by 2050. Other alternative wedges involving the generation of electricity include conversion of coal-generated electricity to wind-generated electricity (by 2050, a 44% reduction in emissions below BAU 2050 levels); conversion of all fossil-fuel electricity to biomass-produced electricity but without carbon capture and sequestration (43% reduction below BAU levels); carbon capture and sequestration for coal-powered electricity production (22% reduction); improved coal combustion efficiency (22% reduction); and conversion of coal electricity to natural gas electricity (16% reduction). These are largely mutually exclusive in terms of serving to reduce carbon emissions, meaning that they could not be combined to generate additive reductions. For example, converting half of Minnesota's coal-based electricity production to wind power and half to biomass would not result in a greater reduction than either of those strategies taken by themselves.

There are a number of other potential wedges that are largely or entirely independent of electricity generation, with the exception of the plug-in hybrid electric vehicle wedge, in which the transportation sector is integrated with electricity production. The following wedges could be added to electricity wedges to achieve greater total reductions. These include conservation of electricity in residential and commercial buildings (by 2050, a 23% reduction in projected GHG emissions below BAU 2050 levels); vehicle miles driven cut to half of 2005 levels (20% reduction from 2050 BAU levels); increase in vehicle fleet fuel efficiency to 55 miles per gallon (19% reduction); fueling all motor gasoline vehicles with switchgrass ethanol (18% reduction); converting the vehicle fleet to plug-in hybrid electric technology while retaining the conventional electricity mix (9% reduction); fueling all motor gasoline vehicles with corn ethanol (7% reduction); and finally, reforestation of 5% of Minnesota's land area (4% reduction).

The wedges described above could be combined in several ways to enable the state to meet the goal of reducing GHG emissions 80% below 2005 levels (note that these measurements of reductions below 2005 levels are different from the wedge sizes described above, which are defined by the difference from the BAU trajectory out to 2050). For example, generating all of Minnesota's electricity from poplar biomass and sequestering the carbon emitted at the generation plants (biomass-CCS), combined with reducing vehicle miles driven by half, improving vehicle fleet fuel efficiency to 55 miles per gallon, and reforesting 5% of Minnesota's land area would together result in a "maximum reduction" portfolio of 95% below 2005 GHG emission levels—essentially making the state carbon-neutral (Figure 2). Electricity production via biomass-CCS sequesters carbon during the biomass growth period and captures the carbon released during the combustion process, thereby pulling carbon out of the atmosphere and counteracting emissions from other sectors. While biomass-CCS is a technologically unproven strategy that faces many implementation challenges at regional scales, it is the only known method for removing carbon from the atmosphere while generating heat and electricity (*21*).

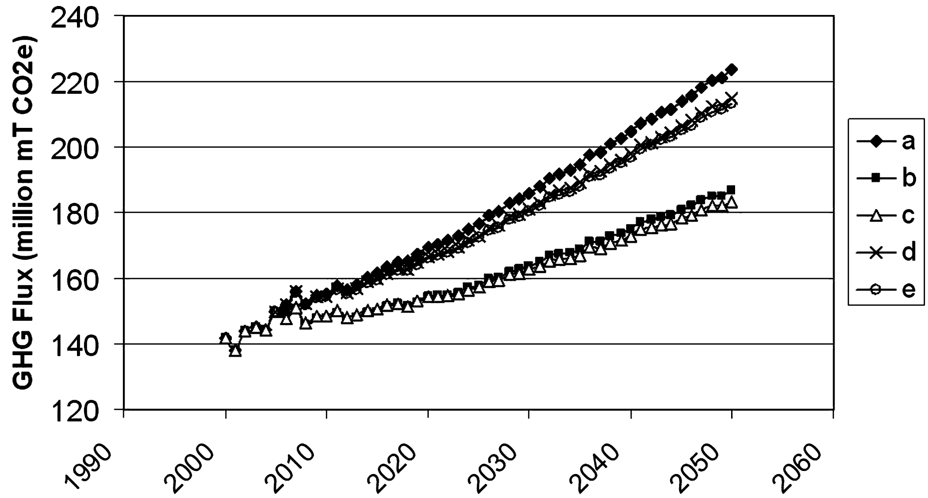

FIGURE 3. Projected GHG emissions defining sensitivity to behavioral changes by Minnesotans (particularly reduced energy consumption). These behavioral changes might be in response to higher energy prices, increased environmental awareness, or other factors. (a) Business as usual scenario; (b) vehicle miles traveled stabilized at 2006 levels; (c) vehicle miles traveled declining to 1999 levels by 2050 (this rate of decline mirrors current national trends); (d) electricity demand stabilized at 2006 levels; (e) electricity demand declining to 1999 levels by 2050.

Other strategic combinations that would meet the 80% reduction goal are biomass-CCS electricity combined with adopting 55 mpg fleet fuel efficiency (90% reduction below 2005 levels) and biomass-CCS electricity combined with conversion of all motor gasoline vehicles to switchgrass ethanol (90% reduction below 2005 levels). This latter combination, in which all of the state's electricity and personal transportation energy needs would be met with biomass, would require 26.5 million acres, or 48% of the state's land area, for biomass production (*12, 22*).

Other wedge combinations not including biomass electricity with CCS would not reach the 80% reduction goal, but some would approach it. A "renewables" reduction portfolio combining a switch from fossil-fuel-generated electricity to wind electricity with a switch from motor gasoline to cellulosic ethanol for personal vehicles would yield a GHG reduction of 43% compared with 2005 levels, far exceeding levels of reductions outlined in the Kyoto protocol but well below those necessary for an 80% reduction (Figure 2).

Although the 80% reduction goal would be very difficult to achieve through conservation alone, conservation strategies could provide significant reductions in GHG emissions. The conservation strategies we examined were reducing commercial and residential electricity use, improving vehicle fleet fuel efficiency, and reducing vehicle miles driven. Combining all of these strategies would result in an 18% reduction below 2005 levels by 2050, or a 45% reduction below the BAU trajectory. A hybrid portfolio of both conservation and renewable fuels strategies would yield a reduction of 65% below 2005 levels (77% below BAU emissions by 2050). This portfolio includes using wind for electricity production, using cellulosic ethanol to power personal vehicles, reducing vehicle miles traveled to half of 2005 levels, increasing vehicle fleet fuel efficiency to 55 miles per gallon, and conserving electricity (Figure 2). When the conservation and renewable strategies are combined, some of the wedges reverse their shape—that is, they are larger in the near future and diminish over time. This is because the added benefits of conservation (in terms of GHG emissions reductions) grow less as more low-carbon renewables are added to the fuel mix, and vice versa.

The recently released report from McKinsey & Company (*23*) allows us to draw some tentative conclusions about the relative implementation costs of some GHG reduction strategies in Minnesota. Two of the strategies we studied, which were also analyzed in the McKinsey report, stand out as potentially having negative costs per ton of avoided emissions (in CO2e). These are improving energy efficiency in buildings and switching from motor gasoline to cellulosic ethanol. Increasing coal plant efficiency could have a negative per-unit-carbon cost, but the Minnesota-based avoided emissions from this strategy would be lower than avoided emissions from improving building energy efficiency, according to our analysis. A notable strategy with potentially high carbon savings and high costs is converting fossil-fuel-generated electricity to wind power. The conversion of coal electricity to biomass was not evaluated in the McKinsey report but would likely be a positive cost, given the relatively low cost of coal at present. Increased vehicle fleet fuel efficiency would likely entail negative costs for consumers and contribute to GHG reductions (*24*). We should emphasize that the application of McKinsey report conclusions to Minnesota should be considered tentative, as the report is based on currently available technology and national data.

The trajectory of GHG emissions in Minnesota is more sensitive to the number of miles Minnesotans drive than it is to the amount of electricity they use (Figure 3). This makes intuitive sense, as driving is a more carbon-intensive activity than electricity consumption in terms of daily emissions. By reducing vehicle miles traveled in the state to 1999 levels by 2050, Minnesota could restrict its GHG emissions growth to only 23% above 2005 levels, rather than 49% as predicted under the BAU projection. This would mitigate the need for Minnesota to adopt as many other carbon-saving technologies. As our analysis demonstrates, implementing a much more aggressive 50% reduction of vehicle miles traveled by 2050 would reduce carbon emissions by 8% compared with 2005 levels (Table 1). Minnesotans were driving half as many miles as recently as 1983, when Minnesota's population was 75% of its current size, indicating that this goal is not completely unattainable. Reducing personal vehicle travel in Minnesota is therefore a promising target for policymakers (*24*).

Achieving or approaching the 80% reduction goal in Minnesota will require a major restructuring of the state's energy production and consumption. To make significant progress in reducing GHG emissions, policymakers must focus on all available options. Some make sense today: focusing on conservation strategies, such as promoting lower electricity use in buildings and adopting more stringent

TABLE 1. Wedge Analysis Applied to Minnesota[a]

Socolow and Pacala options	application to Minnesota (as scenario)
efficient vehicles	adopt UCS' 55 mpg fleet efficiency recommendation; fleet transition to plug-in electric hybrids
reduced use of vehicles	cut vehicle miles driven to half of 2005 levels by 2050
efficient buildings	adopt 2030 challenge for residential and commercial buildings in Minnesota
efficient baseload coal plants	increase efficiency of coal plants in Minnesota to 60% by 2050
replace coal baseload power with gas baseload power	all coal electricity used in Minnesota replaced with natural gas generation by 2050
capture CO_2 at baseload power plant	CCS for all coal electricity produced; also for biomass production scenario
capture CO_2 at coal-powered H_2 plants	not considered (Minnesota currently has no such plants)
capture CO_2 at coal-to-synfuels plant	not considered (would not reduce GHG emissions in Minnesota, as no crude oil is currently produced in the state)
replace coal power with nuclear	not considered (politically unpopular option; also, emissions effects would be same as for renewable scenarios)
replace coal power with wind	all Minnesota coal electricity replaced with wind
replace coal power with PV solar	not considered (total GHG reductions would be same as for wind scenario)
biomass fuel for fossil fuel	corn ethanol/switchgrass ethanol replace all motor gasoline Poplar replaces all coal and natural gas-generated electricity
reduced deforestation and afforestation	deforestation halted; 5% of Minnesota land area reforested
conservation tillage	not considered; scientifically untenable as carbon storage strategy in Minnesota (*7, 8*)

[a] Wedges considered as scenarios for analysis are shown in boldface type.

vehicle fleet fuel efficiency standards. These strategies are likely to save significant carbon emissions over the long term and have negative costs for the state and consumer, which should make them more politically and economically viable than more expensive options. Policymakers should also consider phasing in technologies that are more expensive but would generate large carbon savings, such as converting coal electricity to wind power or pursuing projects that pair biomass with carbon capture and sequestration. Moreover, the relative cost may shrink over time if carbon prices rise sharply and the economic penalty for burning fossil fuel increases—however, at proposed carbon prices of 10−20 \$/ton of CO_2, it is likely that these technologies will not be immediately cost-effective. Technological improvements in the coming decades also may make these options less expensive and more competitive with coal, but waiting for technological breakthroughs or sufficiently high carbon prices before taking action would reduce the likelihood of the state achieving the 80% by 2050 reduction goal. This is a tradeoff that policymakers and citizens will have to weigh carefully, and other tools, like performance standards for electric power plants, may prove to be important bridge policies.

Our analysis demonstrates that even if the electricity and personal vehicle sectors are entirely converted to renewable fuels and aggressive conservation strategies are put in place, further sequestration of carbon (as with CCS of biomass-produced electricity) and/or cuts in GHG emissions will be necessary to meet the 80% reduction goal. Biological sequestration of carbon in vegetation and soils, which is being widely discussed in Minnesota and elsewhere (*25*), is a GHG reduction strategy of very limited potential. Forest regrowth over 5% of the state's land area, which is a signficant amount given strong agricultural and development pressures, would result in only a 4% reduction below GHG emissions under a BAU scenario. The dynamics of soil carbon are less understood, but even with favorable assumptions this would be very unlikely to yield more than a 5% reduction in the state's carbon budget (*26, 27*).

Public acceptance to deploy the wedges will be related to cost and the degree to which they fit within embedded political interests and require a transformation of existing infrastructure—significant for switching to renewable electricity production or reducing vehicle miles driven; less significant for producing motor fuels from corn or improving the efficiency of electricity use. Reducing vehicle miles driven in Minnesota would likely induce spillover effects, such as increased bus traffic, which were not analyzed in this study. An economy-wide transition to renewable fuels would involve overcoming challenges of delivery and production scale-up. These have been described at length in the literature, but we will summarize them here. Wind electricity presents problems in terms of intermittency, storage, and geographical variability (*28*). Cellulosic ethanol is not currently being produced on a large scale, mainly because the production processes are too expensive or too slow for scaling up. Carbon capture and sequestration technologies are contingent upon the state establishing a safe and politically feasible location for injecting the captured gas; as Minnesota seems to lack a suitable geologic formation for injecting CO_2, building a pipeline network to connect to neighboring states remains a possibility (*29*).

This analysis is limited in its lack of interlinkages between GHG-emitting sectors and the economy. It does not incorporate feedbacks or dynamic interactions, such as those between use of the land base for corn or switchgrass ethanol, the price of agricultural products, and economic growth, which drives GHG emissions. Nevertheless, two strategies—making buildings more energy-efficient and transitioning to cellulosic biofuels—stand out as potentially contributing significantly to GHG reduction and having negative costs. Increased fleet energy efficiency would likely have neutral or negative costs and contribute to GHG reductions. Policymakers should target interventions that encourage these actions first. Additionally, policymakers must focus longer-term planning efforts on decarbonizing the coal-intensive electric sector. Here, two technologies stand out: wind and carbon capture and sequestration. Minnesota already has the highest percentage (7%) of electricity coming from wind (*30*), and options for carbon capture and sequestration will require coordination with neighboring states. We recommend a dynamic sector model to further explore how adopting these strategies might affect Minnesota's economy.

Our analysis does not include unexpected technological innovations, which could alter the array of choices available for GHG mitigation. Several emerging technologies show promise for replacing fossil fuel consumption in Minnesota, including diesel production from algae and methane production from agricultural and municipal waste. These technologies may be in commercial production by 2050 and may help contribute to decarbonization of the electricity or personal vehicle fuel sectors. Our basic conclusions about the need to address reduction strategies to these sectors specifically would not be changed in the event these technologies are developed. No technology currently proposed would eliminate the need for infrastructure redevelopment and switching from fossil fuels. The more progress policymakers can make toward these targets in the near future, the more likely achieving the 80% reduction goal will become.

Environmental impacts of implementing these strategies must also be considered. Although the state's growing transportation and electricity needs could be met entirely through biomass production up to 2050, this would take up a substantial portion of Minnesota's land area. The land footprint of these fuels—especially if grown in monocultures—would affect nutrient loss, water cycling, and aquatic and terrestrial wildlife habitat (*31*) and would overlap with lands currently used for producing food and forest products. Wind energy wedges for electricity would have a much lower impact on terrestrial and aquatic ecosystems.

Our conclusions are relevant for exploring GHG reduction policies at the subnational level. Additionally, they may be directly relevant to the many states and regions in highly industrialized, cool northern climates with moderate population densities. Minnesota has adopted an ambitious strategic goal but lacks the tactical policies needed to enable the changes in energy production and consumption required to meet this goal. Decarbonizing electricity production and personal vehicle transport and using less energy for these applications will be necessary in Minnesota and in many other regions to achieve the GHG reductions required for atmospheric carbon stabilization. Conservation strategies, such as improving vehicle and building energy efficiency, could result in significant carbon savings and save money as well. We recommend that policymakers bring their attention to these types of conservation efforts first, but at the same time consider phasing in fuel-switching strategies in the electricity and personal vehicle fuel sectors. Replacing fossil fuels with renewables or carbon capture and sequestration in these sectors will contribute large GHG reductions, and the costs of these technologies will likely drop over time (switching from motor gasoline to cellulosic ethanol is already considered a negative-cost strategy). Strong and effective conservation and implementation of renewable and sequestration technologies could result in major GHG reductions even in carbon-intensive states like Minnesota.

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Supporting Information Available

Equations used to project Minnesota energy use and greenhouse gas emissions up to the year 2050. This material is available free of charge via the Internet at http://pubs.acs.org.

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